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Applying Diagnostics to Enhance Cable System Reliability
(Cable Diagnostic Focused Initiative, *Phase II*)

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In addition, the project brought together utilities, equipment manufacturers, cable diagnostic providers, and other interested parties for the purpose of assessing and enhancing technologies used to diagnose the condition of underground cable systems. The resulting consortium worked for a total of ten years (*CDFI Phases I* and *II*) in an effort administered, coordinated, and largely conducted by Georgia Tech and NEETRAC. The project cost share sponsors appear below.

Ameren
American Electric Power
BC Hydro
Borealis[2]
Centerpoint Energy
Consolidated Edison Company of New York
Eaton's Cooper Power Systems
Dow[2]
Duke Energy
EPRI[2]
Exelon
First Energy
Florida Power & Light[1]
GRESCO[1]
Hydro Quebec
NRECA
Oncor[1]
Pacific Gas & Electric
Pacificorp
PEPCO[1]
Prysmian Cables and Systems
Public Service Electric & Gas
South Carolina Electric & Gas
Southern California Edison
Southern Company
Southwire
TE Connectivity

Note:
Companies in *italic font* are manufacturers/distributors; others are electric utilities.
[1] participated in *Phase I* only
[2] participated in *Phase II* only

Cable system diagnostic providers (equipment or service) also participated in the project by providing in-kind cost sharing in the form of technical advice, test data, test equipment, and/or testing services. The list of participating diagnostic providers appears below.

Cablewise/Utilx
HDW Electronics (Megger)
High Voltage, Inc.
Hipotronics[2]
HV Diagnostics
HV Technologies
IMCORP[1]
Kinectrics[2]
Techimp SPA[2]

Note:
[1] participated in *Phase I* only
[2] participated in *Phase II* only

0.1 EXECUTIVE SUMMARY

The Cable Diagnostic Focused Initiative (*CDFI*) played a significant and powerful role in clarifying the concerns and understanding the benefits of performing diagnostic tests on underground power cable systems. This project focused on the medium and high voltage cable systems used in utility transmission and distribution (T&D) systems. While many of the analysis techniques and interpretations are applicable to diagnostics and cable systems outside of T&D, areas such as generating stations (nuclear, coal, wind, etc.) and other industrial environments were not the focus. Many large utilities in North America now deploy diagnostics or have changed their diagnostic testing approach as a result of this project. Previous to the *CDFI*, different diagnostic technology providers individually promoted their approach as the "the best" or "the only" means of detecting cable system defects. Figure 1 graphically represents the "diagnostic landscape" in 2005: a series of separate non-interacting technologies.

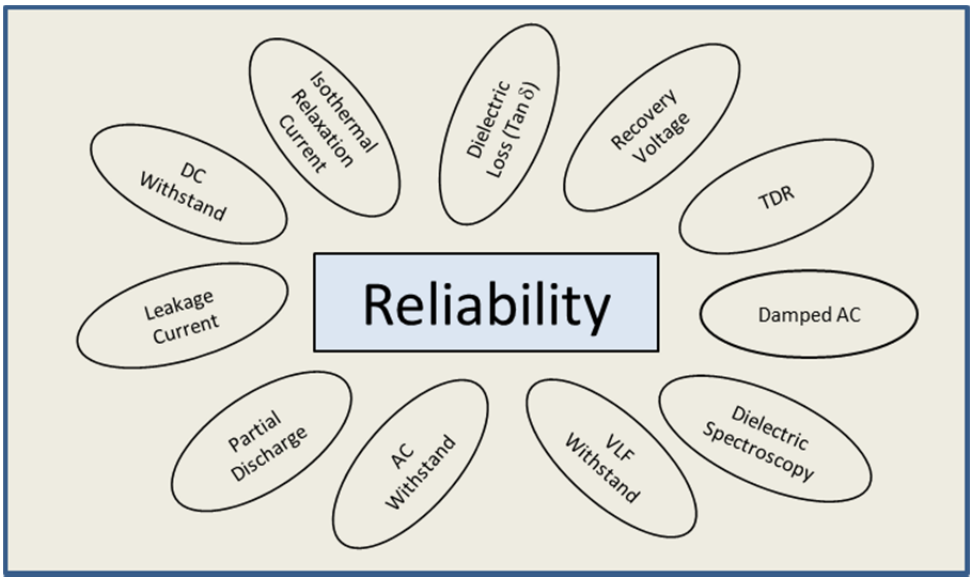

Figure 1: Graphical Representation of Diagnostic / Reliability Landscape in 2005 – Before the *CDFI*

The different available diagnostic technologies were viewed as independent, single approaches with little consideration, if any, for how diagnostics should be used to positively impact reliability. That is, there was no coordinated, objective, independent means of establishing what each technology delivers or how it might be best deployed. Diagnostic providers each had their own positions / perspectives / studies. In addition, there was very little understanding of the efficacy of each technology.

The *CDFI* (*Phases I* and *II*) brought together the resources of Georgia Tech NEETRAC, utilities, manufacturers and diagnostic technology providers under a collaborative umbrella allowing all parties to work together to develop a collaborative and objective framework for effectively deploying diagnostic technologies (or set of technologies) that allow a utility to detect cable system weaknesses and take actions to avoid outages, thereby improving both current and future system

reliability. The support for this effort was notable, with 26 companies providing cash cost share support that exceeded $2M.

The resulting tests, data analysis and collaborative discussions and activities that occurred during the course of the *CDFI* led to a significantly improved understanding of which diagnostic technologies are actually used and how they can be optimally deployed to maximize the benefits of performing diagnostic tests. New approaches and procedures were also developed, with highly evolved assessment criteria, creating far more effective asset management tools. Furthermore, the collaboration and dialogue has enabled, in many cases, the sharing of concepts and mutually supportive approaches to diagnostic testing. The post *CDFI* landscape is represented in Figure 2. Here the interactions and mutual support are identified together with the coordination of diagnostics and asset management principles.

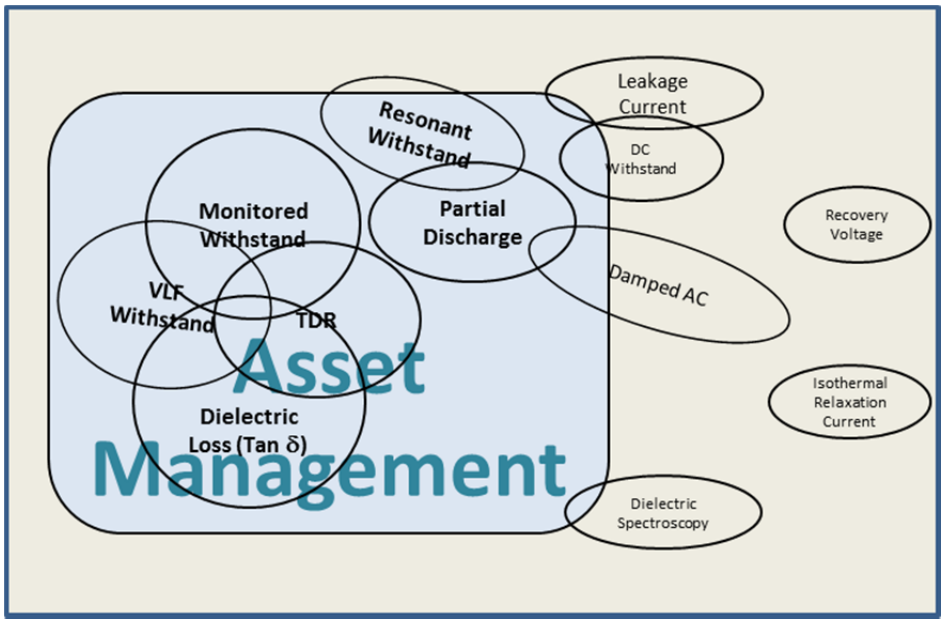

Figure 2: Graphical Representation of Integrated Asset Management / Diagnostic Landscape in 2015 - Post *CDFI*

NOTE: In order to maximize collaboration and cooperation with the industrial sponsors/partners in this project, NEETRAC agreed that the development of new diagnostic testing technologies would not be a part of this program. Rather, the focus was on the study of existing technologies in detail to establish how they could be effectively deployed.

To fully understand the impact of effective use of cable system diagnostics, it is important to appreciate the fact that cable systems are designed to have a long life. Experts anticipate the lifespan of underground cable systems installed in the United States to be in the range of 30 to 40 years. However, a large portion of this cable system infrastructure is now reaching the end of that anticipated life. This is a result of natural aging phenomena and that the technology used in some early cable systems was decidedly inferior compared to current technologies. Complete replacement of old or failing cable systems is not an option. Many billions of dollars and new manufacturing facilities would be required. Electric utilities, cable, and cable accessory manufacturers are simply not in a position to make this kind of investment.

However, complete replacement of these systems is generally not required because cable systems do not age uniformly with time or along their length. Cable researchers have determined that many cable system failures result from isolated degraded cable lengths/accessories or defects within specific circuit segments. Thus, the key to managing this process is to find these "bad actors" and to cause them to fail in a benign manner (no customer affected) or proactively replace them before their repeated failures degrade overall system reliability thereby increasing costs.

Various cable system diagnostic testing technologies have been developed to detect cable system (cable and accessory) defects or deterioration. This project has shown that:

- No one technology or methodology has definitively demonstrated an ability to precisely and reliably assess the full condition of the wide variety of cable systems currently in service.
- There are many situations where the use of diagnostics brings financial and reliability benefits
- Diagnostics work in a probabilistic manner, identifying a sub population that is much more likely to cause an outage. Diagnostics are not very good in establishing the absolute certainty that a specific device or small number of devices will cause outages.

The work in this project was accomplished through the following activities:

- Supporting the growth in the use of diagnostics at MV from 20% in 2006 to between 30% and 40% or North American utilities in 2014
- Supporting the development of a new form of MV cable system diagnostic: Monitored Withstand. This mode of diagnostic operation has grown from <0.5% in 2006 to between 6% to 10% in 2014
- Working with participants to perform tests and analyze data on cable systems in the field.
- Supporting the change in diagnostic use / understanding at five major North American utilities
- Understanding the capabilities of commercially available diagnostic test equipment.
- Supporting national and international standardization activities within AEIC, CIGRE, ICEA, and IEEE;

AEIC CS9	IEEE400	CIGRE B1.28
IEEE400.2	IEEE400.3	IEEE400.5

- Supporting the integration of diagnostics with Asset Management philosophies by simplifying the interpretation of test results through the development and deployment of "Health Index" methodologies using Principle Component Analysis
- Collating diagnostic test and outcome data from tests performed by NEETRAC and tests conducted by *CDFI* participants.
- Disseminating information learned during the execution of the project in the form of papers, presentations, workshops and through working directly with the project participants.
- Undertaking and analyzing the results of repeat diagnostic testing;
- Supporting *CDFI* participants in the implementation and analysis of cable system diagnostic programs.
- Developing a framework to quantify the value/benefit of diagnostic tests

- Extending VLF Tan δ testing to the assessment of three phase circuits;
- Collating results and developing a comprehensive suite of decision rules for Monitored Withstand testing;
- Disseminating knowledge via Excel tools and assessment brochures (Monitored Withstand and VLF Tan δ);
- Undertaking and understanding the issues associated with the testing of HV cable systems;
- Undertaking and analyzing the results of Time Domain Reflectometry (TDR) testing to locate joints and perform a qualitative assessment of the condition of the cable system neutral;
- Estimating degradation and life lines for corroded cable neutrals;
- Understanding and disseminating information on the fundamental issues associated with Partial Discharge testing;
- Resolving long standing concerns associated with the effect of frequency on VLF Simple Withstand tests;
- Exploring simultaneous combined diagnostic tests (Tan δ and partial discharge);
- Understanding the limitations and capabilities of Damped AC tests;

Setting realistic expectations is one of the most important considerations when using cable diagnostic testing technologies. Diagnostic test results are meaningful and useful, but not precise or perfect. When diagnostic test results described in this report indicated no immediate action was required, the failure rate over the next three to five years for circuits with that designation was indeed quite low, but not zero. Conversely, when the diagnostic test results indicated that a circuit required action, they did not necessarily experience failures within a three to five year time horizon. Rather, the action required designation simply means that there is a notably higher risk (3 to 10 times) of failure in service than a circuit categorized as not needing immediate attention.

0.2 GOALS, OBJECTIVES AND ACCOMPLISHMENTS

This project sought to further define diagnostic testing protocol that can be used to accurately establish the condition of underground cable systems. The project objectives were to:

1. Maximize the benefits to utilities that institute a diagnostic testing protocol for underground cable circuits.
2. Establish a thorough understanding of the advantages and disadvantages of each technology for each type of cable system.
    a. Utilities will be better able to decide which cable diagnostic technology(ies) is/are best suited for their situation.
    b. Diagnostic technology and service providers will be able to more readily compare their diagnostic technology against a competing one.
    c. Cable and accessory manufacturers' increased understanding of diagnostic testing will encourage increase marketing of tools for this purpose.

Laboratory and field tests were conducted to establish the accuracy and efficacy of all commercially available cable diagnostic testing technologies as well as those that might be reasonably applied in the future. Unique data analysis techniques such as performance ranking, diagnostic outcome mapping, statistical and heuristic classifiers, probabilistic failure predictions, deterministic and stochastic optimization, and anomalous data identification were deployed.

This overarching goal was to provide electric utilities with the ability to optimally establish which circuits must be replaced, repaired, or rejuvenated in order to avoid electric service failures/interruptions. The evaluation program includes aged cable systems as well as newly installed systems, including both distribution (medium voltage) systems and transmission (high voltage) systems.

A review of the project tasks with a brief discussion of the accomplishments is outlined below.

Task 1: Diagnostic Data Set Analysis – Clarifying Accuracy

To increase reliability and to ensure that cables are not improperly diagnosed and prematurely replaced, NEETRAC worked to:

a) Develop a consistent approach for formatting diagnostic test data and for establishing, understanding and improving the accuracy of diagnostic predictions.

b) Collect large amounts of diagnostic data sets from utilities to perform an analysis with the goal of establishing appropriate pass/fail criteria and improving the ability of these technologies to accurately predict which segments have failed to meet consensus standards with respect to service operability.

The data analysis activity supporting accuracy estimates proved very effective in *Phase I* and it was anticipated that it would be continued. As the diagnostic testing moved from pilot studies to being part of standard operating procedures it actually proved to be very difficult. This was due to the large number of cable systems now being tested, which made it difficult to get utilities to follow and report outcomes to the *CDFI*. Additionally experience garnered in the field de-emphasized the

concerns over accuracy – at the start of the project diagnostic accuracy concerns were ranked 1st or 2nd. Consequently it was decided, in consultation with sponsors, to move the focus of this task to two areas:

1) Conduct repeat field testing and

2) Track, in the short term, the performance of cables tested in *Phase II* of the *CDFI* through regular requests for feedback and close contacts.

Ultimately, this approach has proven very valuable and has delivered good information on accuracy, but from a different standpoint. The results of this work have been published and are described in Chapter 6 and in the project Quarterly Reports (see Section 0.4.5).

Table 1: *CDFI Phase II* Completed Field Tests Task 1 and Task 2

Utility	Time since test (months)	Length (ft)	Fails on Test	Failures after Test
Alabama Power Birmingham	54	30,000	0	0
Hydro Québec	53	35,000	0	0
Duke Energy Carolinas	51	5,700	1	0
Georgia Power Macon	49	5,000	0	0
Alabama Power Montgomery	50	>9,000	0	0
Alabama Power Birmingham	49	60,000	0	0
Ameren Charleston, IL	46	18,900	0	0
Industrial Plant Philadelphia	45	9,300	0	0
Georgia Power Duluth	45	11,700	0	0
AEP Columbus	43	7,900	1	0
Snopud / EPRI Seattle	42	12,400	0	0
Hydro Quebec Quebec City	42	35,400	0	0
Georgia Power Evans	42	16,500	0	0
Duke Energy Matthews	39	3,600	0	1
Alabama Power Varnons	38	1,700	0	0
Duke Energy Charlotte	38	1,400	0	0
Alabama Power Mobile	37	96,900	0	0
Duke Energy Midwest	35	19,250	0	0
Duke Energy Carolinas	34	21,300	0	0
We Energies Milwaukee	34	31,000	1	0
Snopud / EPRI Everett	31	11,500	0	0
Ameren St Louis	29	79,100	0	2
Georgia Power Roswell	29	5,000	1	0
Ameren St Louis	25	14,000	0	0
Snopud / EPRI Everett	19	38,400	2	2
AEP South Bend	18	21,000	0	1
Duke Energy Franklin	18	4,600[1]	0	0
Duke Energy Cincinnati	18	2,800[1]	0	0
Duke Energy Mooresville	18	13,200	0	1
Georgia Power Evans	14	6,000	0	0
Georgia Power Duluth	14	1,000	0	0
Georgia Power Roswell	0	15,300	0	0

Task 2: Field Tests/Circuit Monitoring

The objective of this task was to work with electric utilities to design and conduct diagnostic testing programs on their cable systems to ascertain which protocols (technologies, test voltage levels and test durations) best predict the true condition of the system. The goal was to work with utilities and diagnostic service and equipment providers to deploy commercially available testing services such as:

1. Online partial discharge/signal assessment
2. Offline partial discharge (60 Hz and Very Low Frequency (VLF))
3. Dielectric loss (at selected frequencies (0.02 – 60 Hz) and voltages)
4. Monitored withstand (using dielectric loss and partial discharge)
5. Dielectric withstand at different voltages and times

This task was accomplished in significant detail. Over 600,000 ft of cable was tested on over 32 utility systems. The results of the work are collated and described in Chapters 5 to 11. The details of each visit are contained within the 19 Quarterly Reports for this project. The understanding of the diagnostic selection and interpretation processes employed by utilities was invaluable in developing the learnings described in Chapter 4, which fulfils much of Task 5. Furthermore, the field experience identified the need and the technical specifications for the brochures and tools developed under Task 5.

Task 3: Assessment of Diagnostic Technologies under Controlled Conditions

This task was initiated to conduct tests in parallel with field tests to establish a well-defined correlation between test results and cable condition. Various types of insulated cables with lengths typically found in service were connected together in a variety of configurations using standard cable accessories (joints, terminations and separable connectors) to explore complex issues such as those listed below:

- The effect of corroded concentric neutrals on partial discharge and dielectric loss measurements.
- The ability of various diagnostics to assess cable condition when a circuit consists of various cable insulation types, including HMWPE, EPR, XLPE and PILC.
- The ability of various diagnostic technologies to detect bad accessories on different cable types and lengths.
- Pass/fail conditions for complex circuit configurations.

The “Demonstrator Loops” were constructed and have been used as training & technology proving grounds for a number of project participants; including Hydro Quebec, Georgia Power, Southwire, HDW Electronics, HV Diagnostics, HV Inc, HV Technologies, NEETRAC, and GE. These activities have proven very useful.

The capabilities of Damped AC (DAC) testing were assessed with these configurations. The “Demonstrator Loops” were the only assessment venue available as this technology is relatively new to the North American market and so utilities were unwilling to make service circuits available for pure research work.

These test loops also provided significant value to the *CDFI* and other industry studies in research to detect the corrosion of underground cable metallic shields.

The research work into pass/fail diagnostic criteria was not as extensive as initially anticipated due to the difficulty of locating suitable resources. Nevertheless, test results from the Demonstrator Loops were used to validate the research undertaken with the PCA Health Index Tools developed in Task 5.

Task 4: Diagnostic Assessment of Transmission Cables

In addition to the assessment of the performance of diagnostic technologies on aged distribution class cables, there is significant 46 and 69 kV high voltage (HV) transmission cable system infrastructure installed in the US that is over 30 years old. Furthermore, utilities throughout the US are installing 115 kV – 345 kV circuits at an increasing rate. The Recipient will deploy diagnostic technologies to assess the condition of the older circuits and to help assure that new circuits are installed correctly.

Partial discharge testing is anticipated to be the primary diagnostic technology used on HV cables. However, the effectiveness of using this technology is not well documented and the use of other technologies has not been explored in any detail. The was to begin the process of gathering diagnostic test data on transmission cable circuits for analysis in a manner similar to that was used to analyze data from distribution circuits with an intent to generate new test data as practical.

The task accomplishments include:

- Conducted field tests on four HV cable systems
- Verified a number of assertions / methods used by partial discharge diagnostic providers in the field by conducting partial discharge tests on 12 cable system test loops assembled in four different laboratories
- Participated in the leadership of Group CIGRE B1.28 Working Group for On-Site Partial Discharge Assessment. This work resulted in a CIGRE Technical Report and significant knowledge transfer from the international community to *CDFI* Participants – Chapter 8 and support to Chapter 7
- Continued participation in IEEE ICC Working Group 400.5

Task 5: Expansion of the Knowledge Based System

The Knowledge-Based System (KBS) serves as a valuable tool for helping utilities determine the most appropriate diagnostic technology to use for a given application. As additional information is gathered about the performance of each diagnostic technology, the KBS will be updated and refined as needed to increase its usefulness and accuracy.
The modified version will:

- Include commissioning as well as diagnostic tests and
- Extend estimates to HV cable systems

The web based Knowledge-Based System (KBS) served a valuable purpose in the first phase of the project. However user numbers declined in *Phase II*, due the dissemination of *Phase I* results. In addition, the issuance of IEEE Guide 400 (the choice table in this guide was drawn exclusively from the *CDFI* KBS). Thus when recoding was necessary due to software upgrades at Georgia Tech it was decided that resources would be more usefully deployed to:

a) use advanced statistical methods (similar to the types used for the KBS) to develop brochures and tools (Chapter 16) and
b) develop selection tables to determine the most appropriate diagnostic (Chapter 4).

Under this task, the following brochures and tools were developed and deployed (Chapter 6 and Chapter 10):

Brochures (Chapter 15)	**Tools**
Field Interpretation of VLF Tan Delta data	Health Index estimation for VLF Tan Delta tests
Field Decision Criteria for undertaking Monitored Withstand VLF Tan Delta tests – three insulation specific brochures	
Field Interpretation of Monitored Withstand VLF Tan Delta data – three insulation specific brochures	

Task 6: Economic Benefits Model

An enhanced economic model with broader asset management capabilities will be explored. Considerations will include the development of a common platform for the different remedial actions that various utilities might consider prior to testing, consequence costs to incorporate what is known about the accuracy of a given diagnostic technology and the outcomes associated with failures after testing, and hard-to-define costs associated with utility asset management priorities. The model development will include direct early intervention by stakeholder utilities.

As in *Phase I*, it proved difficult to garner precise system failure, repair and outage cost data. However, it did prove possible to develop cost ranges and test / remediation methodologies that were generally agreed by utility participants. Participants acknowledged that there was a customer outage cost in addition to the costs associated with the repair / return to service. Unfortunately, neither the providers nor the utilities were able to provide such cost estimates. Work in this area was able to proceed towards the end of the project when the DOE Interruption Cost Estimate Calculator was suggested by a few interested parties. This calculator was extensively used within Chapter 13 to discuss the cost scenarios, methodologies and case studies. In addition, Chapter 13 provides support to utilities undertaking cost benefit estimates and also identifies the essentiality of robust Monte Carlo estimation methods.

Task 7: Handbook

A handbook outlining the overall approach to diagnostic testing will be updated to address transmission class cables, expand on the use of diagnostics for commissioning (not just maintenance) activities and to include the additional diagnostic accuracy and application findings.

The overall project report is designed to serve as a cable systems diagnostic handbook. The handbook provides the only available comprehensive overview of the different types of diagnostic techniques used to evaluate the condition of medium and high voltage cable systems with a focus on what they are, how they work, their capabilities and limitations and how they can effectively be deployed to improve cable system reliability. Due to the plethora of techniques and many interacting factors, there are significant, complex details that influence the use of each diagnostic technique. Consequently, to assist a user who is only interested in one specific topic, the handbook was developed as with standalone chapters.

The project cost share sponsors have indicated an interest in having NEETRAC continue with cable system diagnostic testing, research and data analysis after the completion of the DOE sponsored *CDFI*. These users will likely provide additional data that can be used to update a number of chapters (potentially Chapters 5 – 13 & Chapter 15). Consequently, web links are used to provide users the opportunity to access the most up-to-date version of these chapters.

Task 8: Technology Transfer

Throughout this project, multiple interactions/technology transfer activities have occurred. They are summarized in Technology Transfer section of this chapter.

0.3 TECHNOLOGY TRANSFER

The transfer of information and technology occurred in many different forms throughout the *CDFI*.

0.3.1 Direct Interactions with Project Participants

The table below outlines the many technology interactions with the project participants.

Participant Type	Company	Total Meetings
Utility	American Electric Power Represents 7 Operating Utilities	10
	Ameren Represents 2 Operating Utilities	12
	BC Hydro	3
	CenterPoint Energy	--
	Consolidated Edison Represents 2 Operating Utilities	8
	Duke Energy	15
	EPRI Represents Program Participants	12
	Exelon Represents 3 Operating Utilities	2
	FirstEnergy Represents 10 Operating Utilities	3
	Hydro Quebec	15
	NRECA Represents >1000 Utility Members	2
	Pacific Gas & Electric	7
	SCE&G	5
	Southern California	5
	Southern Company Represents 4 Operating Utilities	30
Manufacturer	Borealis	2
	Eaton's Cooper Power Systems	1
	Dow	5
	Prysmian	4
	Southwire	6
	TE Connectivity	1
Diagnostic Provider	Cablewise/Utilx	6
	HDW Electronics	6
	High Voltage, Inc	2
	Hipotronics	1
	HV Diagnostics	12
	HV Technologies	9
	Kinectrics	9
	TechImp SPA	4

0.3.2 Dissemination of information to interested parties

Dissemination Meetings (usually 0.5 to 1 day) were held with the following interested parties that were not *CDFI* Participants throughout the course of this project.

Body	Number of Meetings
Insulated Cable Engineers Association – manufacturer technical association	2
NEETRAC Management Board Representatives – approx. 40 members	3
We Energies – utility	2
Snohomish County PUD (SNOPUD) - utility	3
DOBLE – manufacturer / service provider	2
Southeastern Electric Exchange - utility trade association	2
Tacoma Power - utility	1
Puget Sound Energy - utility	1
Seattle Power and Light - utility	1

0.3.3 Support for Device Improvements

The *CDFI* field testing program (Task 2) and testing on the NEETRAC Cable System Demonstrator setup as a part of the *CDFI* (Task 3) resulted in the development and deployment to the market of at least three technology enhancements from two manufacturers of cable system diagnostic testing devices.

0.3.4 Adjacent Research

This project has been the catalyst to significant and valuable "know how" and expertise developed by NEETRAC. This "know how" has been especially useful in the areas of:

- Decision criteria development
- Principal component analysis for integrating multiple features
- Age lines for prediction the progress of degradation
- Outcome lines for estimating likely impact of condition and future outages

The "know how" has been usefully deployed in projects conducted by NEETRAC for its members in the following adjacent technical areas:

- Understanding temperature measurements undertaken on utility devices in the field using Infra Red (IR) cameras
- Lifetime estimates for transformers in corrosive environments
- Field "moisture test" device and criteria for PILC Cable Systems
- Lifetime estimates for cable systems and cable system components
- Development of Health Index for transformers
- Effectiveness and interpretation of diagnostics undertaken on utility wood poles

- Framework for understanding results and requirements of electronic devices comprising the "smart grid"
- Lifetime estimates for outdoor insulations (insulators / cutouts)

0.3.5 Publications and Presentations

As part of the technology transfer activities presentations, conference papers and technical papers were also generated. The nature of the diagnostic field is such that presentations and the sharing of experience that accompanies it is the most impactful of the transfer modes. The presentations and publications are listed below.

The impact of the work reported in these publications and presentations was recognized with four awards:

1. Best Paper Overall JICABLE15
2. Best Presentation Fall 2014 IEEE ICC Subcommittee A - Cables
3. Best Presentation Fall 2014 IEEE ICC Subcommittee F - Diagnostics
4. Best Presentation Spring 2011 IEEE ICC Subcommittee F - Diagnostics

All papers and technical presentations have been shared with the project sponsors during the course of the project. The documents are available for downloading at:

http://www.neetrac.gatech.edu/publications.html

Conference Papers

1. J. PERKEL, N. HAMPTON, J.C. HERNÁNDEZ; Use of Diagnostics by Utilities on MV Cable Systems; Fall 2015 IEEE PES ICC - Tucson, AZ - November 1-4, 2015
2. PERKEL, J., HAMPTON, R.N., "Cable Diagnostic Focused Initiative Update", SEE Underground Committee Meeting, Fall 2015, Clearwater Beach, FL
3. J. PERKEL, Y. DEL VALLE, J.C. HERNÁNDEZ MEJÍA, and R.N. HAMPTON, "Repeated Field Tests – Utility Case Studies of the Value of Trending," 9th International Conference on Insulated Power Cables 2015 (JICABLE 2015).
4. R.N. HAMPTON, J.C. HERNANDEZ-MEJIA, M. KUNTSEVICH, J. PERKEL, and V. TOMER, "Estimating the Impact of VLF Frequency on Effectiveness of VLF Withstand Diagnostics," 9th International Conference on Insulated Power Cables 2015 (JICABLE 2015).
5. C. RILEY, J. PERKEL, R. HILL, and R.N. HAMPTON, "Experiences of combined HV & EHV qualifications to IEC, AEIC and challenges IEEE 48 & 404," 9th International Conference on Insulated Power Cables 2015 (JICABLE 2015).
6. HAMPTON, R.N., PERKEL, J., RILEY, C., "Power Frequency Testing in Cable, Accessory Standards", IEEE Insulated Conductors Committee – Discussion Group F11D, Fall 2014, Colorado Springs, CO

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Quarterly Reports

Quarterly reports are valuable as they set out the chronology and detail the outcomes of the individual tests / research activities, whereas this document and those referenced herein provide a collated perspective.

Report No.	Quarter	Date Released	Length [Pages]
1	Q3 2010	Oct 2010	36
2	Q4 2010	Jan 2011	32
3	Q1 2011	Apr 2011	293
4	Q2 2011	Jul 2011	64
5	Q3 2011	Oct 2011	231
6	Q4 2011	Jan 2012	260
7	Q1 2012	Apr 2012	79
8	Q2 2012	Jul 2012	149
9	Q3 2012	Oct 2012	198
10	Q4 2012	Jan 2013	95
11	Q1 2013	Apr 2013	44
12	Q2 2013	Jul 2013	78
13	Q3 2013	Oct 2013	84
14	Q4 2013	Jan 2014	145
15	Q1 2014	Apr 2014	70
16	Q2 2014	Jul 2014	64
17	Q3 2014	Oct 2014	192
18	Q4 2014	Jan 2015	57
19	Q1 2015	Apr 2015	59
20	Q2 2015	July 2015	10
TOTAL	All	--	2240

CHAPTER 1

Introduction

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1.0 INTRODUCTION

1.1 Background

Almost all electric power utilities distribute a portion of the electric energy they sell via underground cable systems. Collectively, these systems form a vast interconnected and valuable infrastructure. Estimates indicate that underground cables represent 15% to 20% of installed distribution system capacity. These systems consist of many millions of feet of cable and hundreds of thousands of accessories installed under city streets, suburban developments, and in some cases, in the countryside. Utilities have a long history of using underground systems with some of these cable systems installed as early as the 1920s. Very large amounts of cable were installed in the 1970s and 1980s due to the introduction of economical, polymer-based insulation compounds and the decreasing acceptance of overhead distribution lines in residential areas. Today, the size of that infrastructure continues to increase rapidly as the majority of newly installed electric distribution lines are placed underground.

Cable systems are designed to have a long life with high reliability even though these concepts are not well defined. These goals were achieved via a variety of different technologies since the early 1900's. Regardless of the technology used, the useful life of a cable system is finite. These systems age and ultimately reach the end of their reliable service lives. Estimates set the anticipated lifespan of underground cable systems installed in the United States to be in the range of 30 to 40 years. Today, a large portion of this cable system infrastructure is reaching the end of that anticipated life, and there is evidence that some of this infrastructure is reaching the end of its reliable service life. This is a result of natural aging phenomena and that the technology used in some early cable systems was decidedly inferior as compared to current technologies. Increasing failure rates on these older systems are now adversely affecting system reliability and it is readily apparent that action is necessary to manage the consequences of this trend. Furthermore, complete replacement of old or failing cable systems is not an option. Many billions of dollars and new manufacturing facilities would be required. Electric utilities, cable, and cable accessory manufacturers are simply not in a position to make this kind of investment.

On the other hand, complete replacement of these systems may not be required because cable systems do not age uniformly. Cable researchers have determined that many cable system failures result from isolated degraded cable lengths/accessories or defects within specific circuit segments. Thus, the key to managing this process is to find these "bad actors" and to proactively replace them before their repeated failures degrade overall system reliability. Various cable system diagnostic testing technologies have been developed to detect cable system (cable and accessory) defects or deterioration. The results of diagnostic tests identify potential weak spots within cable systems and then again, after repair, verify that the repair work performed did resolve the problem(s) detected.

Appropriate maintenance and repair practices enable system aging to be controlled and help manage end of life replacements. Diagnostics to determine the health of the cable system are critical to this management program.

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A number of cable diagnostic techniques are now available. Each claims to provide a reliable method for establishing the condition of a cable system. Furthermore, there are a number of different modes of application. No one technology or methodology has definitively demonstrated an ability to precisely and reliably assess the full condition of the wide variety of cable systems currently in service. To address this issue, NEETRAC created the Cable Diagnostic Focused Initiative (*CDFI*) – *Phase I* and *Phase II*. The intent of the *CDFI* was to provide cable diagnostic technology assessment and development via a series of tasks developed by NEETRAC with input from the Initiative participants. The primary objective was to clarify the concerns and define the benefits of cable system diagnostic testing.

Effectively implementing cable system diagnostics involves the careful consideration of a number of issues. This includes the type of system (network, loop or radial), the load characteristics (residential, commercial, high density, government, healthcare, etc.), the system dielectric (XLPE, EPR, Paper, mixed), and system construction (types of accessories, installation technique (conduit or direct buried), etc.).

While the need to establish the condition of underground cable systems is apparent to some, diagnostic tools have not been deployed extensively by electric utilities. Figure 1 shows the results of a 2014 study on the use of cable system diagnostics on MV cable systems in North America.

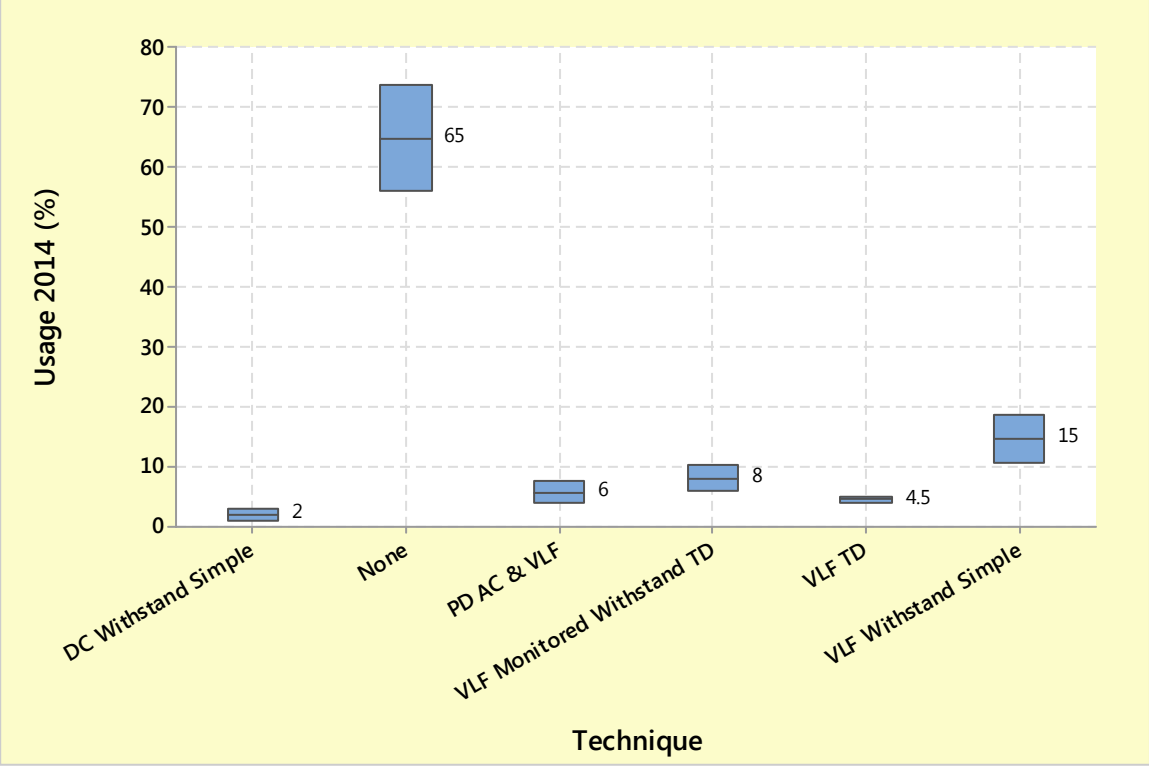

Figure 1: Results of a 2014 Study on the Use of Diagnostics on MV Cable Systems in North America

(PD AC: Online and Offline Partial Discharge in frequency range 20 to 300 Hz including DAC & VLF, TD = Tan δ, VLF = Very Low Frequency AC, Monitored = Withstand while monitoring a diagnostic property, typically Tan δ, Simple = Voltage Application Only without Monitoring)

As shown in Figure 1 between 56% and 74% of utilities do not employ diagnostics. The usage of diagnostics by utilities has grown since the start of the project in 2004. The reasons for the apparently low use of diagnostics are diverse. The studies of usage conducted in 2006 and 2014 clearly show that the reasons for not undertaking testing have changed. A large part of this is due to the development and better understanding of the knowledge gained over the course of the *CDFI*.

It is difficult to determine definitively the typical utility concerns about the use of diagnostics. However some insights can be garnered from the discussions that accompanied the studies carried out on the use of diagnostic methods at utilities (2006, 2011 and 2014) and tests have been carried out with >24 different sets of utility personnel. The concerns from the experience detailed above appear in Table 1. These concerns may not be present in each utility but they present a fair reflection of the overall views encountered in the two broad timeframes. They also serve to show how the thinking and acceptance of diagnostics have changed over time - from hard technical issues in 2006 towards implementation/integration concerns in 2014.

Table 1: Utility Concerns on the Use of Diagnostics in 2006 and 2014 – assessed from Utility Discussions

Concerns affecting the Use of Diagnostics in 2006	Concerns affecting the Use of Diagnostics in 2014
Assessments of diagnostic techniques were conducted either in the laboratory or on a limited scale if carried out in the field or by the diagnostic providers. Thus, there were insufficient independently verified facts either to frame the debate or to make informed judgements.	The wish of managers/engineers for diagnostics to provide a precise/deterministic outcome. Diagnostics applied to aging systems are by their nature probabilistic and this uncertainty is often difficult to accept by utility decision makers.
Concerns that the available diagnostic techniques did not provide information that correlated with service performance of cable systems.	The perceived high total cost (field crew + engineering resource + test equipment or service cost) of diagnostic testing coupled with the difficulty of placing a value on the resulting improved reliability thereby making it difficult to make the "value case".
A belief that diagnostic tests were inherently damaging to aged cable systems. Such that the act of testing reduced the reliability of the cable system.	Concerns with the addition of seemingly complicated/nontraditional activities to an already constrained operation and maintenance arena.
The competing claims of providers of significant superiority of a single diagnostic technology in all situations.	Perception that diagnostic techniques are not useful because of past bad experience.
The belief that the information provided by diagnostic techniques was inaccurate in the deterministic context used at that time.	A variety of embodiments of a particular diagnostic technology, making it unclear to select one that will provide the best value for the application.

The initiation of *Phase I* and *Phase II* of the *CDFI* highlights the importance to the electric utility industry of understanding how best to deploy diagnostics on cable systems. Both phases were co-funded by the United States Department of Energy (DoE) and a wide variety of electric utilities and companies that provide products and services to electric utilities. *Phase I* began in late 2004 and ended in late 2010. *Phase II* began in mid-2010 and ended in mid-2015.

This report reiterates and expands the important information learned from *Phase I* and provides significant additional insights from *Phase II*. While it serves as the final report for *Phase II*, it can also be considered a comprehensive diagnostic handbook that is based on all work performed under the Cable Diagnostic Focused Initiative.

This report is a very large document (>700 pages) containing a wide variety of information, some of it quite detailed, on cable system diagnostic testing. While the report is available as one large .pdf file, note that each chapter is designed as a standalone document that focuses on a specific aspect of diagnostic testing. Each of these individual documents contains this introduction along with the table of contents for the entire report, allowing the user to select the chapters that are most relevant to their needs while maintaining a quick, convenient reference to the overall diagnostic handbook.

1.2 *CDFI* Phases

As mentioned above, the *CDFI* was conducted in two phases. A brief review of the topics covered in each phase appears below.

1.2.1 *Phase I*

Phase I of the Cable Diagnostic Focused Initiative provided a broad overview of how diagnostic testing technologies can be deployed to help understand the condition of underground cable systems. The information gained from condition assessment can be used as an asset management tool to improve reliability, avoid future failures, and optimize cable replacement or restoration programs.

Large amounts of field and lab data were extensively analyzed to characterize and categorize cable systems to better understand which systems needed attention and which systems could be left in service without fear of significant failures in the near future. This analysis revealed the difficulty of cable system condition assessment and emphasized the stochastic nature of cable characterization data. While much was learned from *Phase I*, the need to gather additional data and continue the analysis became readily apparent. This led to the initiation of *Phase II* of the Cable Diagnostic Focused Initiative.

1.2.2 *Phase II*

CDFI Phase II commenced in August 2010 with 31 participants. The project scope included all diagnostic testing technologies that may be practically deployed in the field to assess the condition

of cable systems. To keep the scope manageable and relevant to the broadest possible utility industry stakeholders, the project primarily focused on,

- Aged, shielded medium voltage cable systems;
- Newly installed high voltage cable systems.

Phase II of the Cable Diagnostic Focused Initiative built on selected work performed in *Phase I* including,

- Working with participants to perform tests and analyze data on cable systems in the field.
- Understanding the capabilities of commercially available diagnostic test equipment.
- Collating diagnostic test and outcome data from tests performed by NEETRAC and tests conducted by *CDFI* participants.
- Disseminating information learned during the execution of the project in the form of papers, presentations, and through working with the project participants.

New areas of work in *Phase II* include,

- Undertaking and analyzing the results of repeat diagnostic testing;
- Simplifying the interpretation of test results through the development and deployment of health index methodologies using Principle Component Analysis;
- Understanding the capabilities and limitations of Damped AC tests;
- Extending VLF Tan δ testing to the assessment of three phase circuits;
- Collating results and developing a comprehensive suite of decision rules for Monitored Withstand testing;
- Disseminating knowledge via Excel tools and assessment brochures (Monitored Withstand and VLF Tan δ);
- Supporting national and international standardization activities within AEIC, CIGRE, ICEA, and IEEE;
- Undertaking and understanding the issues associated with the testing of HV cable systems;
- Undertaking and analyzing the results of Time Domain Reflectometry (TDR) testing to locate joints and perform a qualitative assessment of the condition of the cable system neutral;
- Estimating degradation and life lines for corroded cable neutrals;
- Understanding and disseminating information on the fundamental issues associated with Partial Discharge testing;
- Resolving long standing concerns associated with the effect of frequency on VLF Simple Withstand tests;
- Exploring simultaneous combined diagnostic tests (Tan δ and partial discharge);
- Supporting *CDFI* participants in the implementation and analysis of cable system diagnostic programs (AEP, Ameren, APC, Con Ed, Duke, GPC, PG&E, SNOPUD);
- Developing a framework to quantify the value/benefit of diagnostic tests;
- Disseminating information/understanding of diagnostic testing (AEP, Ameren, Borealis, Dow, EPRI, GPC, PG&E, and Southwire).

1.3 Participation

The *CDFI* brought together utilities, equipment manufacturers, cable diagnostic providers, and other interested parties for the purpose of assessing and enhancing technologies used to diagnose the condition of underground cable systems. The resulting consortium worked for a total of ten years in an effort administered, coordinated, and largely conducted by NEETRAC. The project sponsoring companies appear below.

Ameren
American Electric Power
BC Hydro
Borealis[2]
Centerpoint Energy
Consolidated Edison Company of New York
Eaton's Cooper Power Systems
Dow[2]
Duke Energy
EPRI[2]
Exelon
First Energy
Florida Power & Light[1]
GRESCO[1]
Hydro Quebec
NRECA
Oncor[1]
Pacific Gas & Electric
Pacificorp
PEPCO[1]
Prysmian Cables and Systems
Public Service Electric & Gas
South Carolina Electric & Gas
Southern California Edison
Southern Company
Southwire
TE Connectivity

Note:
Companies in italic font are manufacturers/distributors; others are electric utilities.
[1] participated in *Phase I* only
[2] participated in *Phase II* only

In addition to cost sharing with the Department of Energy, many of these companies also supported the project by providing test data, technical advice, and by making their utility systems available for testing.

Cable system diagnostic providers (equipment or service) also participated in the project by providing in-kind cost sharing in the form of technical advice, test data, test equipment, and/or testing services. The list of participating diagnostic providers appears below.

Cablewise/Utilx
HDW Electronics (Megger)
High Voltage, Inc.
Hipotronics[2]
HV Diagnostics
HV Technologies
IMCORP[1]
Kinectrics[2]
Techimp SPA[2]

Note:
[1] participated in *Phase I* only
[2] participated in *Phase II* only

From this collaboration, significant progress was made towards understanding how to effectively deploy diagnostics to evaluate underground cable systems.

1.4 Cable System Diagnostics

Cable system diagnostic technologies usually fall into one of two categories. The first category involves techniques to assess the global or "bulk" condition of a cable system. Though a variety of techniques may be employed, the general approach is to measure electrical losses within a given cable system.

The second category involves techniques to assess localized defects within a cable system. Again, various techniques are used to accomplish this goal, including a withstand test to "blow out" the weak location or the measurement of localized electrical discharges within the system.

Cable system diagnostic tests usually achieve one of the following:

a) They verify that a new circuit installation, or repaired circuit, is suitable to be placed into service. Thus, the test provides some assurance that the circuit does not contain significant workmanship problems and was not subjected to severe mechanical damage during a repair or installation process that would adversely affect the cable system design life.

b) They assess the health of a cable system and thereby determine the likelihood that an aged cable system will experience failures in the near future. In this case, the test could be part of an overall cable system asset management program or a means of minimizing failures on highly critical or problematic circuits.

While these appear to be straightforward goals, it can be difficult to establish exactly how to employ diagnostic technologies effectively. This is due to one or more of the following:

a) The diagnostic testing technologies are in different stages of maturity (i.e. equipment, usability, and/or interpretation).
b) Cable circuits are often very complex with branches or multiple cable and accessory types, each with their own aging characteristics.
c) Multiple diagnostic techniques are sometimes needed to detect different problems.
d) Some diagnostic technologies have not been universally accepted.
e) Independently developed information on the subject is not widely available in a single document.

Cable system diagnostic testing should be considered a process (either continuous or scheduled), not a single event. Ideally, circuits must be studied to match the appropriate technology to the specific components in the circuit as well as any known circuit conditions (e.g. failure history, cause of failures). In many applications, it is best to begin with an easy-to-apply technology, which provides general information that can then be used to select a more focused technology. In many cases, it is desirable to apply diagnostic technologies periodically over the life of the cable circuit to establish, over time, how a circuit is performing.

The basic cable diagnostic testing technologies used to assess cable circuit conditions appear below and are discussed in more detail in the subsequent chapters.

a) Mainstream techniques (routinely deployed at utilities today)
   i. Time- Domain Reflectometry (TDR)
   ii. Tan δ at Very Low Frequencies (VLF)
   iii. Simple Withstand Tests at Elevated Very Low Frequencies (VLF)
   iv. Simple Withstand Tests at Elevated Resonant ac
   v. Monitored Withstand Tests at Elevated Very Low Frequencies (VLF) with simultaneous monitoring of Tan δ
   vi. Monitored Withstand Tests at Elevated Resonant ac with simultaneous monitoring of PD,
   vii. Partial Discharge (PD) at elevated Resonant ac Voltages
   viii. Partial Discharge (PD) at elevated Very Low Frequencies (VLF) Voltages

b) Niche techniques (not routinely deployed but where equipment maybe/has been commercially available)
   i. Partial Discharge (PD) at elevated Damped ac (DAC) Voltages
   ii. Combined Diagnostic Tests at Very Low Frequencies (VLF) using sequential PD and Tan δ
   iii. Dielectric Spectroscopy
   iv. DC Leakage Current
   v. Polarization and Depolarization Current
   vi. Recovery Voltage

Different diagnostic testing technologies assess different cable system characteristics. In many cases, using more than one technology can help establish a reasonably complete picture of the cable system condition. This is a particularly complex problem for hybrid cable circuits that contain more than one type of cable insulation and/or one or more types of cable joints or cable terminations. Whether a cable circuit is simple or complex, diagnostic tests must be employed carefully to assure meaningful results.

Setting realistic expectations is one of the most important considerations when using cable diagnostic testing technologies. Diagnostic test results are meaningful and useful, but not precise or perfect. When diagnostic test results described in this report indicated no immediate action was required, the failure rate over the next three to five years for circuits with that designation was indeed quite low, but not zero. Conversely, when the diagnostic test results indicated that a circuit required action, they did not necessarily experience failures within a three to five year time horizon. Rather, the action required designation simply means that there is a notably higher risk (3 to 10 times) of failure in service than a circuit categorized as not needing immediate attention.

There is no question that when applied properly, diagnostic testing can provide information to help lower cable system failure rates. And the improved reliability using diagnostics can be more strategically achieved than would occur without diagnostic testing. In this respect, cable diagnostic testing is much like a medical examination in which the resulting information induces a patient to take corrective actions that extends their life. However, the information is rarely able to predict the patient's exact life expectancy. Carrying that analogy one step further, applying a technique that looks for a symptom that is not present in the patient will provide no useful information for that patient.

1.5 *CDFI* Findings

The collaboration between the NEETRAC team and the *CDFI* participants led to many interesting discoveries. First and foremost, it is apparent that diagnostic testing is generally very useful, even if imperfect. To maximize effectiveness, test programs must be carefully planned and results thoroughly studied. In addition, it often takes time to see the benefits in the form of reduced failure rates. However, with care and diligence, a cable diagnostic test program can help utilities improve system reliability.

To continue the medical analogy above, note that most diagnostic tests are invasive to the cable system. Thus, they carry risks and benefits that must be carefully weighed before use. It is obvious from the medical analogy that there can be situations where some techniques do not bring sufficient value to warrant the potential risks to the system. Therefore, the risks, benefits, and accuracy of diagnostic tests must be weighed carefully before commencing on the journey.

The work has highlighted a number of general findings that follow:

1. The interpretation of diagnostic data is probabilistic - not deterministic, i.e. diagnostic results indicate what is most likely to happen to a circuit; they do not predict precise outcomes for the circuit.
2. There is no one "right" approach to cable system diagnostic testing – each situation may be different, even within a single utility or area.
3. Effective diagnosis is a process which follows the acronym SAGE – Selection, Action, Generation, Evaluation. It is not appropriate to preselect a particular technique but rather choose one (or more) techniques that match the symptoms/characteristics of the cable circuit.
4. Multiple diagnostics may be needed to obtain sufficient information to understand the condition of the cable circuit under study.
5. Diagnostic test users have to accept that there are finite (non-zero) risks of failure associated with any diagnostic test, including those described as "online" diagnostics.
6. The benefits from diagnostic testing (knowledge/improved reliability) are not instantaneous; they take time to develop. Thus, it is important to stick with a program while continually evaluating the outcomes.
7. "Trending" and "Knowledge Building" are important benefits from diagnostics. However, it is difficult to garner these benefits if the test program parameters (voltages/times/decision criteria) change. It is important to be consistent with testing protocols.
8. Diagnostic testing does not in itself deliver the improvements in reliability; the actions taken based on the diagnostic indications yield increased reliability. That is, testing merely identifies the problems it does not fix them.
9. Most utilities do not currently undertake underground cable diagnostic testing.
10. The most widely utilized voltage source for diagnostic testing in the field is Very Low Frequency (VLF).

At the diagnostic technique level, the details and terminology appear in the individual chapters and the glossary, however the key takeaways are:

Time-Domain Reflectometry (TDR)

- This test should be utilized on all but the most complicated/long circuits to obtain at a minimum the length of the cable system.
- It provides useful information on the number of joints in a cable circuit
- It can be difficult to interpret when multiple joints are present
- It does not provide quantitative data on the condition of the cable neutral.

VLF Tan δ

- With input from the *CDFI*, test protocols are well defined and, with input from the *CDFI*, exist in an approved industry standard.
- Assessment tools are available for interpreting the data into "No Action Required", "Further Study", and "Action Required" classes for all insulation types.
- A Health Index can be determined from: (1) Tan δ voltage dependence during the test (2) Tan δ variability over time during the test, and (3) Tan δ magnitude.
- Age lines (the description of how a diagnostic classification changes with age of the cable system from all "No Action Required" when new to increasingly "Action Required") and Outcome lines (the probabilistic description of what is likely to happen in service for each diagnostic class as the cable system continues to age) can be determined for VLF Tan δ assessment classes.

Simple Withstand

- The benefits of VLF versus dc test voltages both on test and after test have been determined on hybrid cable systems.
- This is the most straightforward diagnostic test to interpret and perform.
- Voltages and times must be carefully chosen. Increasing voltage to reduce the test time does not yield the same performance either on test or in service after the test as the lower voltage and longer test time protocols.
- Outcome lines (the probabilistic description of what is likely to happen in service for each diagnostic class as the cable system continues to age) could be developed for VLF Withstand testing using the protocol described in IEEE Std. 400.2-2013.

Monitored Withstand

- With input from the *CDFI*, test protocols are now defined and are published as approved industry standards.
- NEETRAC developed assessment tools that can be used to make decisions in real time while the test is being performed, significantly increasing test program efficiency. The tools can also be used to make final assessments after the successful completion of the test.
- The health indices were developed based on (1) the tan δ variability during the test, (2) the tan δ trend over time during the test, and (3) the tan δ magnitude.

Damped AC (DAC)

- This technique shows great promise for PD detection in the field by utilities; however, there are no users of this technique in the USA or Canada.

- The technology as currently implemented and described in standards does not meet the criteria for Simple or Monitored Withstand tests and cannot be used for effective withstand field tests.
- The dielectric loss calculation as currently implemented and described in standards, is based on the time constant of a decaying waveform therefore cannot be compared to dielectric loss (Tan δ) measurements made using VLF test equipment.
- Equipment may include the capability of generating other waveforms such as VLF.

Partial Discharge

- There is limited agreement within the industry on the condition assessment if PD is present. There is only agreement that having PD on a cable system is "not desirable" and it is important to know where it is located. No industry standard is available for interpreting PD measurements in the field.
- Field testing cannot be quantitatively related to any tests that might be conducted in the factory.
- This is the most difficult diagnostic to employ in the field, as issues surrounding test setup and execution are diverse and complex.
- Outcome lines (the probabilistic description of what is likely to happen in service for each diagnostic class as the cable system continues to age) have been developed for Online and Resonant ac PD.
- This technique remains too complicated for most utilities to conduct and interpret on their own although recent automation efforts are improving usability.

Metallic Shield Assessment

- OhmCheck and TDR with impedance matching adapter/electronics are techniques that are most commonly used in the field.
- Corroded neutrals occur on jacketed as well as unjacketed cable systems.
- TDR can be difficult for utility personnel to interpret, as results are not quantitative.
- Age lines (the description of how a diagnostic classification changes with the age of the cable system) can be developed for OhmCheck.

1.6 How to Begin (SAGE)

Diagnostic techniques are generally used either to ensure the performance of newly installed equipment (commissioning tests) or to assess the state/health of older systems. Diagnostics do not operate in a vacuum. They are employed to increase the efficiency of reliability improvement programs. It is useful to use the acronym SAGE (Selection, Action, Generation, and Evaluation) to describe the four basic elements of an effective diagnostic program.

Figure 2 illustrates how the four SAGE elements function together over time to yield (if implemented properly) a reduction in the failure rate. It is important to note that this benefit is not realized immediately nor does it cease once the program has ended: there is a lag before the benefit is fully realized. Furthermore, failure rates do not begin to change until the actions directed by the diagnostic testing (Generation) are well underway. Selection, Generation, and Action are each defined stages in time while the Evaluation component is ongoing throughout the entire test program and beyond.

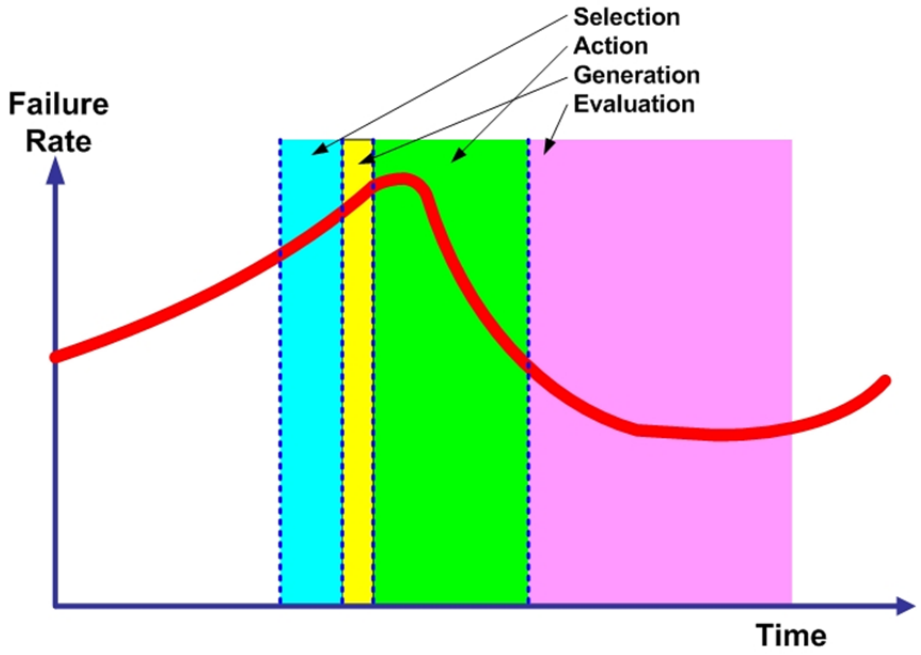

Figure 2: Effect of SAGE on the Failure Rate of a Target Population

Selection – Choose the cable systems for testing that will significantly improve reliability. Typically, this is based on age, failure rate, load sensitivity (hospitals, public buildings, industrial customers, etc.) or other engineering judgment.

Action – What actions are likely to be taken as the result of certain diagnostic outcomes or interpretations? The actions are in two groups (Act or Not Act) and may include replacement, defer action, rejuvenation, and/or repair. These actions are based on those most suitable for the system topology and most prevalent failure mechanisms (local or global degradation).

Generation – Using the prior information (Selection) diagnostic tests are chosen to generate data that support the preferred remediation (Action).

Evaluation – Are the methods employed for Selection, Action, and Generation giving the expected results: lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

It is important to note that the failure rate in Figure 2 continues to increase during the Selection and Generation phases. Only after the actions are completed does the failure rate start to decrease. After some time, the failure rate will begin to increase again (Evaluation phase) and this would retrigger the whole SAGE process.

Chapter 4 provides much more information on how to get started with cable system diagnostic testing. Included in this chapter are some example cable system scenarios with a suggested suite of diagnostic tests.

1.7 Handbook Structure

The remaining chapters of this Handbook are structured as shown in Table 2.

Table 2: Diagnostic Handbook Overall Structure

Part	Chapter	Title
--	1	Introduction
I Aging Mechanisms	2	Medium Voltage Cable System Issues
	3	High Voltage and Extra-High Voltage Cable System Issues
II Diagnostic Techniques	4	How to Get Started
	5	Time-Domain Reflectometry (TDR)
	6	Dissipation Factor (Tan δ)
	7	Medium Voltage Partial Discharge
	8	High Voltage and Extra-High Voltage Partial Discharge
	9	Simple Dielectric Withstand
	10	Monitored Withstand Techniques
	11	Metallic Shield Condition Assessment
	12	Other Diagnostic Techniques
III Deploying Diagnostics	13	Benefits of Diagnostics
--	14	Glossary
	15	Brochures and Tools

Part I: Aging Mechanisms covers the basic defects and aging mechanisms that occur in cable systems either at birth or over time. Part II: Diagnostic Techniques focuses on the detailed work within *CDFI* on each diagnostic technique. Part III provides guidance and tools for deploying diagnostics in the field. **It is highly recommended that users who are new to cable system diagnostics begin with Chapter 4 prior to any other chapter in Parts II or III**.

Each of the diagnostic technique chapters (Chapters 5 through 12) are designed with similar structures with six primary sections in each chapter as outlined in Table 3.

Table 3: Part II Chapter Structure (X denotes any Chapter from Chapter 5 through Chapter 12)		
Section	**Title**	**Description**
X.1	Test Scope	Basic phenomena that is measured
X.2	How it Works	Fundamental measurement model
X.3	How it is Applied	How the technique is used along with its advantages, disadvantages, and open issues.
X.4	Success Criteria	Definition of assessment criteria and relevant documents
X.5	Estimated Accuracy	Accuracy calculations assuming all "Good" circuits should not fail and any "Not Good" circuit should fail.
X.6	*CDFI* Perspective	Details of the reasonable research effort including analysis and experimentation undertaken within *CDFI*. Includes explanation of the development/use of any Criteria/Tools.

A glossary is provided in Chapter 14 with key definitions from all chapters.

CHAPTER 2

Medium Voltage Cable System Issues

Nigel Hampton

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2.0 MEDIUM VOLTAGE CABLE SYSTEM ISSUES

"Cables," in the context of this work, are long, insulated current carrying conductors that operate at elevated voltage with a grounded outer-surface [1- 5]. They are terminated and joined together using accessories to constitute a "cable system". Cable systems form an important part of electrical power transmission and distribution networks, carrying electric energy to areas as an alternative to overhead lines. In general, cable systems have lower fault rates and lower maintenance requirements than overhead lines. It is amusing to note that in 1901, M. Gorham [2] stated the following "…waterproof for 100 years, flexible and extensible, so volt resisting that the thinnest film suffices, sufficiently firm not to decentralize…" Present-day cable technology is pursuing this ideal, but engineers have learned that many factors influence the goal of achieving a long-life, reliable cable system.

It is generally accepted that the first reference to cables or wires was reported in 1812 when a Russian named Schilling used rubber varnish-insulated wires to detonate explosives in a mine. Some of the first electric distribution systems in Chicago, London, and Paris were laid in sewers or under- ground drainage systems between 1870 and 1880. There has been a continuous evolution from the late 1800's to the present day. The most significant advancement in recent years is the industry-wide conversion from lead-covered, fluid-impregnated paper insulated cable systems to polymer-insulated systems and now to EPR and WTRXLPE insulated cables. The primary drivers for moving from paper systems to polymer systems are,

- environmental concerns with lead
- increasing failure rates; initially with paper and then polymer (HMWPE and XLPE)
- reduced maintenance costs
- loss of expertise needed for installing and maintaining paper insulated systems
- reduced installation costs
- concern with fluid leaks that have to be located and repaired
- reduced weight, allowing for the installation of longer cable lengths
- reduced risk of fire
- reduced dielectric losses

Several historical milestones in cable usage appear below:

1812 .....first power cables used to detonate a mine in Russia
1890 .....Ferranti develops the concentric construction for cables
1900 .....cables insulated with natural rubber
1917 .....first screened cables
1903 .....PVC first used
1937 .....PE developed
1942 .....first use of PE in cables
1963 .....invention of XLPE
1967 .....use of HMWPE insulation on underground cables in the US (unjacketed with tape shields)
1968 .....first use of XLPE insulated cables (mostly un-jacketed, tape shields)
1972 .....failures due to water tree growth in polymeric insulations revealed

1972 .....introduction of extruded semiconducting conductor and insulation shields
1973 .....super-clean XLPE insulation used in HV subsea cables Sweden to Finland at 84kV
1978 .....widespread use of polymeric jackets in North America
1982 .....water tree resistant (WTR) insulations introduced for medium voltage cables made in Canada, Germany, and USA
1989 .....supersmooth conductor shields introduced for MV cables made in North America
1990 .....widespread use of WTR-materials in Belgium, Canada, Germany, Switzerland, and USA
1995 ……. use of water blocking in conductor strands (extruded mastic or swellable powders)
2000 …… use of metallic shields and water swellable tapes around the extruded cores

As discussed above, cable constructions have evolved with many major and minor iterations since approximately the mid 1960's (see some of the landmarks above). A number of manufacturing developments ensued. The evolution of cable development in North America is outlined in Table 1 and Table 2. These tables are not inclusive of all changes but rather represent the major changes important in making diagnostic testing decisions.

Table 1: Major Evolutionary Elements in MV Cable Construction (Excludes Wall Thickness)

<table>
<tr><th>Generation</th><th>Insulation</th><th>Semicons
(conductor & insulation shields)</th><th>Jacket</th><th>Barrier</th></tr>
<tr><td>0</td><td>Paper
Oil</td><td>Carbon Tape</td><td>Jacket</td><td>Extruded Lead</td></tr>
<tr><td>1</td><td rowspan="2">Thermoplastic
HMPWE</td><td>Graphite /
Carbon Tape</td><td rowspan="5">None</td><td rowspan="7">None</td></tr>
<tr><td>2</td><td>Extruded
Thermoplastic</td></tr>
<tr><td>3</td><td rowspan="4">XLPE
or
EPR</td><td>Graphite /
Carbon Tape</td></tr>
<tr><td>4</td><td>Extruded
Thermoplastic</td></tr>
<tr><td>5</td><td rowspan="4">Extruded
Thermoset
(crosslinked)</td></tr>
<tr><td>6</td><td rowspan="3">Jacket</td></tr>
<tr><td>7</td><td rowspan="3">WTR
XLPE
or
EPR</td></tr>
<tr><td>8</td><td>Conductor Water Blocked</td></tr>
<tr><td>9</td><td>Conductor & Core Water Blocked
Metal Core Barrier</td></tr>
<tr><td>10</td><td>?</td><td>?</td><td>?</td><td>?</td></tr>
</table>

Table 1 represents the major changes in cable construction, excluding changes in wall thickness. These changes are represented as "Generations" (Generation 0 is the genesis for this work as it is the last incarnation of PILC cables). PILC cables continue to be manufactured today, although at a much- reduced rate. It is useful to note that this class does not include mass impregnated-non draining (MIND) cables. Installation of Generations 1 to 6 has ceased in the US and Canada for all practical purposes. Generation 6 is widely used outside of Canada and the US. Also note that from a non Canadian/US perspective, Generations 3 to 6 include moisture cure silane cross linked compounds using either Sioplas, Monosil, or vinyl silane copolymers (the current most popular approach). Consequently, care is necessary when looking at non Canadian/US experience as the descriptor "XLPE" may pertain to Generation 6 moisture cured cables, or "PILC" may actually refer to MIND cables.

Table 2 represents the major changes in cable core manufacturing. The numbers in Table 3 refer to the generations of the cable core constructions manufactured using these approaches.

Table 2: Major Elements in Cable Core Extrusion Correlated with Generations of Cable Construction from Table 1

Material Handling	Extrusion Technology	Cure Technology		
		None	Steam	Dry (Nitrogen)
Open	Multiple Pass	1, 2	3	-
	1 + 2 2 + 1		4, 5, 6	4, 5, 6
Closed	True Triple	-	4, 5	5, 6, 7, 8, 9, 10

Table 3: Summary of the State of the Art for Both MV and HV Cables in North America		
Attribute	**Medium Voltage (MV)**	**High Voltage (HV)**
Voltage Range (kV)	5 – 30 (5 – 46 in North America)	30 -150 (46 – 150 in North America)
Typical Conductor Size Range (mm^2)	34 - 500	240 - 2500
Mean Electrical Stress (kV/mm)	1.8	3.8
Conductor Screen Material	Thermoset Bonded Semi Conducting	Thermoset Bonded Semi Conducting
Insulation Material	Thermoset WTR XLPE Thermoset EPR	Thermoset XLPE Thermoset EPR
Insulation Screen Material	Thermoset Strippable Semi Conducting	Thermoset Bonded Semi Conducting
Metallic Screen	Wire Tape Foil	Wire & Foil Lead Aluminum
Protective Jacket	UV Resist LLDPE or HDPE	UV Resist LLDPE or HDPE
Accessories	Elbows Joints Terminations	Joints Terminations
Material Handling Systems	Closed Bulk Supply	Closed Box Supply
Extrusion Technology	True Triple CCV Dry N2 Cure	True Triple CCV & VCV Dry N2 Cure

In addition to the summary information provided in Table 1, Table 2, and Table 3, Figure 1 shows the voltage stress ranges for MV, HV, and EHV cables. In this chapter, the discussion pertains to the issues associated with MV cable systems (grey column in Table 3 and the green area in Figure 1. It is important to recognize that although they have many similarities, MV cable systems are distinctly different from HV cable systems with respect to insulation shield materials and stress control philosophies of the accessories as well as the levels of the electrical stress.

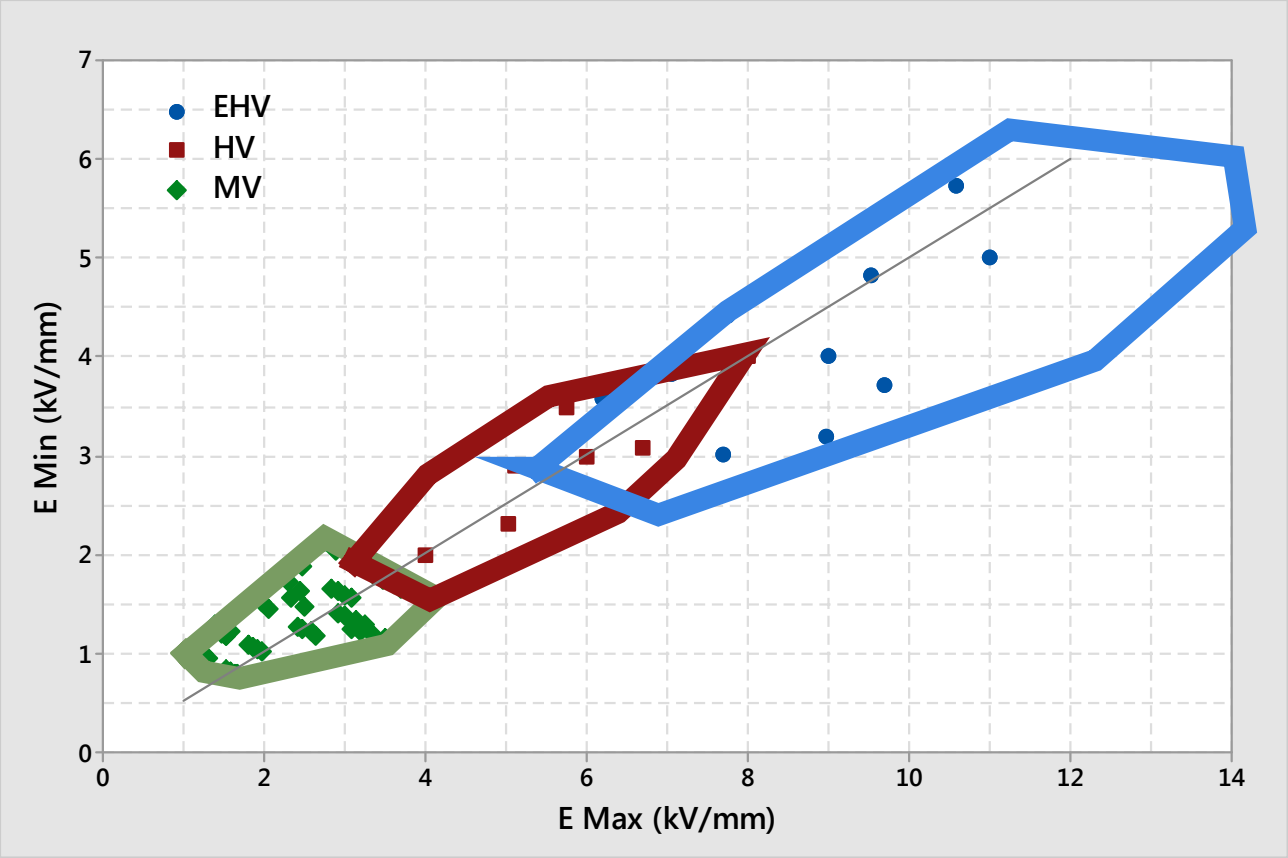

Figure 1: Range of Typical Electrical Stresses employed in cable systems - Emax = electrical stress in the insulation adjacent to the conductor, Emin = electrical stress in the insulation at the outer edge; note that the straight line represents the condition where Emax = 2 Emin

2.1 The Industry Problem

While the evolution in cable construction, materials, and manufacturing processes intended to produce continual increases in reliability with associated reductions in total cost of ownership, the process did not always yield the expected benefits. This observation is important because it drives much of need for and development of cable system diagnostics.

2.1.1 History

The earliest MV cables in North America (Figure 2) employed oil impregnated paper insulation with a lead sheath [1, 16] i.e. Paper Insulated Lead Cables (PILC). However by the 1950's – 1960's this was a mature technology. However, early work showed that the polymer (HMWPE and XLPE) insulated cables had lower failure rates with lower weights and costs coupled with the absence of the concerns/complexity associated with oil and lead (Figure 2). The acceptance of this technology was rapid. Within 15 years of its adoption, the length installed was more than twice that of PILC.

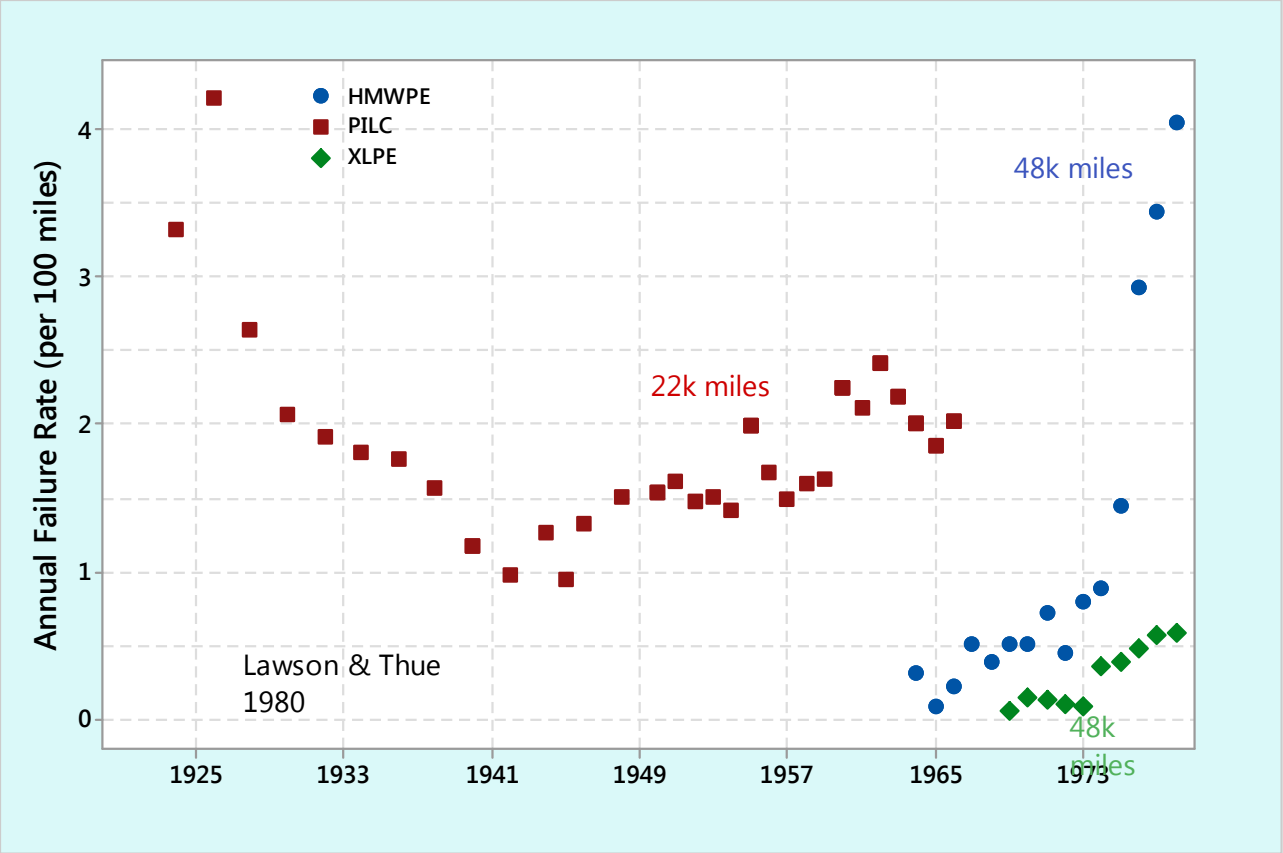

Figure 2: Failure Rates for PILC, HMWPE and XLPE Cables – 1924 to 1978; from Lawson and Thue (1980) [16]

Unfortunately, the initially low failure rate had increased (compare 1969 vs 1978 - Figure 2) due to what we now know as the phenomenon of water treeing. This was not just a North American issue [16] as water trees were found contemporaneously in Europe (Figure 3) and Japan. Figure 3 [4, 15] shows the ages at which cable failures started to occur and the lengths of trees that were observed. These data suggest that trees (on average) grow thru 27% of the insulation in eight years, which is on the order of 3.5% - 7% per annum or 0.12 – 0.24 mm/yr. At this rate, half of the cable would have full thickness (100%) water trees in 15 to 29 years.

The concern was that the treelike structure grows continuously across the insulation until it bridges the insulation so that failure occurs or it is weakened so that any transient might cause the growth of an electrical tree.

Thus included in the outcomes shown in Figure 2 and Figure 3 are the three phases of water treeing:

1. initiation
2. growth
3. transformation to an electric tree

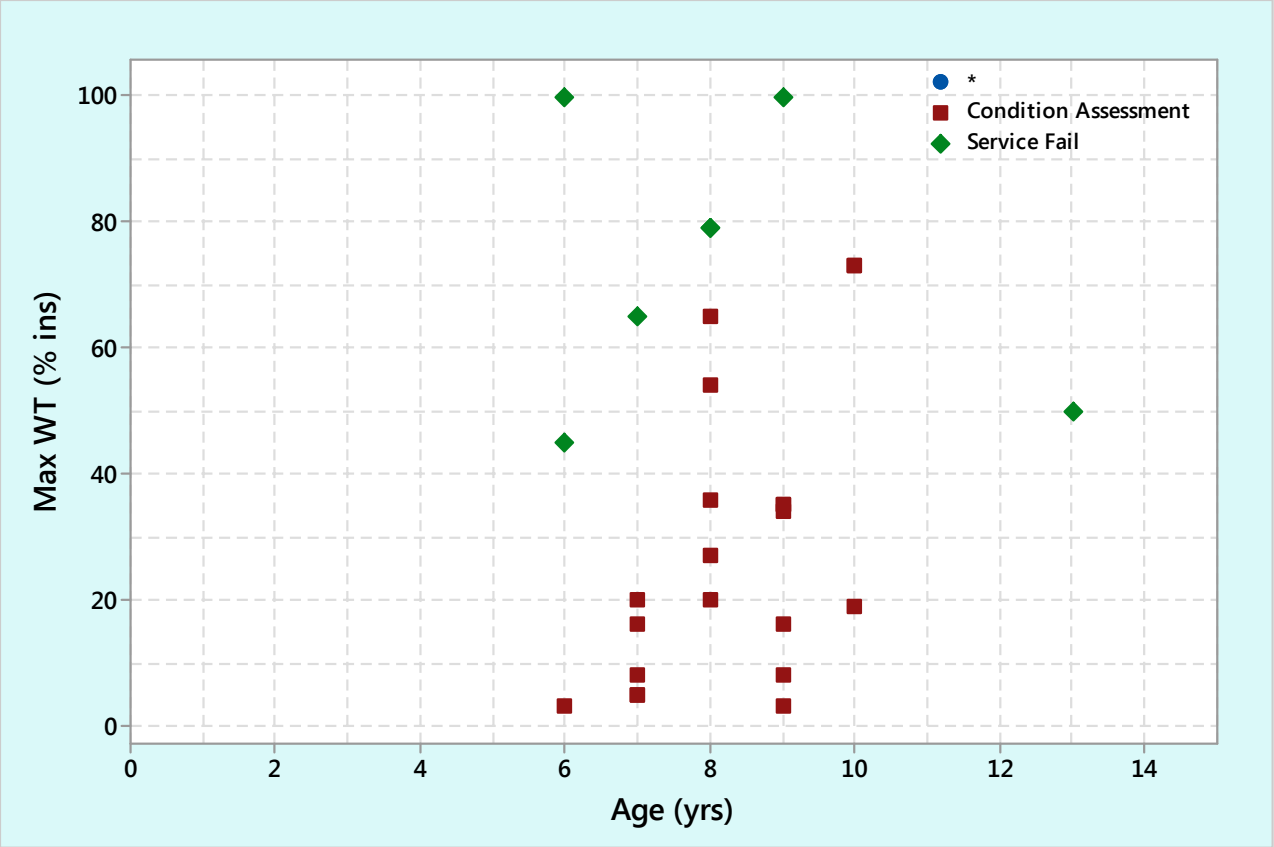

Figure 3: Water Tree Lengths (Maximum) versus cable age segregated by type of investigation for cables installed in The Netherlands (Steenis) [15] - Generations 3 and 4 Moisture Cure (Table 1)

Why do water trees have such a deleterious effect? Water has a higher dielectric constant than cable insulations (80 vs 2.5 or 3.5 for XLPE and EPR respectively) and is quite conductive. As the water tree grows so does the region of higher permittivity (due to the included water). This, in turn, increases the electrical stress in front of the water tree. Furthermore, the conducting water increases the dielectric loss within the water tree so that there is internal and highly localized dielectric heating. On a microscopic level, the breakdown strength of a dielectric decreases as the temperature increases. Thus, through multiple mechanisms (stress enhancement and dielectric heating), the integrity of the dielectric becomes more compromised as the water tree grows.

Some of the most comprehensive and widely disseminated work on the effect of tree growth on electrical performance was carried out by Fred Steenis (of TU Delft now of KEMA) in the mid 1980's [15]. His curves are not the only examples of the correlation, but they are famous and often quoted. This work sets the background for much of the current thinking in this area. Before describing the Steenis work, it is important to recognize the generation of cable constructions on which he has based his work – the data refer to Generations 3 and 4 (Table 1) manufactured using Steam and Silane technologies (Table 2).

The left hand side of Figure 4 shows the impact of the water tree growth (as reflected by the longest water tree (bow tie or vented) on the breakdown strength of the samples in the laboratory. There are

two main classes of samples analyzed - cables that had previously failed in service and those which had not failed but were removed to assess their condition.

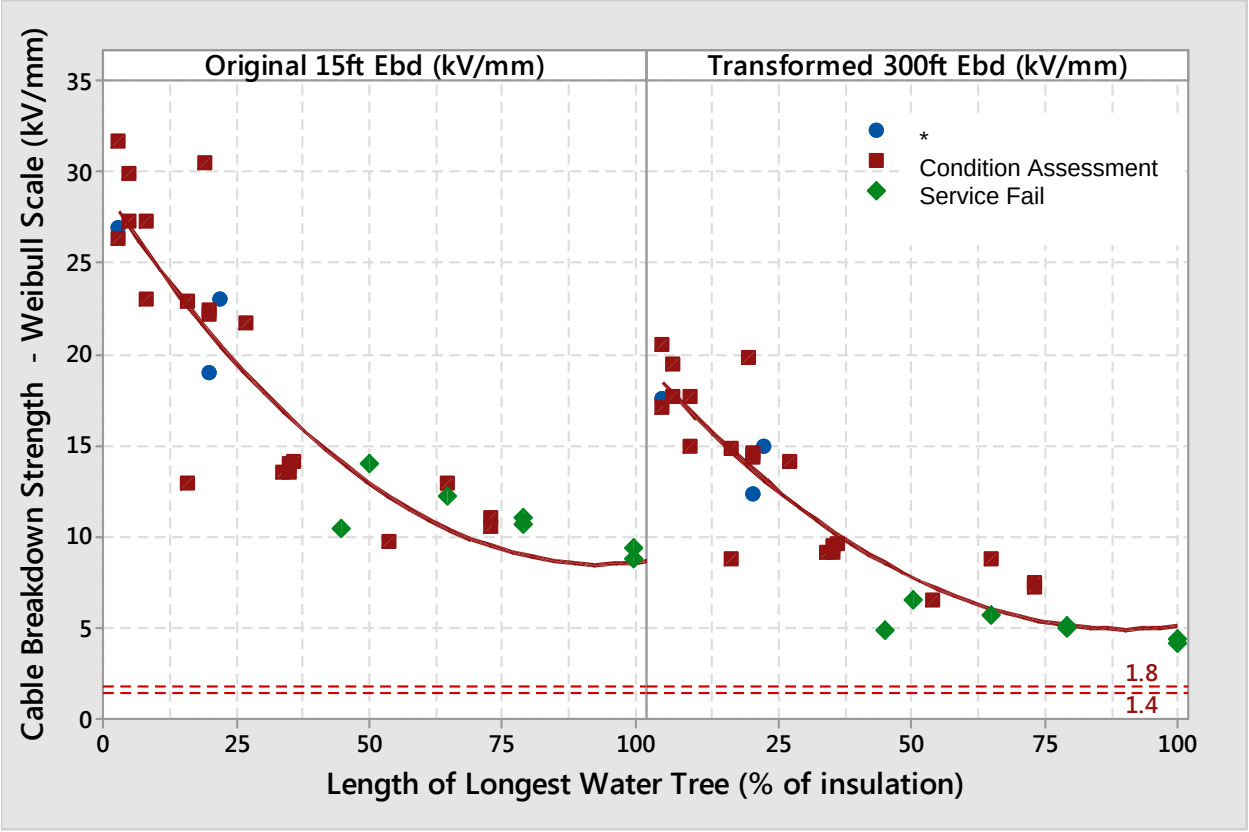

Figure 4: Cable Breakdown Strengths versus Water Tree Lengths (Maximum) segregated by type of investigation (Steenis 15) – left: measured for 15 ft test lengths, right: simulated for 300 ft installed lengths – 1.4 to 1.8 kV/mm indicate the typical mean operating stresses

Figure 4 shows that as the water trees grow, the breakdown strength diminishes. This reduction is due to two interacting effects:

a) the electric stress is enhanced by the geometry and size of the tree

b) the reduced strength of the insulation in advance of the tree front.

These curves reveal the important implications for diagnostics:

1. The dielectric strength reduction is not linear with tree growth and the rate of reduction diminishes as the tree advances.
2. The dielectric strength reduction is insufficient to reduce the strength to zero i.e. water trees do have some dielectric strength.
3. There are general trends, but the results show that there is an associated uncertainty band indicating the probabilistic nature of the relationship between water tree growth and dielectric strength.

At first sight there is another perplexing aspect of this data, namely that the strength reductions establish an equilibrium at approximately 8 to 9 kV/mm, a figure six times higher than the operating stress (even though the factor has reduced from 20 when new). Thus, it is difficult to reconcile why failure should have occurred given this margin. Steenis himself makes an important comment on this, namely that lab tests use short samples whereas cable systems employ longer lengths, which are likely to have a higher likelihood of containing more "weak links".

An estimate of the impact of this uses the well-known Enlargement Law:

$$\alpha_L = \alpha_l \left(\frac{L}{l}\right)^{1/\beta} \qquad \textbf{Equation 1}$$

Where

α_L is the characteristic breakdown strength (Weibull Scale) on length L
α_l is the characteristic breakdown strength (Weibull Scale) on length l
l is the length used for the tests
L is the length for which the breakdown strength (α_L) estimate is desired
β is the Weibull shape parameter for the tests

This equation provides a means of estimating the lower strengths that would reasonably be expected on longer lengths of cable. In these tests, 5m (15ft) were used for the measurements but it was assumed that the length of interest is more likely to be 90 m (300ft). With β values between 7 and 2 for new cables and cables that failed in service, the reduction multipliers are 0.65 to 0.17. These factors result in the left hand curve of Figure 4. These strengths are lower than those for the tests are (short lengths) and show a reduction to levels that are much closer to the operating stresses.

Consequently, this work shows that:

- trees grow slowly – Figure 3
- they grow to sizes that can be detected – Figure 3
- there is an increasing risk of failure with increasing tree length, failure is not certain – Figure 4

2.1.2 The Present Day

There are many studies in the literature on water treeing and we have selected only two to illustrate the important issues related to cable system diagnostics. However, it would be wrong to assume that water treeing is only of historical interest. The current generations of cable (Generation 9 of Table 1) now installed have characteristics that retard the growth of water trees so that significant initiation is not observed until after 25 to 35 years, as compared to the 5 to 10 years of the first cables with polymer-based insulations (Figure 2 and Figure 3). However, these early generations with lower water tree initiation ages represent a significant portion of the population of installed cable. Utilities are currently dealing with the consequences of the installation of Generations 1 to 6 (Table 1).

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Examples of how this affects utilities appear in the recently conducted Weibull analyses based on data gathered by NEETRAC during the course of *Phase I* and *II* of the *CDFI*. See Figure 5 (Weibull Curve for different components of the cable system) and Figure 6 (Survivor Curve – the decrease in population with time - derived from a number of Weibull Curves).

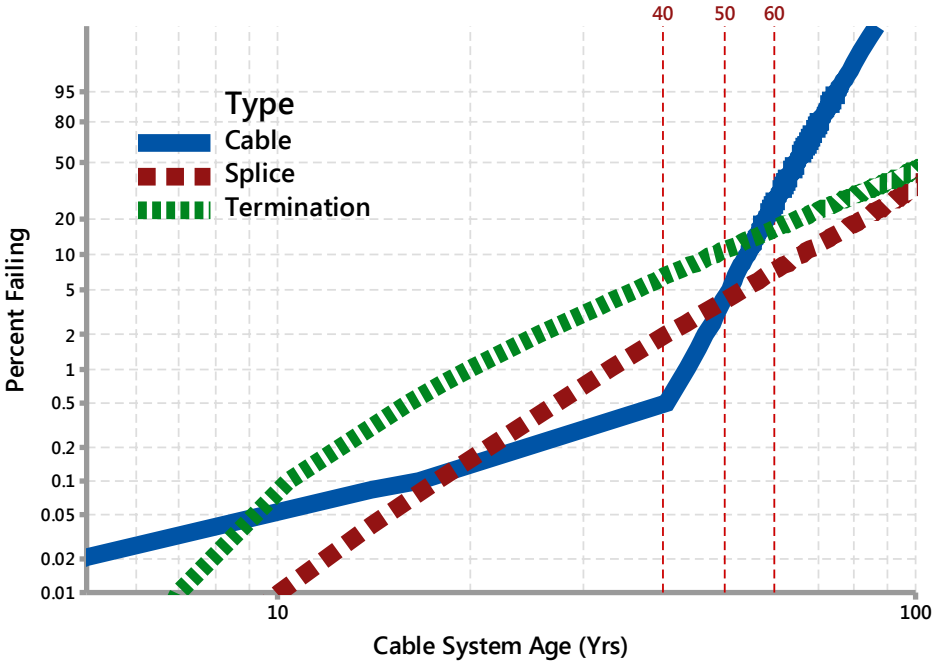


Figure 5: Component Segregated Weibull Curves for Failures in Service on an XLPE Cable System – Estimated in 2014

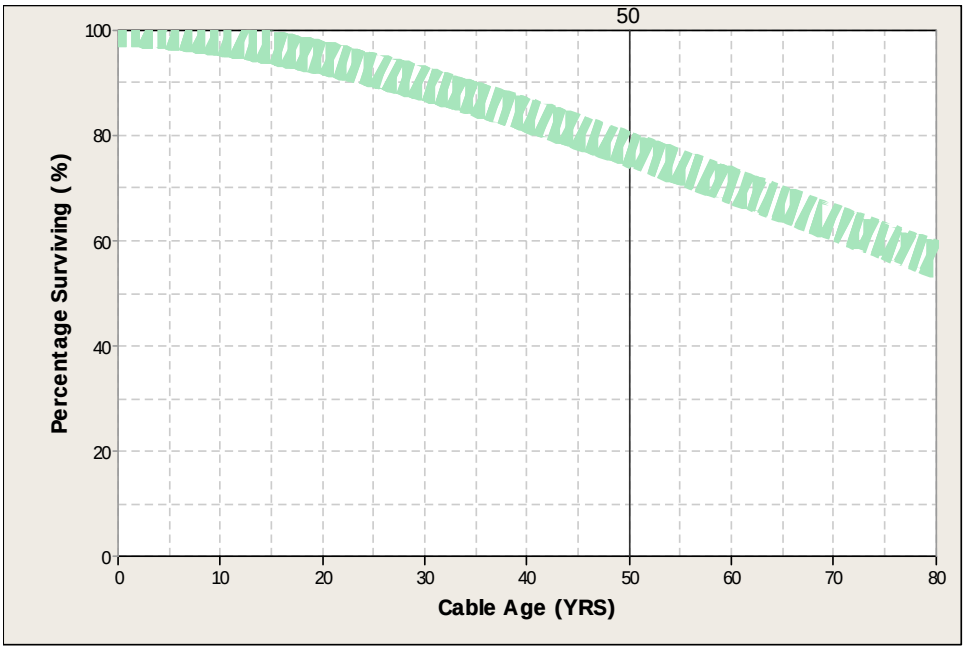


Figure 6: Survivor Curve for Cable Only Failures on an XLPE Cable System – Estimated in 2014

It is useful to comment on one of the most appropriate ways of expressing the information contained in Weibull or Survivor Curves. When cables with polymeric insulations were first installed, it was often stated that they were expected to last for 20 years – this being the common statement attributed to PILC at the time. This was soon revised to a 40-year life expectancy once the full life of PILC was considered. However, these are difficult statements to interpret. What does 20 years refer to? The average life, i.e. the time by which 50% have failed? Additionally under what conditions (loading, environment, cable construction, etc.)? Thus, to describe cable life in a practical and useful manner the life statement needs to include not only the time, but also the amount of cable affected at a specific time and include as much precision about the conditions as can be determined.

Thus, a cable life statement consists of three parts. As such, Figure 6 helps fashion reasonable life statements for a given utility cable system:

78% of direct buried un-jacketed MV cable segments using polyethylene-based insulations at utility Q are expected to survive to age 50.

Or

A 30-year life for direct buried un-jacketed MV cable segments using polyethylene based insulations at utility Q is based upon the survival of 90% of the cable segments.

Although the cable life statement is an unfamiliar concept for cable systems, it can be very useful, especially when considering cable system diagnostics. A utility engineer is likely to interpret a "life expectancy" as being the time that a set of components will last without any failures i.e. a deterministic view. Unfortunately, that is not how life expectancy works. Consider the current human life expectancy at birth of 67 years. We all know there are earlier and later fatalities. Not everyone will live to age 67. Consequently, life expectancy is probabilistic. Furthermore, life expectancy depends on locality, among other factors. Life expectancy is 84 years and 46 years in Japan and Sierra Leone respectively. Suffice it to say, age is not a precise indicator of future performance as life expectancy is imprecise. Diagnostic condition assessment provides additional resolution on the cable system health beyond that provided by age alone. Although diagnostics will improve clarity, they themselves are probabilistic. Consequently, the image will be sharper, but not necessarily crystal clear. This represents a significant challenge for utility engineers who are used to considering life from a deterministic point of view.

2.2 Aging In MV Cable Systems

We have seen that power cable systems, regardless of the dielectric, age, and fail. To further understand the process, it is useful to consider the mechanisms of aging (and subsequently failure). A power cable system fails when the *local* electrical stresses (E) are greater than the *local* dielectric strength (α) of a given dielectric material. The reliability and thus the rate of failure of the whole system depends on the difference between the *local* stress and the *local* strength. Failure of the dielectric results in an electrical puncture or flashover. The failure can result from the application of

the normally applied 60 Hz voltage or during a transient voltage such as a lightning or switching surge.
The probability of a failure occurring is described by Equation 2.

$$P_f = 1 - e^{\frac{E}{\alpha}^{\beta}}$$ **Equation 2**

Where

P_f is the probability of failure
α is the characteristic breakdown strength (Weibull Scale) associated with the length tested
β is the Weibull shape parameter for the tests
E is the relevant stress that is considered to drive the system to failure;

- in a ramp or step test then this will be the appropriate electric stress,
- in a constant electrical stress test then it will be the time at which failure occurs (Figure 5)

In MV cable systems, failure is generally treated as an *increasing local stress (an increasing E)* problem rather than a decreasing strength (a decreasing α). As time progresses, conditions that raise the local stress (primarily water trees, loss of bonding between contaminants and the surrounding dielectric or the development of voids) can occur over time. The net effect appears as aging.

Figure 7 shows the effect of different electrical stresses on the endurance (time to failure) for cables when tested in the laboratory after selected aging times. The estimates have been transformed from laboratory lengths to more practical lengths using the approach suggested by Steenis. The figure shows that as the electric stress is increased, the endurance (or the time to failure) will decrease. This is not a linear effect, as can be seen by the log-log scales. It is generally accepted that a twofold increase in stress (such as increasing the stress from 300 V/mil to 600 V/mil) will cause a fivefold reduction in time to failure. This is why so much attention is focused on the increasing electrical stress enhancement that occurs when a water tree grows in an MV insulation.

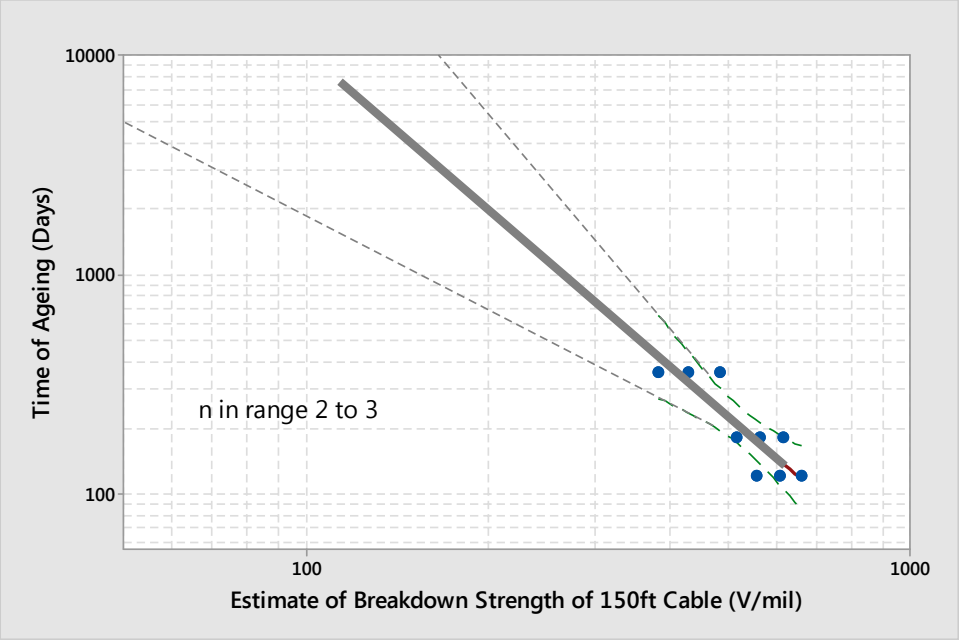


Figure 7: Endurance Reduction in a MV Cable with Elevated Electrical Stresses in laboratory tests (Fitting the Inverse Power Law $E^n t=K$ to data gives n in range 2 to 3)

This is also why it is possible, and often common, for a system to experience aging at different rates along the cable length. In a cable with an isolated, large vented tree, there can be a low level of bulk aging but a high level of local aging at the water tree due to the higher stress at the contaminant or other artifact that caused the water tree initiation. Therefore, the area that immediately surrounds the artifact experiences the dual effects of higher stress and higher aging. On the other hand, in a cable with many bow tie trees distributed throughout the insulation, there will more likely be a moderate level of general, bulk aging. The distinctions may seem arbitrary, as failure will always occur at the weakest point. However, this does have a notable impact on how repair decisions are made. In the case of an isolated defect, a repair after the failure will result in a system with dielectric strength that is very often quite high. If the failure was due to more dispersed deterioration, then repairs may not provide much benefit as the remaining system is only marginally stronger than the weakest part that failed.

Figure 7 and most related references represent dielectric strength and endurance as lines, implying that they are single valued or deterministic results. Nothing could be farther from the truth. Even in well-controlled laboratory assessments there is considerable scatter, or randomness, in the data. Furthermore, this scatter is enhanced when considering the less well-controlled environment of a cable system. This is important for engineers to bear in mind because diagnostic tests, in general, determine if there are weak locations within the cable circuit. A cable system will begin failing long before the average dielectric strength of the system is below the operating stress. It is not only the dielectric strength that displays statistical scatter, but it applies to all measured characteristics of a cable system.

As noted earlier, utility engineers often anticipate that there will be no failures up to the anticipated life expectancy of the cable system, but we know that some number of failures will occur over time. Engineers are likely to be quite concerned long before 50% of the population experiences a failure.

Thus, it is the lower strengths represented by the lower dotted line of Figure 7 rather than the average that are the ones that are probed by diagnostic techniques. Additionally it is the reason why the cable life statements generally consider 90%, 80%, or 70% survival when making their estimates of life.

2.3 Causes of Increased Local Stress

Turning to the specific mechanisms by which the electrical stress is increased, excessive electrical stress in the cable system dielectric can result from,

- Manufacturing imperfections: tends to increase the local stress leading to either initial failure or higher rates of aging.
    - voids
    - contaminants in insulations
    - poor application of shield material
    - protrusions on the shields

- Poor workmanship: tends to increase the local stress leading to either early failure or higher rates of aging.
    - cuts
    - interfacial contamination in accessories
    - missing applied components or connections
    - misalignment of accessories

- Wet environment: tends to reduce increase the local stress after ingress of water (either through normal migration through polymeric materials or breaks in seals or metallic sheaths):
    - bow tie trees
    - vented water trees
    - high rates of corrosion

- Changed electrical environment: tends to reduce the dielectric strength. The impact is usually local if the environmental influence is local.
    - neutral corrosion causing a change in the external ground plane

Although increased local stress is considered the main concern in MV Systems, a reduced local strength can contribute resulting from,

- Overheating: tends to reduce the dielectric strength. The impact can be restricted to short lengths (local) if the adverse thermal environment is localized.
    - poor accessory workmanship – mostly connectors
    - incorrect choice of accessory
    - excessive conductor current for a given environment and operating condition (global)
    - proximity to other cable circuits or other heat sources for short distances (local)

- Aggressive environment: tends to reduce the dielectric strength. The impact can be local if the environmental influence is local.
    - chemical attack (transformer oil leaks, petrochemical spills, fertilizer)
    - flooding that creates a step change in environmental conditions

Defects in cables with extruded insulation that can lead to failure are shown schematically in Figure 8. These defects include protrusions, voids, cracks, delamination, conductor shield interruptions, water trees, and electrical trees [5].

Within PILC cables, areas with insufficient oil due to oil migration and water ingress can also create failures over time [5].

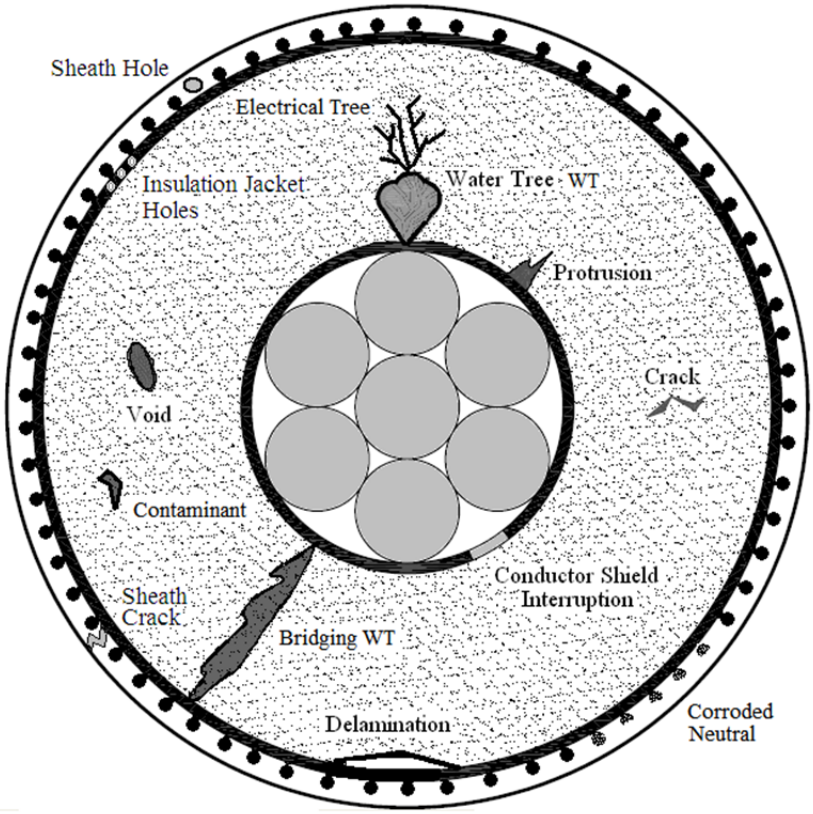


Figure 8: Typical Power Cable Defects

In addition, typical defects that can evolve into failures in a cable joint installed on cables with polymeric insulations appear in Figure 9. These defects include voids, interface discharge (tracking between the interfaces of the cable insulation and the joint insulation), and knife cuts made during the insulation shield cutback operation. The same types of defects that can occur in joint constructions, both taped and prefabricated, can also occur in terminations.

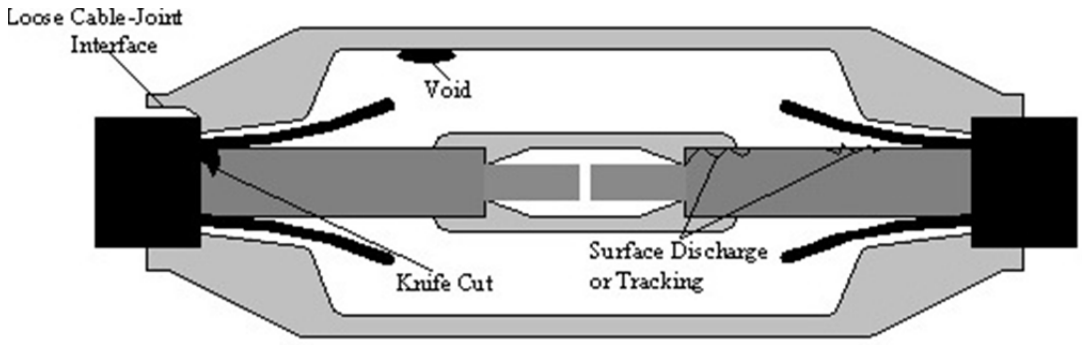


Figure 9: Typical Cable Joint Defects

As the system ages, the dielectric strength of various components tends to weaken. Since the aging mechanism depends on factors that involve the cable characteristics, accessory characteristics, and operating conditions, different power cable systems will age in different ways. Because the aging process is statistical in nature, there can be substantial variations in how the mechanisms develop and evolve over time with respect to cable length and accessories. This leads to significant differences between power cable systems operating under the same conditions and exposed to similar environments. Moreover, the power cable system properties measured through diagnostic testing will also show statistical features. This means that when utility engineers try to estimate the statistical time to failure for a given cable segment, the data should be interpreted correctly, e.g. with a sufficient number of data points to provide a reasonable assessment of trends and predictions.

Table 4 through Table 7 list typical deterioration or aging mechanisms along with the associated causes of each for various accessory and cable types. Mechanisms that lead to rapid failure (thermal runaway and extremely high local stresses from contaminants) are omitted as they typically bypass the degradation step and lead to failure before any type of intervention is possible.

It is useful to recall that the dielectric loss within a system depends upon the electrical stress (E), frequency (ω), permittivity (ε), and Tan δ:

$$\text{Dielectric Loss} \propto \omega E^2 \varepsilon \tan\delta \qquad \textbf{Equation 3}$$

Before any failure, there is either tracking or an electrical tree. Thus, it should be noted in all of the flow diagrams in Table 4 that tracking and electrical treeing precede all failures. The only question is how long they can be observed before the failure occurs.

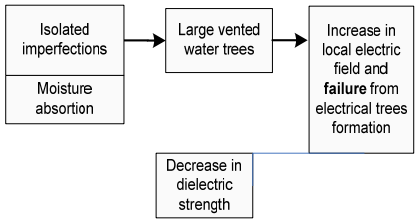
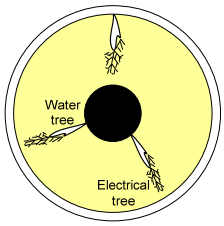
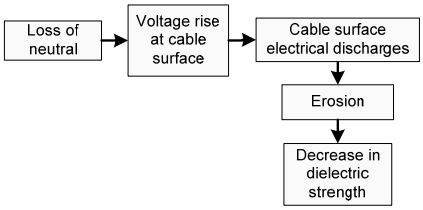
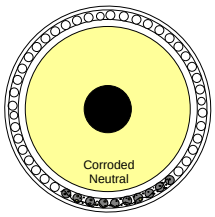
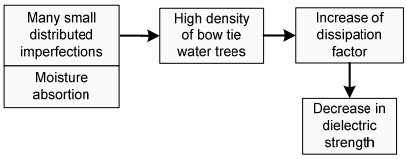
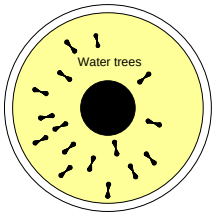
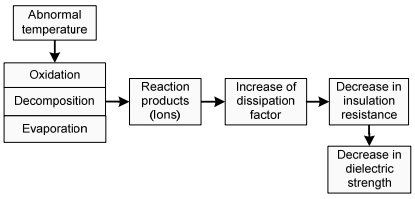
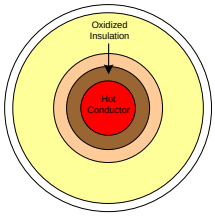
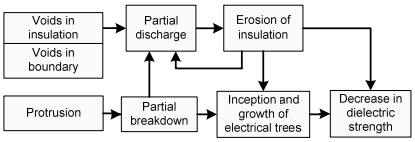
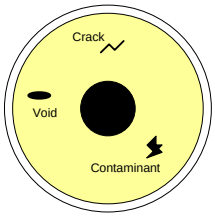
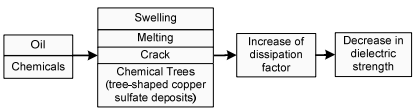
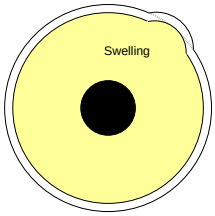
Table 4: Aging and Degradation Mechanisms for Extruded MV Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Large Water Trees		Moisture ingress	
Neutral Corrosion		Unjacketed cable in soil Water retained in jacketed cables Sometimes enhanced by chemicals in the soil	
High Density of Small Water Trees		Moisture ingress (external and via conductor)	
Thermal		Poor connector installation Incorrect choice of accessory Excessive conductor current for given environmental and operating conditions	
Dry Electrical		Manufacturing imperfections (voids, contaminants)	
Chemical		Petrochemical spills (transformer oil leaks, fertilizers)	

Table 5: Aging and Degradation Mechanisms for PILC Cable

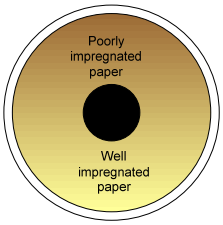
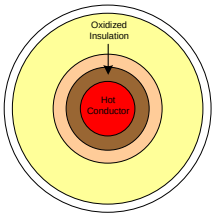
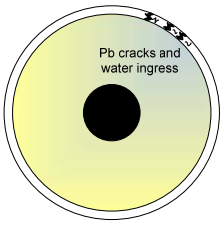
Type of Deterioration	Aging Process	Typical Causes	Example
Oil Starvation	Oil migration → Partial discharge / Localized dielectric heating → Paper oxidation → Changes in paper characteristics → Increase in dissipation factor → Decrease in dielectric strength	Extreme elevation changes, Lead (Pb) breach (cracks and corrosion)	
Thermal	Abnormal Temperature → Paper Oxidation / Paper Deterioration → Reaction Products (ions) → Insulation Degradation → Increase in dissipation factor → Decrease in dielectric strength	Excessive conductor current for a given environment and operating conditions	
Water Ingress	Water ingress → Localized or bulk dielectric heating / Insulation losses increase → Paper oxidation → Changes in paper characteristics → Increase in dissipation factor → Decrease in dielectric strength	Lead (Pb) breach (cracks and corrosion)	

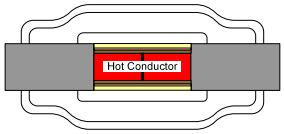
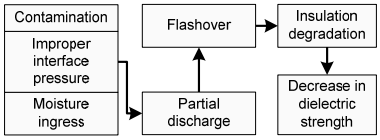
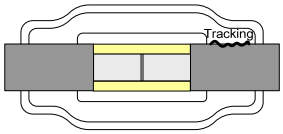
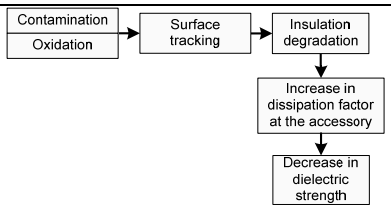
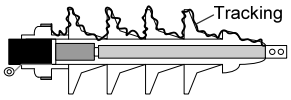
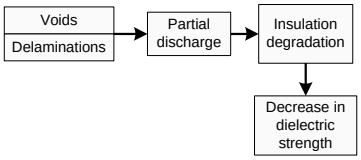
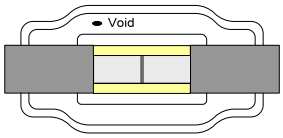
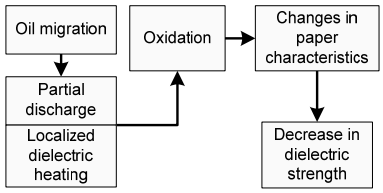
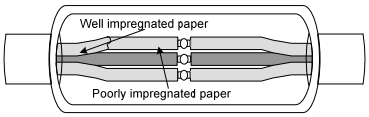
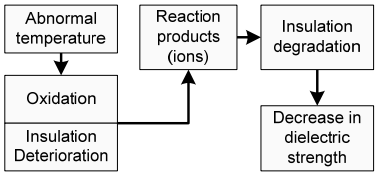
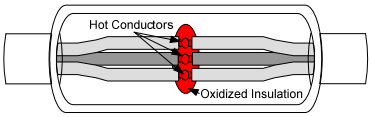
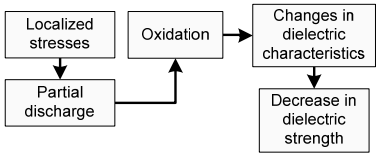
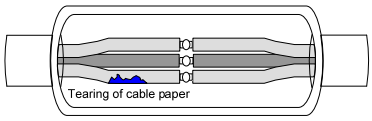
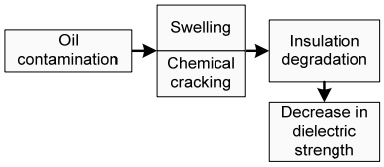
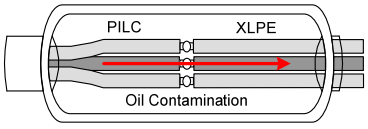
Table 6: Aging and Degradation Mechanisms for Accessories of Extruded MV Cable				
Type of Deterioration	**Aging Process**	**Accessory Type**	**Typical Causes**	**Example**
Thermal	NEW	Joint, termination, separable connector	Poor workmanship Incorrect choice for the application	
Contaminated Interface		Joint, termination, separable connector	Moisture ingress Poor workmanship	
Electrical External		Termination	Pollution, Ultraviolet (UV) degradation	
Dry Electrical		Joint, termination, separable connector	Manufacture defects, Natural aging Poor workmanship	

Table 7: Aging and Degradation Mechanisms for Accessories of PILC Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Oil Starvation		Extreme elevation changes, lead (Pb) breach: cracks and corrosion	
Thermal		Poor workmanship Moisture ingress Excessive conductor current for a given environment and operating conditions Poor connector design for installation	
Localized Electrical Stresses		Tearing or separation of cable paper due to poor workmanship	
Oil Contamination from Paper to Extruded Cable in Transition Joints		Poor accessory design, Poor workmanship	

2.4 Installed Population

The diversity of cable system failure mechanisms comes not just from the different ways that a given dielectric can age and ultimately fail, but also from the broad array of different cable systems currently in service (Generations 1 to 6 in Table 1). Figure 10 provides an estimate of the quantity of different cable system insulation types used in North America. Although this survey was

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conducted in 2006 – 2008, it still represents the best available estimate. An update was attempted within *CDFI Phase II* but there were insufficient responses to provide a higher quality update. This figure shows that the diversity in the cable infrastructure is significant. Thus, it is important to understand how to match a given diagnostic technology to a specific cable system problem, but also to a specific cable system generation/design. It is also important to recognize that the wide variety of issues associated with the degradation of various cable system designs, implies that it is very unlikely that one diagnostic technique will be effective for assessing the true condition of each system.

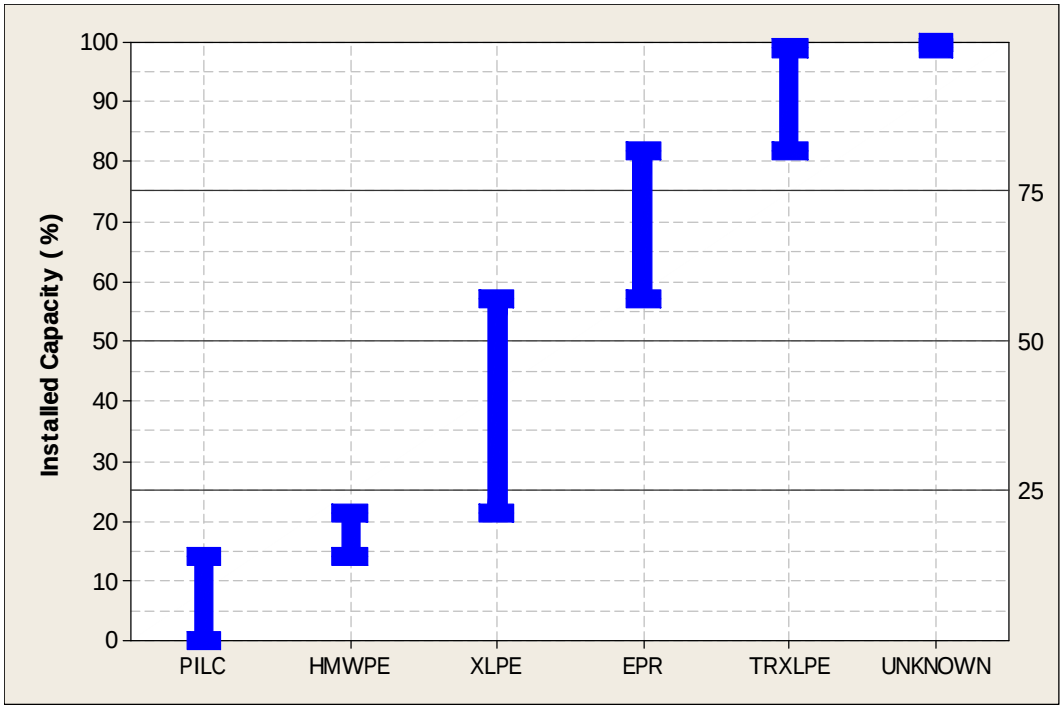

Figure 10: Estimate of North American Installed MV Cable Capacity, Segregated by Cable Insulation Type from Surveys Conducted 2006 To 2007 – from Table 1: PILC= Generation 0, HMWPE = Generation 1 to 2, XLPE = Generation 3 to 6, WTR XLPE = Generation 7 to 9, EPR = Generation 7 to 9

Additionally, it is important to know which portion of existing cable systems are failing and at what rate. Figure 11 suggests that while some utilities are experiencing very high failure rates of over 100 failures/100 miles/year, the mean is approximately 12 failures/100 miles/year. This information is useful because it sets the stage for understanding the economic considerations associated with diagnostic testing as well as setting expectations for improved reliability.

Figure 12 shows that failures occur not just in cable, but also in joints (splices) and terminations, so diagnostic technologies must be able to detect weaknesses in all cable system components. Finally, this figure shows that a significant percentage of utilities do not deploy cable system diagnostic testing programs and about half of those use only one technique. This information implies that in general, utilities do not fully appreciate the potential benefits of performing diagnostic test programs on their cable systems and the importance of using the right technique for the application. It is instructive to note that these data come from surveys conducted in 2006 and 2007.

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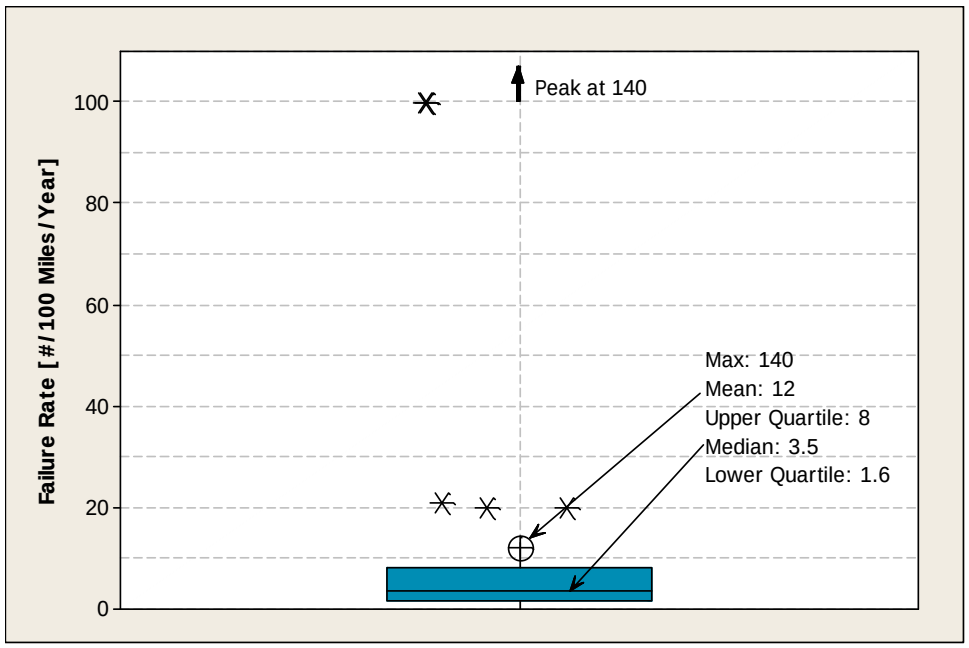

Figure 11: Estimate of North American MV Cable System Failure Rates

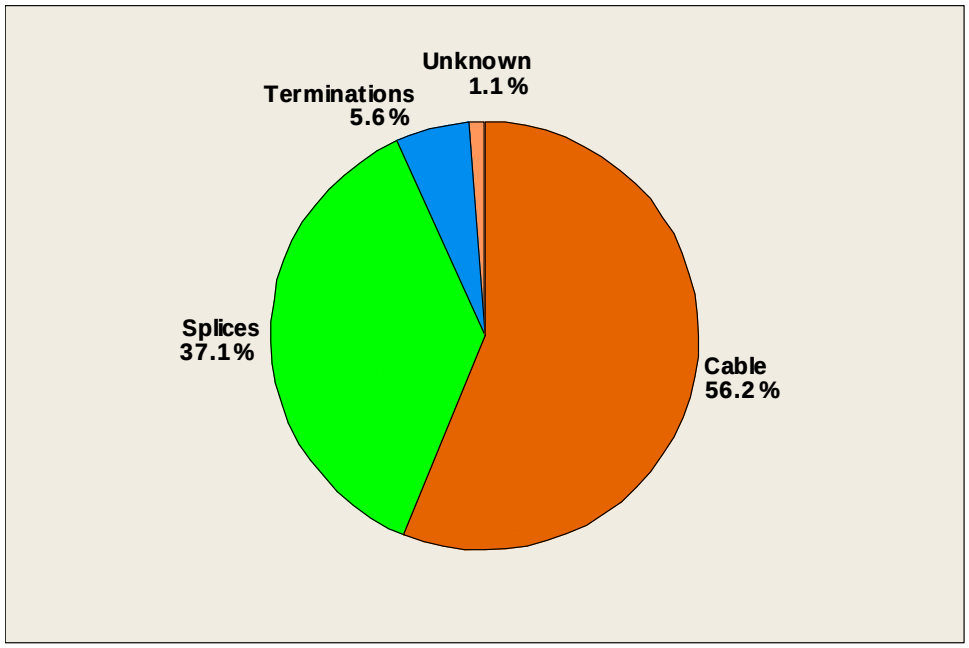

Figure 12: Estimated Dispersion of North American MV Cable System Failures by Equipment Type as Reported by Utilities

2.5 Conclusions

Returning to the discussions of MV cable system degradation that started this chapter it is possible to relate the preferred usage of diagnostics to the degradation. Data in Chapter 3 shows that the

Hipot (short for High Potential) or Simple Withstand testing is often the preferred diagnostic approach because it is so straightforward and easy to use. The Hipot or Simple Withstand Test approach makes use of the findings in Figure 4 (reproduced again here as Figure 13).

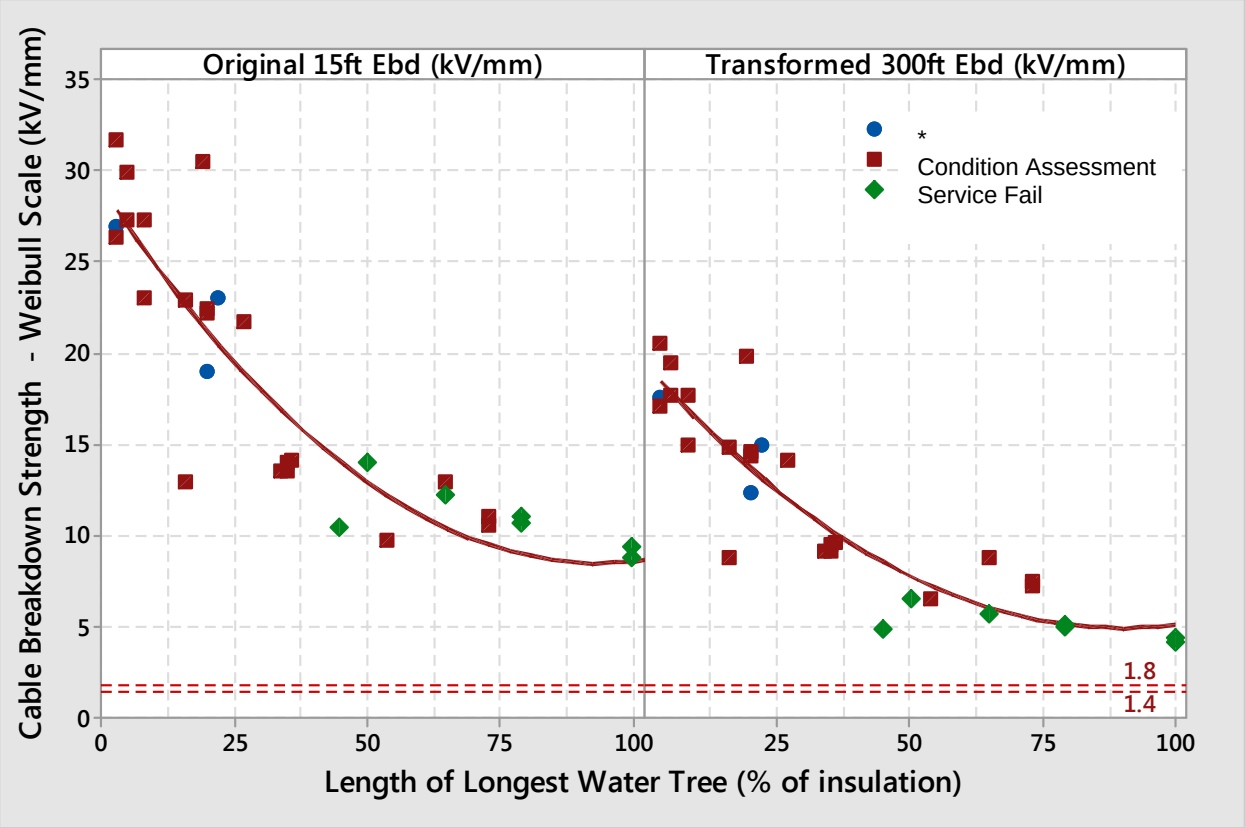

Figure 13: Cable Breakdown Strengths versus Water Tree Lengths (Maximum) segregated by type of investigation (Steenis 15) – left: measured for 15 ft test lengths, right: simulated for 300 ft installed lengths – 1.4 to 1.8 kV/mm indicate the typical mean operating stresses

It seeks to find an appropriate time/voltage combination that can be applied to the cable system so that weak spots (in the cable or the accessory) may be caused to fail in a reasonable time. However, the nonlinearity in the aging rate (Figure 7) means that the defects (water trees) only grow infinitesimally and will not be detected using this technique.

Using a more discriminating diagnostic approach (approximately 17% of utilities utilize such an approach as discussed in Chapter 4) does not make use of the reduction of the insulation strength as the diagnostic mechanism but probes the growing degradation caused by water tree growth. The water tree growth is assessed by measuring the change in the dielectric loss due to the water entrapped within the water trees and the water dissolved in the surrounding insulation. This useful measurement has grown in popularity with the increased use of Tan δ (TD) diagnostic methods. Partial discharge methods become useful later in the degradation chain when either water trees convert, irreversibly, to electrical trees or when discharges occur within voids in a cable accessory (most usually along the interface).

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CHAPTER 3

HV and EHV Cable System Aging and Testing Issues

Nigel Hampton

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3.0 HV AND EHV CABLE SYSTEM AGING AND TESTING ISSUES

As with medium voltage cables, high voltage cables are defined as long, insulated, current carrying conductors with a grounded outer surface that operated at high voltage [2 - 4]. They are terminated and joined together by accessories to constitute a “cable system”. Cable systems form an important part of the electrical power transmission and distribution networks as they carry power to areas that are not accessible by overhead lines and generally are more reliable (lower fault rates) and have lower maintenance requirements than overhead lines. For information on the evolutionary history of underground cable systems, see Chapter 2.

Looking specifically at North America, HV & EHV cable constructions have evolved over the years with many major and minor improvements. This evolution includes a number of manufacturing developments. These changes are presented here in a tabular format as shown in Table 1 and Table 2 for cable and Table 3 for accessories.

Table 4 represents the major changes in cable construction, excluding changes in wall thickness. These are represented as generations. Generations A, B, and C are the genesis for this work as they embody the last developments in fluid impregnated paper taped cables. Installation of Generations 1 and 2 has ceased in US and Canada for all practical purposes. Generation 5 represents the majority of the cables installed at the present time.

Table 1: Major Developments in HV/ EHV Cable Construction (Excludes Changes in Wall Thickness)				
Generation	**Insulation**	**Semiconducting Insulation Screen**	**Jacket**	**Barrier**
A	*Paper Oil*	*Carbon Tape*	*Jacket*	*Self-Contained Lead*
B	*Paper Oil*	*Carbon Tape*	*Steel Pipe*	
C	*Paper Polypropylene Laminate Oil*	*Carbon & Aluminum Tapes*		
1	XLPE or EPR (up to 138kV only)	Extruded Thermoplastic	Jacket	Lead Or Wires
2		Extruded Thermoset (crosslinked)		Lead Or Copper Wires & Aluminum Foil
3				Copper Wires & Aluminum or Copper Foil Or Lead
4				Copper Wires & Aluminum or Copper Foil Or Lead Conductor Water Blocked
5				Copper Wires & Aluminum or Copper Foil Or Lead Conductor Water Blocked Core Water Blocked
6	?	?	?	?

Table 2: Major Developments in Cable Core Extrusion Correlated with Generations of Cable Construction (numbers refer to construction technologies defined in Table 1)			
Material Handling	**Extrusion Technology**	**Cure Technology**	
		Steam	**Dry (Nitrogen)**
Open	1 + 2 2 + 1	2	2
Closed	True Triple	2	3 - 5

Table 3: Major developments in HV/ EHV accessory cable construction		
Generation	**Terminations**	**Joints**
i	Porcelain Oil Filled Condenser Cone	Hand Taped
ii	Porcelain Oil Filled EPDM Stress Cone	Machine Taped
iii	Porcelain Oil Filled EPDM & Silicone Stress Cone	Pre-molded Multi Part EPDM
iv	Composite & Porcelain Oil Filled EPDM & Silicone Stress Cone	Pre-molded Single & Multi Part EPDM
v	Composite & Porcelain Oil Free EPDM & Silicone Stress Cone	Pre-molded Single & Multi Part Silicone & EPDM

The steps in the evolutionary path of design and manufacturing are described above in Table 1 and Table 2 as well as the current state of the art for both MV and HV cables is summarized in Table 4 and Figure 1. In this chapter the discussion is essentially confined to the issues associated with HV cable systems (grey column in Table 4 and green area in Figure 1). It is important to recognize that although they have many similarities, HV Cable Systems are distinctly different from MV cable systems, primarily with respect to the materials used for the insulation and insulation screens as well as the electrical stress. See the green area in Figure 1.

Table 4: Summary of the State of the Art for both MV and HV cables in North America		
Attribute	**Medium Voltage (MV)**	**High Voltage (HV)**
Voltage Range (kV)	5 – 30 (5 – 46 in North America)	30 -150 (46 – 150 in North America)
Typical Conductor Size Range (mm^2)	34 - 500	240 - 2500
Mean Electrical Stress (kV/mm)	1.8	3.8
Conductor Screen Material	Thermoset Bonded Semi Conducting	Thermoset Bonded Semi Conducting
Insulation Material	Thermoset WTR XLPE Thermoset EPR	Thermoset XLPE Thermoset EPR
Insulation Screen Material	Thermoset Strippable Semi Conducting	Thermoset Bonded Semi Conducting
Metallic Screen	Wire Tape Foil	Wire & Foil Lead Aluminium
Protective Jacket	UV Resist LLDPE or HDPE	UV Resist LLDPE or HDPE
Accessories	Elbows Joints Terminations	Joints Terminations
Material Handling Systems	Closed Bulk Supply	Closed Box Supply
Extrusion Technology	True Triple CCV Dry N2 Cure	True Triple CCV & VCV Dry N2 Cure

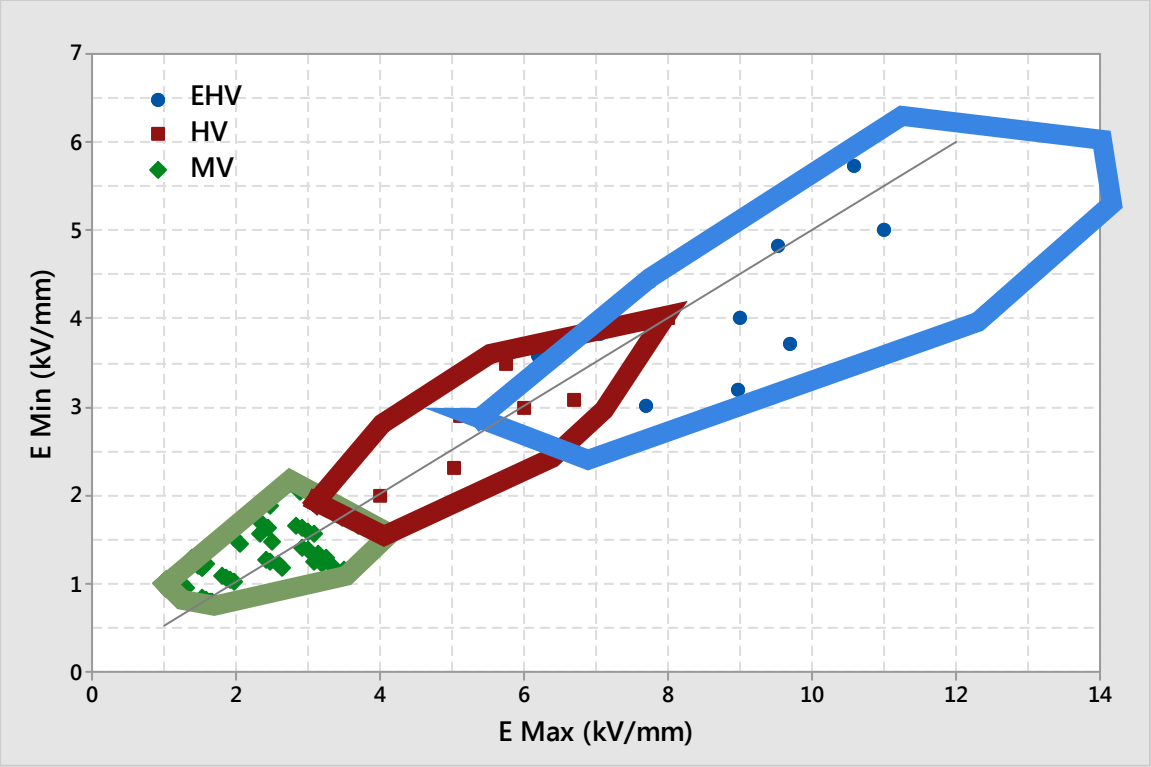

Figure 1: Range of Typical Electrical Stresses Employed in Cable Systems (E_{max} = electrical stress in the insulation adjacent to the conductor screen, E_{min} = electrical stress in the insulation adjacent to the insulation screen; note that the straight line represents the condition where $E_{max} = 2\ E_{min}$)

3.1 The Industry Problem

While the evolution in cable construction, materials and manufacturing processes was intended to produce continual increases in reliability with associated reductions in total cost of ownership, the process did not always yield the expected benefits. This observation is important because it drives much of need for and development of cable system diagnostics.

3.1.1 History

HV and EHV cable systems have been installed in North America for a number of years. On the whole, they have provided very reliable performance in recent years. A research study conducted by NEETRAC for extruded cable systems installed since 2000 led to estimates of the reliability (hazard plot or bath tub curve) of these systems as shown in Figure 2.

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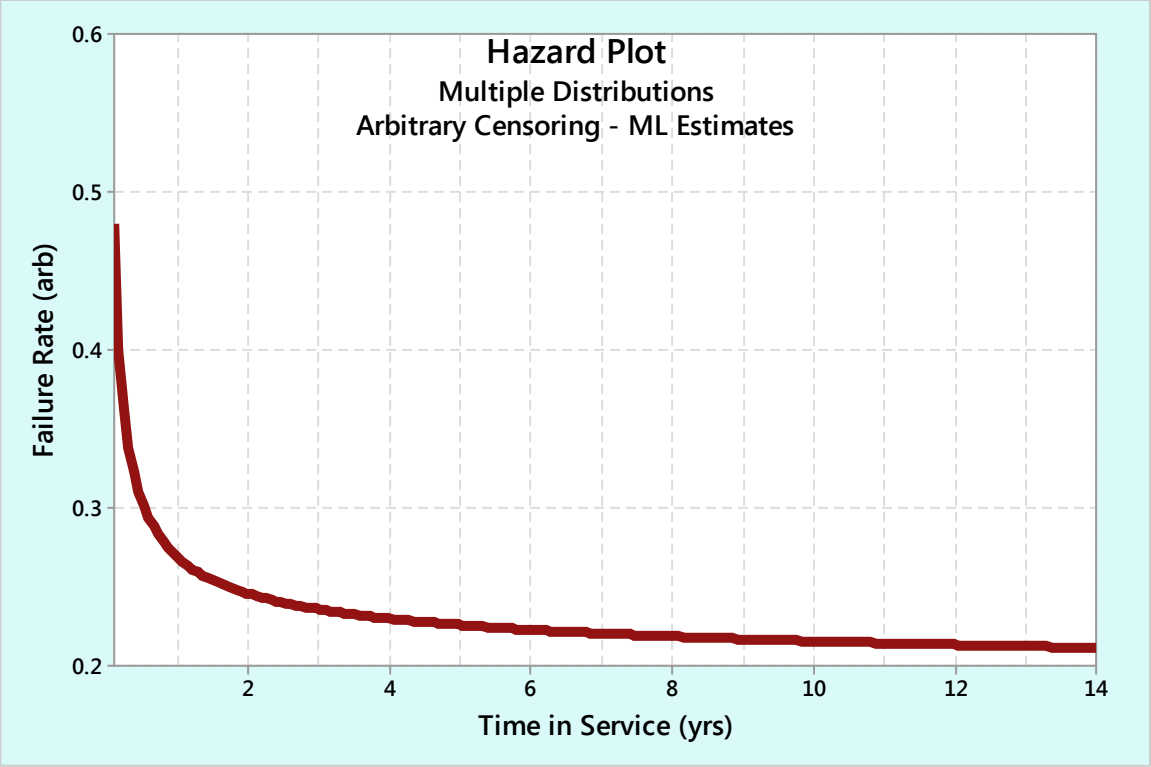

Figure 2: Cable System (HV and EHV combined) Hazard Plot (Derived from the Weibull Analysis for Installations Since 2000)

Figure 2 shows that the failure rate in the first three years of life is slightly higher than the failure rate after three years. As would be expected the right hand edge of the bathtub curve is not visible because the cable systems studied have not yet reached the wear out stage of life. Only the left hand (infant mortality) and the central (normal operation) portions of the curve can be seen for this data set.

Except for some very early 69 and 115kV designs that did not utilize metallic water barriers, water treeing has not been shown to be a significant issue in the aging/failure of HV & EHV cable systems.

It is equally interesting to see how failures are distributed among the components of the cable system as shown in the Figure 3 pie chart. In this graph, the termination category includes both outdoor sealing ends (ODSE) and gas insulated structures (GIS).

The experience captured in Figure 2 and Figure 3 indicates why the current interest in diagnostics for the HV and EHV cable systems is focused on the infant mortality failures that are occurring, for the most part, in the cable accessories.

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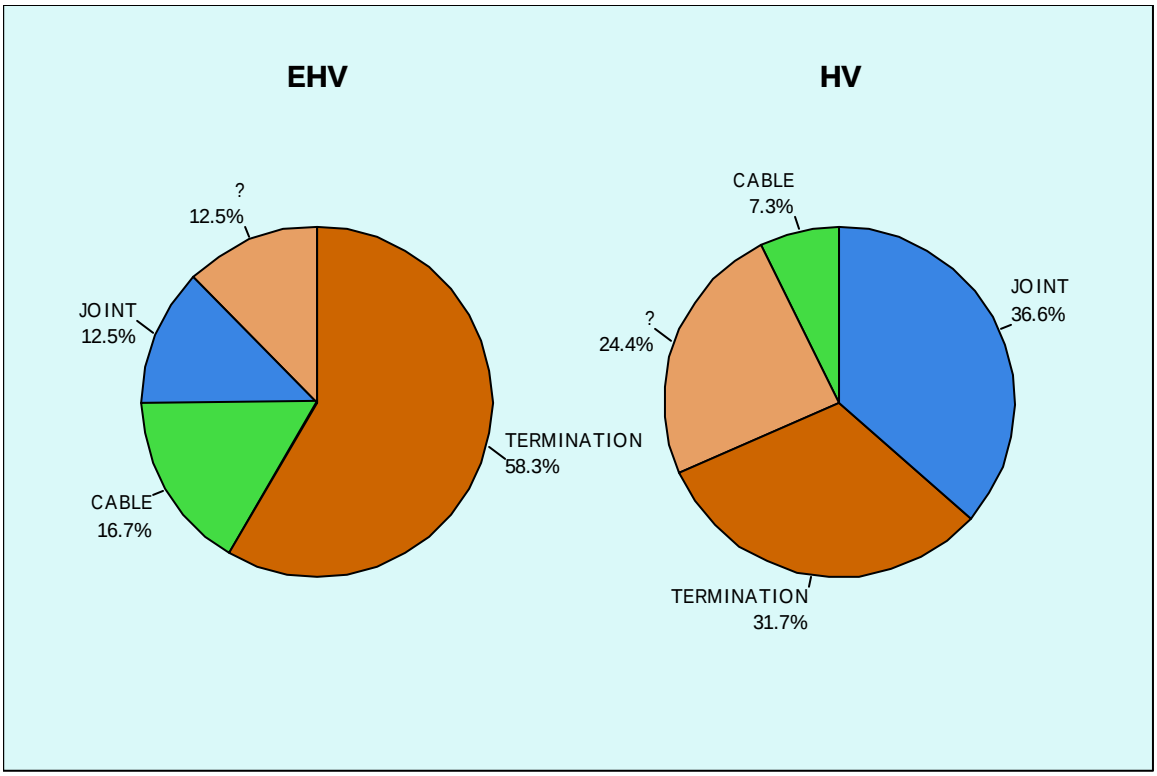


Figure 3: Distribution of Cable System Failures by Failing Component Segregated for HV and EHV Classes

3.2 Aging in HV Cable Systems

All cable systems, regardless of the dielectric type, age and fail. Thus it is useful to understand the aging failure mechanism(s) and therefore the cause of failure. A cable system fails when *local* electrical stresses (E) are greater than the *local* dielectric strength (α) of the involved dielectric material(s). The reliability and the rate of failure of the whole system depend on the difference between the *local* stress and the *local* strength. Failure of the dielectric results in an electrical puncture or flashover. The flashover can occur across the cable dielectric, across the accessory dielectric or along the interface between two dielectric surfaces such as the cable insulation and joint insulation. It can also occur as an external flashover at cable terminations. The failure can occur as a result of the normally applied 60 Hz voltage or during a transient voltage such as lightning or switching surges.

$$P_f = 1 - e^{\frac{E^{\beta}}{\alpha}}$$ **Equation 1**

Where

P_f is the probability of failure

α is the characteristic breakdown strength (Weibull Scale) associated with the dielectric material

β is the Weibull shape parameter for the dielectric material. It is determined from a breakdown test in the laboratory

E is the relevant stress (determined in a laboratory breakdown test) that is considered to drive the system to failure;

- in a ramp or step test, this is the stress at which the system breaks down
- in a constant electrical stress test, it is the time at which failure occurs

In HV systems, failure is generally treated as a decreasing strength (a decreasing α) problem due to a change in isolated defects rather than an *increasing local stress (an increasing E) problem*. As time progresses, artifacts that raise the local stress (loss of bond between the defect/contaminant and the surrounding dielectric and/or the development of voids) can develop with time. The net effect is considered an aging process.

3.3 Causes of Increased Local Stress

The specific mechanisms by which the dielectric strength is reduced by electrical stress induced aging can occur as a result of:

- Manufacturing Imperfections: These tend to increase the local stress, leading to either early failures or increased rates of aging. Examples include:
  - voids
  - protrusions extending into the dialectic from the semiconducting screens
  - contaminants in the dielectric

- Poor Workmanship: These issues tend to increase the local stress, which also leads to either early failures or increased rates of aging. Examples include:
  - cuts
  - interfacial contamination in accessories
  - missing components or connections
  - misalignment of accessories

- Wet Environment: Tends to reduce increase the local stress after ingress of water (either through normal migration through polymeric materials for cables without a metallic moisture barrier or beaks in seals or metallic sheaths): The result is:
  - bowtie trees
  - vented water trees

If the HV cable system does not have a metallic moisture barrier, it is likely useful to consider a diagnostic approach that is similar to that deployed for MV cable systems, though very little work was performed on this type of cable system in the *CDFI*.

The following elements are often considered in the degradation of MV cable systems. However, due to the differences in design and construction practices employed at HV, they are generally not considered:

- changes in the electrical environment (system voltage changes or lightning protection changes)
- overheating
- aggressive environment (contact with petrochemicals, fertilizer, etc.)

Defects in cables with extruded insulation that can lead to failure are shown schematically in Figure 4. These defects include screen protrusions, voids, cracks, contamination, delamination and semiconducting screen interruptions.

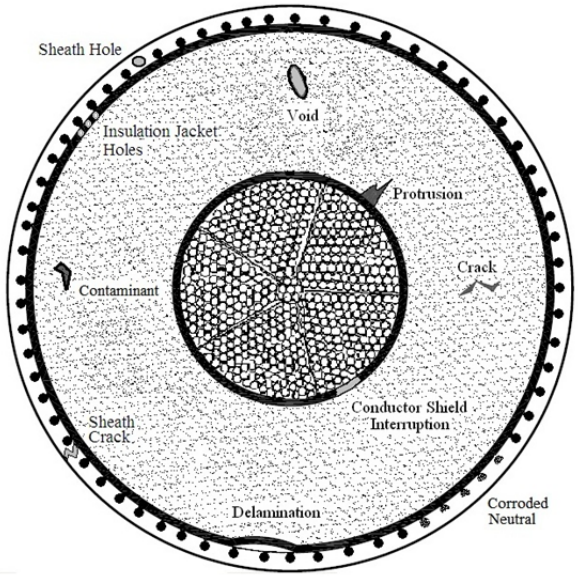


Figure 4: Typical Power Cable Defects

In addition, typical defects that can evolve into failures in a molded or extruded cable joint are shown in Figure 5. These defects can cause interface discharge (tracking at the interface of the cable insulation and the joint insulation) and/or partial discharge. It is instructive to note that the same types of defects that can occur in joint constructions, both taped and prefabricated, can also occur in terminations.

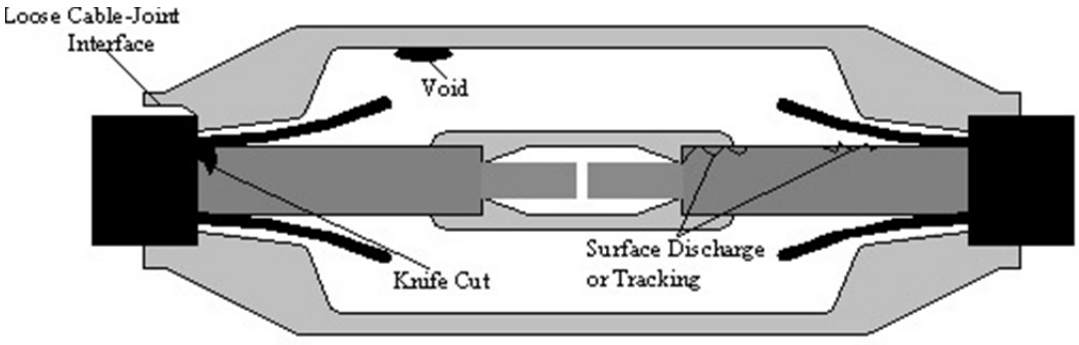


Figure 5: Typical Cable Joint Defects

As the aging mechanism depends on factors that involve the cable characteristics, accessory characteristics and operating conditions, different power cable systems will age in different ways at different rates. As the system ages, the dielectric strength of various components tend to reduce. In

fact, aging, degradation, and failure mechanisms are statistical in nature. Therefore, there may be substantial variations in how the mechanisms develop and evolve over time with respect to cable length and accessories. This can lead to significant differences in the performance of different power cable systems even though they may be operating under the same conditions and exposed to similar environments. Moreover, due to the statistical behavior of these mechanisms, the power cable system properties measured through diagnostic testing will also show statistical differences. As a result, when utility engineers try to estimate the statistical time to failure for a given cable segment, the data should be interpreted correctly, (e.g. with a sufficient number of data points to provide a reasonable level of confidence for the assessment of trends and predictions.

Table 5 through Table 7 list typical deterioration or aging mechanisms along with the associated causes of these mechanisms for various accessory and cable types. Mechanisms that lead to rapid failure (thermal runaway and extremely high local stresses from contaminants) are omitted as they can occur so rapidly that they typically bypass the degradation step and thus do not permit intervention or prevention that might be possible from performing a diagnostic test.

It is useful to recall that the dielectric loss within a system is a function of the electrical stress (E), the applied voltage frequency (ω), dielectric permittivity (ε), and Tan δ:

$$\text{Dielectric Loss} \propto \omega E^2 \varepsilon \,\text{Tan}\,\delta \qquad \textbf{Equation 2}$$

In the case of HV and EHV cables, E, the electrical stress, is so much higher than in MV systems that dielectric heating can be very important. In fact, only ¼ of the Tan δ is required at HV stress to have the same heating effect as at MV stress.

Before failure, there is either tracking or an electrical tree. Thus it should be noted in all of the flow diagrams in Table 5 that tracking and electrical treeing precede all failures. The only question is how long they can be observed before the failure.

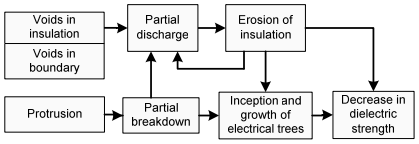
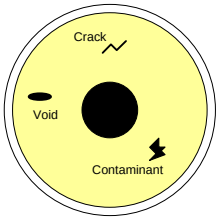
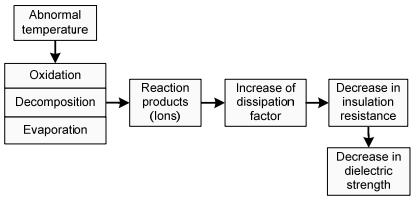
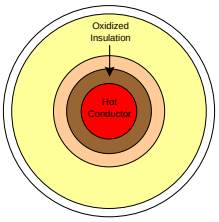
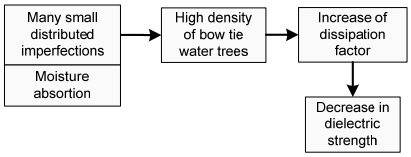
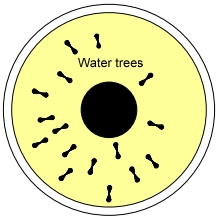
Table 5: Aging and Degradation Mechanisms for Extruded MV Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Dry Electrical		Manufacturing imperfections (i.e. voids, contaminants)	
Thermal		Poor workmanship on accessories Incorrect choice of accessory Excessive conductor current	
High Density of Small Water Trees		Moisture ingress (external and via conductor)	

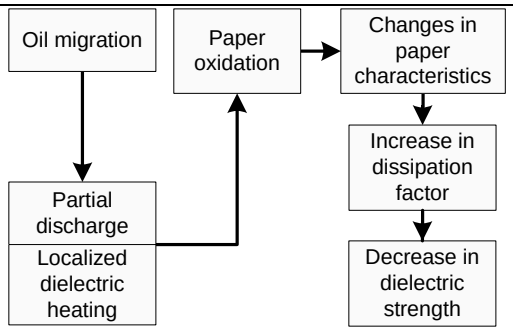
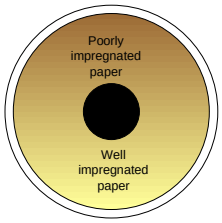
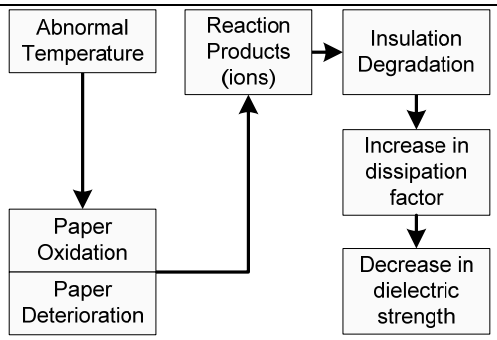
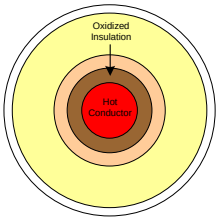
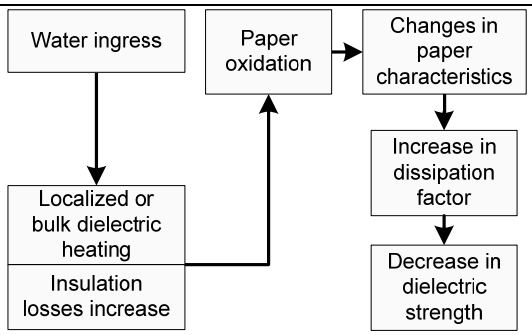
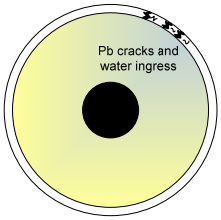
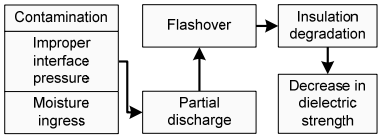
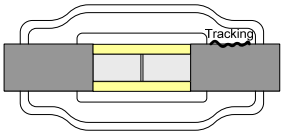
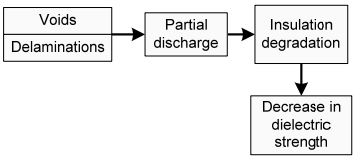
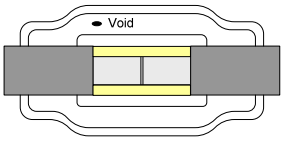
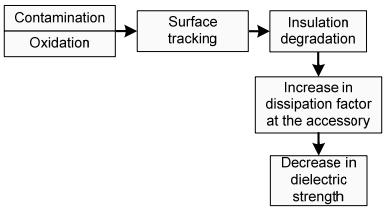
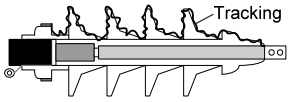
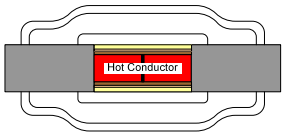
Table 6: Aging and Degradation Mechanisms for Paper Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Oil Starvation		Extreme elevation changes, Lead (Pb) breach: through cracks and corrosion	
Thermal		Excessive conductor current for a given environment and operating conditions	
Water Ingress		Lead (Pb) breach through : cracks and corrosion	

Table 7: Aging and Degradation Mechanisms for Accessories of Extruded MV Cable				
Type of Deterioration	**Aging Process**	**Accessory Type**	**Typical Causes**	**Example**
Contaminated Interface		Joint, termination, separable connector	Moisture ingress, poor workmanship	
Dry Electrical		Joint, termination, separable connector	Manufacture defects, natural aging, poor workmanship	
Electrical External		Termination	Pollution, Ultra Violet (UV) degradation	
Thermal	NEW	Joint, termination, separable connector	Poor workmanship Incorrect choice	

3.4 Diagnostic Testing at HV and EHV

As noted previously, the propensity of HV and EHV cable systems to fail in infancy (<1.5 yr) as well as the propensity of the failure to occur in the accessories (3 to 4 times more frequently than the cable), means that diagnostics in the HV and EHV arena has been focused on commissioning tests using either Simple Withstand tests using resonant ac test voltage systems or Monitored Withstand tests using resonant ac test voltage systems with partial discharge detection.

Figure 6 shows the PD inception voltage (PDIV) for a large number of tests carried out in different countries (as reported in the research study conducted within CIGRE B1.28). As shown in the figure, the occurrence of PD at U_0 is low. Thus online PD testing is rarely performed.

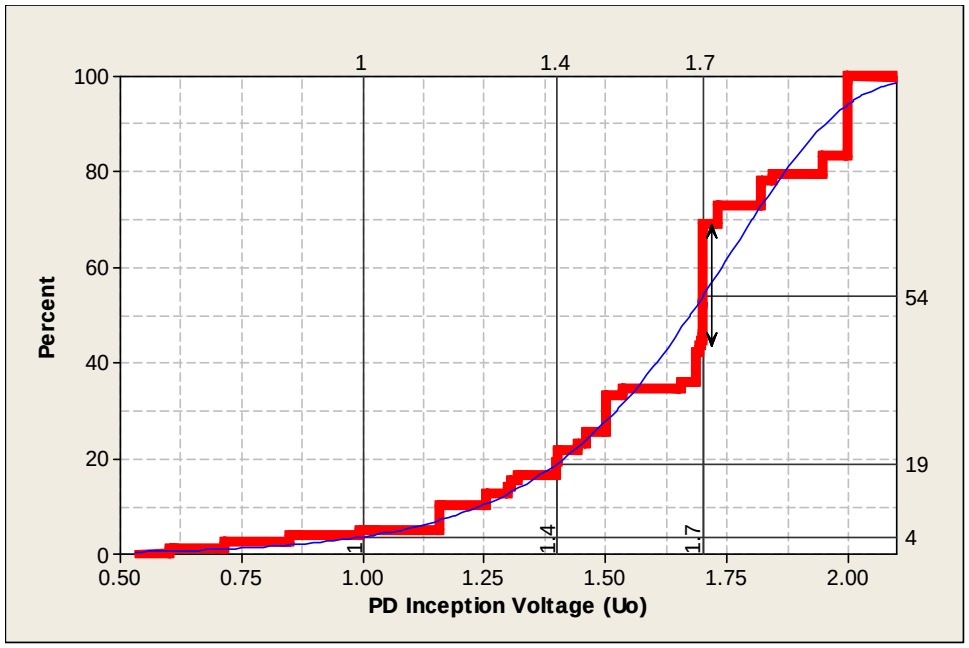


Figure 6: Distribution of PDIV (Based on Available Data from Service Providers)

An alternative approach that was postulated within the CIGRE working group was to test at $1.4U_0$. This will definitely have a greater chance of detecting defects that lead to partial discharge than tests performed at U_0, but it would miss the discharges that occur up to $2U_0$. The most technically solid voltage level is $1.7U_0$, which is the basic recommendation in IEC60840 and 62067. At this level, it is anticipated that between 44 and 70% of the discharges will be detected.

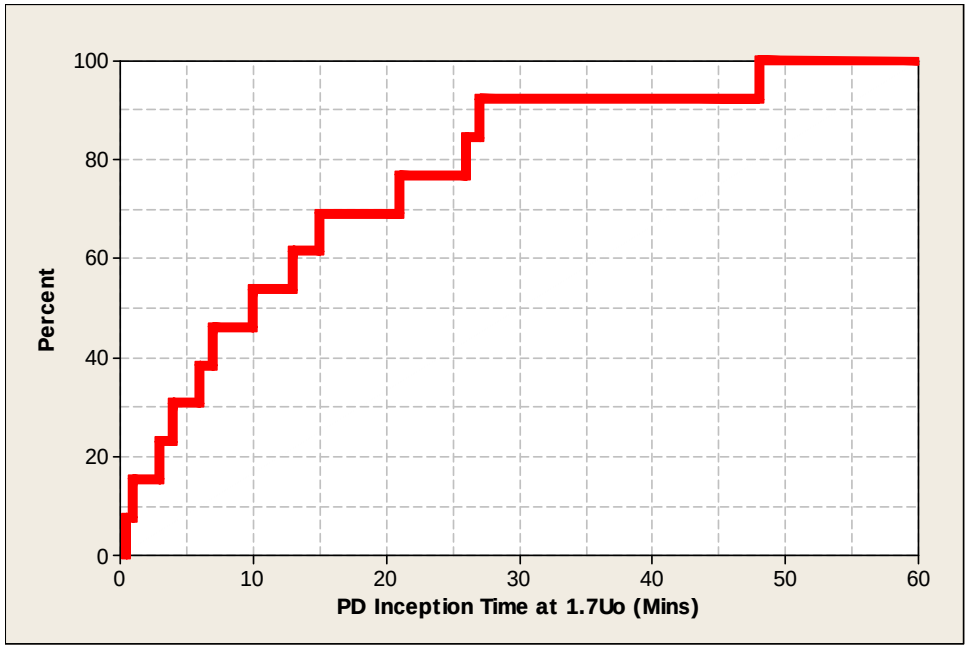


Figure 7: PD On-Set time at $1.7U_0$ (Based on Available Data from Service Providers)

As noted previously, $1.7U_0$ is the most preferred test voltage level. However, the other portion of a withstand test is the exposure time at the selected voltage level. The information in Figure 7 is for a

60 min time window. Although it is not known how many discharges would have been detected after 60 min, it is clear that the detection level was approaching an asymptote. The general feeling within the CIGRE working group is that the test time should be at least 30 min at $1.7U_0$ for both Simple and Monitored withstand tests. However, most practitioners take the view that most of the testing cost for HV cable systems is associated with the setup and thus the incremental cost to go on from 30 to 60 min is inconsequential and outweighed by the opportunity to identify the last 8% of the PD sites that may occur.

3.5 Summary

Only a limited amount of diagnostic testing or data analysis was performed on HV or EHV cable systems in the *CDFI*. However, this chapter points out the fact that there are demonstrable difference between MV and HV/EHV cable systems with respect to how they age and how diagnostics are deployed on these systems. As a result, the approach to diagnostic testing and deployment on HV/EHV cable systems is different. Simple Withstand tests and Monitored Withstand using partial discharge appear to be the most practical approaches. However, as discussed in Chapter 8, partial discharge testing is a complex process and many factors have to be taken into consideration when performing this test on HV/EHV cable systems.

3.6 References

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CHAPTER 4

How to Start

Nigel Hampton

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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4.0 HOW TO START

The section of a diagnostic technology should be made near the start of the process, but not right at the start, of the diagnostic testing process. At first sight, the choice may appear to be simple and might be based on prior experience or recommendations from colleagues/fellow utilities or sales/marketing materials. However, the decision is actually quite complex and requires a review of many influencing factors. This chapter provides guidance on how to optimize the selection process.

Section 4.1 provides a historical perspective of diagnostics and serves to provide information such that prior experience and recommendations of colleagues/fellow utilities can be used in the right context.

Section 4.2 charts several paths such that a user may best benefit from the accumulated experience of utility practitioners. It addresses the selection of the optimal test location and gives a five step process for arriving at a short list of diagnostics to consider. The prime benefit of such a process is that the decision making is transparent and each part of the decision making process is preserved for future review.

4.1 Evolution of Cable System Diagnostics

Research into the evolution started with a survey to establish the use of cable system diagnostics in North America was conducted in 2006 as part of *CDFI Phase I* and this provided one of the first industry wide estimates of diagnostic test deployment on electric utility systems. NEETRAC repeated the survey in 2014 using interviews with knowledgeable personnel. The work is now complete and results are reported for 103 utility entities in Canada and the US. Typically, the utilities contacted had more than 200,000 customers and information could be gathered for more than 70% of these utilities. Consequently, the sampling is believed to be representative of the utilities in the US and Canada.

The information was captured at the utility operating company level so that regional variations and preferences could be captured. Furthermore, there can be much discussion over what constitutes "utility use". In this work, to be considered a diagnostic used by a utility, the technique has to be part of a normal/established activity for determining cable system asset health on new and aged systems. Thus, pilot studies and laboratory experiments are not included. Some information is available for Mexico; however the usage could not be established to the same level as for entities in Canada and the US, thus data for Mexico are not included at this time.

Each utility entity is considered on its own and given equal weighting, which addresses the fact that individual operating companies within a utility corporation (e.g. AEP, Exelon, FirstEnergy, PPL etc.) often have different approaches. This is very much in line with the manner in which diagnostic test usage was reported in the initial study of 2006. It is important to note in this approach that each respondent is considered equally (same weighting regardless of entity size). Viewed in this manner, over 73% of utilities surveyed report they do not employ cable system diagnostics. The most widely deployed technique reported to date is Simple VLF Withstand.

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The operating entity approach detailed above gives equal weighting to all entities independent of the size of the operating company. Another perspective may be gained if it were possible to consider the utility size. In principle, the optimal way to incorporate this would be to use the size of the underground MV system. However, this is known and knowable for only a very small fraction (5% – 10% of the sample) of the respondents. The main issue with the reduced number of respondents would be "confirmation bias" (i.e. the folks using diagnostics would be systematically more likely to provide the length information and thus bias the survey). Thus, it was determined that the information would be more useful if the large number of respondents was retained and some other means of size adjustment established. One approach is to use the number of customers served by a utility as an alias for the size of the underground system. It is recognized that this weighting is not entirely correct but it is reasonably pragmatic. Using this approach, each utility response was weighted by the reported number of customers that the utility serves. This perspective estimates that the use of diagnostics increases from 26.5% to 43.9% when adjusted for size.

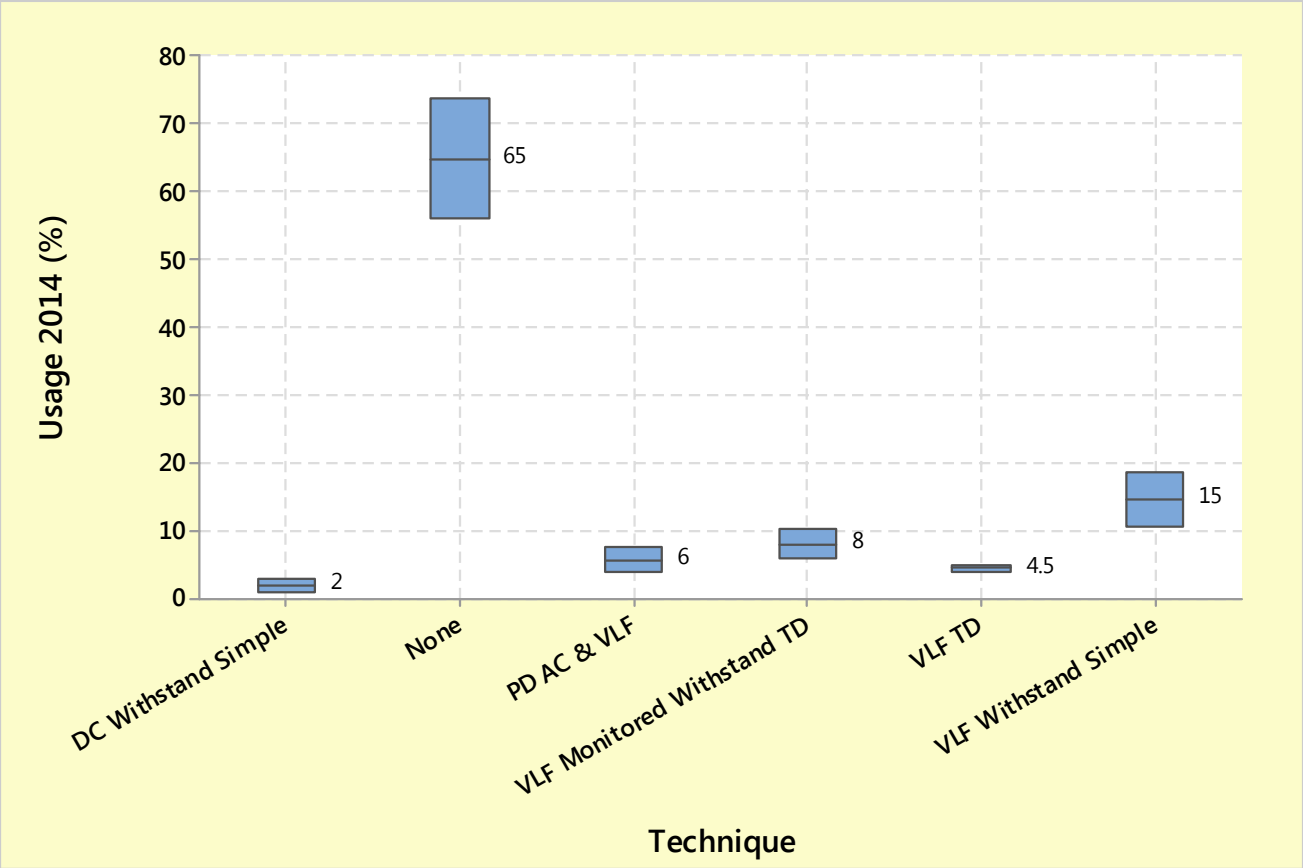

Figure 1: Range of Usage for the different diagnostic techniques - 2014

As mentioned, neither the entity approach or customer approach described above are likely to provide the "correct" usage; however, they most likely define the upper and lower ranges of the usage. Thus, it is possible to refine the estimated diagnostic usage with a process somewhat analogous to Bayesian Analysis which combines available estimates and engineering knowledge to provide a more accurate/complete estimate. Figure 1 shows the improved estimates by providing likely ranges for each diagnostic technique (drawn from the two different approaches) as well as the "no use" category. At this time, it is recommended that the midpoint of these ranges be used if a

single value is needed. The analysis completed thus far suggests that, for example, the VLF Simple Withstand usage lies somewhere between 10.8% and 18.7%, with 15% being a reasonable number to use if a range is not appropriate.

Multiple voltage sources are available for use by those utilities that currently deploy diagnostics on their systems. These include using resonant ac (10 – 300 Hz), Very Low Frequency (VLF), damped ac (DAC), and dc. These sources may be used in one of two modes: diagnostic (Tan δ, PD, etc.) or withstand (Simple and Monitored). This analysis takes the same quasi-Bayesian approach described above to estimate the usage ranges. It is not possible to establish the most common testing mode as Withstand (HiPot) and Diagnostic modes overlap.

The preceding information described the survey that was completed in 2014. Additionally, the basic information from the entity only analysis completed in 2006 can be applied to develop an estimate for 2006. This has been done using the same approaches outlined above to provide a side by side usage evolution of diagnostic techniques (see Figure 2 through Figure 5). In the figures below the following terms are used: TD = Tan Delta, PD = Partial Discharge, VLF = Very Low Frequency AC waveforms, AC = AC waveforms with frequencies in the range 10 to 300 Hz (usually derived from resonant systems), Withstand = Hipot, DAC = Damped AC or Oscillating Wave.

At first sight this analysis may appear to be only from a historical interest. However, the changes reflect changes in equipment, improvements in application knowledge and standards activities that have been ongoing during the intervening eight years.

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2006

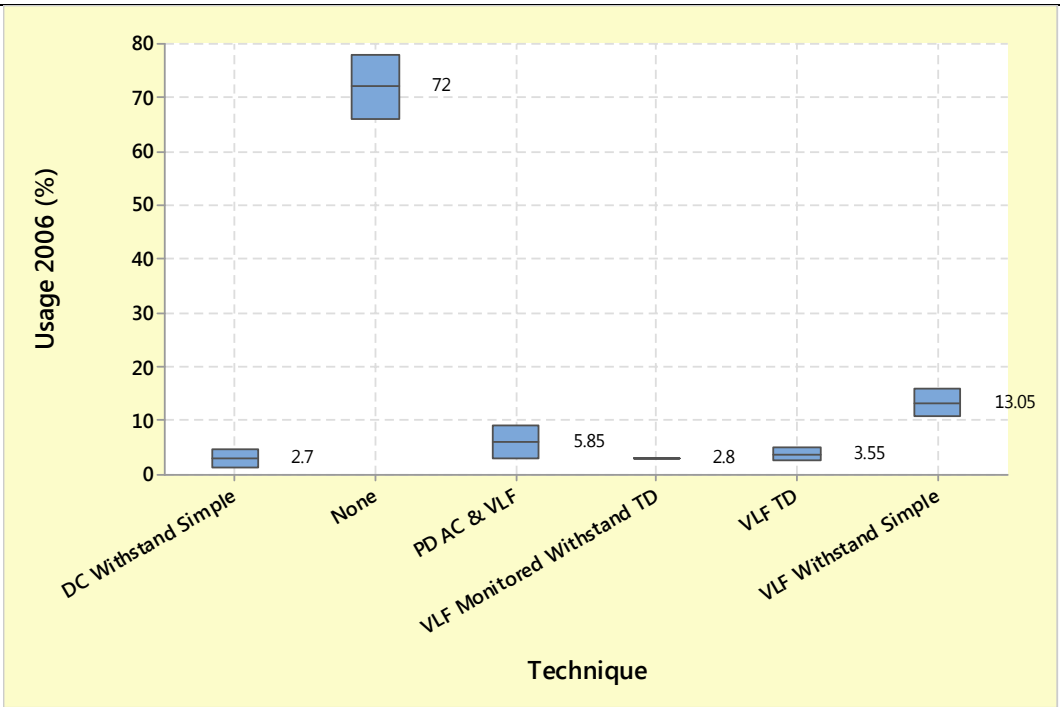

Figure 2: Range of Usage for the different diagnostic techniques – 2006

2014

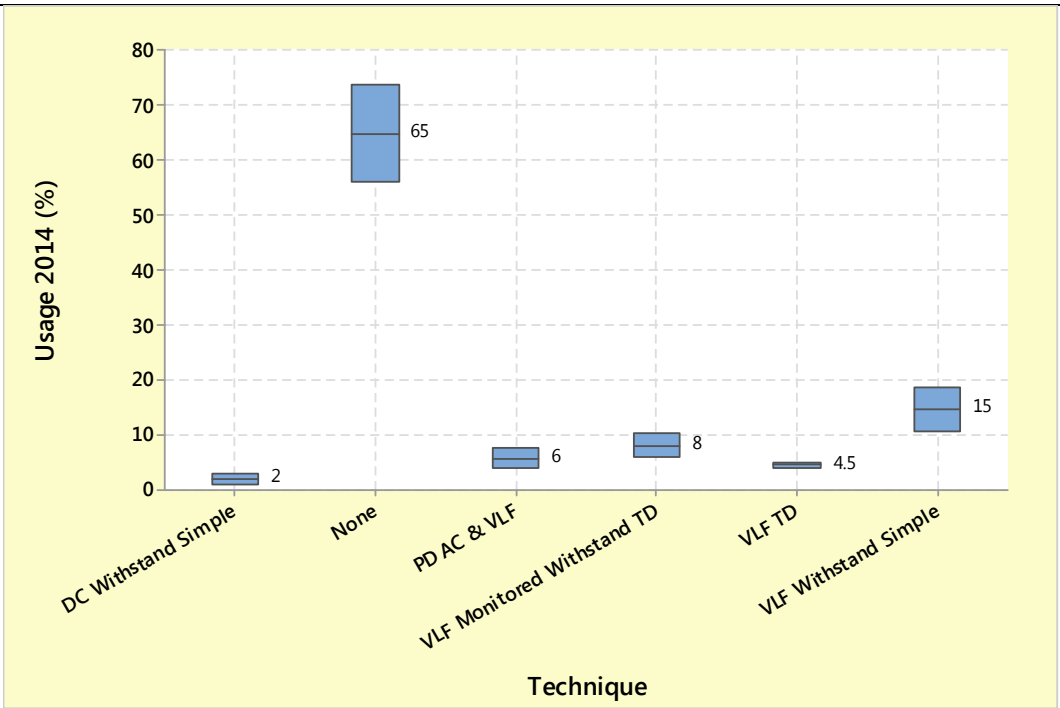

Figure 3: Range of Usage for the different diagnostic techniques – 2014

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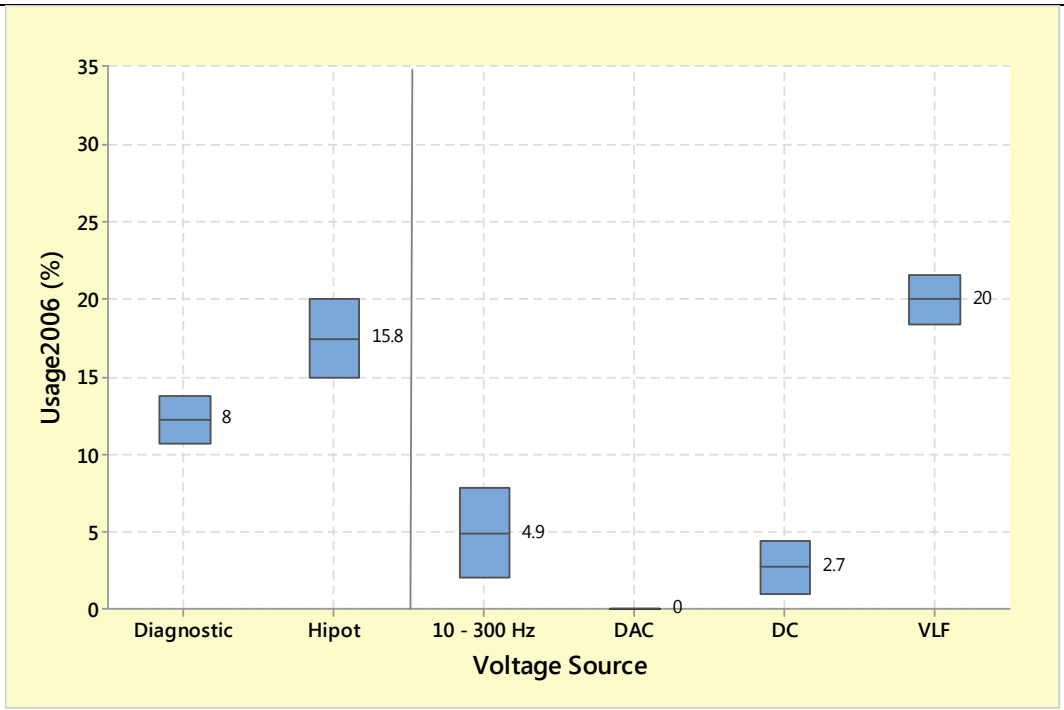

Figure 4: Usage for diagnostic approaches (left) & voltage sources (right) – 2006

2014

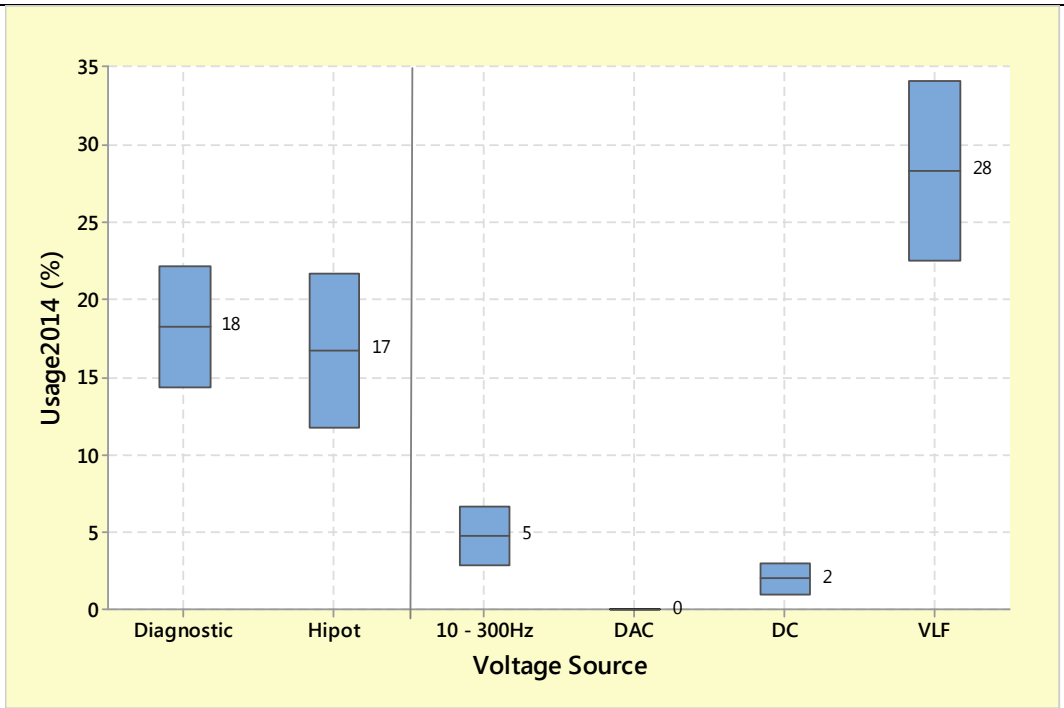

Figure 5: Usage for diagnostic approaches (left) & voltage sources (right) – 2014

Inspection of the cable diagnostic testing technology usage above at MV enables the techniques to be grouped into two broad categories: Mainstream & Niche.

a) Mainstream techniques
    i. Time- Domain Reflectometry (TDR);
    ii. Tan δ at Very Low Frequencies (VLF);
    iii. Simple Withstand Tests at Elevated Very Low Frequencies (VLF);
    iv. Simple Withstand Tests at Elevated Resonant ac – HV & EHV only;
    v. Monitored Withstand Tests at Elevated Very Low Frequencies (VLF) with simultaneous monitoring of Tan δ;
    vi. Monitored Withstand Tests at Elevated Resonant ac with simultaneous monitoring of PD – HV & EHV only;
    vii. Partial Discharge (PD) at elevated Resonant ac or Very Low Frequencies (VLF) Voltages.

b) Niche techniques (not routinely deployed but where equipment maybe/has been commercially available);
    i. Partial Discharge (PD) at elevated Damped ac (DAC) Voltages;
    ii. Combined Diagnostic Tests at Very Low Frequencies (VLF) using sequential PD and Tan δ;
    iii. Dielectric Spectroscopy;
    iv. DC Leakage Current;
    v. Polarization and Depolarization Current;
    vi. Recovery Voltage.

At the diagnostic technique level, evolutionary key takeaways are:

Time-Domain Reflectometry (TDR)

- Usage is difficult to determine.
- The level of usage is estimated to be in the range of 6% -10% in 2014, which is up from the 5% - 8% level of 2006.

VLF Tan δ

- Since 2006 the greatest evolution is in the areas of VLF sources and Tan δ measurement / interpretation. In 2006 the devices were large, complicated to set up and difficult to transport - a trailer or van was required. In 2014 these devices are now portable (one man can move them) with complete integration of the VLF source and Tan δ measurement device in one box.
- The level of usage has increased from 3.5% to 4.5%. However, this likely underestimates that activity as there are a number of users who, between 2006 & 2014, adopted Tan δ and then migrated to Monitored Withstand.
- The guidance provided in the updated IEEE Std. 400.2 has very likely supported the change.

Simple Withstand

- The use of Simple dc Withstand has continued to decline with the conversion to Simple VLF Withstand. The rate of conversion would likely have been higher but it has been limited by the availability of funding for new VLF test units.
- The growth of Simple VLF Withstand has continued (13.5% - 15%) both from adoption and transfer from dc.

Monitored Withstand

- The biggest growth over this period was in the area of the Monitored Withstand: 2.8% in 2006 to 8% in 2014.
- The drivers of the growth have been two-fold:
  - Miniaturization / simplification / availability of the equipment
  - Guidance & familiarity stimulated by IEEE Std. 400 & IEEE Std. 400.2

Damped AC (DAC) Partial Discharge

- This technique shows great promise for PD detection in the field by utilities; however, there are currently no users of this technique in the USA or Canada.

Partial Discharge

- The use of PD in the offline mode has been essentially static over the time period in the utility space

VLF Simple Withstand

- The estimates for 2014 show that VLF is the most preferred of the test voltages
- The increase in usage since 2006 (20% - 28%) is notable and statistically significant

Withstand (Hipot) vs Diagnostic

- In 2006 Withstand (Hipot) was the most preferred mode of operation
- In 2014 the use of withstand (Hipot) increased by 1.2%, while diagnostic tests have increased by 10%
- In 2014 both withstand (Hipot) and diagnostic tests usage are equal

In all the above comments it is important to recall that in this work, for a technique to be considered a utility diagnostic used by a utility, the technique has to be part of a normal / established activity for determining cable system asset health on new and aged cable systems. Thus pilot studies, industrial applications, commercial energy generation (wind farms etc.) and laboratory experiments are not included. Usage estimates that include these applications might be at variance with those provided here.

4.2 Choosing the Most Appropriate Diagnostic Program for an MV Cable System

As noted in other chapters "there is no one *right* approach" to cable system diagnostic testing. Each situation/cable circuit/area/region/utility is likely to have conditions and priorities that will dictate an approach that is unique for that segment. This section offers a general perspective on how the information included in other chapters of this report can be used to select the most appropriate diagnostic for the circuit or set of circuits under consideration.

The preceding section has shown how the usage of diagnostics has changed over the relatively short span of this project. Thus it is unwise to use the simple expedient approach of using previous experience / recommendations to guide the choice as the whole arena has changed so dramatically.

At first sight, the diagnostic selection process would appear to be solely based on technical principles. However, experience gained from 10 years of conducting the CDFI research (from surveys of practitioners, internal discussions and working with more than 25 CDFI participants) shows that diagnostic testing decisions are very often based on a variety of perspectives, including asset management, reliability engineering, dielectric science as well as a very good dose of social science.

The social science perspective can cause the most difficulty for engineers. However, it is a vital part of the diagnostic selection process because it requires engineers to consider topics that are qualitative in nature, such as,

- risk tolerance;
- interfaces with field personnel (including the operators and test crews before, during and after test);
- likely outcomes from the test;
- skill level required to perform the test;
- decision making process during the test; and
- decision making process after the test is performed.

The comments and guidance included in this chapter encompass all of these elements and thus may be considered as a tabulated (rather than software based) expert system.

Thus this chapter is primarily directed towards:

- Personnel who are not familiar with diagnostic testing
- Experienced personnel who are looking to test in new geographic areas and / or test cable systems they have not previously tested

The approaches discussed are offered as only as suggestions and are based on what has worked for others unfamiliar with the topic. It is important to recognize that any approach should start from the needs of the program (essentially the social science) rather than first choosing a diagnostic technology and then trying to find a good location to use it.

4.2.1 Getting Started

To begin, it is important to remember the following:

1) Treat the cable circuits as a system – not simply a cable or a cable accessory. It is not possible to perform a diagnostic test on just a segment of cable or just an accessory. All cable circuits consist of both elements so the circuit it must be treated as a system.
2) Gather as much information as possible about the cable system including its age, accessory types, cable design, insulation type and the failure history
3) Establish why diagnostic tests should be performed on your cable system.
4) Establish the potential diagnostic technologies are available for performing the evaluation and what it takes to deploy each technology (skills required, switching by field crews, etc.).
5) Establish your options for corrective actions (run to failure, repair, rejuvenate, replace).

So 'why perform diagnostic tests on a cable system'? Interestingly, the reasons are quite varied. Outlining the reason(s) does not directly dictate the specific diagnostic test approach to take. However, a clear understanding of why you are performing diagnostic tests on your cable system will help guide the decisions that need to be made once diagnostic data is obtained.

There are a number of drivers/motives for performing diagnostic tests on cable systems, including a need to:

1. Help assure that a new system was properly installed
2. Help assure that an existing system was effectively repaired
3. Improve cable system reliability (reduce failures)
4. Prevent failures before they occur
5. Optimize the use of maintenance dollars
6. Optimize the use of capitol (cable replacement) dollars
7. Follow a management directive to use a specific diagnostic technology

4.2.2 The Process - SAGE

The NEETRAC research has led to the development of the acronym SAGE to describe the four basic phases of an effective diagnostic program. SAGE was first developed in *CDFI Phase I* and has been refined in *Phase II*.

These elements are described as follows:

Selection: This phase encompasses two actions:
a) choose the cable circuits to be tested; and
b) determine the constraints for the testing

Taken together, these actions lead to the selection of the most appropriate diagnostic technology to use for the evaluation.

Action: This phase involves answering the question: What actions are likely to be taken as the result of the diagnostic outcomes (results) or interpretations? The actions are in two groups (Act or Not Act) and may include replacement, defer action, rejuvenation, and/or repair. These actions are chosen based on what is most suitable for the cable system topology and most prevalent failure mechanisms (local or global degradation).

Generation: This phase has been expanded to include two sequential parts:
a) Generating the test data
b) Using the measured data (singly or in combinations) to determine a final result which may involve placing the cable system segments or circuits into an act or not act class or to establish a health index.

Ultimately these two parts help to establish the preferred remediation (Action).

Evaluation: This phase provides answers to the questions: Are the methods employed for Selection, Action, and Generation giving the expected results - lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

Figure 6 illustrates how the four components function together over time to produce, if implemented properly, a reduction in the failure rate. Note that this benefit is not realized immediately nor does it cease once the program has ended - there is a lag before the benefit is fully realized. Furthermore, failure rates do not begin to change until the actions directed by the diagnostic testing (Generation) are well underway. Selection, Generation, and Action are each defined stages in time while the Evaluation component is ongoing throughout the entire test program and beyond.

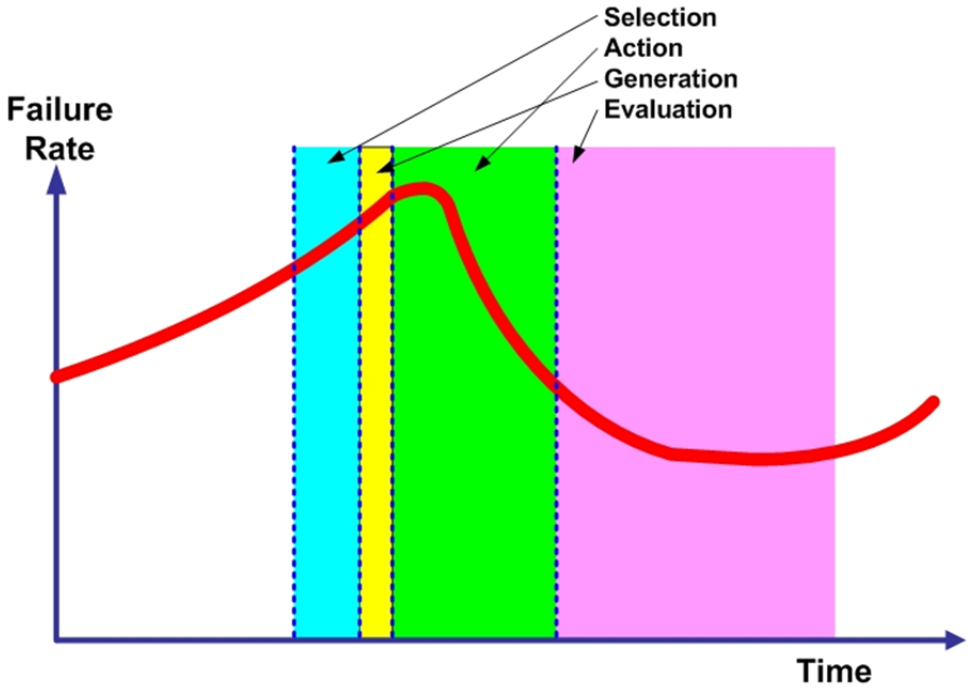

Figure 6: Effect of SAGE on the Failure Rate of a Target Population

Note: the failure rate in Figure 6 continues to increase during the Selection and Generation phases. Only after the actions are completed does the failure rate start to decrease. After some time, the failure rate will begin to increase again and this would retrigger the SAGE process. Each phase of the SAGE process is discussed in more detail in the following sections of this chapter.

4.2.2.1 Selection

The selection phase represents the first stage of the SAGE process. This process should be performed *before* a diagnostic technology is chosen. Elements of the selection process that help the user decide which circuits to test are outlined as follows:

Choosing the cable circuits to be tested

The utility should use all available data / knowledge to identify those circuits that may be susceptible to failure within a chosen time horizon, generally 5-10 years. These circuits may be in

areas that have historically experienced higher than usual failure rates or may simply be of critical importance to system operation or a combination of both. Regardless of the criteria used, the size and composition of this population greatly affects potential reliability improvements and economic savings resulting from the program.

These circuits constitute the "target population" that will be tested and acted on using one or more diagnostic tests. Important considerations for the Selection process are:

System Construction

- How are the circuits used in the system?
- Is the system a radial, looped or network system?
- What level of redundancy is present?
- Can circuits be easily isolated without impacting customers?
- What is the cable design?
  - voltage class
  - insulation thickness
  - insulation material (Polyethylene, EPR, fluid impregnated paper)
  - metallic shield type (tape, LCT, wires)
  - jacket (yes or no)

Available Historical Data

- Number of circuits of the same type in service
  - their ages
  - their failure histories
- If data are not available then simple heuristics may suffice – see Table 1.

Failure Projections

- How fast are failure rates increasing?
- If there are cable or accessory designs in use, in which are the failure rates increasing fastest?

Prevalent Failure Mechanism

- What causes the most failures?
- What is the failure the mechanism?
  - electrical (electrical or water trees)
  - mechanical (damage)
  - environmental (neutral corrosion)
  - inherent (manufacturing imperfections)
  - thermal in nature (overheating connectors)?

Objective

- Is the objective to:
  - improve reliability?
  - reduce maintenance costs?
  - garner knowledge of system health before determining action to take?
  - a combination of all three?

- Has a budget been allocated to achieve the objective?

The above information is invaluable in determining which circuits to test. However, the relative importance of a circuit(s) is also essential since they will often supply important customers where an outage would result in notable economic or newsworthy consequence for the utility.

Determine the testing constraints
It is very important to establish in advance what you can and cannot do or accept during a diagnostic test program. A list of things to consider is outlined below.

Acceptability of Failure During Testing
- How much risk of failure can be tolerated?
- Is a failure tolerable during testing if circuits are subjected to elevated test voltages?

This is important because in many cases once a cable segment fails, testing in that area is curtailed until a repair can be affected. This will noticeably impact the throughput/efficiency of the test program.

Tolerance of Uncertainty
- How accommodating is the organization of uncertainty? Does your organization insist that answers be black or white or is it accepting of shades of grey?

Performing Tests and Interpreting Results
- Will testing be performed by internal resources or subcontractor resources?
- Who will interpret the test results?
- Is the test interpretation processed internally or externally or by a subcontractor?
- Is the subcontractor part of the remediation process and therefore subject to bias when making the interpretation?

Acceptance of Complexity and Transparency
- Is it institutionally acceptable to have a complex process for interpreting the results or is a simple answer required?
- Does your company accept an answer without knowing how the data is processed (opaque process), or does your company want to know, or be able to know at some future date, exactly how the test results are used to make recommendations (transparency)

Note that as the information content of a diagnostic technique increases, so does the complexity.

Nimbleness of Decision Making - as the information content of a diagnostic technique increases so does the need for real time decision making Is it institutionally appropriate for decisions to be devolved to test crews or a subcontractor; both of these are often stakeholders in the remediation process

Cost of the Diagnostic
- Does the estimated cost (cost per circuit = cost per day / throughput) of the diagnostic represent a large portion of the replacement cost of the component?

Resolution of the Diagnostic

- Does the diagnostic provide enough information to classify the components into the desired number of subpopulations?

The two part process above (choosing the circuits and establishing the constraints) results in very good context information but is difficult to make actionable. The following example (Table 1) illustrates how a company could collate this information as a means of classifying the circuits they may want to test. The example area contains 14 circuits, which are classified by a two dimensional selection matrix which balances failure rate against the impact of service failures.

Table 1: Example Selection Matrix - Qualitative – Residential Customers

FAILURE RATE	More than Twice Average Failure Rate	2 circuits		
	Between Average and Twice Average Failure Rate		2 circuits	2 circuits
	Less than Average Failure Rate	3 circuits	2 circuits	3 circuits
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

Numeric information (number of circuits) is preferred to describe the cells. However, this information may not be available. When that occurs, the cost of an outage could potentially be used as an alias for the impact of service failures. The example in Table 2 is similar to Table 1, but the data used is based upon the economic cost of a failure ($ pa) using the established DOE model discussed in Chapter 14. In this table, the cost of an outage (failure) for the circuit(s) represented in the cell is shown in bold. It is a function of the number of customers on the circuit(s) along with the impact cost of an outage per 1000 customers. The cost of a failure per 1000 customer is a function of the SAIFI and SAIDI rates for the circuits in question.

Table 2: Example Selection Matrix – Semi Quantitative – Residential Customers

FAILURE RATE	140% Average SAIFI (High SAIFI)	**$600** 100 customers $6k/1000 customers	**$0** 0 $8k/1000 customers	**$0** 0 $10k/1000 customers
	Average SAIFI	**$0** 0 $4k/1000 customers	**$1200** 200 customers $6k/1000 customers	**$1800** 200 customers $9k/1000 customers
	60% Average SAIFI (Low SAIFI)	**$900** 300 customers $3k/1000 customers	**$1000** 200 customers $5k/1000 customers	**$2100** 300 customers $7k/1000 customers
		50% Average SAIDI	Average SAIDI	160% Average SAIDI
		IMPACT OF A FAILURE		

Ultimately, some decision making overlay is required. Work in the CDFI has shown that that a new user of diagnostics should approach testing somewhat differently than an experienced user.

The differences are shown in Table 3 and Table 4. One of the most significant errors that new users make is that they immediately attempt to test in the upper right hand area, where their experience level is not sufficient to deal with the multitude of issues associated with an area that has a large number of problems. A much more effective strategy is to start testing in either of the green areas and then move to the green areas of Table 4 as experience increases.

Table 3: Interpretation of the Selection for a *New* User of Diagnostics

FAILURE RATE	More than Twice Average Failure Rate	Useful for gaining experience, but benefits are likely low		Not optimal for a new user - too many issues to handle/consider
	Between Average and Twice Average Failure Rate		Useful for learning, with increasing benefits but also increasing risks	
	Less than Average Failure Rate	Not optimal – likely low benefit		
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

Table 4: Interpretation of the Selection for an *Experienced* User of Diagnostics

FAILURE RATE	More than Twice Average Failure Rate	Not Optimal – likely low benefit		Optimal – maximum benefits (with maximum risks)
	Between Average and Twice Average Failure Rate		Optimal - increasing benefits / risks	
	Less than Average Failure Rate	Not Optimal – likely low benefit		
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

4.2.2.2 Action

The Action stage of the SAGE process refers to the establishment of possible repair and replacement actions based on the results from the diagnostic test. Ideally, a specific action can be established for each circuit tested based on the condition indicated from the diagnostic test. The goal is to perform the minimum level of actions that will restore the circuit to reliable operation for the next several years.

Each action has an associated cost and level of reliability improvement that it will deliver. For example, the cost of replacing a bad splice in a 500 ft segment is very different from the cost of replacing the entire segment. On the other hand, the reliability of the repaired segment is not likely to be as high as the reliability of the replaced segment. An economic analysis can be used to quantify the value for one action compared to another.

When considering cable systems, the list of available actions is relatively short and includes:

a) Wholesale Replacement – complete replacement of the entire target population;
b) Targeted Replacement – replace only the segments that the diagnostic test indicates are degraded;
c) Repair – remove short length(s) of cable and replace with two joints and a piece of cable or replace problematic accessories;
d) Rejuvenation – liquid injection (PE-based insulations); and
e) Do Nothing.

The choice of actions will affect the choice of diagnostic technique(s) since some diagnostics are unable to locate specific points of degradation within a given segment. Furthermore, the composition of the target population might limit the actions a utility is able to take.

Once a suitable approach for each diagnosis exists, tests may be performed on the target population to generate the diagnostic data. This constitutes the next phase of the process – the Generation phase.

4.2.2.3 Generation

The generation stage of the SAGE process starts with the choice of a suitable diagnostic followed by testing on the target population of circuits. By definition, the diagnostic techniques measure specific characteristics of the circuit thought to be symptomatic of known failure mechanisms.

Generation has two sequential parts:
a) generating the test data; and
b) using the measured data (singly or in combinations) to determine a final result (Action Class or a Health Index).

The different diagnostic technologies available for generating test data are discussed in Section 4.3. However, at this point it is useful to consider some examples.

The first example is for cable diagnostic tests made using Tan δ (dielectric loss measurements). The actual measured values are:

- sequences (usually 6) of Tan δ data at 0.5Uo;
- sequences (usually 6) of Tan δ data at 1.0 Uo; and
- sequences (usually 6) of Tan δ data at 1.5Uo.

These measurements permit, derived parameters to be calculated:

- Tip Up;
- Tip Up of the Tip Up (Tu Tu);
- Standard deviation of Tan δ at 1.0Uo; and
- Mean Tan δ at 1.0 Uo.

The derived parameters enable, one of two determinations can be made:

a) The tested cable segment can be placed in one of the three classifications:
   i. action required (AR);
   ii. further study (FS); or
   iii. no action required (NA).

   OR

b) A Health Index can be calculated used to indicate where the tested cable segment lies along the spectrum of cable segments tested to date i.e. *this segment is the x^{th} percentile of all similar cable systems tested to date.*

The second example is for cable diagnostic tests made using Damped ac (DAC) partial discharge measurements. In this case the actual measurements indicate one of the following and are qualitatively/subjectively used to determine whether or not the tested cable segment falls into the action required, further study or no action required category:

- discharge present above the background noise below $1U_0$ at location X;
- discharge present above the noise in range of U_0 to $1.4U_0$ at location X; or
- discharge present above the noise above $1.4U_0$ at location X.

Although numerical values may be ascribed to this type of measurement, there is no adequate or definitive method of interpreting the different numbers such that the tested cable circuit may be placed into a specific condition category. This means that partial discharge measurements made on similar cable circuits cannot be compared and partial discharge measurements made using different technologies cannot be compared.

4.2.2.4 Evaluation

The final stage of the SAGE process is the evaluation stage. This is the stage where utility engineers ask themselves: Are we getting what we expected? This question covers many issues, but can be summarized in two key topics: (1) Cost and (2) Reliability. A diagnostic program must deliver improved reliability at a lower cost as compared to other maintenance strategies to be considered effective. Evaluation tools, such as those presented in Appendix A can be used to assess the impact the program has made on system reliability. Furthermore, the utility can then adjust in real time to improve program performance. The evaluation phase represents an ongoing process that remains in place until the need again arises to conduct another diagnostic program.

Commissioning diagnostics are used shortly after a system is installed or after a repair. When diagnostics are used for this purpose, the health (classification) of the system is not of primary interest. The engineer simply wants to know if there are any significant defects caused by installation workmanship. Generally, most new components are factory-tested (recognize that the

standards and implementations may be quite different from component type to component type) so there is an expectation that there are no built-in defects. Thus the goal of performing the diagnostic test is to help ensure that the system is free from gross defects. Importantly, the test technology and test conditions selected for commissioning tests are generally not designed for aged systems and should not be applied to aged systems. However, when new components or cable segments are installed on an aged system, modifications to the test program may be required.

Condition assessment diagnostics are applied to aged cable systems. This is much more of a process approach rather than spot check assessment using a pass/fail criterion. Consequently, it is important to focus on classification and avoid doing harm (further weakening) to the system.

4.2.3 Information on the Diagnostic Techniques

Utility engineers have voiced a desire for guidance on the experience levels necessary for conducting diagnostic tests and interpreting test results (the Generation phase of SAGE). Table 5 provides basic information garnered from the research activities on available diagnostic techniques, their expected output and who is involved.

Table 5: Typical Diagnostic Technique Deployment					
Technique		**Testing performed by**	**Interpretation of Raw Data**	**Form of Output to end user**	**Condition Assessment performed by**
Time Domain Reflectometry (TDR)		Utility or Provider Technician	Utility or Provider Technician or Engineer	TDR Trace	Utility or Provider by comparison with library of curves
Offline Partial Discharge Resonant ac		Provider Engineer	Provider Engineer	Report with classification data [1]	Provider using Proprietary Criteria [4]
Offline Partial Discharge VLF		Provider or Utility Technician or Engineer	Utility or Provider Engineer	Data or Report with numeric data [2]	Provider or Utility using Knowledge Rules [5]
Offline Partial Discharge DAC		Utility or Provider Technician			Utility or Provider using Knowledge Rules [5]
Online Partial Discharge		Provider Technician or Engineer	Provider Engineer	Report with classification data [1]	Provider using Proprietary Criteria [4]
Tan δ (VLF)		Utility Technician	Utility Technician or Engineer	Numeric data [2]	Utility using Knowledge Rules from IEEE Std. 400.2™ or CDFI Tools
Withstand	AC Resonant	Utility Technician	Utility Technician or Engineer	Survival data [3] (Pass / Fail)	
	VLF				
Monitored Withstand	PD	Provider or Utility	Provider or Utility Engineer	Survival data [3] (Pass / Fail) & numeric data [2]	Utility using Knowledge Rules from CDFI Tools
	Tan δ	Utility Technician	Utility Technician or Engineer		

[1] Classification Data – results are described in terms of the membership of a number of classes ranging from good to poor performance (A, B, C; Repair, Replace, etc.); no information is conveyed about the relative position within a class (it is not possible to prioritize within a class); class membership can be determined by either Proprietary Criteria or Knowledge Rules.

[2] Numeric Data – results are described in terms of a continuous variable (inception voltage, loss, count etc).

[3] Survival Data – two classes: Pass / Not Pass; no information is conveyed about the margin within a class.

[4] Proprietary Criteria – the membership in a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are not open to scrutiny; the receiver of the classification data (see footnote 1 above) is unable to reassess the class membership as they do not (generally) have access to the measured data or the criteria; the receiver of the data has no means to verify whether the criteria have changed (improved of degraded).

[5] Knowledge Rules – the membership in a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are open to scrutiny; the receiver of the classification data (see footnote 1 above) is able to reassess the class membership as they have

access to the measured data and the criteria; the receiver of the data has a means to verify that the criteria have remained unchanged over time.

As discussed earlier, the assessment provided by diagnostic testing technologies generally falls into two location categories: global and local. Table 6 describes which diagnostic tests are most commonly used for global and local assessments.

Table 6: Local vs. Global Assessments for Diagnostic Techniques

Technique		Identifies Local Defects	Identifies Global Degradation
Time Domain Reflectometry (TDR)		X	
Offline Partial Discharge (AC Resonant)		X	
Offline Partial Discharge (VLF)		X	
Offline Partial Discharge (DAC)		X	
Online Partial Discharge		X	*
Tan δ (VLF)			X
Withstand	AC Resonant	X**	
	VLF	X**	
	DC (PILC Only)	X**	
Monitored Withstand	AC Resonant PD	X	
	VLF PD	X	
	Tan δ	X**	X

* While traditional PD measurements focus on local defects, online providers sometimes provide an assessment that is related to global condition assessment.
** The location is determined by TDR when dielectric puncture occurs

4.2.4 Choosing the most appropriate diagnostics - Selection

4.2.4.1 Basic Approach

In principle, the issues outlined in Section 4.2.1, Table 1 through Table 6 with the detailed information in the diagnostic specific chapters provide sufficient information to select the most appropriate diagnostic. However, those with little or no diagnostic testing experience may find the information provided below to be a more convenient way to start the selection process.

The approach uses five questions help to identify options to consider:

1. Who do you anticipate will perform the tests?
2. How would you best describe your tolerance to dielectric failures on test (FOT)?
3. How would you best describe the majority of cable circuits in the portion of the system under consideration?
4. How would you describe the age of the cable system?

5. Do you know what is failing?

Questions 1 and 2 are used in Table 7 to select the appropriate table with which to consider the outputs from Questions 3 to 5.

The diagnostic suggestions take into account both the reliability engineering (electrical engineering and dielectric science) and social science elements of the decision making process. Some of the main rule of thumb/experience/heuristic based approaches are provided below:

Time-Domain Reflectometry (TDR)

- This test should be utilized on all but the most complicated / long circuits to obtain at a minimum the length of the cable system.
- It provides useful information on the number of joints in a cable circuit.
- It can be difficult to interpret when multiple joints are present.
- It does not provide quantitative data on the condition of the cable neutral.

VLF Tan δ

- Test protocols are well defined and exist in approved industry standard (IEEE 400.xx).
- Assessment tools are available for interpreting the data into "No Action Required", "Further Study", and "Action Required" classes for all insulation types.
- A Health Index can be determined.
- Is often conducted and interpreted by utility personnel.

Simple Withstand Voltage

- Test protocols exist (AC Resonant & VLF) and are described in approved industry standards (IEEE 400.xx).
- AC Resonant, DC & VLF voltages meet the criteria for Withstand Tests.
- VLF withstand tests are useful for evaluating hybrid cable systems.
- This is the most straightforward diagnostic test to interpret and perform.
- This test is almost always conducted by utility personnel.

Monitored Withstand Voltage

- Test protocols are available (AC Resonant & VLF) and are described in an approved industry standard (IEEE 400.xx).
- Assessment tools are available, for VLF Tan δ, to make decisions in real time while the test is being performed, significantly increasing test program efficiency.
- Can be conducted and interpreted by utility personnel.

Partial Discharge (Damped AC (DAC))

- Technique is promising; however, there are no users of this technique in USA or Canada.
- May be conducted and interpreted by utility personnel.

Partial Discharge (AC Resonant & VLF)

- There is limited agreement in the industry on condition assessment if PD is present.
- No industry standard is available for interpreting PD measurements in the field.

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- This is the most difficult diagnostic to employ in the field.
- This technique remains too complicated for most utilities to conduct and interpret on their own, although recent automation efforts are improving usability.

It is important to recall that all the tables in this chapter should be useful for an experienced user but are designed for:

- People first embarking on diagnostic testing; and
- People who have performed some diagnostic testing but are considering moving to a different location / cable type / mode of operation.

4.2.4.2 Specific Guidance

Questions 1 and 2 (above) are used in Table 7 to select the appropriate table with which to consider the outputs from Questions 3 to 5. Table 7 summarizes the research findings and provides specific diagnostic technique suggestions based on a user's tolerance for failures on test (FOTs) and who is anticipated to conduct the test.

Table 7: Initial Diagnostic Screening Matrix

How would you best describe your tolerance to dielectric Failures on Test (FOT)	**Who do you anticipate to undertake the tests?**	
	Utility Personnel	**Sub-Contractor**
Acceptable to avoid Failures in Service (FIS)	See Table 8	See Table 9
Should be Minimized but Acceptable to avoid Failures in Service (FIS)	See Table 10	See
Not Acceptable (Very Few) even to avoid Failures in Service (FIS)	See Table 12	See Table 13

Table 8 through Table 13 use the research results to suggest reasonable tests to consider based on what is known about the cable circuits under consideration from Table 7. If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

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Table 8: Acceptable Risk of Failures on Test (FOT), Test by Utility Personnel

	How would you describe the age of the cable system?			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
				TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
				TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9

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Table 9: Acceptable Risk of Failures on Test (FOT), Test by Sub-Contractors				
	How would you describe the age of the cable system?			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, And TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, And TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

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Table 10: Minimal Risk of Failures on Test (FOT), Test by Utility Personnel

	How would you describe the age of the cable system?			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9

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Table 11: Minimal Risk of Failures on Test (FOT), Test by Sub Contractors				
	How would you describe the age of the cable system?			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
		TDR – Chapter 5 & 11 And Offline PD – Chapter 7 or 8		TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And Offline PD – Chapter 7 or 8
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Monitored VLF Withstand – Chapter 10
				Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, And TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, And TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9
				TDR – Chapter 4 & 11 And Online PD – Chapter 7 or 8

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

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Table 12: Failures on Test (FOT) Not Acceptable, Test by Utility Personnel				
	How would you describe the age of the cable system			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11	Don't know what is failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
	Hybrid	Nothing Available	Don't know what is failing	Nothing Available
			I think that accessories are failing	Nothing Available
	Paper	Nothing Available	Don't know what is failing	Nothing Available
		Nothing Available	I think that accessories are failing	TDR – Chapter 5 & 11

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

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Table 13: Failures on Test (FOT) Not Acceptable, Test by Sub Contractors				
	How would you describe the age of the cable system			
How would you best describe the majority of cables in the cable system		New	Old	
	Extruded	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8
			I think that accessories are failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8
				Online PD – Chapter 7
	Hybrid	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	Nothing Available
			I think that accessories are failing	Online PD – Chapter 7
	Paper	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	VLF Tan Delta – Chapter 5
				Online PD – Chapter 7
				Offline DAC PD – Chapter 7
		Online PD – Chapter 7	I think that accessories are failing	Online PD – Chapter 7
				Offline DAC PD – Chapter 7

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

The Decision Tables (Table 8 - Table 13) above can be quite intimidating as they display the plethora of options and the potential solutions revealed by this research. In an effort to make them more understandable, two Case Studies are presented to demonstrate their use.

Case 1:
Assume that you are a new user, the failure rate is 150% of average and failures in service have a high impact. Table 3 shows that we know that diagnostic testing is a reasonable thing to do (Useful for learning, with increasing benefits but also increasing risks).

Now we need to answer additional questions (see section 4.4.1):

1. *Who is the service provider?* Diagnostic testing would be performed by a sub-contractor.
2. *What is the acceptability of Failures on Test (FOT)?* Failures on test are acceptable but should be minimized.
3. *What is the cable type?* Majority of the cables on the system are extruded
4. *What is the cable age?* Old
5. *What is failing?* Accessories

With this information, Table 7 tells us that we should go to Table 11. Table 11 indicates to us that the following diagnostic test technologies are recommended and directs us to the specific chapter for further guidance:

1. **TDR – Chapter 5 & 11**
2. **Monitored VLF Withstand – Chapter 10**
3. **Offline PD – Chapter 7 or 8**

Case 2:
Now assume that you are a new user, the failure rate is 250% of average and failures in service have a low impact. Table 3 shows that we know that diagnostic testing should be very beneficial (Optimal – maximum benefits with maximum risks).

Now we need to answer additional questions:

1. *Who is the service provider?* Diagnostic testing would be performed by a utility crew.
2. *What is the acceptability of Failures on Test (FOT)?* Failures on test are acceptable.
3. *What is the cable type?* Hybrid (mixture)
4. *What is the cable age?* Old
5. *What is failing?* Don't know

With this information, Table 7 tells us that we should go to Table 8. Table 8 indicates to us that the following diagnostic test technologies are recommended and directs us to the specific chapter for further guidance:

1. **Simple VLF**

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A blank assessment template is provided below as a convenient method for recording the circumstances for your situation and the answers to the five questions.

FAILURE RATE	More than Twice Average Failure Rate			
	Between Average and Twice Average Failure Rate			
	Less than Average Failure Rate			
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

Describe Area chosen for Testing:	
Relevant History of Cable System	
1. Who do you anticipate to undertake the tests?	
2. How would you best describe your tolerance to dielectric Failures On Test (FOT)?	
Table 7 indicates Table	
3. How would you best describe the <u>majority</u> of cables in the cable system?	
4. How would you describe the age of the cable system?	
5. In your Old Cable System - Do you know what is failing	
Consider the following Diagnostics (Taken from relevant Table (Table 8 to Table 13)	

4.3 Summary

The complexity of cable system diagnostic testing can be daunting for those unfamiliar with the process. The research information in this chapter is intended help by condensing a plethora of information on diagnostic testing into a series of easy to follow steps or processes. The discussion is designed to help potential cable diagnostic technology users a way to focus on the relevant issues. It does this by providing an overview of how to approach diagnostic testing with a quick review of available technologies and how they might reasonably be deployed under a given set of circumstances.

It is important to reinforce the fact that these are general guidelines. Someone with an advanced knowledge of diagnostic testing may choose to take a different approach and still achieve positive outcomes. However the intent is to point unfamiliar users in the right direction such that they can avoid costly mistakes and maximize the potential value of performing a cable system diagnostic test program.

CHAPTER 5

Time Domain Reflectometry (TDR)

Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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5.0 TIME-DOMAIN REFLECTOMETRY (TDR)

5.1 Test Scope

A time-domain reflectometer locates and characterizes changes in impedance in a cable system. These changes can be caused by:

- faults (shorts)
- joints (splices)
- open connections
- taps in the cable system
- deteriorated neutrals
- water ingress into insulation material or joints
- bad (high resistance) connectors
- Any other type of anomaly affecting the characteristic impedance of the system.

5.2 How It Works

A TDR works like radar. A fast rise time pulse is injected into the cable system at one end (near end). As the pulse travels down the cable, any change in the characteristic impedance (impedance discontinuities) will cause some of the incident signal to be reflected back towards the source. The reflected pulse components will be positive or negative depending on whether the impedance is greater or less than the cable's characteristic impedance. The initial pulse and the reflection are plotted against time on the instrument display, like an oscilloscope. Since the instrument can be calibrated to determine the speed of the pulse in the cable, the conductor distance to the end of the system can be determined.

This information can also be used to locate discontinuities indicated by reflected pulses. In addition, the shapes of reflected pulses on the instrument display help the operator to determine the nature of the discontinuity.

The magnitude of the reflection at a discontinuity is calculated as the reflection coefficient or ρ. It is calculated as:

$$\rho = \frac{Z_d - Z_o}{Z_d + Z_o} \qquad \textbf{Equation 1}$$

Where,
Z_o: is the characteristic impedance of the cable and Z_d is the impedance of a discontinuity.

The value of ρ ranges from 1 (open circuit) to -1 (short circuit). A reflection coefficient of zero indicates there is no reflection, implying that the cable system terminates at impedance equal to the characteristic impedance of the tested system.

5.3 How It Is Applied

Typically, this technique is performed offline. A fast rise time, low voltage pulse is applied between the conductor and the insulation shield of a cable system at an elbow or termination. As the pulse travels through the cable system, reflections are produced by discontinuities and changes in system impedance. The initial and reflected pulses are displayed against time on an oscilloscope type display and interpreted by the operator. Since the velocity of propagation (VoP) of the TDR pulses is known or can be estimated, the time can be converted to distance or location. An experienced operator can often determine the source (cause) of an impedance discontinuity by the shape and magnitude of the reflected signals.

The test duration (including interpretation) is between five and ten minutes once the TDR and the cable system are connected.

Table 1: Overall Advantages and Disadvantages of TDR Measurements

Advantages	• Testing is easy to employ. • Test equipment is small and inexpensive. • Test equipment uses low test voltage (less than U_0). • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires maintaining accurate data. • Locates areas of the cable system with impedance related problems.
Open Issues	• The ability to perform the test online is unclear. • Proper interpretation of TDR data may require the history of cable system construction. • The test voltage of a low voltage TDR may not be high enough to detect some dielectric imperfections. • It is difficult to interpret some impedance discontinuities. • It is difficult to interpret results on tape-shielded cables. • Selecting the pulse width for optimal resolution and distance can be problematic. • Interpreting results on circuits with multiple taps is challenging. • Length measurement requires that the start of the TDR pulse be identified, this can be difficult.
Disadvantages	• Skilled operators are required for testing and post analysis. • Blind spots due to the ringing effect occur at the near end where the pulse is injected. The length of cable within the blind spot depends on the injection method and width of the pulse. • Electrical noise may interfere with the low voltage TDR signal. • Successful location of an impedance discontinuity depends on having the correct velocity of propagation in combination with the underground cable system layout.

However, one of the more important issues when performing TDR measurements is to understand that the length reading on the TDR unit is uniquely related to the cable system conductor length and not the surface distance between the near and far ends of the system under test. This fact causes two challenges that are addressed in detail later in this chapter (see section on *CDFI* Perspective). The first challenge is related to the relationship between how the cable system was arranged underground and how that affects precisely locating an accessory or anomaly; secondly, the error on the velocity of propagation that directly affects the length readings and thus TDR trace interpretation results. An illustration for different underground cable system layouts appears in Figure 1.

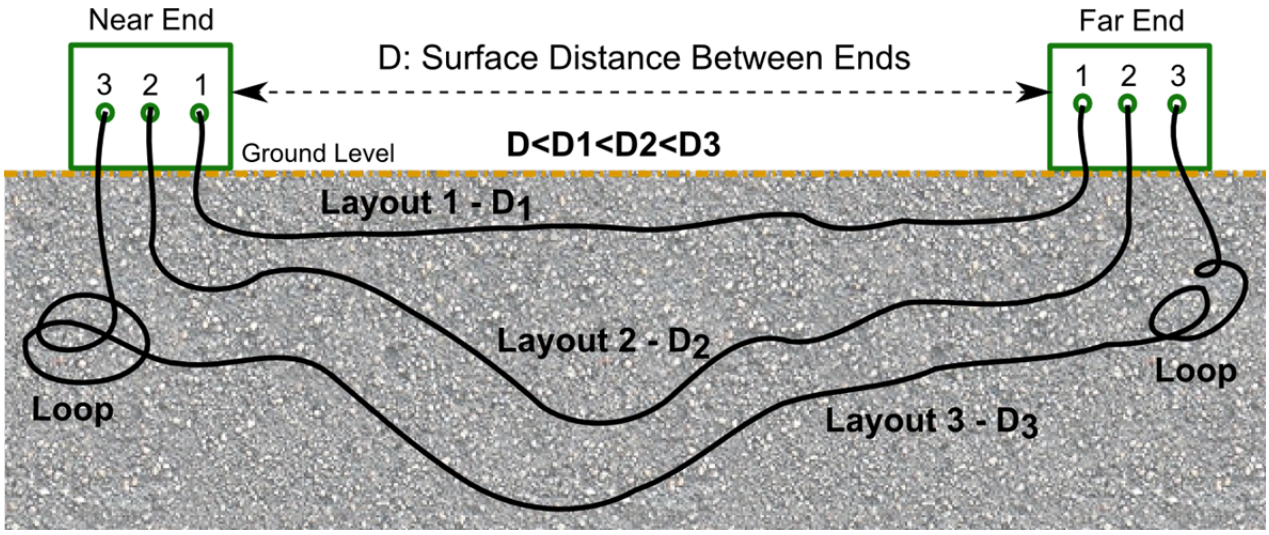
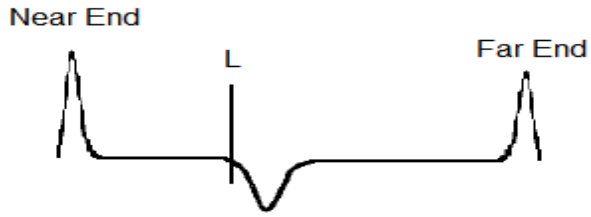
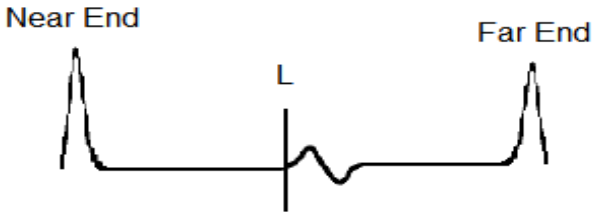
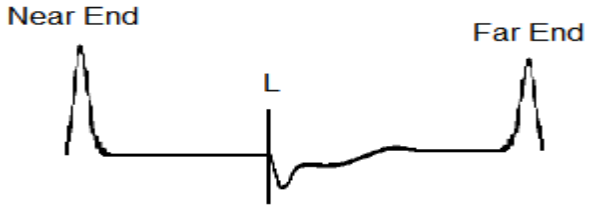
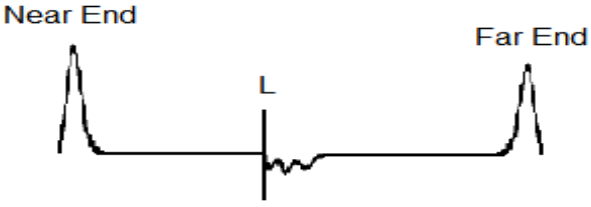
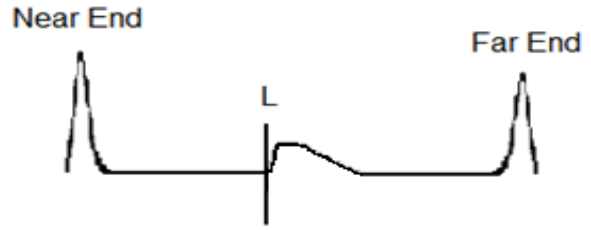


Figure 1: Illustration for Different Underground Cable System Layouts

As observed in Figure 1, there are different ways in which a cable system can be configured underground which directly affects the conductor length and thus the TDR results. The relationship between the conductor lengths for all layouts (D_1, D_2, and D_3) and the separation surface distance between ends (D) appears in Figure 1. Figure 1 figure also illustrates an extreme case where loops could be included in the cable length that could be left under the base of a switchgear cabinet, for example.

5.4 Success Criteria

Typical waveforms and their interpretation appear in Table 2. The actual appearance of the waveforms varies and will not exactly match those shown in references. Therefore, there are no unified success criteria for TDR testing.

Table 2: Cable System Conditions Distinguishable using TDR [1]	
Case	**TDR**
Uniform cable system with no joints.	
Uniform cable system with no joints and shorted conductor at distance L from Near End.	
Cable system with a joint at a distance L from Near End.	
Cable system with a wet joint at a distance L from Near End.	
Cable system with water ingress at a distance L from Near End.	
Cable system with localized corroded neutrals at a distance L from Near End.	

5.5 Estimated Accuracy

The amount of TDR data needed to compare test results and actual findings is insufficient to calculate accuracies. In addition, most TDR results are not provided in pass/fail terms, but rather as

general information concerning the tested cable system.

5.6 *CDFI* Perspective

Research shows that TDR is a useful tool for diagnosing potential cable system problems. It is an easy and fast way to scan a cable system, associated accessories (joints and terminations), and anomalies that affect the system characteristic impedance. TDR is especially valuable during field measurements where portability is essential and cable systems are often long. TDR has been used here to obtain preliminary data on the cable system to be tested, *i.e*. length and number of splices. It is also used as a diagnostic tool providing an initial condition assessment of the cable system, *i.e*. neutral condition, possible water ingress, and others.

A TDR unit typically uses very low power. Because of the non-destructive nature and usefulness of the data provided, it is highly recommended that it be performed prior to any other diagnostic test. The TDR may even provide some information for hybrid cable systems. While the distances/locations would not be correct for some of the system, the number of joints would still be measurable. Unfortunately, branch systems present an additional challenge that has yet to be overcome for the TDR.

During the *CDFI* project a considerable amount of knowledge has been accumulated regarding the use of TDR as a useful tool for diagnosing potential cable system problems. As with any diagnostic tool, accurate data interpretation maximizes the value of the resulting data. Thus, a variety of issues addressing TDR deployment and applicability have been found, analyzed, and understood, they include:

- Examination of the waveform/trace to understand the tested system characteristics and identify anomalies.
- Comparison the length of one phase of a cable system against a companion phase.
- Importance of understanding the cable system characteristic impedance and velocity of propagation.
- Relevance of the TDR pulse width and amplitude.
- Practices used for TDR pulse injection.
- TDR for condition assessment of cable system neutral.
- The role of TDR leads.
- Identification of the cable system far end.
- TDR dual-ended deployment.
- Operator training.

All these issues are discussed in detail in the following sections and they represent the main contribution of the *CDFI* to the TDR measurements for condition assessment of cable systems.

5.6.1 Diagnosis via Waveform Analysis

Interpreting the signal to provide an accurate TDR condition assessment requires experience. TDR traces with similar condition assessments can look different from the examples shown here, even if the cable system is the same type and length. During one series of field tests, a failure occurred at a splice after testing a PILC feeder cable in an area that had experienced several failures. Upon examination, water was found in the splice. Evidence of the water appears in the TDR trace for that cable (Figure 2). The length of the cable system tested and a rough estimate location of the water ingress given by the TDR correlated with both the actual length and the failure site location.

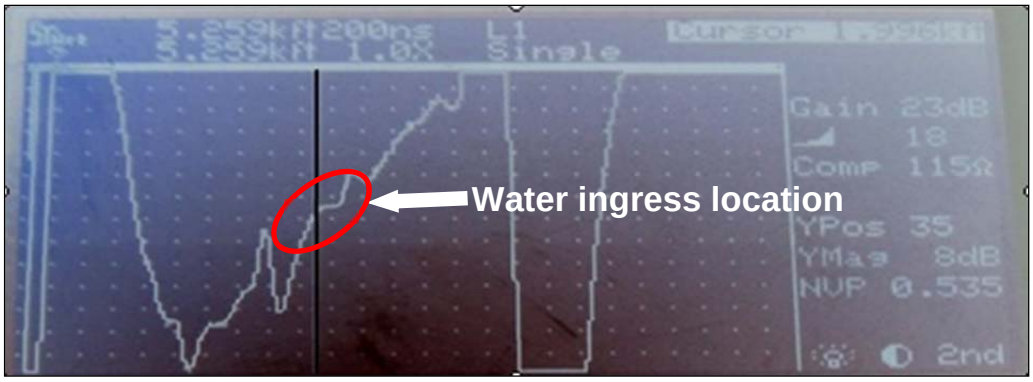


Figure 2: TDR Trace - Moisture in Splice

During another series of field tests performed on PILC cable systems, a significant change in the characteristic impedance of the cable insulation was detected at a specific location using a TDR test. Figure 3 shows a sharp negative peak on the TDR trace indicating the location of the change in insulation impedance. Examination of the cable system in that area found the manhole full of water with signs of oil leakage.

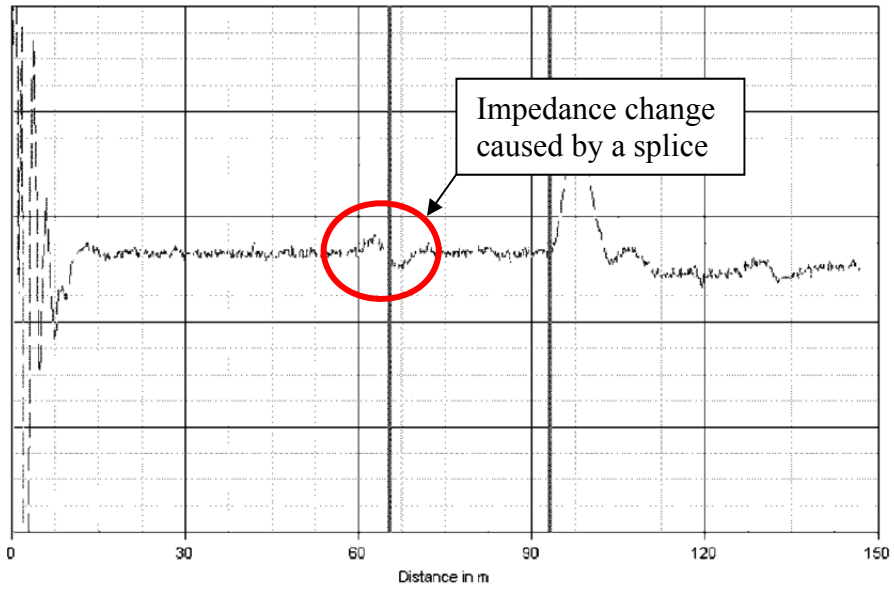


Figure 3: TDR Trace – Significant Change in Cable System Impedance

Anomalous reflections on adjacent phases of three-phase cable systems suggest additional investigation. Figure 4 shows an example of how measurements made on an XLPE cable system are used to assess the overall characteristics of a tested cable system. The solid circles indicate a splice location while the open circles indicate anomalous reflections.

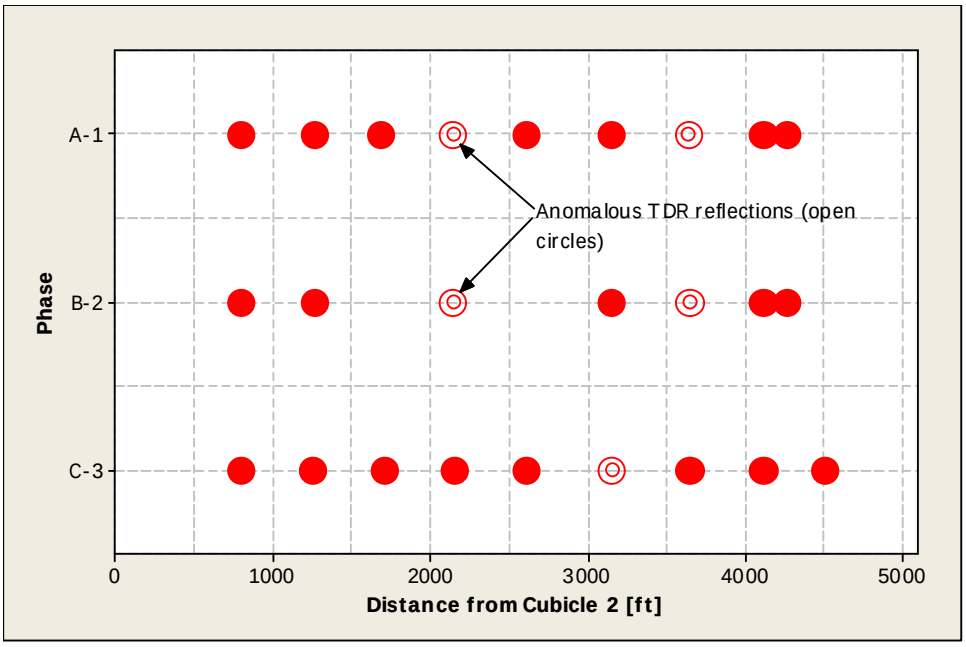


Figure 4: Example of Anomalous TDR Reflections on Adjacent Phases

5.6.2 Diagnosis Via Length Comparison

Length comparisons are especially useful (and simple) on three-phase circuits since the length of the phases are nearly identical. Measurements made from both ends of the system are effective for identifying single or multiple breaks in the neutral wires. As an illustration, consider a three-phase cable system with a neutral wire metallic shield as shown in Figure 5.

Figure 5: Three-Phase Section under Test Using TDR

The TDR length results for all phases measured from Location 1 appear in Table 3. Phases A and B measure nearly identical lengths at approximately 1,500 ft. while Phase C measures only 690 ft.

Table 3: TDR Results from Location 1	
Phase	**Length [ft]**
A	1,500
B	1,503
C	690

The TDR results clearly indicate a break/discontinuity in the Phase C metallic shield (neutral wires). A TDR measurement from Location 2 will determine if there are multiple breaks. Table 4 shows the results of these measurements.

Table 4: TDR Results from Location 2	
Phase	**Length [ft]**
A	1,500
B	1,503
C	380

Comparing the Phase C measurements from Table 3 with Table 4 it is apparent that there are multiple (at least two) neutral wire breaks since the sum of the measured lengths is only 1,070 ft. Had the two lengths summed to approximately 1,500 ft then there is only a single break.

5.6.3 Characteristic Impedance (Z_0) and Velocity of Propagation (VoP)

When TDR pulses travel through a cable system, the system is modeled as a transmission line. In electrical engineering, a transmission line is a specialized tool design to withstand certain operating voltage and carry alternating low frequency (60 Hz) current (powers systems applications) or high frequency signals (communications applications).

A cable system is modeled as a transmission line by using an equivalent circuit of passive elemental components; the schematic representation of the equivalent circuit model appears in Figure 6.

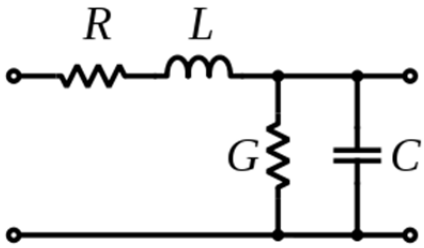


Figure 6: Per Unit Length Transmission Line Equivalent Circuit Model

The transmission line model in Figure 6 represents the transmission line as an infinite series of two-port elementary components each representing an infinitesimally short segment of the transmission line. They are as follows:

- The distributed resistance *R* of the conductor and the neutral is represented by a series resistor (expressed in Ω per unit length).
- The distributed inductance *L* (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (expressed in H per unit length).
- The capacitance *C* between the conductor and the neutral is represented by a shunt capacitor (expressed in F per unit length).
- The conductance *G* of the insulation and semicons between the conductor and the neutral is represented by a shunt resistor (expressed in S per unit length).

The model consists of an infinite series of the elements shown in Figure 6, and that the values of the components are specified per unit length so the picture of the component can be misleading. *R*, *L*, *C*, and *G* may also be functions of frequency. However, it is generally assumed that they do not change with frequency. These quantities can also be known as the primary electrical cable system parameters. A series of useful constants can be derived from these parameters such as propagation constant, attenuation constant, phase constant, velocity of propagation and others. The constants are used depending on the type of diagnostic technology deployed and thus, in some cases, knowing the cable system parameters is essential.

The TDR is an extremely accurate instrument. However, if cable system parameters and constants are in error, they might cause incorrect data interpretation. For the specific TDR case, knowing the parameters or propagation constants is imperative: they are necessary for any analysis of TDR signals.

The more important constants for TDR are the characteristic impedance (Z_0) and the velocity of propagation (VoP), the characteristic impedance is used for TDR pulse injection settings; the TDR device should have the same characteristic impedance as the cable system in order to improve the pulse energy transfer from the TDR to the system; this is not a simple task and thus it is discussed later in this Chapter in detail.

In contrast, the VoP is used to characterize the cable system structure and pinpoint the locations of joints and possible anomalies present in the system. One way to minimize error in pinpointing is to use the correct VoP of the cable system under test. The VoP is a specification of the cable indicating the speed at which high frequency signals travel down the cable system. Different cables have different VoPs. In order to assure the most accurate distance measurements, the cable VoP must be determined.

The VoP is generally defined in terms of the speed of light in a vacuum (~1 ft/ns), which accounts for reference as 100%. All other signals would travel through the cable system at slower speeds, e.g. a cable system with a VoP of 85% would transmit a TDR pulse signal at 85% of the speed of light (0.85 ft/ns). Knowing the VoP of a cable system is the most important factor when using a TDR for accessory or fault location. The instrument can be calibrated to the particular cable system by entering the correct VoP.

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The VoP number of a cable is determined by the insulation dielectric material, operating temperature, and age; however, as a rule of thumb when the VoP is unknown, it can be assumed to be approximately 50% (0.5 ft/ns). Typically, the VoP of the cable system under test will be listed in the cable manufacturer catalog or specification sheet. If not, one approach is to compute it from the cable parameters (*L* and *C*) or simply measure or estimate the length of the cable system and change the TDR VoP setting until the display shows at the far end the same distance reading as the measured/estimated length. A partial listing of typically used MV cable types with their inductance, capacitance, characteristic impedance (Z_0), and VoP appears in Table 5.

Table 5: Important Cable Constants for TDR

Conductor Size/ Insulation	Class/ Insulation Thickness	Inductance		Capacitance		Characteristic Impedance Z_0 [Ω]	VoP[1] [%]
		mH/m	mH/ft	pF/m	pF/ft		
1/0[2] AWG XLPE[3]	15 kV/175 mils	171	56	211	69	28	55
	15 kV/220 mils	193	63	178	59	33	57
	25 kV/260 mils	211	69	159	52	36	58
	35 kV/345 mils	244	80	132	43	43	59
1/0[2] AWG EPR[4]	15 kV/175 mils	171	56	257	84	26	50
	15 kV/220 mils	193	63	217	71	30	51
	25 kV/260 mils	211	69	193	63	33	52
	35 kV/345 mils	244	80	160	52	39	53
1,000[2] MCM XLPE[3]	15 kV/175 mils	101	33	505	166	14	47
	15 kV/220 mils	112	37	414	136	16	49
	25 kV/260 mils	121	40	359	118	18	50
	35 kV/345 mils	140	46	284	93	22	53
1,000[2] MCM EPR[4]	15 kV/175 mils	101	33	615	202	13	42
	15 kV/220 mils	112	37	504	165	15	44
	25 kV/260 mils	121	40	437	143	17	46
	35 kV/345 mils	140	46	346	113	20	48

[1]: Velocity of propagation (50% ~ 0.5 ft/ns or 0.16 m/ns)
[2]: Compressed stranded round conductor
[3]: XLPE dielectric relative permittivity of 2.3
[4]: EPR dielectric relative permittivity of 2.8

5.6.4 Relevance of TDR Pulse Amplitude and Width

Cable systems have an impulse response that distorts the original injected TDR pulse signal as it travels through the system. The distortion is caused by several types of cable system losses which are frequency dependent. The longer the cable system is, the greater the distortion [2-6]. The physical processes that characterize the losses are well known and defined; they are skin effect, dielectric loss, reflection and radiation [6]. In a simple manner, these physical processes can be represented by two major sources of TDR pulse distortion: attenuation and dispersion.

To understand the sources of distortion, the typical parameters of a TDR pulse must be introduced. The typical parameters of a TDR pulse are its amplitude and width. On the one hand, the amplitude is defined as the peak amplitude of the TDR pulse; in other words, it is the maximum magnitude that the TDR pulse reaches independently of its shape. On the other hand, the pulse width is generally defined as the difference in time between those points in the TDR pulse that have amplitude of 50% of the peak amplitude. The amplitude and width of a TDR pulse are illustrated in Figure 7.

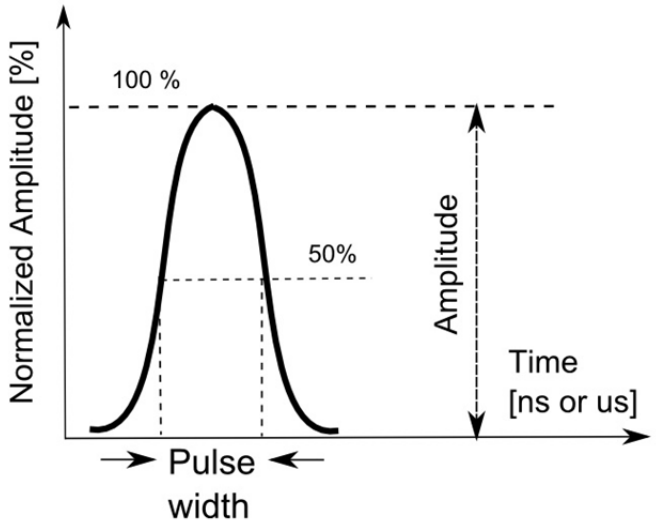

Figure 7: Typical Parameters of TDR Pulse

The TDR pulses are generated by the TDR unit as fast pulses having fast rise and decay times with a width that generally ranges from a few nanoseconds to hundreds of nanoseconds. When the TDR pulses travel along the cable system, the system behaves as a lossy transmission line; therefore, it can be modeled in this way. The lossy line behavior causes the TDR pulses to change their shape as they travel along the system. The change in their shape is due to two mayor important effects: (1) change in pulse shape due to loss of energy (attenuation) and (2) change in pulse shape due to different travel speeds for different frequencies without any energy loss (dispersion). In addition, spurious pulses will appear that are introduced by reflections of TDR pulses at the system ends and splices. The attenuation and dispersion are discussed in more detail in the next paragraphs.

Attenuation: While traveling along lossy transmission lines, TDR pulses lose energy. This energy loss is a function of the distance traveled by the pulse and its frequency components. In a cable

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system, the attenuation is due to losses in the bulk insulation and propagation through the resistance of the conductor, neutral, and semiconductive jackets. Normally, attenuation increases with frequency; energy losses may be significant for frequencies of the order of a few megahertz. As a consequence, fast TDR pulses can only travel short distances (because of their high frequency components) before they are attenuated to a level at which they are hidden by the induced background noise. Therefore, as the length of the cable system increases slower TDR pulses have to be used to overcome the cable system attenuation. Figure 8 shows the relationship between attenuation per unit length and TDR pulse width for a 300 ft of 33 kV, 630 mm^2, XLPE cable. Note in Figure 8 that faster pulses show higher attenuation magnitudes.

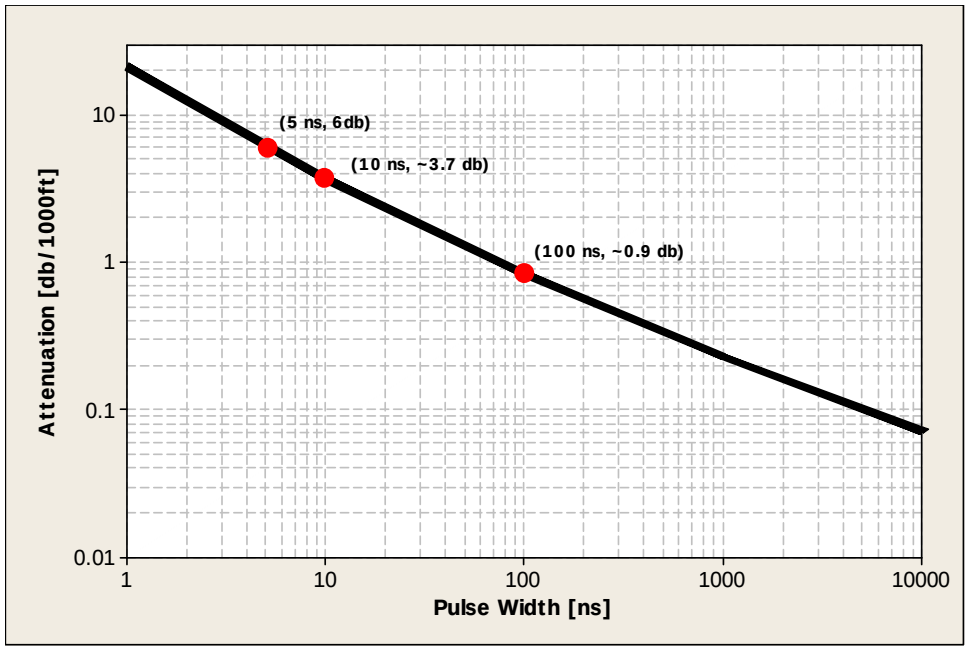


Figure 8: Calculated Attenuation as a Function of TDR Pulse Width for 300 ft of 33 kV, 630 mm^2, XLPE Cable [2]

Knowing the attenuation per unit length versus the TDR pulse width can provide useful information regarding how far a TDR pulse can travel through the cable system before reaching a specific level of attenuation. Using the example in Figure 8, several observations follow:

- A 5 ns TDR pulse has an attenuation of 6 dB/1000 ft, which means the pulse has to travel 1,000 ft to show 50% of its initial amplitude.
- Similarly, a 10 ns TDR pulse has an attenuation of approximately 3.5 dB/1,000 ft, which means the pulse has to travel approximately 1,700 ft to show 50% of its initial amplitude.
- Additionally, a 100 ns TDR pulse has an attenuation of approximately 0.9 dB/1,000 ft, which means the pulse has to travel up to approximately 6,700 ft to show 50% of its initial amplitude.

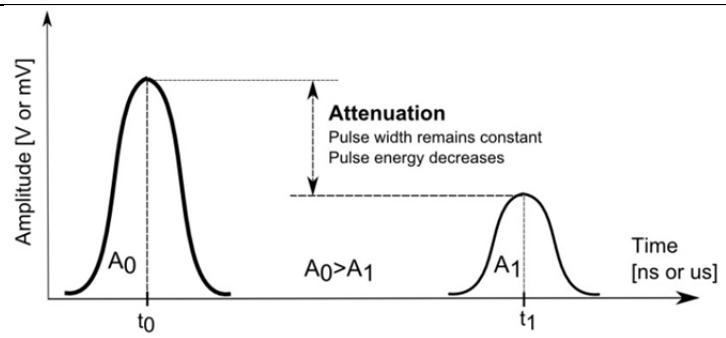
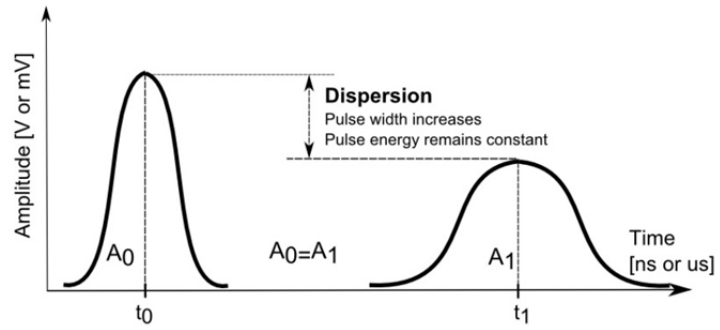
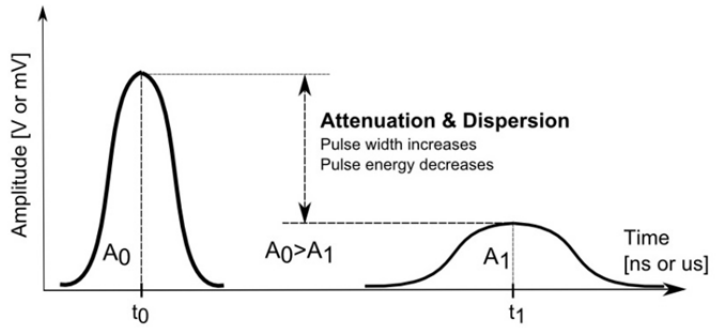
Even though the attenuation information is useful; generally, it cannot be considered alone. The TDR pulse distortion due to attenuation and dispersion is always present. In some cases, the dispersion would dominate the attenuation (low loss); and in other cases, the attenuation would

dominate the dispersion (high loss). In the context of cable systems, both attenuation and dispersion are systemic and must be analyzed on a case by case basis.

Dispersion: As mentioned before, a TDR pulse is composed of different frequencies that travel along the cable system at different speeds. This change in speed causes distortion known as dispersion. The distortion can be seen as a phase shift of each of the individual frequency components of the TDR pulse and is a function of the distance traveled by the pulse and its frequency component profile. Dispersion distorts TDR pulses regardless of whether the system is lossy or not. This can affect the accuracy of locating splices and possible anomalies.

As a rule of thumb, it can be understood that attenuation causes the loss of frequency content of the TDR pulses while they are distorted and spread out in time due to the dispersion effect. Table 6 presents the cases on how a TDR pulse is distorted by attenuation, dispersion, and both.

Table 6: Overall Advantages and Disadvantages of TDR Measurements

Observations	Case
Attenuation: • Reduced amplitude. • Constant pulse width. • Reduced energy.	
Dispersion: • Reduced amplitude. • Increased pulse width. • Constant energy.	
Attenuation & Dispersion: • Reduced amplitude. • Increased pulse width. • Reduced energy.	

The performance of the TDR technique for diagnosing cable systems can be best comprehended by

the concept of resolution. Resolution, in the context of engineering, is generally defined as the act or process of separating into constituent or elementary parts. TDR is not an exception. Specifically, for TDR two types of resolution should be considered when performing tests.

Resolution in TDR is basically the ability of the TDR system (the TDR system includes the hardware, software, and skilled operator) to identify very small changes in the characteristic impedance (Z_0) of the cable system, and that these small changes become visible as reflections in the display of the TDR unit. The resolution can also be defined as the ability to identify two closely spaced changes in the characteristic impedance as having separate reflections (in common words, two "bumps" in the TDR display instead of one). Therefore, the two types of resolution that should be considered are: amplitude and time resolution; it is desirable that a TDR system exhibit both good amplitude and time resolution.

Amplitude Resolution (Range): Refers to the ability of the TDR system to display a reflection signal from an accessory or abnormality that produces a small variation of the reflection coefficient. When there is a good amplitude resolution, very small characteristic impedance discontinuities along the cable system length can be displayed by a TDR system. A discontinuity causing a reflection signal that is smaller than the displayed background noise is difficult to observe. Displayed noise is therefore a good reference to use in comparing the amplitude resolution of various TDR systems. To improve the amplitude resolution, the displayed noise can be filtered or TDR waveforms can be acquired and then averaged.

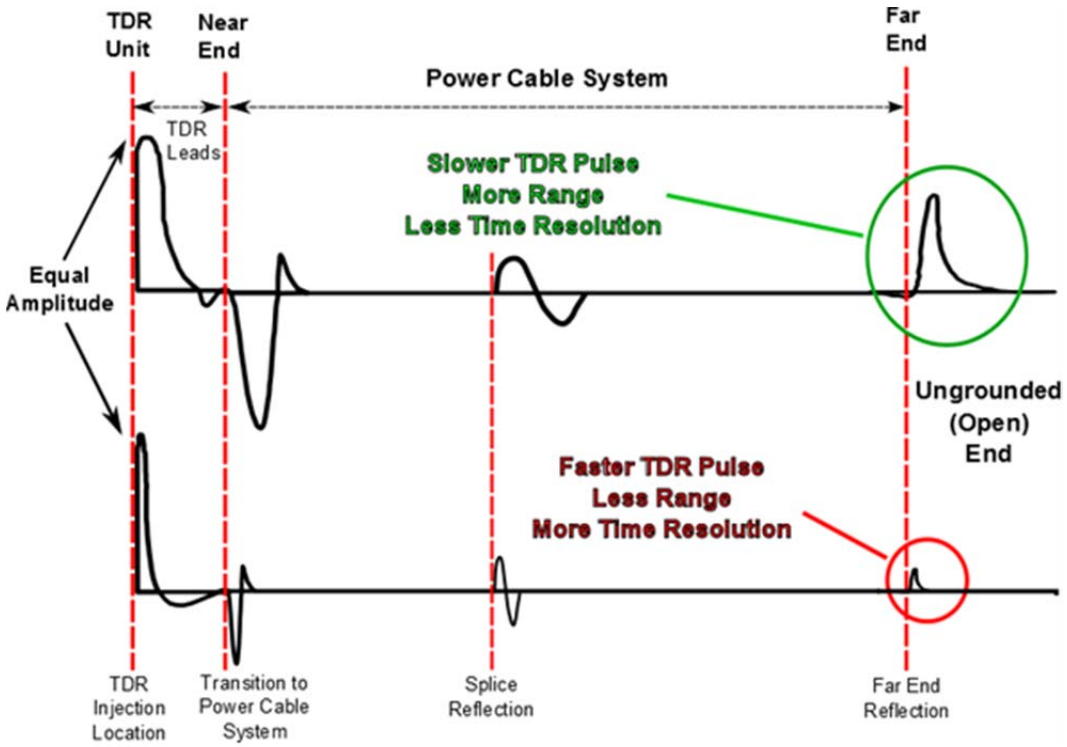


Figure 9: Illustration of Amplitude Resolution (Range) for TDR Systems

Thus, the amplitude resolution of a TDR system may then be defined as: the minimum change in

the characteristic impedance that is equivalent to the displayed background noise amplitude without any filtering or averaging of the TDR acquired waveforms. The amplitude resolution can also be understood as the range of the TDR pulse, the range in the case refers to the distance that the TDR injected pulse or reflection is able to travel before it gets attenuated and dispersed to the background noise level. An illustration of the amplitude resolution concept (range) appears in Figure 9.

Time Resolution: Refers to the ability of a TDR system to distinguish between two point anomalies that are located very close together. The time resolution is then defined as the minimum time spacing (can also be seen as cable system length) of two similar anomalies which give rise to a distinguishable valley between the two displayed reflections [6]. An illustration of the time resolution concept appears in Figure 10.

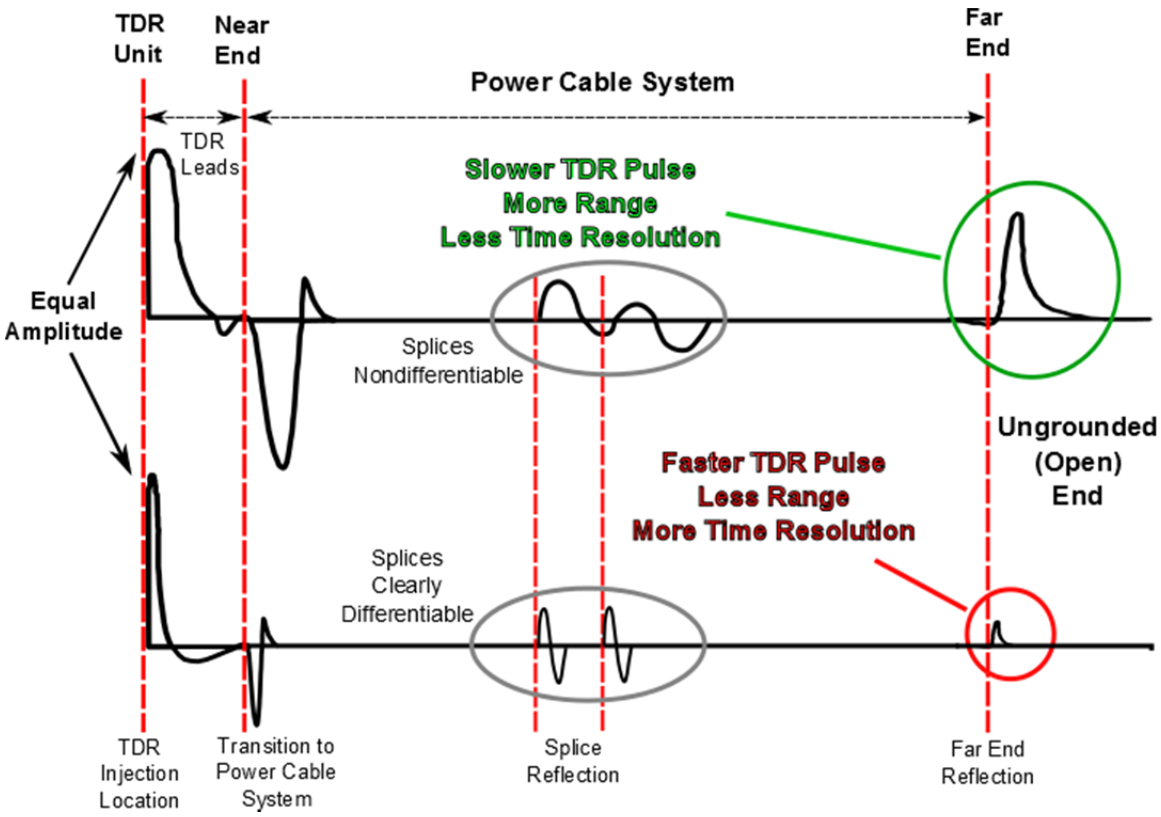


Figure 10: Illustration of Time Resolution for TDR Systems

A comparison between TDR traces taken in the field for a 25 kV, approximately 5,000 ft, XLPE, jacketed cable systems, appears in Figure 11; pulse widths of 100 ns and 25 ns have been considered. In Figure 11, the red and green traces correspond to the 100 ns and 25 ns TDR pulse widths respectively. The amplitude of injected TDR pulse at the near end is kept constant.

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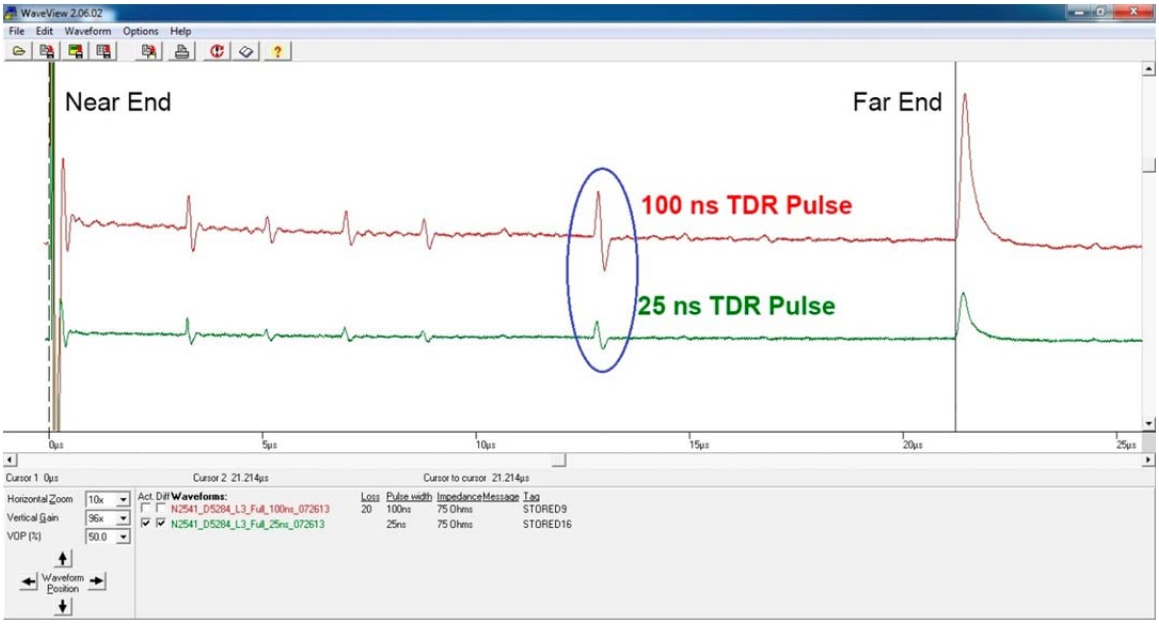


Figure 11: Comparison between TDR Traces from Field Tests of a 25 kV XLPE Cable System for 100 ns and 25 ns TDR Pulses

As observed in Figure 11, both TDR traces indicate that there are five noticeable splices in the system. Also note that the amplitude resolution decreases with faster TDR pulses. However, as mentioned before, faster TDR pulses not only affect the amplitude resolution but also the time resolution. To show the influence of the TDR pulse width on both resolutions in a real cable system, a closer look at the splice reflection circled in blue in Figure 11 is considered and presented in Figure 12.

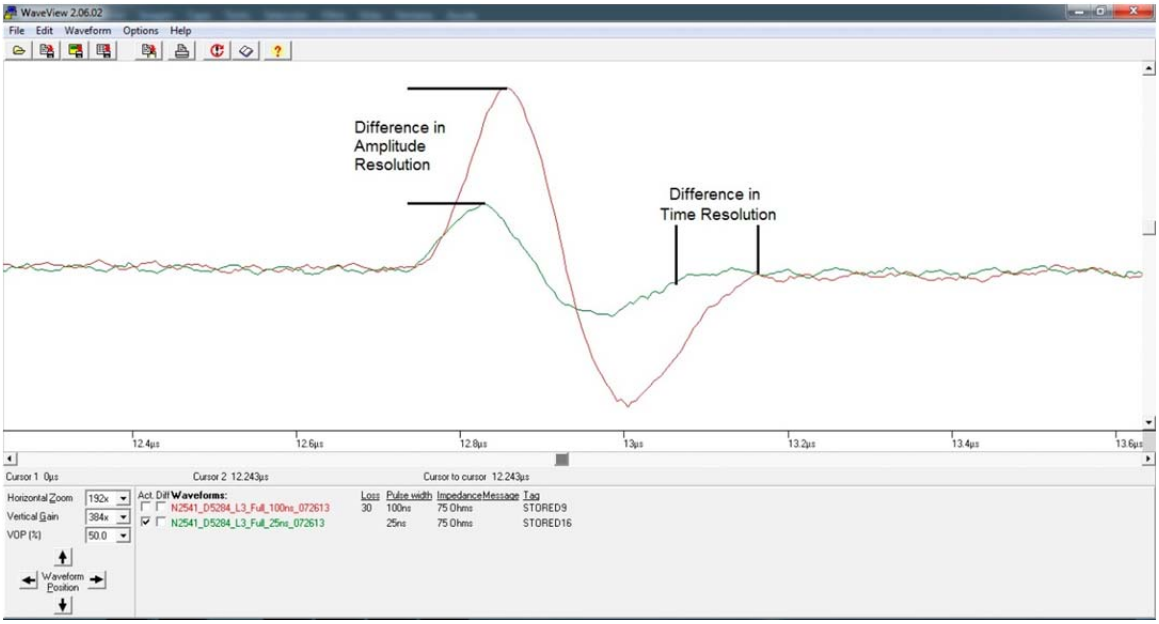


Figure 12: Changes in Amplitude and Time Resolutions in TDR Field Tests

Figure 12 shows that there are issues when dealing with amplitude and time resolutions of TDR systems as follows:

- Dispersion and attenuation affect both resolutions.
- When the amplitude resolution is improved by sending wider TDR pulses through the cable system, then the time resolution is compromised, i.e. more time for the 100 ns TDR pulse compared to the 25 ns TDR pulse.
- On the contrary, when the time resolution is improved by sending narrower TDR pulses through the cable system, then the amplitude resolution is compromised, i.e. less amplitude for the splice reflection for the 25 ns TDR pulse compared to the 100 ns TDR pulse.

The two last issues are based on the assumption that the amplitude of the sent TDR pulses remains constant. Thus, to overcome this situation, modern TDR systems provide a means of adjusting the amplitude in addition to the width of the pulses; which provides another degree of freedom to the skilled operator. However, in a real case, the operator would have to compromise amplitude or time resolution to find an optimal point for condition assessment using the TDR technique. A conceptual map of the relationship between amplitude and time resolutions appears in Figure 13.

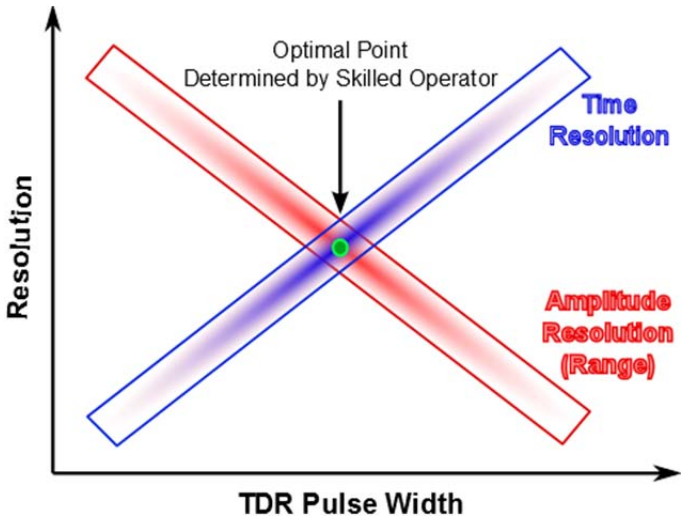


Figure 13: Conceptual Map of the Amplitude (Range) and Time Resolution Relationship

5.6.5 Importance of TDR Pulse Injection

Research shows there are several ways to inject a TDR pulse into a cable system. The main reason for having different pulse injection practices relies on that TDR systems and leads have different characteristic impedance than the cable systems they test. Thus, two issues arise and have to be considered here, they are as follows:

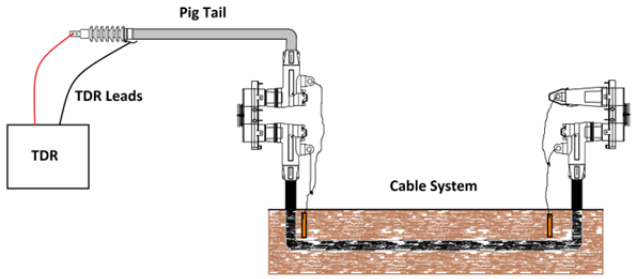
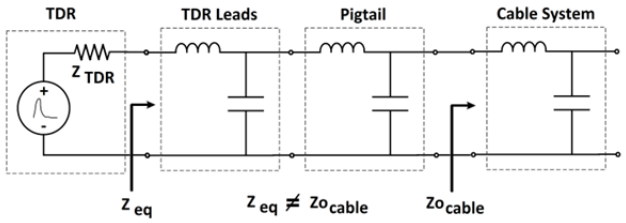
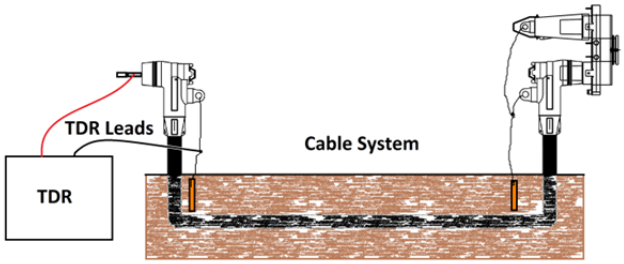
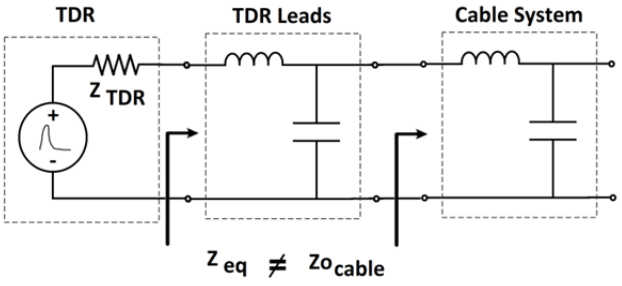
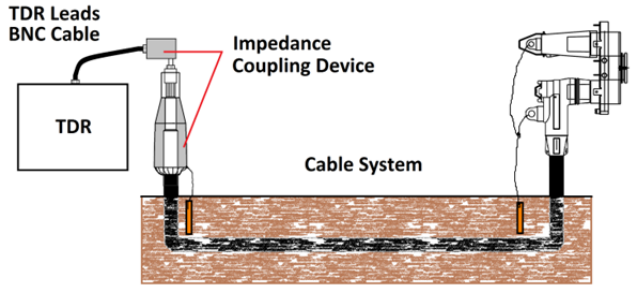
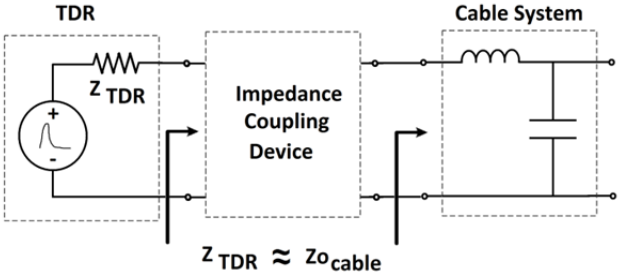
- Initial reflections are expected at the transition point to the cable system; this would cause the TDR pulse energy that is effectively injected into the cable system to be compromised. A reduction in the effectively injected energy of the TDR pulse diminishes both amplitude

and time resolutions which consequently adversely affects the possibility of achieving a condition assessment.

- The initial reflection at the transition point would also travel back and forward to the TDR unit, which results in a ‘”ringing” effect on the TDR trace. The ringing effect is observed on the TDR trace beyond the near end position and thus does not allow any resolution at the near end of the cable; i.e. TDR signature of cable anomalies cannot be established. Therefore, when the ringing is present, the TDR system is “blind” for the first few tens of feet after the near end position; this situation spans up until the TDR trace stabilizes to reference.

Table 7 shows the known practices for TDR pulse injection, the typical deployment and equivalent circuit showing the transition points and characteristic impedance changes are also presented.

Table 7: Known Practices of TDR Pulse Injection

Typical Deployment§	Equivalent Circuit
Common Practice/Simplest Approach	
	
Better Practice/Approach	
	
Best Practice/Most Comprehensive Approach	
	
§: Far end can also be a termination	

As seen in Table 7, the known practices for TDR pulse injection to a cable system are classified as common, better, and best practices. The ordering here is established by considering the level of ringing for each case, the common practice has the highest level of ringing and the best practice has the lowest.

The common practice considers injecting the TDR pulse through the TDR leads (leads can also be BNC (Bayonet Neill-Concelman) cables) and a pigtail; thus, it has two impedance changes, from the TDR to the pigtail and from the pigtail to the system as seen in the equivalent circuit. This practice is preferred by the utilities since accessories are not removed, and if a follow-up high voltage test is to be deployed after TDR, then only the TDR unit is removed.

To reduce the ringing, the better practice considers injecting the TDR pulse directly into the elbow (or termination). In this case, there is only one transition point from the TDR unit to the cable system. If a high voltage follow-up test is to be deployed, then the pigtail has to be reconnected, which in some cases can be time consuming due to the particular utility's switching policies.

The ringing is driven to its minimum value by the best practice. For this case, the elbow or termination is removed and an impedance coupling device is used to match the cable system characteristic impedance. The impedance coupling device works on the basis that it is possible to change the dimensions of a transmission line without giving it a reactive nature or changing its characteristic impedance. If, for instance, a bigger conductor is used in the impedance coupling device, even though the inductance per unit length is changed (reduced), increasing the spacing proportionately between the conductor and the metallic shield will also reduce the per unit length capacitance and thus the characteristic impedance could remain unchanged, this approach is known as geometrically based impedance coupling (see Figure 14). The changes in the physical dimensions of the geometrically based impedance coupling device are made gradually over a short distance (short relative to the highest frequency wavelength of the TDR pulse spectrum) in order to avoid a sudden change in the characteristic impedance at the transition.

Another possible way of coupling the cable system impedance is to use a network that couples the impedance between the TDR and the system (see Figure 14). This approach has the advantage that the network can be fine-tuned to match as best as possible the system impedance while the geometrical based impedance coupling device is limited to a particular cable size and power system voltage.

As mentioned before, the best practice requires the near end accessory to be removed which adds testing time. The removed accessory is generally replaced by a new one and then a follow-up high voltage test can be deployed.

It is important to mention that in most cases a perfect impedance coupling is not possible; however, practice has shown that the ringing effect can be diminished to an acceptable level thus improving TDR pulse energy transfer to the cable system and amplitude and time resolutions along the full system length. The impedance coupling device is also known as an impedance match (or matching) device; however, as the impedance is never completely matched the term coupling is more suitable

for describing such a device. Figure 14 shows the different types of TDR pulse injection using impedance coupling devices.

Impedance Coupling - Geometrically Based **Impedance Coupling - Network Based**

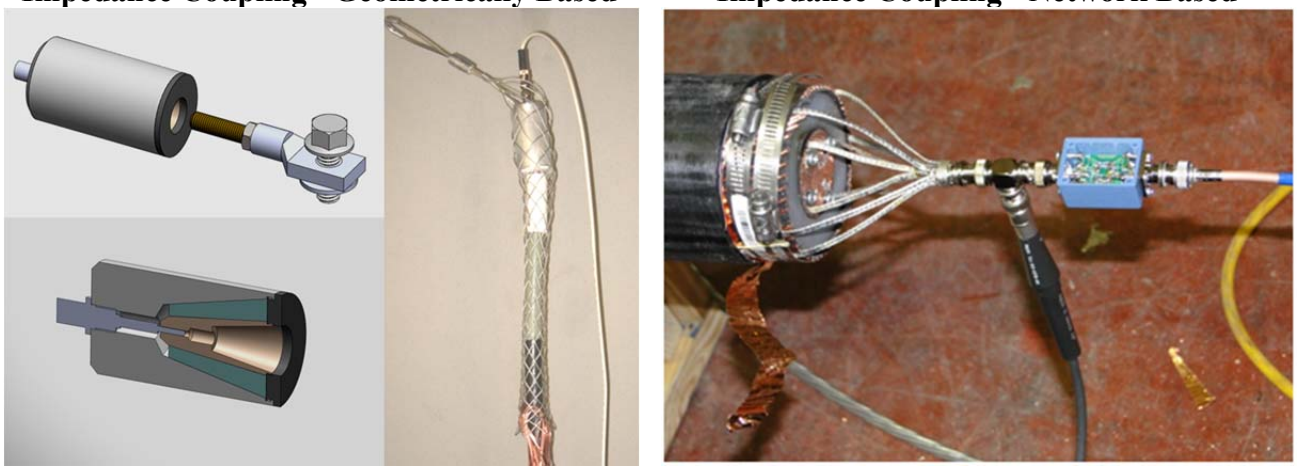


Figure 14: Different Types of TDR Pulse Injection using Impedance Coupling Devices

Figure 15 shows an illustrative example for comparison between two TDR traces, one for injection with TDR leads and pigtail, and the other one for injection with an impedance coupling device.

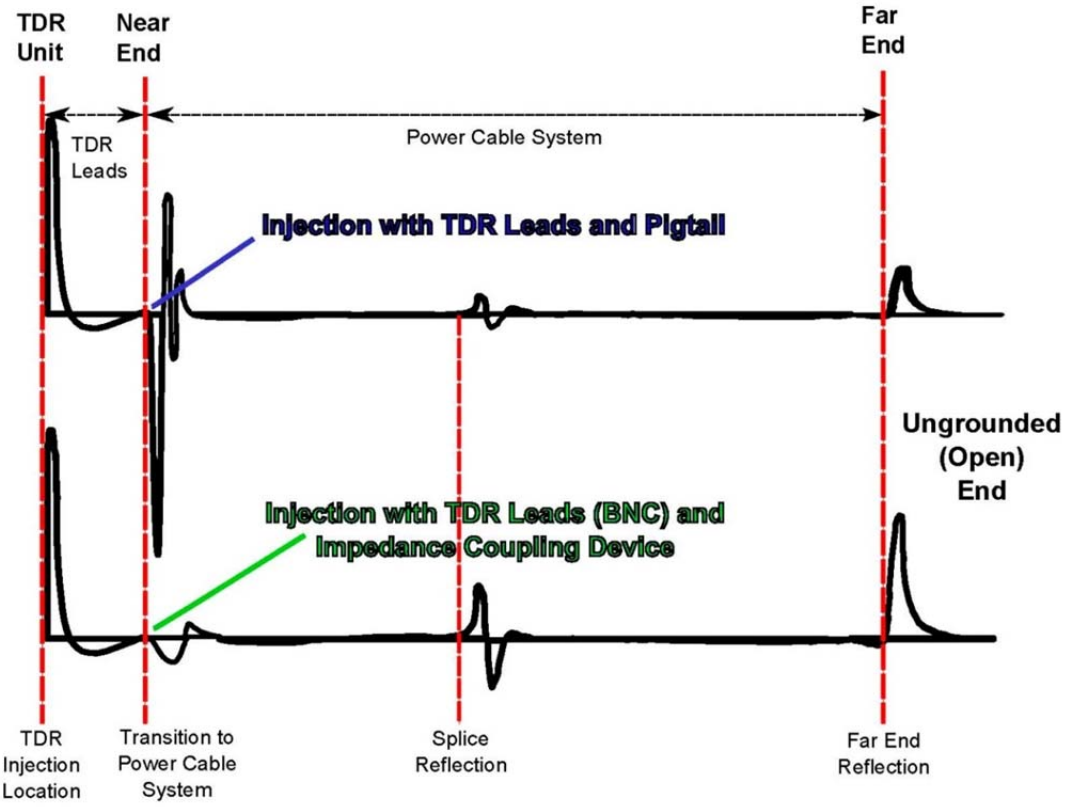


Figure 15: Illustrative Comparison between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device

As seen in Figure 15, when an impedance coupling device is used, then the ringing effect at the transition point to the cable system is reduced and the TDR pulse energy that is injected into the system is higher; this is represented by the better amplitude resolution of the splice and far end reflections.

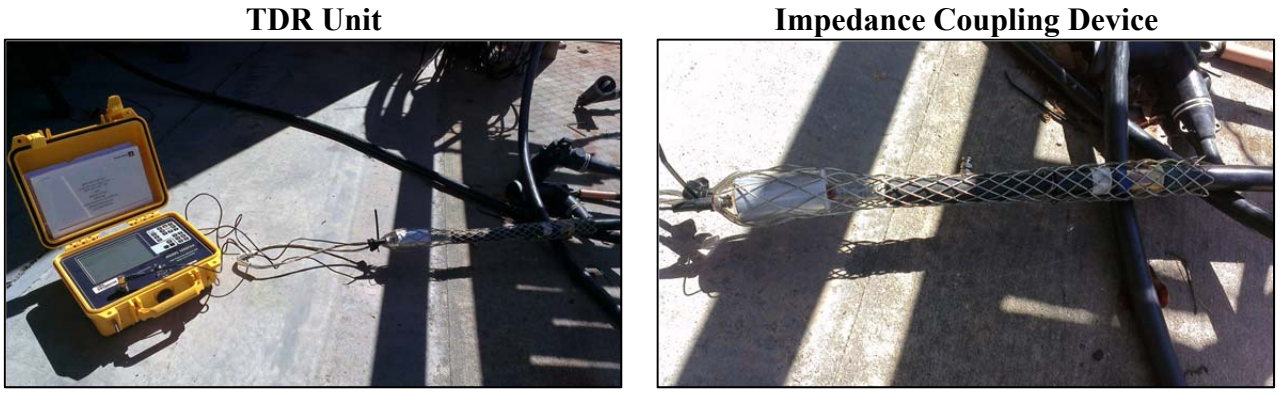


Figure 16: Test Setup for Comparison of Laboratory Measurements between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device.

To test the concept of TDR pulse injection using an impedance coupling device, laboratory research was undertaken. The laboratory setup appears in Figure 16 and the results are shown in Figure 17. In this case, a geometrically based impedance coupling device is used. The cable is a conventional 15 kV, 1/0, jacketed, XLPE cable.

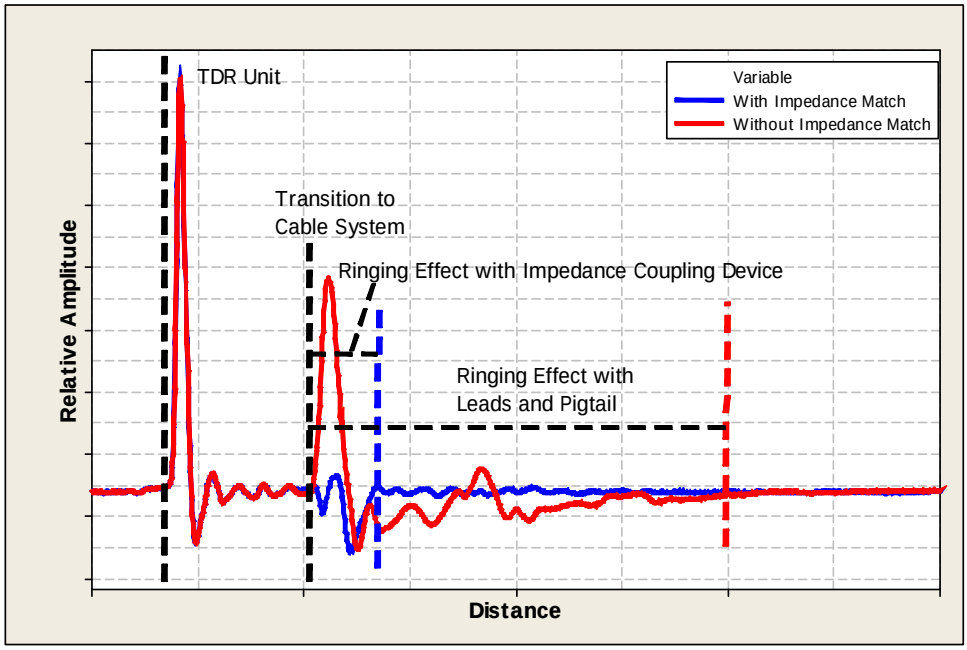


Figure 17: Results for Comparison of Laboratory Measurements between TDR Traces for Pulse Injection Using Leads with Pigtail and Impedance Coupling Device

As seen in Figure 17, the impedance coupling device minimizes the ringing effect at the transition point to the cable and thus increases the energy transferred to the system improving the amplitude and time resolutions.

5.6.6 TDR Based Cable Neutral Assessment.

TDR systems can also be used to detect neutral issues; in fact, cable injection providers routinely use them as a means of providing a condition assessment on the neutral prior to injection [2-4]. The neutral condition is imperative before deciding whether to inject a cable system.

A trained operator can provide a qualitative assessment of the amount of neutral corrosion and its location within a circuit by interpreting apparent noise and the reflections in a TDR trace. The apparent noise is correlated with uniform neutral corrosion while the reflections are correlated with localized neutral corrosion or neutral breaks [8-10]. Figure 18 shows examples of the types of signals that may be seen in a TDR trace for both uniform and localized corrosion.

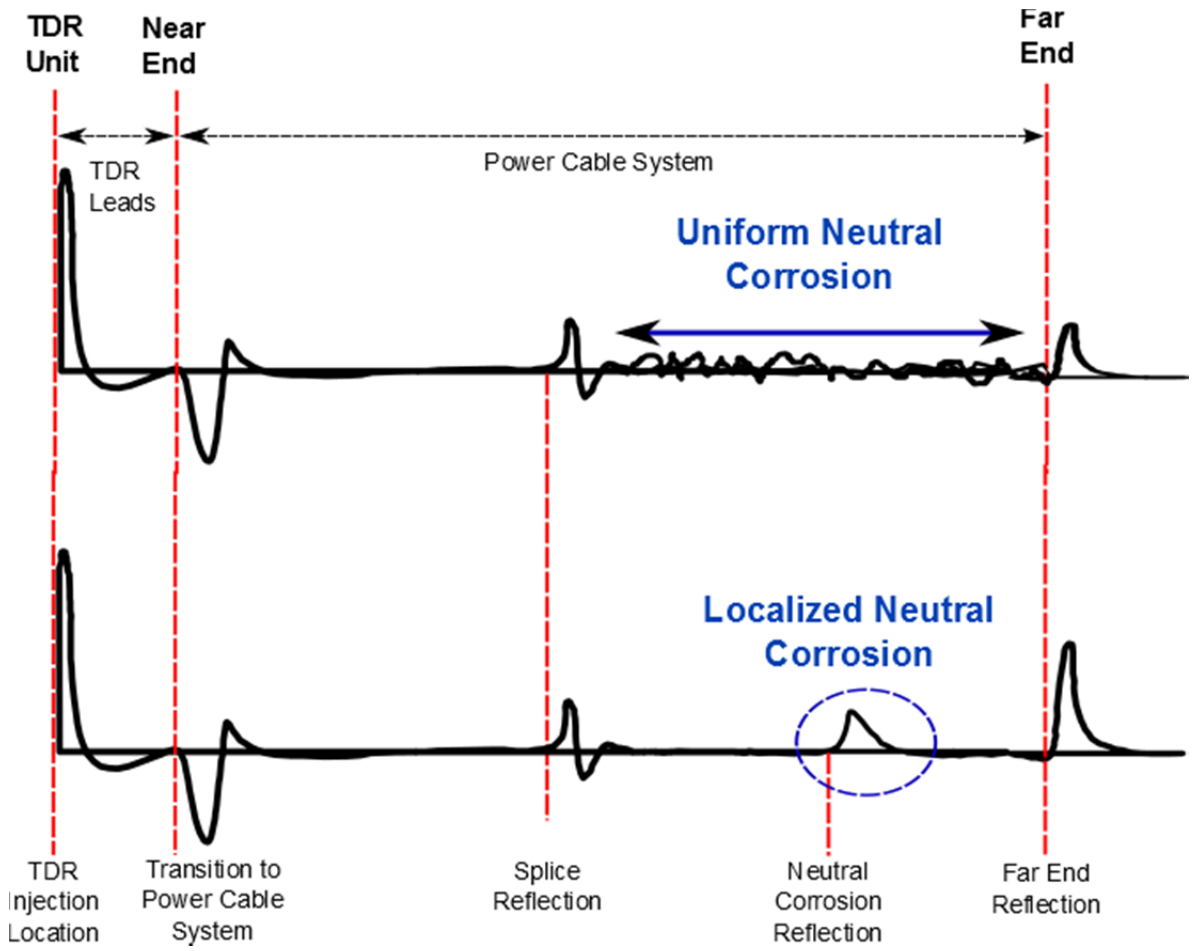


Figure 18: TDR Trace Showing Uniform and Localized Neutral Corrosion Issues

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Observe also in Figure 18, that uniform neutral corrosion causes the amplitude resolution to decrease as the reflection from the far end is in this case considerably less than the case of localized neutral corrosion. In a real scenario, both issues could be present in the cable system and one could dominate the other, then it is up to the skilled operator to reach a neutral condition assessment. However, in all cases both types of neutral corrosion are treated as no pass, i.e. the cable system cannot be injected and remedial action must be planned for the future.

Therefore, the *CDFI* perspective regarding cable systems neutral condition assessment via TDR considers either "Good" or "Poor" classes. Alternatively, it has been proposed [7] that the relative heights of the "bumps" in the TDR trace coming from localized neutral issues may be used to assign a condition level to the neutral under test. In fact, this claim is the basis for corrosion categories for detection and evaluation of corrosion of concentric neutral wires presented in the IEEE Std. 1617 [7] (Table 1). The claim appears to be based on practical experience and no literature exists quantifying the issue. Thus, this claim has been proven in laboratory research by performing TDR on a cable system with concentric neutral in which the neutral wires can be switched in and out progressively at a specific location. The actual location at which the neutral wires can be switched in and out appears in Figure 19 and the correlation between the percentage of remaining neutral and amplitude of the reflected TDR pulses appears in Figure 20.

Figure 19: Cable System with Concentric Neutrals in Which Neutral Wires Can Be Switched In and Out Progressively

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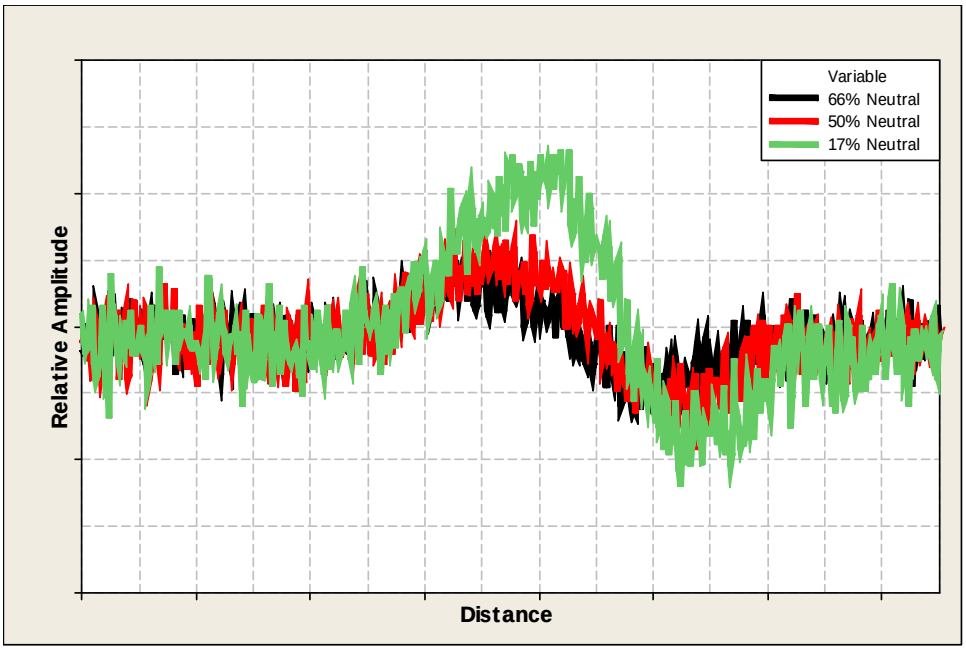
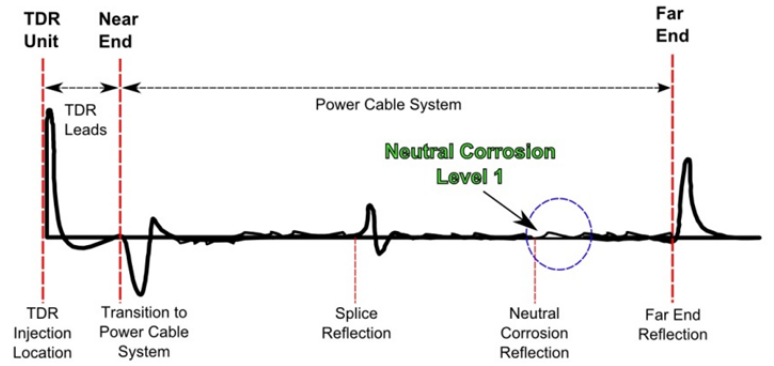
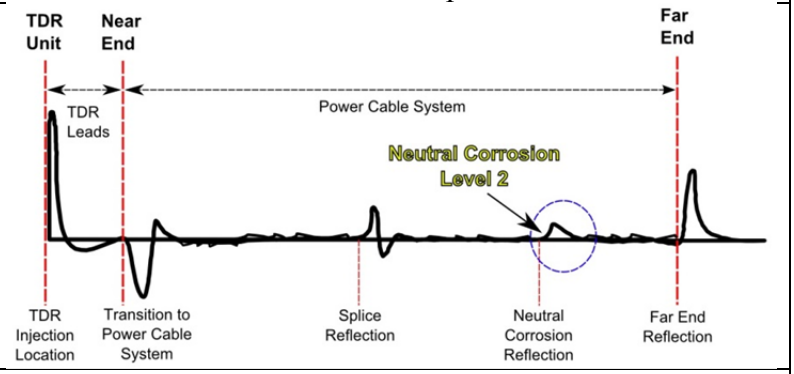
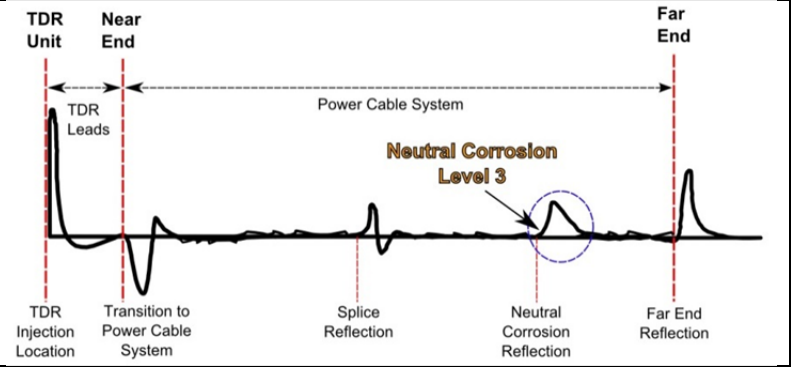
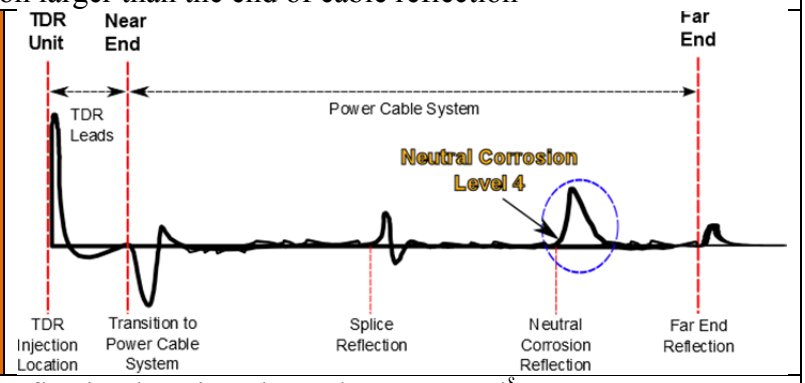
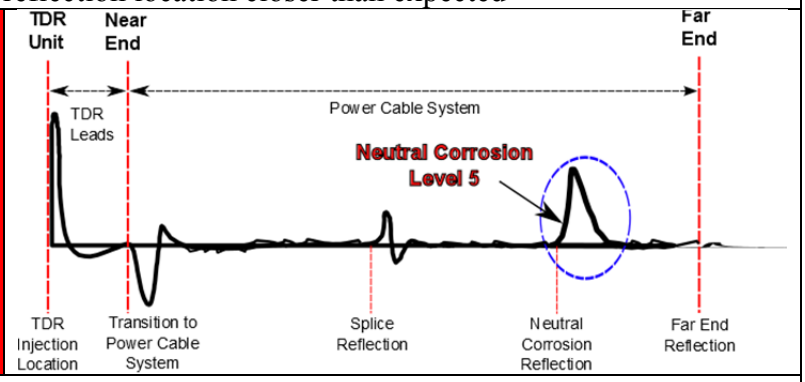


Figure 20: Correlation between Percentage of Remaining Neutral Wires and Amplitude of Reflected TDR Pulses

In Figure 20, there is no question that the percentage of remaining neutral is correlated to the TDR reflection pulse amplitude; small differences are observed between the 50% and 66% while the 17% can be clearly distinguished from both. Thus, the amplitude of the reflected TDR pulse can be used to estimate the level of localized neutral corrosion.

Instead of expressing the level of corrosion in terms of the percentage of the remaining neutral the IEEE Std. 1617 [7] uses the percentage of wires broken or percentage of neutral loss, four levels are considered; however, given the levels, the standard does not provide a prognosis for the condition of the cable system. Guidelines for these levels are provided in IEEE Std. 1617 and appear here in Table 8.

Table 8: Summary of IEEE Std. 1617 [7] Metallic Shield TDR Assessment Levels		
Wires Broken	**Condition**	**Illustrated from Assertions in IEEE Std. 1617 [7]**
Level 1 - No recognizable reflections		
0 – 25%	**Good**	
Level 2 – Recognizable reflection but smaller than a splice		
25 – 50%		
Level 3 – Reflection larger than a splice but smaller than the end of the cable		
50 – 75%		

Level 4 – Reflection larger than the end of cable reflection		
75 – 99%		
Level 5 – Far end reflection location closer than expected§		
100%	Bad	
§ - Not presently described in IEEE Std. 1617 [7]		

Within the *CDFI*, a number of issues that might limit the usefulness of the guidelines shown in Table 8 are:

- Not all cable systems have splice locations usable for reference; guidelines should be established to handle such cases.
- Distance from the TDR unit affects the amplitude of the received reflection – a splice located far away has lower amplitude than one located near the sending end.
- Signal amplitudes depend on several factors – system lengths, pulse injection method, pulse width, etc.

Hopefully, these issues will be reviewed during the next update of IEEE Std. 1617 [7]. However, as mentioned before, for purposes of the testing performed in most systems, the five levels in Table 8 are condensed into "Good" and "Poor". Generally, a "Poor" condition will lead to a full system replacement.

Correlation between Percentage of Remaining Cable Neutral Wires and Age

During *CDFI Phase II*, approximately 500 TDR tests have been performed on a variety of cable systems including URD and transmission. If the age of the cable system is known, then the neutral condition assessment based on TDR measurements in conjunction with the age can be used to estimate the change in the percentage of the remaining neutral wires vs. age of the cable system.

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Once this information becomes available, it is extremely useful for asset management. For instance, the utility cable engineer can then more ably manage the cable system by taking into account the statistical probabilities of neutral degradation during a given time frame.

Unfortunately, when determining the change in the percentage of the remaining neutral wires in tandem with their ages, the complete dataset of approximately 500 TDR tests cannot be used. Only those TDR tests that showed neutral corrosion with documented cable ages were considered; accordingly, approximately 100 cable systems met these criteria. Between those that are considered, the condition assessment of the neutral wires is set at the 50% for class separation; i.e. if the percentage of remaining neutral wires is less than 50%, then the system is considered to have a "Poor" neutral and thus it is classified as a "Fail". In contrast, if the percentage of the remaining neutral is greater than 50 %; then, the cable system is considered to have a "Good" neutral and it is classified as a "Pass." It is important to note two issues about the threshold level for the percentage of remaining neutral, they are as follows:

- Due to the nature of the statistical analysis, the threshold level is not a definite value and thus has a confidence interval related to a probability that the value is accurate.
- A value of 50% is considered here; however, it can be adjusted to another level according to the utility requirements, heuristic rules learned with time, correlation between classification and performance, and simply because of evolution of the database.

The correlation between percentage of remaining neutral wires and age appears in Figure 21. The information presented in Figure 21 can also be understood as a probabilistic predictive model for neutral corrosion based on TDR measurements.

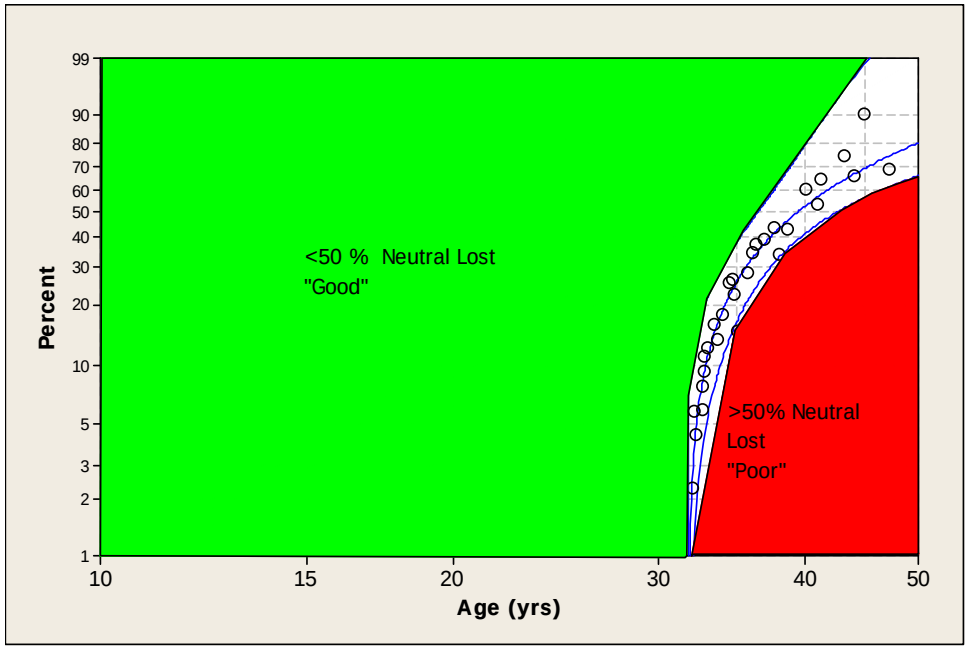

Figure 21: Research Showing the Correlation between Percentage of Remaining Cable Neutral Wires and Age

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In Figure 21, the "Good" neutral condition is represented by the green area and the "Poor" neutral condition is represented by the red one. The confidence intervals are also shown and represent the 95% confidence level. Another important issue to note is that there is a threshold age level of approximately 30 years before a cable system reaches any neutral loss. Figure 21 also shows that the correlation between neutral condition and age is not linear and the percentage of cable affected increases rapidly after the age threshold level. This can be better understood by looking at Table 9 which contains information extracted from Figure 21 of the mean percentage of remaining cable neutral wires as a function of age.

Table 9: Percentage of Lost Cable Neutral Wires as a Function of Age

Age [yr]	Mean Percentage [%]
30	< 1
35	27
40	54
45	70
50	80

As seen in at Table 9, research shows that it takes on average 40 years to lose approximately 50% of the neutral wires and 50 years for an 80% loss.

5.7 Outstanding Issues

5.7.1 Connection Leads

When using TDR, it is always advisable to be consistent with the TDR leads. When the TDR leads are simply a pair of wires attached to the unit, there is variability in the measurements since the capacitance between leads changes according to how they are placed for the test. Therefore, using BNC TDR leads with as short as possible transition wires is always advisable.

Another issue for the TDR leads is their length. If short leads are used, the ringing effect at the near end of the system might make that location challenging. The location of the near end is important for accessory and anomalies location and pinpointing. Therefore, to overcome this issue and always have a clear position for the near end, the use of long leads is recommended. In field tests, a length of 30 ft. has shown to be a good choice as at that length the leads have a low attenuation and dispersion and perform well in most cases. In addition, the same length and thus leads must be used for all tests. In this case, comparisons between different tests become possible because the attenuation and dispersion due to leads is equal. Figure 22 shows an illustration for comparing the use of short and long TDR leads.

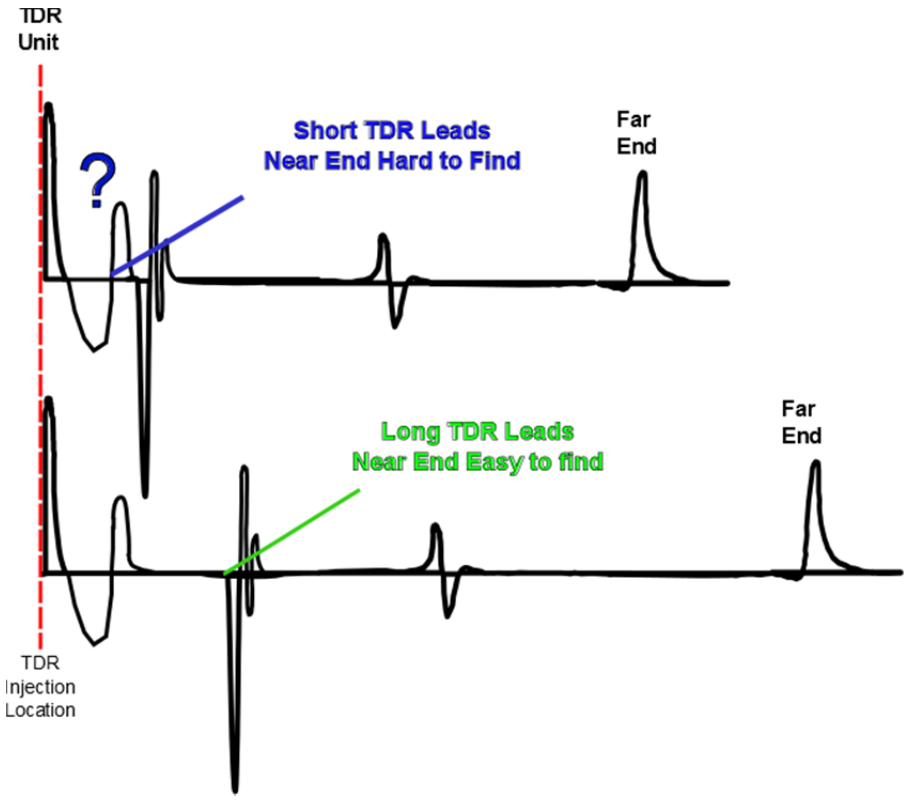

Figure 22: Illustration for Comparing the Use of Short and Long TDR leads

5.7.2 Identifying the Far End

If there is doubt about the far end location on the TDR trace, a good practice for identifying it is to simply compare the TDR traces for the conditions of grounded and ungrounded far end. In this case only the far end reflection is affected by changing polarity, not amplitude. This situation is illustrated in Figure 23 where a comparison between TDR traces for the same cable system for grounded and ungrounded far end is presented.

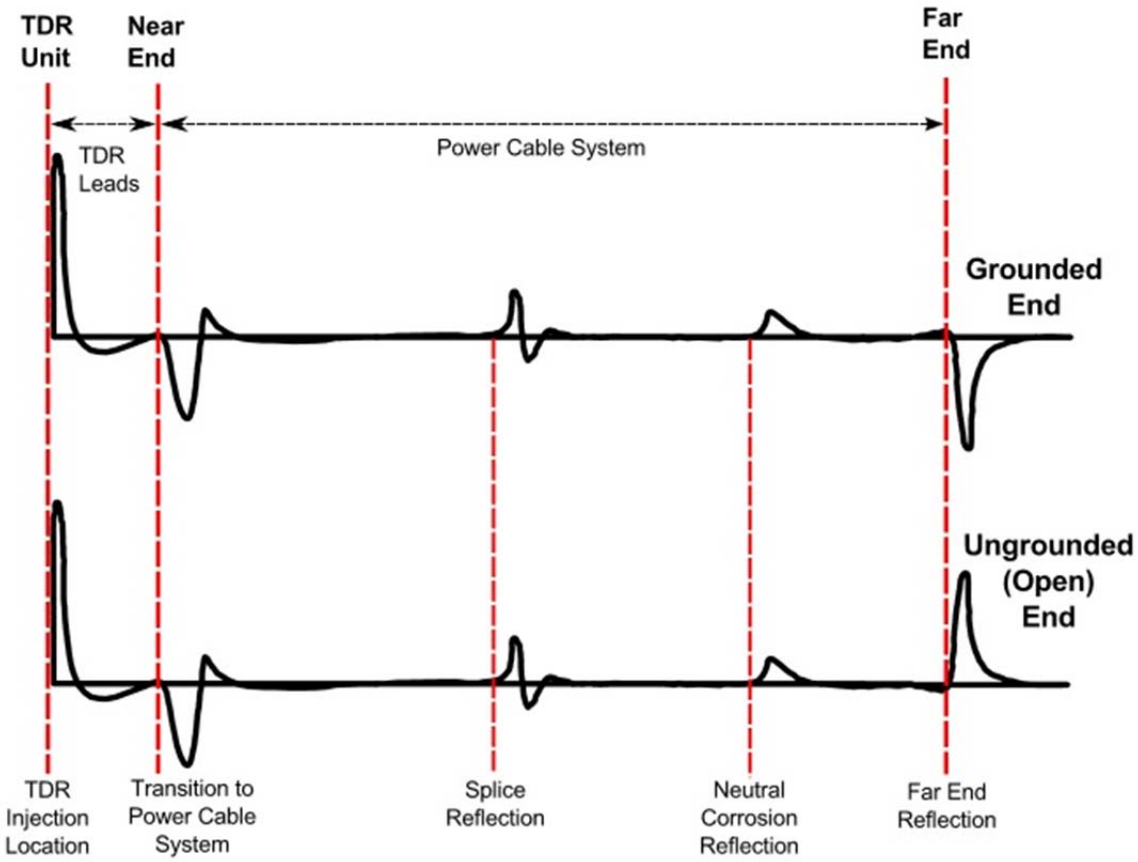

Figure 23: Comparison between TDR Traces for the Same Cable System for Grounded and Ungrounded Far End.

5.7.3 "Ghost" Reflections

Even though TDR is a useful tool for diagnosing potential cable system problems, there are some issues when interpreting the TDR trace. If the issues are not understood and addressed, they can lead to confusing results that do not correspond to the actual condition of the cable system under test. In particular, the issues are related to what it is called here TDR "Ghost" reflections.

The TDR "Ghost" reflections are signatures that appear on the TDR trace that do not correspond to any splice or anomaly present in the system. They are the result of the reflected and transmitted TDR pulses travelling along the system in both directions, i.e. from near to far end and vice versa. The TDR "Ghost" reflections depend on three variables: 1) the location of splices or anomalies, 2) the number of splices or anomalies, and 3) how they affect the cable characteristic impedance. Thus, the TDR "Ghost" reflections are pervasive with hundreds to thousands of possible combinations when considering all possible cable system configurations, splice and anomaly types, and operating conditions.

The extensive nature of the TDR "Ghost" reflections makes it impossible to cover and understand

all of the possible cases. However, a better understanding of TDR "Ghost" reflections can be attained through the analysis of basic case studies. This knowledge would hopefully lead to improved TDR trace interpretation in real field testing scenarios. . Six case studies are presented here (see Table 10):

- **Case 1:** Cable system with no splices or anomalies.
- **Case 2: C**able system with one splice located farther than 50% of the cable system length as measured from the near end.
- **Case 3:** Cable system with one splice located at the exact midpoint of the cable system length.
- **Case 4:** Cable system with one splice located between the near end and midpoint of cable system length.
- **Case 5:** Cable system with two splices located at arbitrary positions.
- **Case 6:** Same as Case 5; however, it considers the use of impedance coupling at the near end.

Keeping track of the TDR pulse reflections and refractions as they travel back and forth on the cable system is tedious. However, this analysis can be accomplished graphically by the use of bounce diagrams. The bounce diagram is a graphical analysis technique which greatly simplifies the analysis of transients on a transmission line and thus provides a tremendous amount of clarity regarding how transients are perceived at any point in the system. In other words, the bounce diagram provides a pictorial tool showing clearly how incident TDR pulses reflect, refract, and combine along the length of the cable system over time. To draw a bounce diagram for the initial incident, reflected, and transmitted TDR pulses, a series of parameters and facts must be considered. Therefore, prior to interpreting the bounce diagram, some cable system parameters must be estimated and facts established including:

- The characteristic impedance of the cable used in the cable system.
- Knowledge of the reflection coefficients at the cable system ends and splice or anomaly locations.
- The horizontal axis (X-axis on the bounce diagram) represents the position along the cable system.
- The vertical axis (Y-axis on the bounce diagram) represents the elapsed time from the initial injected TDR pulse at the near end.
- The bounce diagram is a zigzag line that clearly shows the progress of TDR pulses as they travel and get reflected and transmitted through the cable system.
- The near end is shown on the left side, whereas the far end is shown on the right side of the bounce diagram.
- The initial injected TDR pulse starts at X=0 (near end position) and Y=0 (time zero), and travels to the far end.
- The first reflected TDR pulse occurs at the first splice or anomaly that produces a change on the cable characteristic impedance.
- The amplitudes of the reflected and transmitted TDR pulses decrease as they travel due to the attenuation and dispersion phenomena.

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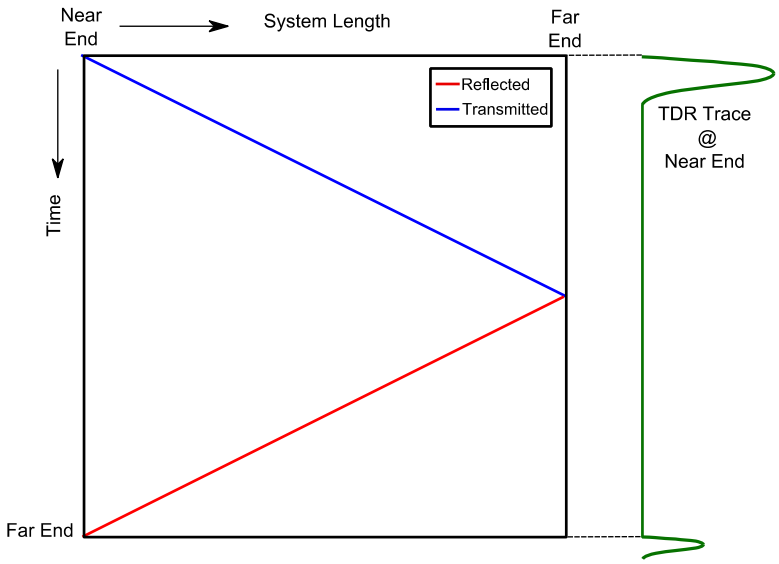
- The TDR trace as seen in the near end can be determined from the bounce diagram by following the vertical line that goes through X=0 (near end position).
- Slopes/gradients represent the velocity of propagation of the TDR pulses through the system; lower gradients equal higher propagation velocities.

The case studies, their corresponding bounce diagram and TDR trace appear in Table 10.

Table 10: Illustrative Case Studies for TDR "Ghost" Reflections

Case 1: Cable System with no Splices or Anomalies

- No TDR "Ghost" reflections observed.



Case 2: Cable System with One Splice Located Farther than the 50% of the Cable System Length as Measured from the Near End

- No TDR "Ghost" reflections observed before the far end reflection.
- "Ghost" reflections arrive after far end reflection and are discounted.

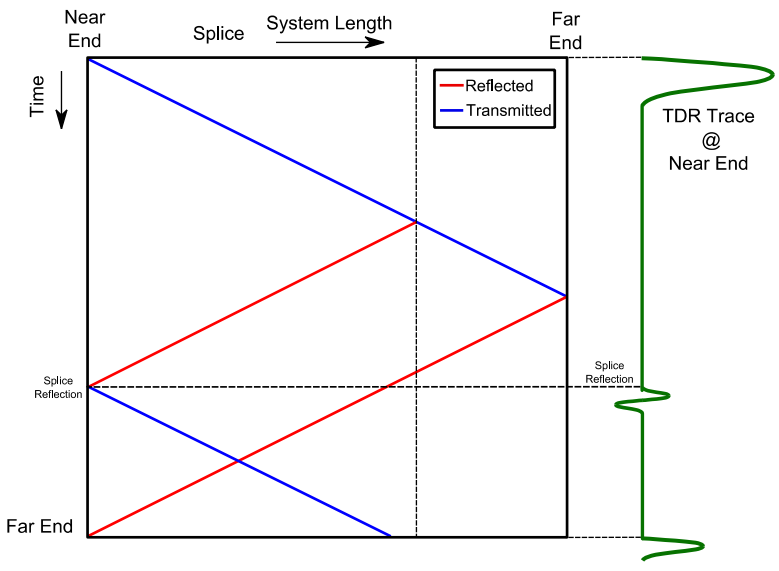


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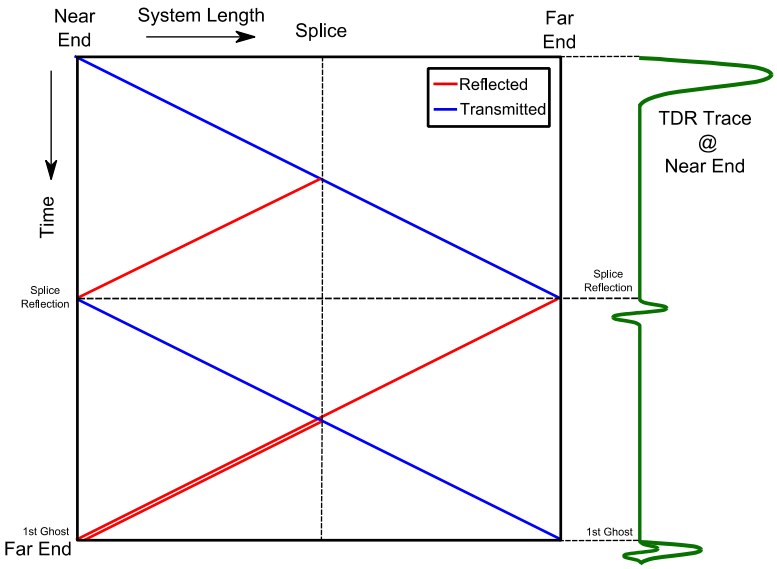
Table 10: Illustrative Case Studies for TDR "Ghost" Reflections

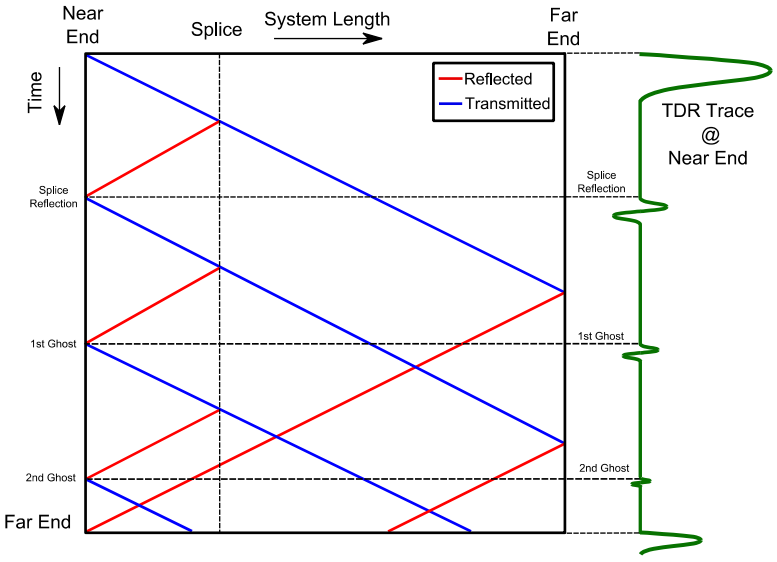
Case 3: Cable System with One Splice Located at the Exact Midpoint of the Cable System Length

- No TDR "Ghost" reflections observed before the far end reflection.
- Critical location for splices or anomalies for not having "Ghosts."
- First splice "Ghost" superimposes the far end reflection.



Case 4: Cable System with One Splice Located between the Near End and the Midpoint of the Cable System Length

- At least one TDR "Ghost" reflection observed before the far end reflection.
- Generally easy to interpret taking into account the attenuation and dispersion.



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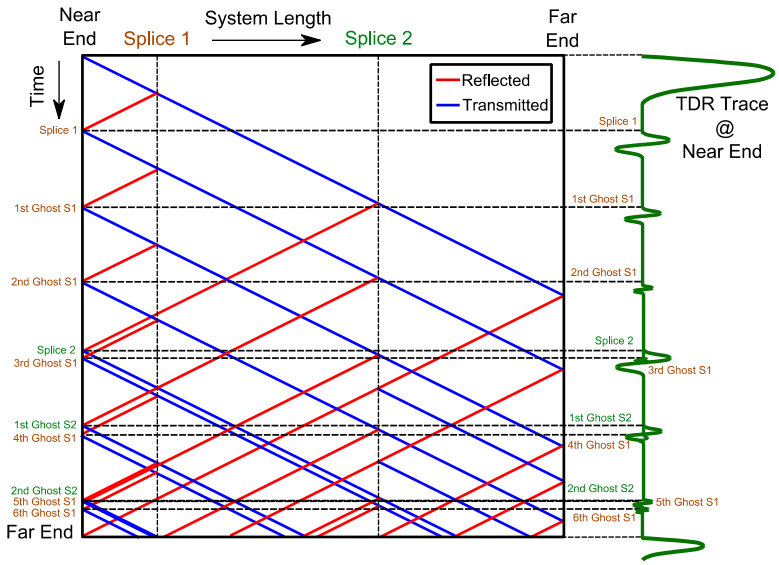
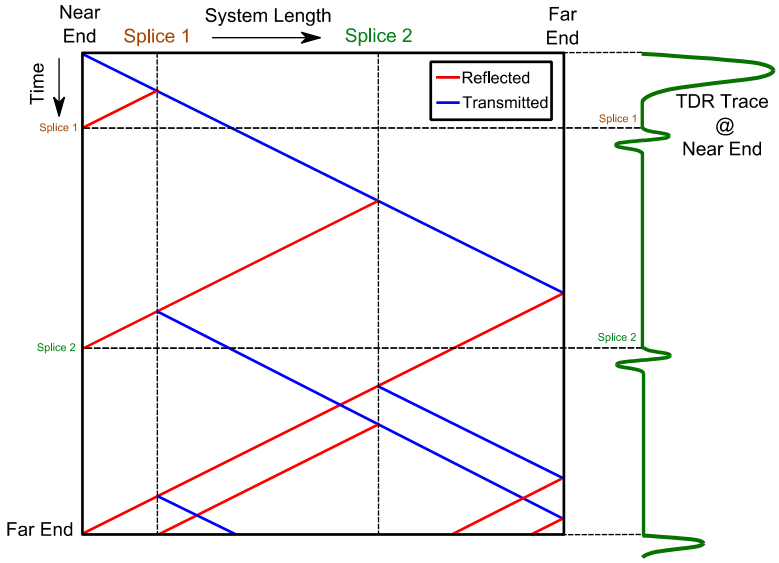
Case 5: Cable System with Two Splices Located at Arbitrary Positions	
• At least one TDR "Ghost" reflection observed • Generally challenging to interpret even by taking into account the attenuation and dispersion	
Case 6: Same as Case 5 Considering the Use of Impedance Coupling at Near End	
• All TDR pulse reflections are absorbed at the near end. • No "Ghosts" are observed on the TDR trace before far end reflection. • The presence of "Ghosts" is still possible depending on splice/anomaly location and separation.	

As seen in Table 10, when dealing with TDR "Ghost" reflections, the following points are important:

- The first reflection captured by the TDR unit always corresponds to a splice or anomaly irrespective of where the splice/anomaly is located.
- When one splice or anomaly exists beyond 50% of cable system length, then TDR "Ghost" reflections are not an issue.
- The TDR "Ghost" reflections start to appear only if the splices or anomalies are located within the first 50% of the cable system length.
- Care must be taken when interpreting TDR traces with "Ghost" reflections, since the

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"Ghosts" might be interpreted as nonexistent splices or additional anomalies.

- The attenuation and dispersion effects as well as spacing between "Ghosts" can help identify TDR "Ghost" reflections.
- The issue can be ameliorated by having a better TDR pulse injection and impedance coupling device. In this case, the impedance match between the TDR unit and cable system would absorb all the reflections coming back from splices or anomalies at the near end; therefore, potentially avoiding many TDR "Ghosts".
- The TDR "Ghosts" reflections between splices or splices and anomalies are impossible to control and are always present at some level; however, the magnitude of their presence depends on the number of splices or anomalies, their relative locations,, and the length of the cable system.
- When dealing with "Ghost" reflections, it is always advisable to perform a far end TDR deployment; a discussion on far end TDR deployment is contained in the next section.

The TDR "Ghost" reflections have been observed in the field, see Figure 24, for a 25 kV WTRXLPE URD cable system of approximately 5,211 ft. and with two splices. A TDR pulse of 100 ns was injected without an impedance matching device. The cable system structure (splice locations) was known beforehand.

Figure 24: Splice and Ghost Reflections as seen in a TDR Unit from Field Tests of a 25 kV XLPE Cable System with Two Splices (TDR pulse of 100 ns)

As seen in Figure 24, two "Ghosts" for each splice are visualized in the TDR trace. The "Ghosts" can be easily identified here because of the correlation between the spacing between them and their respective splice and also their attenuation and dispersion. For example, the distance between "1st Ghost S1" and the "Splice 1" is the same as the distance between "1st Ghost S1" and "2nd Ghost S1"; conversely, "2nd Ghost S1" is more attenuated and dispersed than "1st Ghost S1" and "1st Ghost S1" more attenuated and dispersed than "Splice 1". The same also holds true for "Splice 2" and its "Ghosts". In fact, the bounce diagram presented in Table 10 for two splices corresponds to the TDR trace shown in Figure 24; however, the other predicted "Ghosts" for "Splice 1" are not observed on the TDR trace. This is due to the attenuation and dispersion they suffer causing them to fall below

the noise level and thus making them undetectable by the TDR unit.

The interpretation of the TDR trace shown in Figure 24 has been relatively straightforward, this is because the cable system configuration could be postulated and thus a correlation can be made between the expected TDR "Ghost" reflections and the observed TDR trace. In a more realistic case, if the system structure is unknown, then an operator unaware of this issue could conclude that the system has six splices - a completely erroneous assessment. A well-trained operator, before reaching a TDR condition assessment, would have to correlate the TDR trace with different possible scenarios and choose the one that best represents the situation observed on the TDR trace; this is when the bounce diagram is most valuable.

5.7.4 Far End Deployment

In the common case, TDR is only deployed from only one end (near end) of the cable system. This is generally enough for determining the system structure and possible existing anomalies; however, in some cases, there is benefit when the TDR is deployed from both ends. Therefore, it is advisable to repeat TDR measurements from the far end if:

- The far end is not visible on the TDR trace or there is a mismatch between the estimated and actual lengths.
- There is doubt about the presence and type of an anomaly.
- There is a need to pinpoint an accessory or anomaly.

5.7.5 Pinpointing an Accessory or Anomaly

From a financial and power quality perspective, the importance of pinpointing an accessory or anomaly in a cable system is increasing; knowing the cable system structure with some level of certainty is becoming imperative. This is because faults that occur in any part of the system may often engender severe economic losses. A more accurate knowledge of the cable system structure would facilitate inspections, maintenance, and repairs; yielding a more reliable and secure system by reducing outage times, revenue losses, and repair crew costs.

As seen in the previous section, the TDR technique when deployed from both ends can effectively pinpoint an accessory or anomaly in a cable system. However, there are several factors to consider when maximizing the benefits of the TDR results.

- Influence of the VoP: As mentioned earlier, different cables have different VoPs. To assure the most accurate conductor distance measurements, the cable VoP must be determined. Therefore, the *CDFI* perspective shown here is only valid if the correct VoP has been selected.
- System layout: The layout is directly related to the conductor length and thus affects the TDR results. Figure 25 is the same as Figure 1 and shows different underground cable system layouts. Figure 26 shows the corresponding illustrative TDR traces for the different layouts in Figure 25.

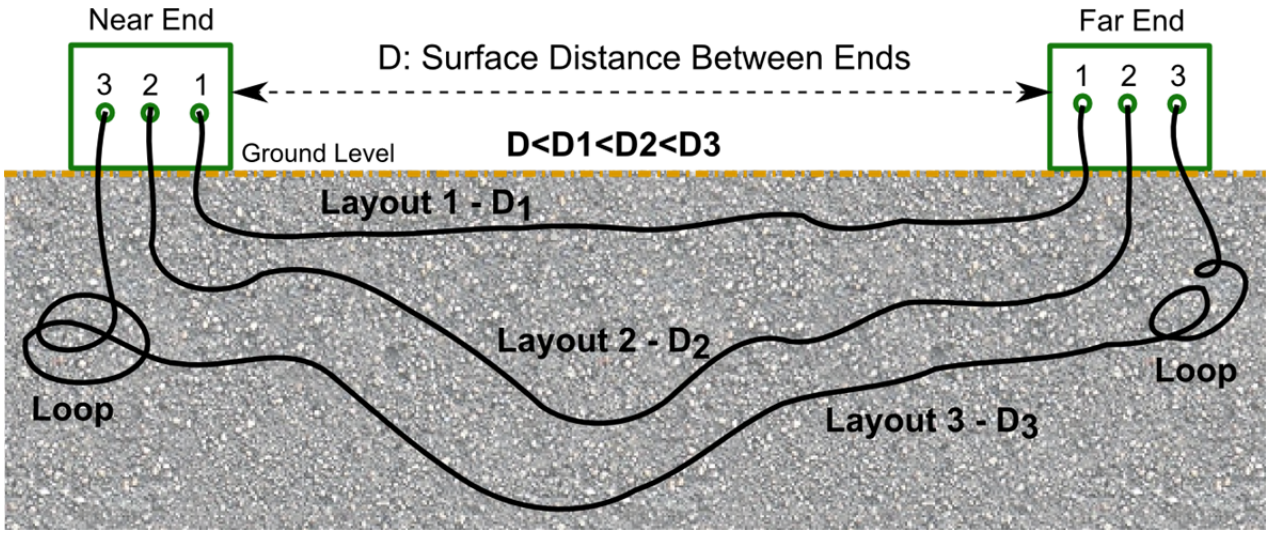

Figure 25: Different Underground Cable System Layouts

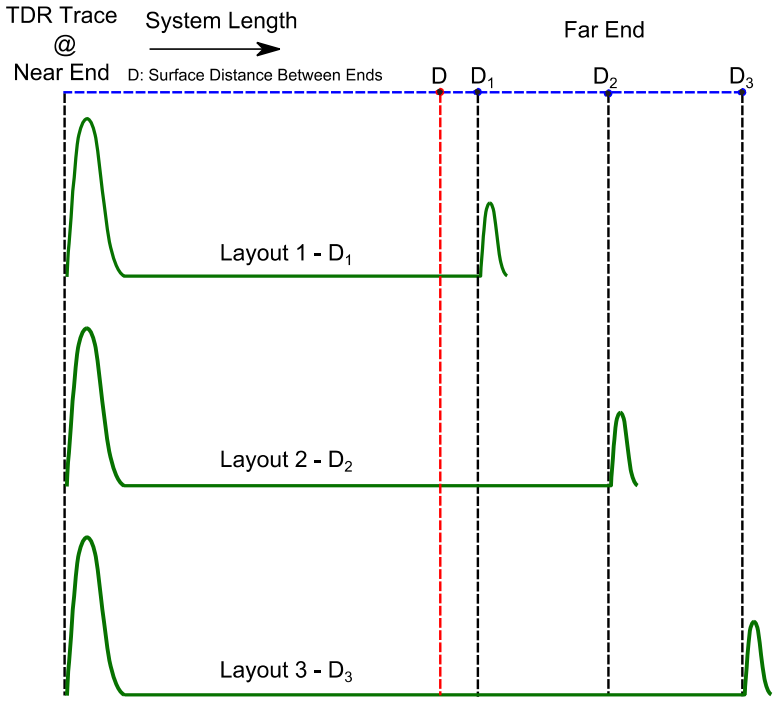

Figure 26: Illustrative TDR Traces for the Different Underground Cable System Layouts Shown in Figure 25

As seen in Figure 26, when the correct VoP is used, the estimated distance of the far end, as compared to the surface distance between ends, is always over estimated; this situation intensifies for layouts 2 and 3 as more buried cable and thus conductor length affects the TDR unit. It may be thought; that this overestimation issue can be solved by adjusting (increasing) the VoP up to the level that causes the TDR measured distance to be the same as the surface distance between ends.

While this could be a good practice for layout 1 (small difference between D and D_1), it does not work for layouts 2 and 3. In addition, because of the uncertainty regarding the precise cable system layout, adjusting the VoP to match the surface distance between ends is not a good practice and should be avoided. The VoP has to be determined or estimated according to the cable under test.

This situation imposes an issue which is a conundrum for pinpointing a splice or anomaly on a cable system based on TDR measurements. This is illustrated in Figure 27.

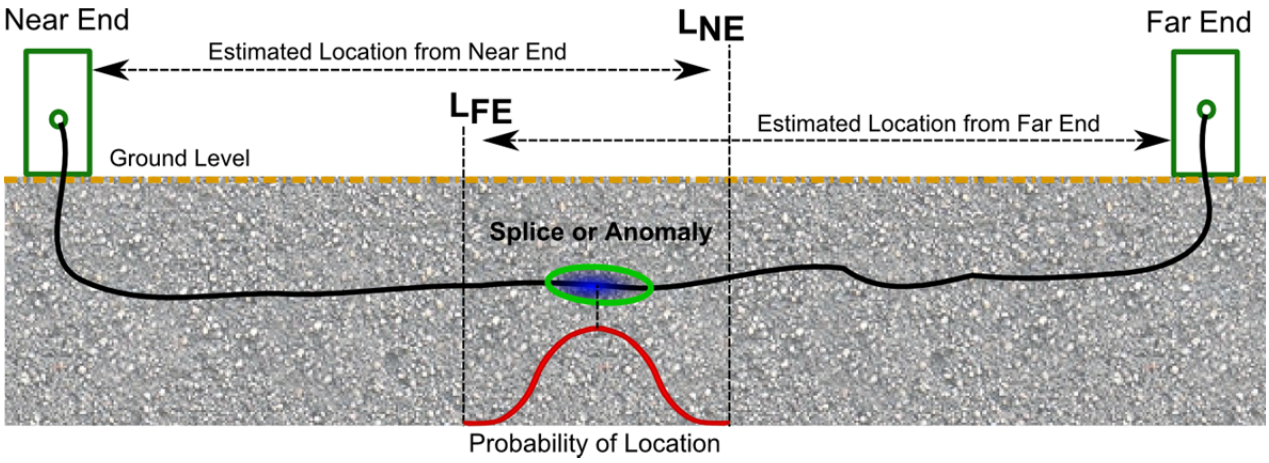

Figure 27: Conundrum for Pinpointing a Splice or Anomaly based on TDR Measurements

As seen in Figure 5, the TDR is deployed from both ends and in each case the splice or anomaly location is over estimated; however, the TDR pinpointing has the advantage that the limits L_{NE} and L_{FE} are identified, the splice or accessory would be located with a high degree of certainty between them. In Figure 27, the probability of the location of the splice or accessories occurring between the limits is represented by the red curve; note that the probability has its maximum at the midpoint of the range established by L_{FE} and L_{NE}; therefore, if digging for repairs is required, this location is the best choice. If the splice or anomaly is not found at that location; then repair crews should start digging in both directions until it is found. This is the best practice when using TDR to find splices or anomalies on an underground cable system.

It is important to mention that to increase the accuracy in pinpointing splices or anomalies, the TDR technique can be used in combination with other locating methods. There are several methods to achieve the aim and the previously specified benefits. However, some of them (especially those based on high voltage testing) can diminish the integrity, or even more, be destructive to the cable system. Some of these might require equipment that is not easy to handle and deploy, or some might involve detection methods that are unfamiliar to the utility cable engineer. There is no question that an understanding of all available methods is essential to maximizing the effectiveness of successfully locating a splice or anomaly; however, such a comprehensive study falls beyond the scope of the research and practical work considered here.

5.7.6 Operator Training

Beyond hardware and software, the success of cable system condition assessment using TDR relies on the skill of the operator. Therefore, an excellent operator training program would provide a higher probability for correctly assessing the cable systems. Training should not be a trivial process. Initially the operator must understand the basic concepts of transmission lines and how a high frequency signal travels through them. The concepts of frequency components, attenuation, dispersion, noise coupling, and filtering are also important. The operator must study and develop a command of the TDR unit hardware and software. Next would be learning acquired from the basic accessory or anomaly TDR signatures. Hands-on experience would then become paramount. Tailored solutions appropriate for their specific system would be learned and correlated with the TDR measurements. Finally, heuristic rules and procedures would be developed. This would round out training and should result in the development of a skilled operator.

5.7.7 VoP Error

It may be thought that variations in VoP would make it almost impossible to locate an accessory or anomaly accurately. Fortunately, there are ways to minimize the error in the VoP when testing, resulting in very accurate distance measurements. The most common technique used to reduce VOP error is to test the system from both ends (TDR dual-ended deployment) to establish two lengths thereby localizing the accessory or anomaly between the two ends. The procedure is as follows:

- Determine the path of the cable system. With a measuring wheel, estimate the length of the cable system being tested. Set the VoP to 50%, test the cable from one end, and record the distance reading to the accessory or anomaly. Next, using the same VoP setting, test from the opposite end of the cable system and also record the distance reading. If the sum of the readings is the length of the cable system that was initially estimated, the VoP is correct and the fault has been located with some good degree of certainty.
- If the sum of the two readings is more than the initial estimated distance, reduce the VOP setting and re-test. This process can be repeated until a match between the computed and estimated distances is found.
- Similarly, if the sum of the two readings is less than the measured distance, increase the VoP setting. This process can be repeated until a match between the computed and estimated distances is found. However in this case, the operator must also consider the possibility of two accessories or anomalies.
- Same results can be obtained mathematically. Take the estimated cable system length and divide by the sum of the two TDR readings obtained by the tests from each end. This gives the adjustment factor. Then multiply each of the TDR readings by the adjustment factor. These results will be the corrected length readings.

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5.9 Relevant Standards

- IEEE Std. 1617 – 2007: *IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables*.

CHAPTER 6

Dissipation Factor (Tan δ)

Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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6.0 DISSIPATION FACTOR (TAN δ)

6.1 Test Scope

Tan δ measurements determine the amount of real power dissipation in a dielectric material. A comparison of this measured value to a known reference value for the type of dielectric measured is used to establish the condition of the tested system based on how much the dielectric loss differs from the reference value. For cable systems, reference values can be based on:

- values measured on adjacent phases (A, B, C)
- values measured on cables of the same design and vintage within the same location
- values measured when the cable was new
- how the values vary over time (trending)
- how the value varies during the measurement (stability)
- how the value changes as a function of applied test voltage
- how the value changes as a function of frequency
- industry standards
- an experience library.

Tan δ is most powerful if the specific cable and accessory components under test are known. This allows for a direct comparison between the measured value and:

- The expected values for known materials/components or
- Previous measurements on the same system.

6.2 How It Works

Applying an ac voltage and measuring the phase difference between the voltage waveform and the resulting current waveform provides the Tan δ value. This phase angle is used to resolve the total current (I) into its charging (I_C) and loss (I_R) components. Tan δ, also called Dissipation Factor (DF), is the ratio of the loss current to the charging current, as shown in Equation 1.

$$DF = \frac{I_R}{I_C} = \frac{\sqrt{I^2 - I_C^2}}{I_C} \qquad \textbf{Equation 1}$$

The angle δ appears in a phasor diagram in Figure 1.

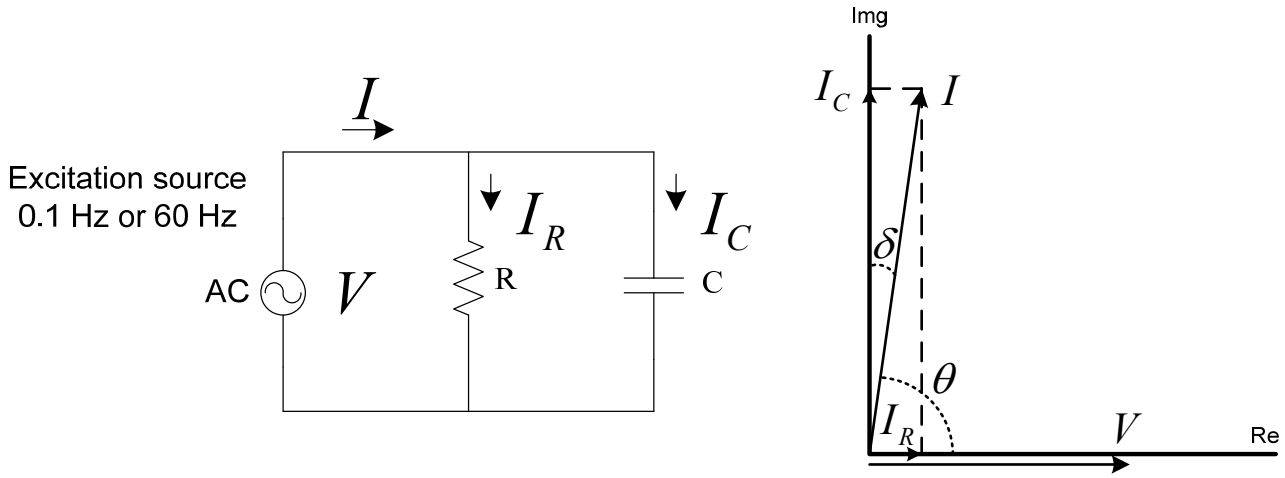

Figure 1: Equivalent Circuit for Tan δ Measurement and Phasor Diagram

Figure 1 shows an equivalent circuit for a cable, consisting of a parallel connected capacitance (*C*) and a voltage dependent resistance (*R*). The Tan δ measured at a frequency ω and voltage V, is the ratio of the resistive (I_R) and the capacitive (I_C) currents according to Equation 2.

$$DF = \tan(\delta) = \frac{I_R}{I_C} = \frac{V/R}{V/(1/\omega C)} = \frac{1}{\omega RC} \qquad \textbf{Equation 2}$$

The terms "Tan δ" and dissipation factor are used interchangeably.

6.3 How It Is Applied

The cable system under test is disconnected from the grid and energized from a separate power supply with a fixed ac frequency (e.g. 60 Hz or Very Low Frequency (VLF) ac). The system is typically energized using a voltage level of 0.5 to 2 times the system operating phase to ground voltage, U_0. Each Tan δ system utilizes different connection methodologies. Users should consult their equipment literature and/or vendor for specific details. In general, once the measurement system is connected to the circuit, a pre-programed series of voltage steps are used to energized the cable system while at the same time the system measures the Tan δ. Field measurements are generally performed at 0.1 Hz and so currently available measurement systems generate a single Tan δ measurement with each 10 s cycle of the voltage.

Summaries of the advantages and disadvantages of using Tan δ as a cable system diagnostic appear in Table 1 and Table 2.

Table 1: Advantages and Disadvantages of Tan δ Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
60 Hz ac Offline	• Testing voltage waveform has the same frequency as the operating voltage. • Voltages higher or lower than the operating voltage can be applied.	• Energizing test equipment is large, heavy, and expensive and is typically not used for Tan δ measurements. • No field data available for establishing criteria. • Tan δ is less sensitive at 60 Hz than at lower frequencies due to the increased magnitude of the capacitive current [2].
0.01 – 1 Hz ac Offline VLF	• Energizing test equipment is small and easy to handle. • Tan δ is more sensitive at lower frequencies than at 60 Hz due to the reduced magnitude of the capacitive current [3]. • Can test long systems. • Clear and accepted criteria available (IEEE Std. 400.2 - 2013). • Significant experience available. • Widespread use and multiple vendors.	• Testing voltage waveform is not the same frequency as the operating voltage. • When using a Cosine-rectangular waveform, Tan δ has to be approximated.

Table 2: Overall Advantages and Disadvantages of Tan δ Measurement Techniques	
Advantages	• Test results provided as simple numerical values can easily and quickly be compared to other measurements or reference values. • Four basic Tan δ features at VLF can be ranked in order of importance in making an assessment. (Features are discussed later.) • Provides an overall condition assessment (cable, terminations, and joints). • Measurements on a given phase can be compared to adjacent phases, so long as the phases have the same configuration. (Also applies to T-branched or other complex system configurations if all phases are essentially the same.) • The value can be an indication of the overall degree of water treeing in XLPE cable. • There is minimal influence from external electric fields/noise. • Periodic testing provides numerical data for comparison with future measurements to establish trends. • Data obtained at lower voltages (U_0 versus 2 U_0) are often as useful as data obtained at higher voltages. • Measured values that change as a function of test system length can be indicative of problems such as corroded neutrals. • When measured values change (are unstable) during a test, it may indicate that a component is progressing to failure. • Simple numeric results enable a quick risk assessment prior to testing at higher voltage levels. • Data may be reanalyzed and reinterpreted if needed as better criteria emerge. • Results are obtainable regardless of system length or number of accessories. • Results can detect poor performing accessories or cable lengths. • There is a low risk of failure on test. • Can be used to differentiate the loss characteristics of different EPR insulation materials. • Measurements made over time can be used to predict the rate of aging/degradation of a cable system.
Open Issues	• Methods to interpret results for hybrid systems need to be established. • Initial analysis indicates tan δ measurements may detect corroded neutral problems, but further exploration is needed to establish the relationship between Tan δ and degree of corrosion. • How different applied VLF voltage frequencies affect the measured loss criteria is not yet determined. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz ac and VLF has not been established. • Effect of single or isolated long water trees on Tan δ measurements. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable system must be taken out of service for testing. • By itself is not an effective test for commissioning newly installed cable systems.

The application of high voltages (voltages above the normal system operating voltage) for a long period (defined by either cycles or time) may cause some level of further degradation of an aged

cable system (see more detailed discussion in Section 2.0). The impact of this effect should be considered for all offline elevated voltage applications, including those that involve dielectric loss measurements. The precise degree of degradation depends upon the cable type, voltage magnitude, frequency, and time of application. Thus, when undertaking dielectric loss measurements, a utility should consider that a system can fail during the test and they may want to consider having a repair crew on standby. The subsequent section on expected outcomes provides some guidance on the likelihood of failure on test.

To enhance the effectiveness of a Tan δ test in assessing cable degradation, the dielectric loss should be periodically observed, preferably over a period of several years. In general, an increase in the Tan δ in comparison to previously measured values indicates additional degradation has occurred [1-8].

Dielectric loss is also measureable as a function of frequency. This approach, Frequency Dielectric Spectroscopy (FDS), is more commonly employed in the laboratory then the field and so is beyond the scope of this chapter.

Some accessories specifically employ stress relief materials with non-linear loss characteristics (dielectric loss changes nonlinearly as a function of voltage). Some researchers have suggested that these materials might have an influence on the measured loss values. However, the evidence available indicates that the type of stress relief may have a smaller effect on the overall loss measurement for the system than losses associated with severely degraded or improperly installed accessories.

Generally speaking, the best practice is to perform periodic testing at the same voltage level(s) using the same voltage frequency and waveshape over a period of several years so that a general trend in Tan δ over time can be established.

6.4 Success Criteria

The success criteria presented here corresponds to the approach outlined in the recent update of the IEEE Std. 400.2 – 2013 [9], which was the result of important research contributions from *CDFI Phase I*. In this new standard, Tan δ results appear in terms of three specific diagnostic features. The features in order of importance are:

- **Tan δ Stability** – This feature represents time dependency and is normally reported as the standard deviation (STD) of sequential measurements at U_0. However, the inter-quartile range (span of the middle 50% of the data) may also be used.

- **Differential Tan δ (Tip Up)** – This feature represents voltage dependency and is normally reported as the simple algebraic difference between the means of a number of sequential measurements taken at two different voltages (the difference between medians may also be used). In this case the voltage levels are 0.5 U_0 and 1.5 U_0.

- **Tan δ** Magnitude – This feature represents the level of loss and is normally reported as the

mean of a number of sequential measurements (the median of these measurements may also be used) at U_0.

Figure 2 shows examples of measured Tan δ data and diagnostic features from a polyethylene (PE) insulated cable system in service that illustrate graphically the features defined above. The diagnostic features for other insulation systems are the same, though their magnitudes may be different.

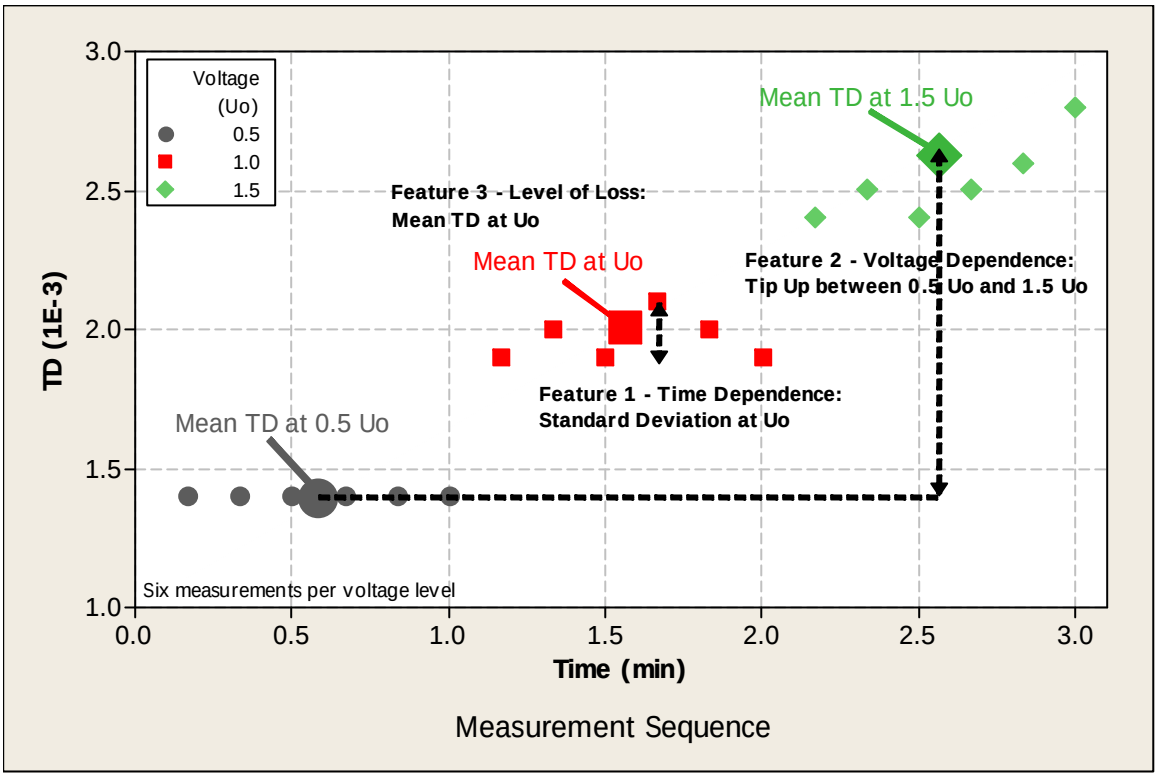

Figure 2: Example of Measured Tan δ data from a PE Cable System in Service and Tan δ Diagnostic Features

The Tan δ measurement results are often interpreted using rules such as those in Table 3 to Table 6 where test values fall into three classes: "No Action," "Further Study Advised," and "Action Required." However, the basic measured data are usually reported, which is valuable as it makes it possible to:

- Reinterpret the data when/if new assessment knowledge becomes available,
- Track trends, and
- Compare with adjacent cable lengths.

Establishing the success criteria for dielectric loss measurements is complicated in that the values depend not only on the cable system quality and degradation/aging, but also on the cable and accessory technologies employed on the tested cable system. More importantly, it must be understood that, for different insulations, installations, and cable types, the STD, Tip Up, and Tan δ figures of merit can vary significantly from each other. Therefore, the Tan δ diagnostic features

work best when comparing present measurements against established historical figures of merit for a particular cable system type as a whole (i.e. the cable +terminations+ joints). Table 4 through Table 8 show historical figures of merit derived from the research effort (note that some of these data were provided by the project participants) that may be used for condition assessment for aged PE-based (i.e. PE, XLPE, TRXLPE cables), aged filled insulations (i.e. EPR and Vulkene® cables), and aged oil impregnated paper (i.e. PILC cables) respectively. In Table 4 to Table 6, U_0 is the cable phase to ground operating voltage. The values given in Table 4 to Table 8 can also be given in percentages, in which case the values are multiplied by 100, for example, 0.1E-3 becomes 0.01 %. Finally, the columns in Table 4 to Table 8 are listed in the order of importance of the diagnostic features to insulation deterioration, i.e., the time dependence is the most important followed by the voltage dependence followed by absolute value of the level of loss.

Table 3: Pass and Not Pass Indications for Tan δ Measurements

Test Type	Cable System	Pass Indication	Not Pass Indication
0.1 Hz	XLPE	See Table 4 to Table 8 for IEEE Std. 400.2 – 2013 Criteria See *CDFI* Perspective Section for 2013 *CDFI* Criteria Utility specific criteria may be developed using the same principles used for IEEE Std. 400.2 – 2013 and the *CDFI* Perspective	
	HMWPE WTRXLPE		
	EPR		
	PILC		
>0.1Hz, <60 Hz	XLPE	Data is limited, so there is no unified criteria	
	HMWPE WTRXLPE		
	EPR		
	PILC		
60 Hz	XLPE		
	HMWPE WTRXLPE		
	EPR		
	PILC		

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Table 4: Figures of Merit Based on CDFI Research (2010) for Condition Assessment of Service-aged PE-based Insulations (i.e. PE, XLPE, and TRXLPE) using Tan δ Measured at 0.1 Hz					
Condition Assessment	**STD @ Uo (E-3)**		**Tip Up (E-3)**		**Tan δ @ Uo (E-3)**
No Action Required	<0.1	**and**	<5	**and**	<4
Further Study Advised	0.1 to 0.5	**or**	5 to 80	**or**	4 to 50
Action Required	>0.5		>80		>50

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Table 5: Figures of Merit Based on CDFI Research (2010) for Condition Assessment of Service-aged Filled Insulations using Tan δ at 0.1 Hz						
Condition Assessment	**Filled Insulation System**	**STD @ Uo (E-3)**		**Tip Up (E-3)**		**Tan δ @ Uo (E-3)**
No Action Required	*** If it is not possible to definitively identify a Filled Insulation**	**<0.1**	**and**	**<5**	**and**	**<35**
	Carbon-filled (Black) EPR	<0.1		<2		<20
	Mineral-filled (Pink) EPR	<0.1		<4		<20
	** Discharge resistant EPR	<0.1		<6		<100
	** Mineral-filled XLPE	-		-		<100
Further Study Advised	*** If it is not possible to definitively identify a Filled Insulation**	**0.1 to 1.3**	**or**	**5 to 100**	**or**	**35 to 120**
	Carbon-filled (Black) EPR	0.1 to 2.7		2 to 120		20 to 100
	Mineral-filled (Pink) EPR	0.1 to 1		4 to 120		20 to 100
	** Discharge resistant EPR	0.1 to 1		6 to 10		100 to 350
	** Mineral-filled XLPE	-		-		100 to 350
Action Required	*** If it is not possible to definitively identify a Filled Insulation**	**>1.3**	**or**	**>100**	**or**	**>120**
	Carbon-filled (Black) EPR	>2.7		>120		>100
	Mineral-filled (Pink) EPR	>1		>120		>100
	** Discharge resistant EPR	>1		>10		>350
	** Mineral-filled XLPE	-		-		>350

* Experience has shown that it is quite difficult to precisely identify the type of filled insulation used for field-installed cable. The issues encountered include: incorrect or missing records, missing or obscured markings on the cable jacket, indistinct coloring, etc. In these cases it is recommended to use the criteria for the collated datasets.

** Insufficient data have been collected to make precise estimates of criteria; consequently, the criteria are likely to contain considerable errors. However, they are included here to provide some guidance to engineers encountering these insulation systems in the field.

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Table 6: Figures of Merit Based on CDFI Research for Condition Assessment of Service-aged Paper Insulated (PILC) using Tan δ at 0.1 Hz					
Condition Assessment	**STD @ Uo (E-3)**		**Tip Up (E-3)**		**Tan δ @ Uo (E-3)**
No Action Required	<0.1	**and**	-35 to 10	**and**	<85
Further Study Advised	0.1 to 0.4	**or**	-35 to -50 or 10 to 100	**or**	85 to 200
Action Required	>0.4		<-50 or >100		>200

Annex G of IEEE Std. 400.2 – 2013 also provides guidance for interpreting Tan δ results of new power cable systems. The criteria appear in Table 7 and Table 8. However, the standard also points out that the data available (2010) from VLF diagnostic tests on the different types of newly installed power cable systems are limited; thus, the values given in Table 7 and Table 8 may change as additional data are accumulated. Therefore, at this time the values must be considered as provisional criteria and they may be used as guidelines for engineering information only. A well thought out condition assessment of newly installed power cable systems involves the deployment of additional diagnostic tests.

Table 7: Criteria Based on CDFI Research for Assessment of NEWLY Installed Power Cable Systems with PE-based Insulations (XLPE and TRXLPE)*					
Condition Assessment	**STD @ Uo (E-3)**		**Tip Up (E-3)**		**Tan δ @ Uo (E-3)**
Acceptable	<0.1	**and**	<0.8	**and**	<1.0
Further Study Advised	>0.1	**or**	>0.8	**or**	>1.0

* Provisional criteria due to sparse data; thus they may be used for engineering information only

Table 8: Criteria Based on CDFI Research for Assessment of Newly Installed Conventional Mineral-filled EPR Cable Systems*					
Condition Assessment	**STD@ Uo (E-3)**		**Tip Up (E-3)**		**Tan δ@ Uo (E-3)**
Acceptable	<0.1	**and**	<0.8	**and**	<1.0
Further Study Advised	>0.1	**or**	>0.8	**or**	>1.0

* Provisional criteria due to sparse data; thus they may be used for engineering information only

As seen from Table 4 to Table 8, the Tan δ diagnostic includes values that are time dependent (STD at U_0), voltage dependent (Tip Up between 0.5 U_0 and 1.5 U_0), and values that are absolute (Tan δ at U_0). They are used as figures of merit or compared to historical data to grade the condition assessment of the power cable insulation:

- The "**No Action Required**" condition assessment means that the cable system does not exhibit unusual dielectric loss characteristics, but it should be retested at some later date to observe the trend of the Tan δ diagnostic characteristics over time.
- The "**Further Study Advised**" condition assessment means that additional information is needed to make an assessment. The additional information could come from previous system failure history or additional assessment from an additional diagnostic test; for example, a monitored withstand test can be performed after the Tan δ test and the information from the monitored withstand test could be used to enhance the diagnostics leading eventually to a condition assessment of "No Action Required" or "Action Required." In other cases, a partial discharge diagnostic test may be warranted.
- The "**Action Required**" condition assessment means that the cable system has an unusually high set of Tan δ characteristics that may be indicative of poor insulation condition and should be considered for replacement or repair immediately after the test or in the near future. These results may also be used to trigger further testing using additional diagnostic techniques.

The above condition assessment classes are intended to guide the remedial actions, if any, the cable system user should take to return the system to a reliable operating condition. As defined above, systems that are assessed as "**No Action Required**" do not require immediate additional actions. However, if a cable system is assessed as "Further Study Advised" or "Action Required," then additional actions should be undertaken. The timing of the additional action will be a function of the circuit sensitivity and available resources. Naturally, a circuit that falls into the "Action Required" category would likely need more urgent attention than a circuit that falls into the "Further Study Advised" category.

Actions following a **"Further Study Advised"** assessment might include:

- Review data for a rogue measurement values – most common in the first voltage cycle,
- Confirm insulation type to ensure that criteria apply,
- Clean or re-clean terminations and repeat measurements,
- Compare with previous tests or results from other phases of the circuit,
- Conduct a VLF withstand test (30 min) according to the voltage levels established by IEEE Std. 400.2 – 2013, or,
- Place on "watch list" and plan a retest in the future (three to five years).

In addition to the first four actions following a "Further Study Advised" condition assessment, actions following an "**Action Required**" condition assessment might also include:

- Conduct a VLF withstand test (60 min) according to the voltage levels established by the

current IEEE Std. 400.2 – 2013 or

- Retest in the near future and observe trends (one to two years).

In addition, if the tested circuit exhibits Tip Up or Tan δ stability values that are outside the limits provided in Table 4 to Table 8, there may be a section of severely damaged/degraded cable or accessory insulation. Similarly, if there is a significant increase in the Tan δ level during the test with increasing voltage from 0.5 U_0 to U_0, there may not be a need to raise the voltage to test at 1.5 U_0, as the significant increase is an indication that the cable system is highly degraded and there is a risk of initiating electrical trees in the severely damaged insulation that could degrade it further or cause it to fail during the test. In this case, the cable system condition should be assessed as "Action Required".

The figures of merit presented in Table 4 to Table 8 have been derived from empirical cumulative distribution functions (CDF) for the data consisting of data points obtained during maintenance tests on aged cable systems, mainly in utilities from North America. To determine the threshold level between classes, the tables use the probability criteria of the 80 %. This was selected based on the Pareto principle that the best ranked 80 % of a population only accounts for 20 % of the issues/problems and 95 % of the poorest values are considered to be extremely unusual. The figures of merit are constructed so that they may be used with the basic insulation system information available to test engineers at the time of the field investigation. More details of how the figures of merit are derived are given later in the section that provides *CDFI Phase I* and *Phase II* perspectives.

There are some circumstances where the precise cable design (e.g., shielded or belted paper insulated cables and conducting or non-conducting insulation shields on some types of filled insulation cables) or system composition or insulation material or vintage is known. In these cases, the figures of merit are useful guides. However, a utility can develop its own "cable system specific" criteria to provide better discrimination using the approach described above. These nuances are not included in these tables because only a small number of installations were precisely identified to enable the discrimination. As an example, several formulations of EPR (the mineral-filled class) have been used; however the formulations that may be definitively identified represent only 2% of all filled insulation data.

6.5 Estimated Accuracy

CDFI Phase I explored, developed, and completed success criteria that the IEEE Std. 400.2 – 2013 Working Group considered and have included in the update of the standard. As a reminder, according to the IEEE Std. 400 – 2001, the success criteria for the Tan δ diagnostic measurements at VLF of 0.1 Hz are:

- **Pass** – Tan δ value at 2 U_0 of less than 1.2E-3 and a Tip Up (difference in Tan δ between 2U_0 and U_0) of less than 0.6E-3 and,
- **Not Pass** – Tan δ value at 2 U_0 of more than 1.2E-3 and a tip up (difference in Tan δ between 2U_0 and U_0) of more than 0.6 E-3.

Subsequently, Table 9 was generated, which shows the resulting estimated accuracies based on IEEE Std. 400 – 2001 using Pass/Not Pass criteria. In this case, accuracy is defined as the percentage of the time that the diagnostic correctly predicted the performance of the tested cable system segment over the evaluation horizon (1-3 years after the test was performed). Pass accuracy is the percentage of the time that the test results indicated the segment was good and the segment did not fail over the evaluation horizon. Table 9 shows that pass accuracy is quite high. Not pass accuracy is the percentage of the time that the test results indicated the segment was not good and the segment did fail over the evaluation horizon. Table 9 shows that not pass accuracy is much lower than the pass accuracy. Fortunately, far more circuits fall into the pass category than the not pass category.

Table 9: Summary of Tan δ Accuracies
(Pass and Not Pass Criteria are based on IEEE Std. 400 – 2001 Criteria)

Accuracy Type		**Tan δ**	
		Raw	**Length Adjusted**
Overall Accuracy (%)	Upper Quartile	74.8	59
	Median	60.0	59
	Lower Quartile	45.8	59
	Number of Datasets	8	8
	Length (miles)	136	136
Pass Accuracy (%)	Upper Quartile	100	98.7
	Median	100	98.7
	Lower Quartile	92.0	98.7
	Number of Datasets	7	7
	Length (miles)	134	134
Not Pass Accuracy (%)	Upper Quartile	53.5	9.8
	Median	7.9	9.8
	Lower Quartile	0.1	9.8
	Number of Datasets	8	8
	Length (miles)	136	136
Time Span (years)		2000 – 2008	
Cable Systems		XLPE, WTRXLPE, PAPER, HMWPE	

6.6 *CDFI* Perspective

Participating utilities provided several extensive Tan δ datasets for both phases of the *CDFI*. Because the data provided was numerical and represented a physical property measurement, it lent itself to extensive analysis and processing. Although a significant amount of discussion and analysis was performed on Tan δ data in this project, the *CDFI* does not endorse this (or any other) diagnostic. The significant focus on this technique is a natural consequence of having large volumes of analyzable numeric data from utilities willing to make it available for use in this project.

Dielectric Loss data are numerical values that make field analysis and real-time decision making possible. This has contributed to the volume of work performed in the *CDFI*. Dielectric Loss measurements are a transparent diagnostic in that the raw data are available to the user. These data are numeric and can easily be compared to critical values for decision-making. They may also then be re-analyzed should the critical values change. This allows for the accumulation of large amounts of data since the testing method and the values it produces do not change. Only the critical values change, so there is little need to conduct additional pilot programs to verify the impact of these changes since the relevant data are already available.

6.6.1 Changes in Perspective From *Phase I* To *Phase II*

The *CDFI Phase II* has allowed further study of the application of Tan δ as a diagnostic tool for cable systems. While the contributions made during *Phase I* were extremely important, the contributions of *Phase II* have proved to be equally important. Both phases of the project have influenced the way this technology is deployed in the field and induced utilities to deploy condition-based maintenance programs. The project also showed the dielectric loss measurement technique can be applied to HV power cable systems and has led Tan δ equipment manufacturers to develop smaller, easier to use diagnostic test units.

Phase I of the *CDFI* showed how a significant amount of data may be collated to garner data driven assessment criteria for power cable systems. Specifically in the case of VLF Tan δ, data classified using a single set of percentiles has enabled a consistent and relatable set of performance criteria to be established. To put this in perspective, Table 10 shows the evolution of Tan δ criteria for condition assessment of cable systems.

Table 10. Evolution of VLF Tan δ Criteria for Condition Assessment			
Year	**Assessment Hierarchy**	**Criteria & Issues**	**Comments**
< 2001	Tan δ	None	-
2001 – 2004	Tan δ Tip Up ($2U_0$ & U_0)	PE criteria only included in IEEE Std. 400™ – 2001	IEEE Std. 400 – 2001 release No technical basis Not based on data
2004	***CDFI Phase I***		
2007	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0)	Qualitative	Contribution of *CDFI Phase I* research – based on statistical analysis of data from North American cables and first *CDFI* Tan δ Brochure
2008 – 2010		• Criteria based on data. • Included in update of IEEE Std. 400.2 – 2013.	
2011	***CDFI Phase II***		
2011	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0) Tip Up of the Tip Up (TuTu)	• Criteria based on data. • PCA* analysis. • Combined diagnostic features added. • HV Subprotocol established.	Contribution of *CDFI Phase II* research – based on statistical analysis of data from North American cables and update of *CDFI* Tan δ Brochure
2013	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0) Tip Up of the Tip Up (TuTu)	• Verification of Tan δ diagnostic features. • Value of adding data. • Tan δ and Injection. • Tan δ mode analysis. • Principle for making feeder assessment.	Contribution of *CDFI Phase II* research – based on statistical analysis of data from North American cables and continuing update of *CDFI* Tan δ Brochure IEEE Std. 400.2 – 2013 release

*Principal Component Analysis

As Table 10 shows, Tan δ criteria for power cable systems have evolved considerably over the last 12 years. The contribution of the *CDFI* research has been significant not only in the evolution of the diagnosis criteria, but also how to approach real scenarios in the field. The number of diagnostic features has increased and the condition assessment is now made considering a combined "Health Index", which will be discussed in later sections. The analyses have been formatted such that they may be readily used in the field to provide real-time guidance on the appropriate decisions that a user might take to proactively manage their cable system

assets.

Other contributions of the *CDFI Phase II* research include:

- Update on reporting and interpretation of VLF Tan δ measurements as a diagnostic tool for condition assessment of power cable systems including a new diagnostic feature that takes into account the non-linear voltage dependence.
- The nature and importance of the Tan δ diagnostic features have been verified.
- The Tan δ database has increased in size including measurements from many different types of power cable systems.
- The VLF Tan δ features have been combined using advanced data analysis tools to provide a single condition assessment metric that defines a "Health Index" for the power cable system.
- The value of correctly acquiring new data and thus increasing the size of the Tan δ database has been demonstrated.
- The uncertainty of the diagnostic threshold levels has been presented and understood.
- A protocol for condition assessment using VLF Tan δ for HV has been proposed and verified through field test measurements.
- The changes in the condition assessment classes over time have been analyzed and presented.
- A method for analyzing power cable systems at the feeder level has been proposed.
- Indication of the effect of cable rejuvenation (injection) on Tan δ measurements and power cable systems has been analyzed and demonstrated.
- The application of VLF Tan δ as a tool for assessing the condition of hybrid power cable systems is introduced.
- Comparisons between the development of local and global criteria have been discussed.

The following sections provide the detail behind these contributions.

6.6.2 Measurement Approaches

There is one primary means of measuring dielectric loss: Constant ac (VLF or 60 Hz). This approach includes 60 Hz ac, VLF ac – sinusoidal, and VLF ac – cosine-rectangular voltage sources. They both measure capacitive and resistive currents to determine the system dielectric loss. The 60 Hz ac and VLF ac– sinusoidal approaches use relatively conventional measurement algorithms.

In all cases, the result is a numeric value. The excitation voltage may be varied in either approach so a differential Tan δ or Tip Up may be determined. In addition, the change in Tan δ with time may be monitored, quantified, and analyzed to obtain further information about the cable system. The reporting of numeric data and consistent measurement processes makes comparison between approaches and re-assessments straightforward.
Most of the data reported within the *CDFI* has come from the VLF ac – sinusoidal approach.

6.6.3 Reporting and Interpretation

The success criteria presented in this section represent the latest data analysis performed during *Phase 2* of the *CDFI*. It is an expansion of the criteria presented previously in that it considers an additional diagnostic feature identified by the research (the Tip Up of the Tip Up or TuTu). The Tan δ diagnostic features considered here are listed in order of importance as follows:

- **Tan δ Stability** – This feature represents the time dependence and is normally reported as the standard deviation (STD) of sequential measurements at U_0. However, the inter-quartile range (span of the middle 50% of the data) may also be used.
- **Differential Tan δ or Tip Up** – This feature represents the voltage dependence and is normally reported as the simple algebraic difference between the means of a number of sequential measurements taken at two different voltages (the difference between medians may also be used), in this case the voltage levels are 0.5 U_0 and 1.5 U_0.
- **Tip Up of the Tip Up (TuTu)** – This feature represents the nonlinear voltage dependence and it is reported as the algebraic difference between two Tip Ups: the Tip Up between 1.5 U_0 and U_0 and the Tip Up between U_0 and 0.5 U_0.
- **Tan δ Magnitude** – This feature represents the level of dielectric loss and is normally reported as the mean of a number of sequential measurements (the median of these measurements may also be used) at U_0.

Figure 3 shows examples of measured Tan δ data and diagnostic features from a PE cable system in service for illustration of the new feature. The diagnostic features for other insulation systems are the same as those described in Figure 3.

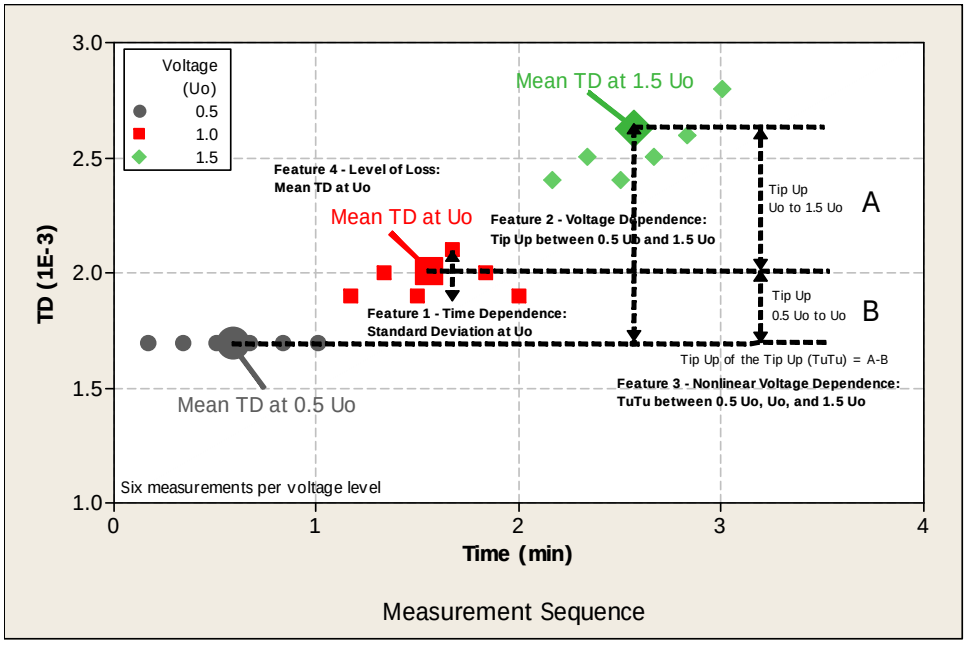


Figure 3: Example of Measured Tan δ data from a PE Cable System in Service and Tan δ Diagnostic Features for the *CDFI Phase II* Perspective

To aid in understanding the meaning of the TuTu, Table 11 shows the guidelines for

characterizing this voltage dependent diagnostic feature. Table 11 presents three cases. The first case considers linear voltage dependence. In this case, the value for the TuTu is zero since the change in Tan δ values between testing voltages are the same (see systems A and B in Figure 3). In the second (nonlinear, convex) case, the TuTu is always positive and indicates that changes on the insulation losses increase more dramatically as the test voltage increases. Lastly, the third nonlinear (concave) case exhibits a TuTu that is always negative indicating that changes in insulation losses decrease as the test voltage increases. The changes in the TuTu for the different insulation types are discussed later in this Chapter.

Table 11: Guidelines for Interpretation of Voltage Dependence Feature (TuTu)

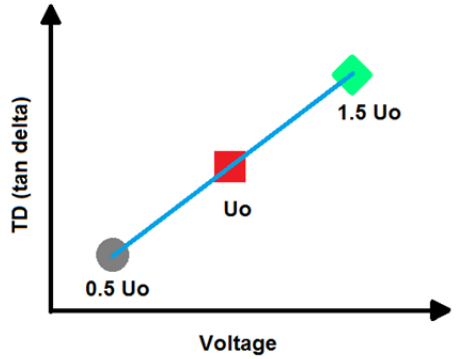
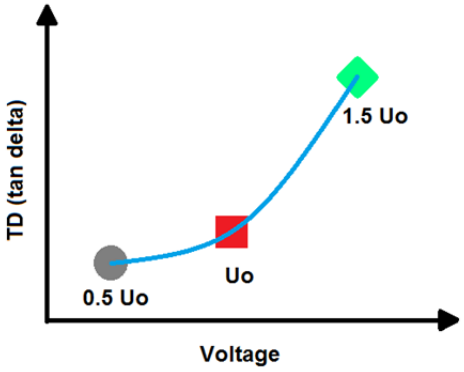
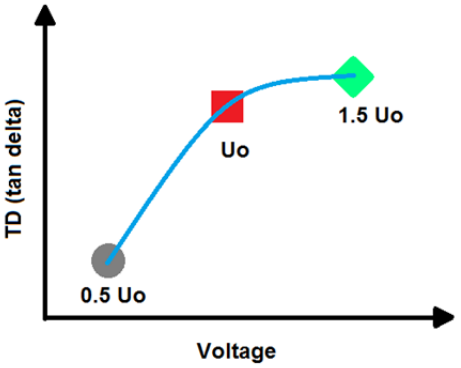
Voltage Dependence	Illustration of Tan δ vs. Voltage	TuTu Sign	Implications
Linear		0	Tip Up (U_0 and 0.5 U_0) = Tip Up (1.5 U_0 and U_0)
Nonlinear Convex Unusual PD or non-linear		+	Tip Up (U_0 and 0.5 U_0) < Tip Up (1.5 U_0 and U_0)
Nonlinear Concave Time Issue – drying out		-	Tip Up (U_0 and 0.5 U_0) > Tip Up (1.5 U_0 and U_0)

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Figure 4 shows a majority of the Dielectric Loss data collected in the *CDFI* in a box and whisker format. This excludes the data from the Monitored Withstand technique that is covered in Chapter 10. Figure 4 also includes the four Tan δ diagnostic features for all cable insulation types tested; filled, paper, and PE.

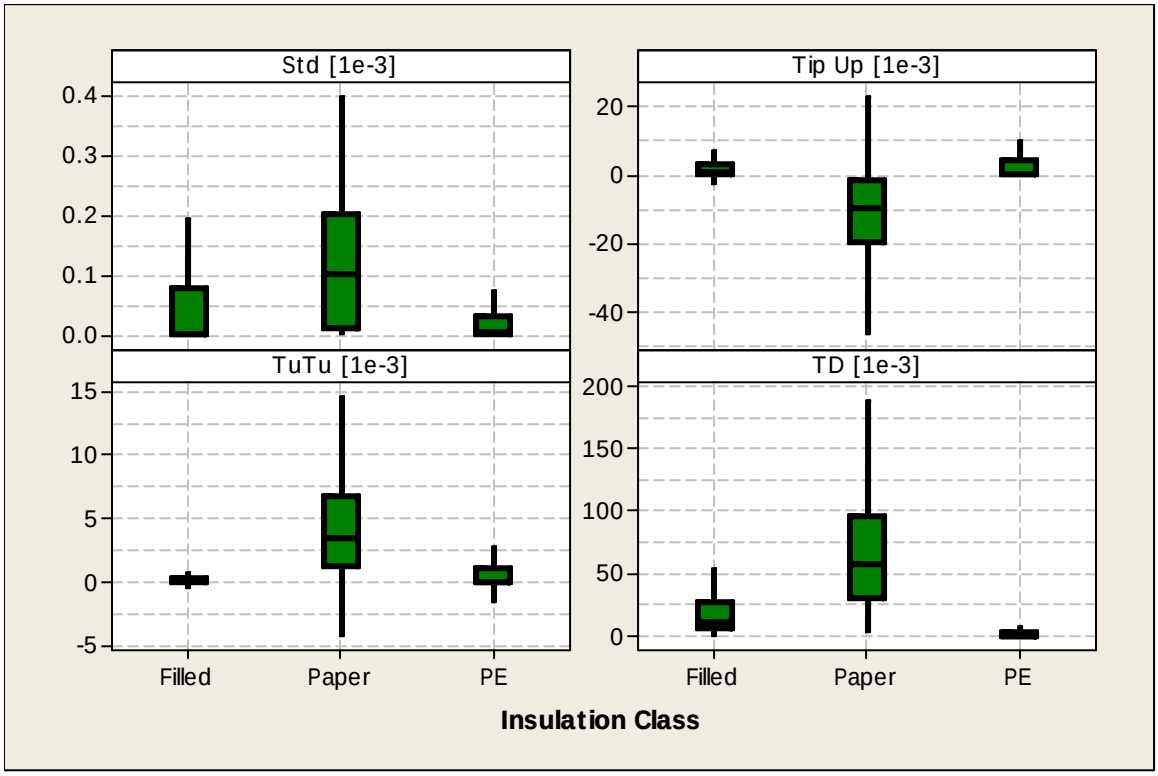

Figure 4: Dielectric Loss Feature Data segmented for Insulation Class

The data in Figure 4 represent more than 3,500 cable segments with a mean length of approximately 1,000 ft. The total length for this population exceeds 770 conductor miles. The horizontal lines within the boxes represent the median and the box itself the inter-quartile range between the first and third quartiles.

6.6.4 Establishing Critical Levels With Multiple Features

In the past, engineers have tried to find "perfect" criteria that absolutely separate the Tan δ values of components that go on to fail from those that do not. Naturally, it is not possible for a diagnostic to be that accurate. Even to approach this goal requires a significant amount of service data on Tan δ and failures, which are difficult to acquire. This is especially true for dielectric loss data that are typically collected by utilities. An alternative approach developed from the research in the *CDFI* identifies critical dielectric feature levels that separate "usual" from "unusual" data. This is the classic Shewart or control chart approach, which uses the mean and standard deviation as a metric to define a "normal" value. In the simplest form, data are unusual if either:

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a) One value lies more than three standard deviations from the mean or
b) Two sequential values are more than two standard deviations from the mean.

This approach is useful, but it does not take full advantage of the information available in Tan δ data. As an alternative to this approach, NEETRAC developed a database for Dielectric Loss data based on NEETRAC field tests and augmented it with data provided by participating *CDFI* utilities (AEP, Duke Energy, Intermountain REA, National Grid, and PG&E). As a result, knowledge rules for Tan δ could be further refined. The following sections describe the current database and its use in determining Tan δ critical diagnostic levels. This work relies on a hierarchy for Dielectric Loss features:

- First Tier – Stability
- Second Tier – Tip Up or Differential Tan δ
- Third Tier –Tip Up of the Tip Up or TuTu
- Fourth Tier –Tan δ

The database covers at least 22 discrete test areas and more than 3,500 data entries. The number of data with the associated system lengths and the percentage of data as a function of system lengths appear in Figure 5 and Figure 6, respectively. The term "Filled" refers to all cables with EPR or Vulkene® insulation, "Paper" refers to PILC cables, and "PE" refers to all cable with polyethylene based insulations, including HMWPE, XLPE, and WTRXLPE insulations.

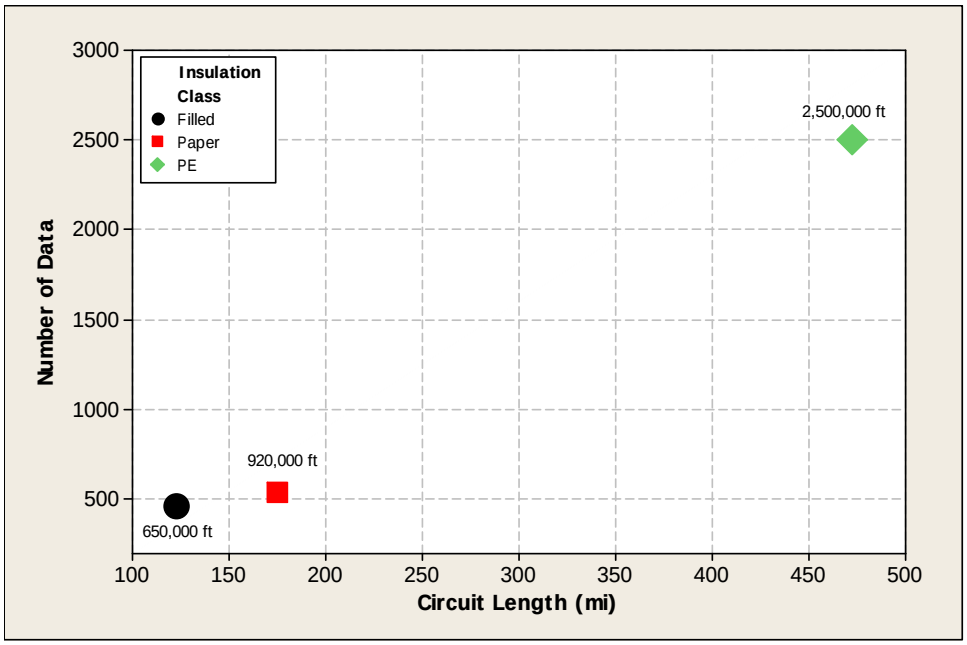

Figure 5: Tan δ Data and Corresponding Circuit Length (4.1 Million Feet)

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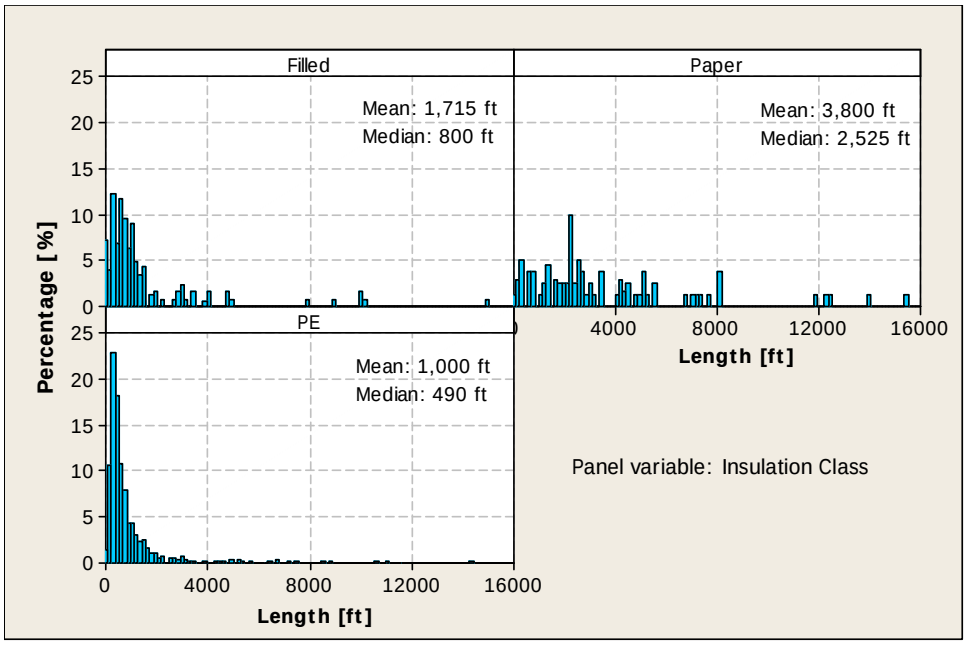

Figure 6: Histograms of Tested Lengths by Insulation Type

To determine Tan δ critical diagnostic levels, the Pareto Principle discussed earlier is applied to set two critical levels at the 80th and 95th percentiles of the data. The choice of the 80th percentile comes from the principle that says that 80% of the problems come from the worst 20% of the population. In contrast, the choice of the 95th percentile relies on the fact that any data point above this level is considered to be highly "unusual." The power of this approach is that it utilizes the whole dataset (cable systems that perform well and those that do not). Thus, it is self-updating as more data becomes available. However, as the decision points are made at the upper percentiles, updating can cause what appear as large changes in values. This is due to the shallow nature of the curves in the upper reaches that produce large changes in value for small changes in percentile.

Figure 7 shows the distribution of Tan δ stability measurements at U_0 for each insulation class (PE, Filled, and Paper). Stability, in this case, is assessed by the standard deviation of the data.

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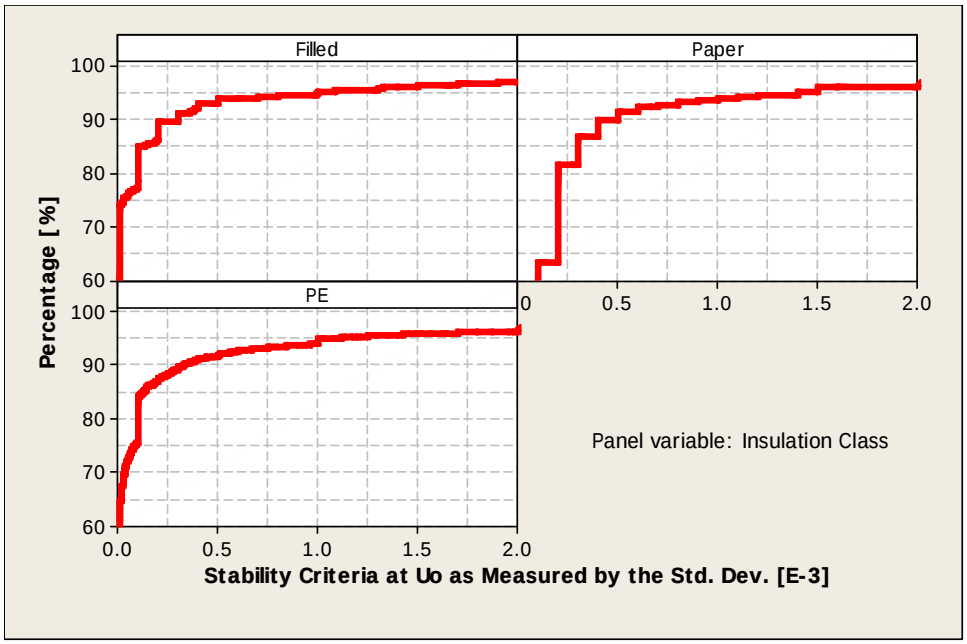

Figure 7: Cumulative Distribution of all Cable System Stability Values at U_0 Collated as Part of *CDFI* Research

Figure 8 and Figure 9 show the distributions of Tip Up data for different ranges of Tip Up where Tip Up is the difference in Tan δ measured at $1.5U_0$ and $0.5U_0$.

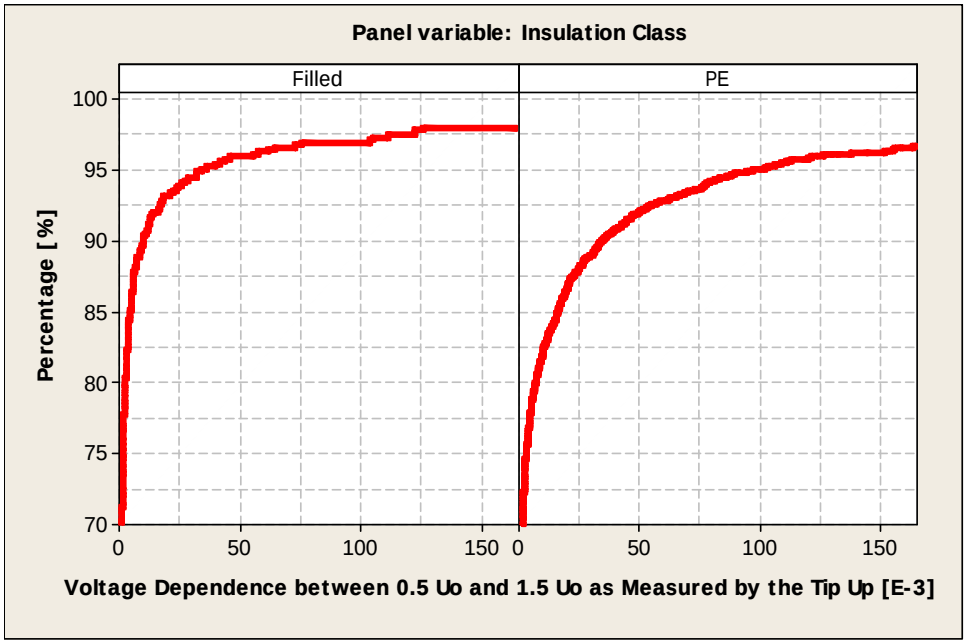

Figure 8: Cumulative Distribution of all Cable System Tip Up Criteria – Filled and PE Collated as Part of *CDFI* Research

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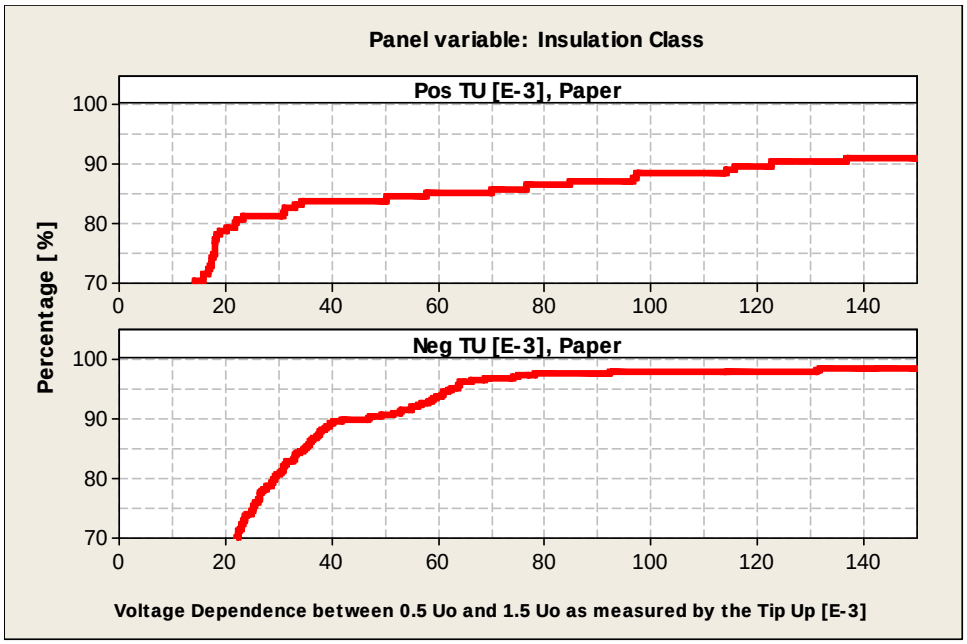

Figure 9: Cumulative Distribution of all Cable System Tip Up Criteria – Paper Collated as Part of *CDFI* Research

Figure 10 shows the cumulative distributions of all the cable system TuTu values.

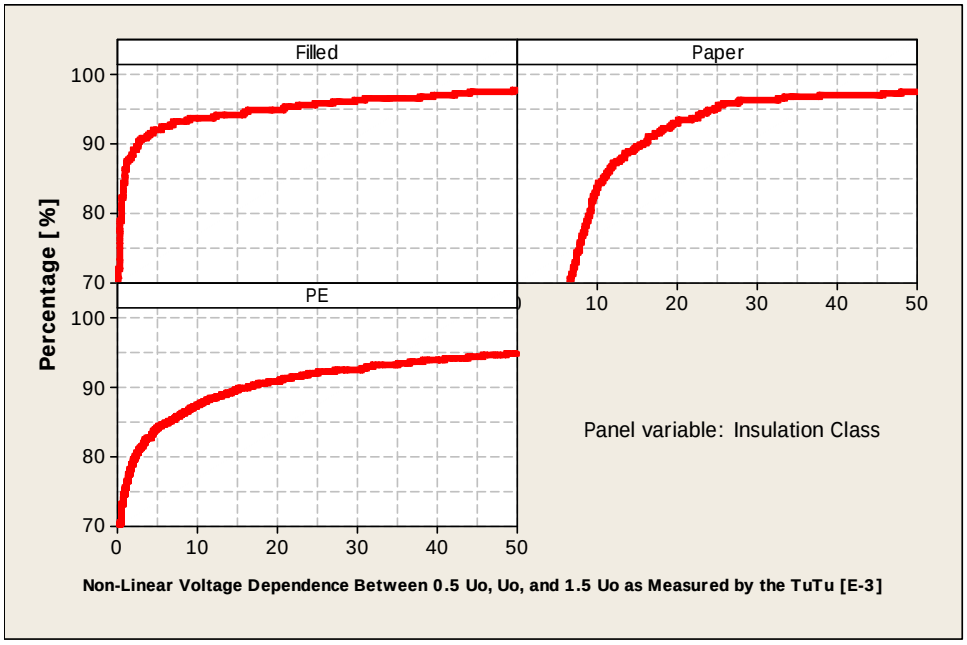

Figure 10: Cumulative distribution of all the Cable System TuTu Collated as Part of *CDFI* Research

Finally, Figure 11 shows the distributions of Tan δ measured at U_0.

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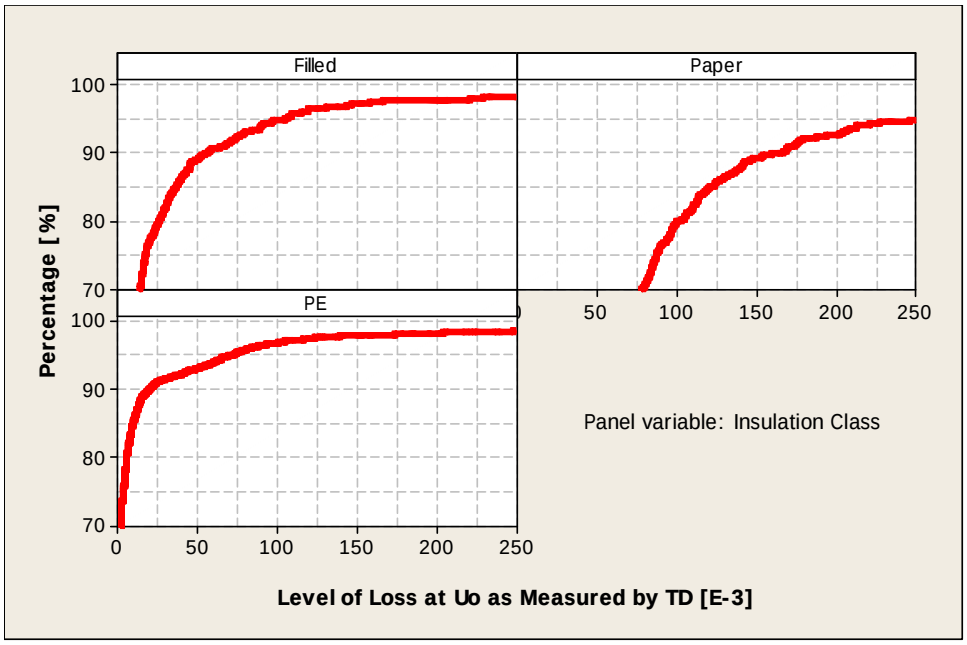

Figure 11: Cumulative distribution of all the Cable System Tan δ at U_0

Taking into account the 80th and 95th percentiles for the Tan δ features presented in Figure 7 through Figure 11, criteria for condition assessment of the different types of insulations were developed. Underlying these criteria is the basic understanding of what values represent good and poor performance, i.e. unstable time data (high standard deviations), large voltage dependences (high tip ups and tip ups of the tip ups), and large losses (high Tan δ values) are all characteristics of a poorly performing cable system. In other words, "good" segments lie to the left and "poor" segments lie to the right of the graphs in Figure 7 to Figure 11. The criteria developed from the research work appear in Table 12 to Table 14. As before, the condition of a cable system is assessed as: "No Action Required", "Further Study Advised", and "Action Required". Each of these assessments is defined by specific percentiles as follows:

- "No Action Required" encompasses the lowest 80% of the data,
- "Further Study Advised" encompasses the next lowest 15% (80% - 95%) of the data, and,
- "Action Required" encompasses the highest 5% (95% -100%) of the data.

These definitions appear graphically in Figure 12.

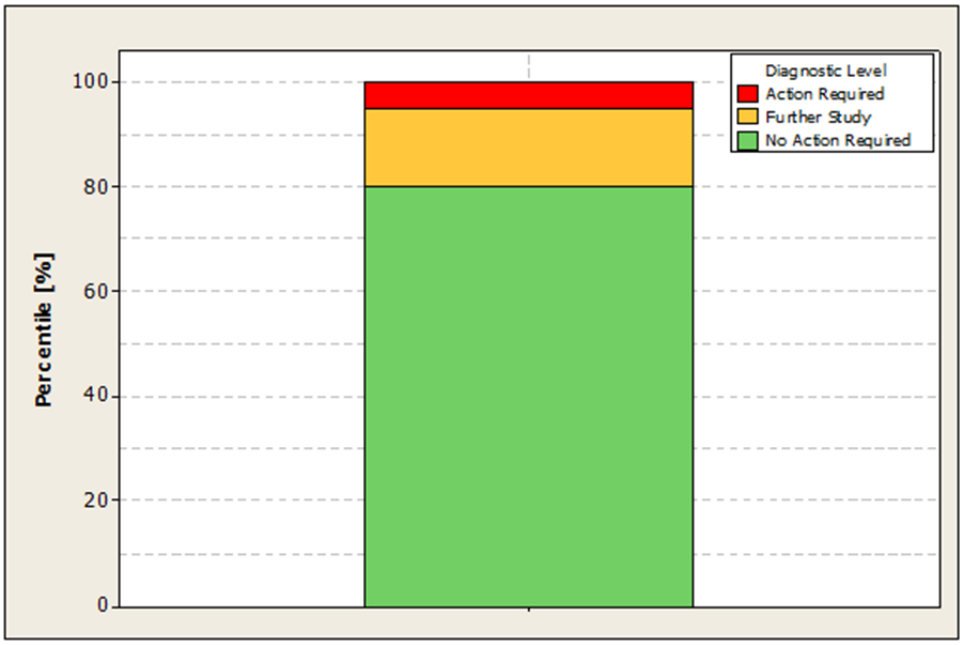

Figure 12: Percentiles Included in Each Diagnostic Level

Table 12 through Table 14 are based on these guidelines. As part of the ongoing dissemination of information from the *CDFI*, NEETRAC has made these tables available to the *CDFI* members. The hierarchy for diagnosis using Tan δ is as follows:

1. Tan δ Stability – stability is assessed by the standard deviation of dielectric loss at U_0 (other approaches are possible)
2. Tip Up – difference in the mean values of Tan δ at selected voltages
3. Tip Up of the Tip Up – difference between Tip Ups
4. Tan δ (mean value at U_0).

The criteria shown in Table 12 through Table 14 (2013) are different from those shown in Table 4 to Table 6 (2010), criteria that correspond with the IEEE Std. 400.2 – 2013, as they were developed with later and more complete datasets. The IEEE Std. 400.2 Working Group plans to include the additional diagnostic feature (TuTu) for the next standard revision.

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Table 12: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of PE-based Insulations (PE, HMWPE, XLPE, & WTRXLPE)			
Condition Assessment [E-3]	**No Action Required**	**Further Study Advised**	**Action Required**
Assessment of PE-based Insulations (i.e. PE, XLPE, WTRXLPE)			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.0	>1.0
	&	**or**	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<6.7	6.7 to 94.0	>94.0
	&	**or**	
Tip Up Tip Up $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
	&	**or**	
Mean TD at U_0	<6.0	6.0 to 70.0	>70.0

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Table 13: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of Filled Insulations (EPR & Vulkene®)			
Condition Assessment [E-3]	**No Action Required**	**Further Study Advised**	**Action Required**
Assessment of Unidentified Filled Insulations (i.e. EPR, Kerite, & Vulkene®) *			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.2	>1.2
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<3.0	3.0 to 30.0	>30.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<1.0	1.0 to 18.0	>18.0
	&	or	
Mean TD at U_0	<25.0	25.0 to 150.0	>150.0
Condition Assessment of Mineral Filled Insulations (i.e. EPR) *			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 0.8	>0.8
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<2.0	2.0 to 40.0	>40.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<1.0	1.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<16.0	16.0 to 75.0	>75.0

* Experience has shown that it is difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect /missing records, missing or obscured markings on the cable jacket, indistinct coloring, etc. In these cases it is recommended to use the criteria for **Unidentified Filled** data.

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Table 14: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of Paper Insulations (PILC)			
Condition Assessment [E-3]	**No Action Required**	**Further Study Advised**	**Action Required**
Assessment of Paper Insulations (i.e. PILC)			
Stability for TD_{U_0} (standard deviation)	<0.2	0.2 to 1.5	>1.5
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-30.0 to 22.0	-30 to -60 or 22 to 220	<-60.0 or >220.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<100.0	100.0 to 250.0	>250.0

The above condition assessment classes are intended to guide the remedial actions, if any, that the cable system user should take to return the system to a reliable operating condition. Criteria for a newly installed cable system have not changed and are the same as those presented earlier in Section 5.4.

As defined above, systems that are assessed as "No Action Required" do not require immediate additional actions. However, if a system is assessed as "Further Study Advised" or "Action Required," then additional immediate actions should be undertaken as follows.

As discussed earlier, actions following a "Further Study Advised" assessment might include a number of factors to consider. They were discussed earlier under Table 8, but are worth repeating here:

- review data for a rogue measurement value – most common in the first voltage cycle
- confirm insulation type to ensure that criteria apply
- clean or re-clean terminations and repeat measurements
- compare with previous tests or other results from other phases of this system if possible
- conduct a VLF withstand test (30 min) according to the voltage levels established by the IEEE Std. 400.2 – 2013
- place on "watch list" and plan a retest in the future (three to five years).

In addition actions following an "Action Required" condition assessment might also include:

- conduct a VLF withstand test (60 min) according to the voltage levels established by the current IEEE Std. 400.2 – 2013
- retest in the near future and observe trends (one to two years)

If there is a significant difference in Tan δ with increasing voltage (Tip Up) or a significant variation of Tan δ with time (STD), there may be a section of severely damaged or degraded insulation in the cable or accessory. Similarly, if there is a significant increase in the Tan δ level during the test with increasing voltage from 0.5 U_0 to U_0, there may not be a need to raise the voltage to test at 1.5 U_0, as the significant increase is an indication that the cable system is highly degraded and thus there is a considerable risk of initiating electrical trees in the severely damaged insulation. In this case, the cable system condition is assessed as "Action Required."

There are some circumstances where the precise cable design (e.g., shielded or belted paper insulated cables and conducting or non-conducting insulation shields on some types of filled insulation cables) or system composition or insulation material or vintage is known. In these cases the figures of merit are useful guides. However, a utility can develop its own "cable system specific" criteria to provide better discrimination, using the approach described above. These nuances are not included in these tables because only a small number of installations are identified with enough precision to make it worthwhile. Furthermore, the differences that have been identified are not statistically significant for the data available. As an example several formulations of EPR (the mineral-filled class) have been used, however the formulations that may be definitively identified represent 2% of the filled data.

The overall condition assessment of the system is defined by the most "serious" condition of any of the dielectric loss features. In other words, if any one criterion indicates the system is "Action Required," then the final assessment is "Action Required" regardless of what the other two criteria indicate. See Table 15 for examples. Prioritizing or differentiating between systems with the same overall assessment requires looking at the remaining two criteria. This scheme is very similar to the level-based systems used for other diagnostic techniques. However, in this case, the knowledge rules (i.e. the critical levels, the level criteria (80 % and 95 %), and the database) are available to the user.

Table 15 shows all possible combinations for establishing the overall condition assessments resulting from several combinations of Stability, Tip Up, and Tan δ assessments made using the above criteria. As Table 15 shows, there is one way to produce a "No Action Required" overall assessment while there are seven and 21 combinations that would produce "Further Study Advised" and "Action Required," respectively. Fortunately, in practice the most common condition assessments are "No Action Required."

Table 15: Overall Assessments for all Stability, Tip Up, TuTu, and Tan δ Combinations No Action Required = Green, Further Study = Orange, Action Required = Red					
Case	**Stability**	**Tip Up**	**TuTu**	**Tan δ**	**Overall Assessment**
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
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21					
22					
23					
24					
25					
26					
27					

This approach uses the most severe feature assessment to generate the overall condition assessment. A more sophisticated approach would recognize the extra information held within the 2nd, 3rd, and 4th (tip up tutu and tan δ) features. This is explored later in the Chapter where a Principal Component Analysis (PCA) is used to determine a more precise assessment that considers all four features.

6.6.5 Feature Selection

The methodology described in Section 6.6.4 is applicable to any multi-modal data (i.e. data that cannot be modeled with a single probability distribution). In the case of Tan δ, the available features include Tan δ at different voltages, Differential Tan δ, and Tan δ Stability. Ideally, one

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would prefer to use as few features as possible to make a condition assessment but then the question becomes: What features to use?

There are a number of ways to approach the problem of feature selection when there are only a few features available. One of the methods adopted by the *CDFI* is Performance Ranking. This method looks at the diagnostic feature's ability to correctly rank a group of tested systems as to their relative performance in service. This work took place in the laboratory and the metric used to evaluate service performance is the breakdown strength. Figure 13 shows the results of the first laboratory assessment of the breakdown strength of 1970's vintage XLPE insulated cables under VLF excitation. As this figure shows, there can be significant differences in the breakdown strength of aged cable systems. Figure 26 shows a field verification of this approach.

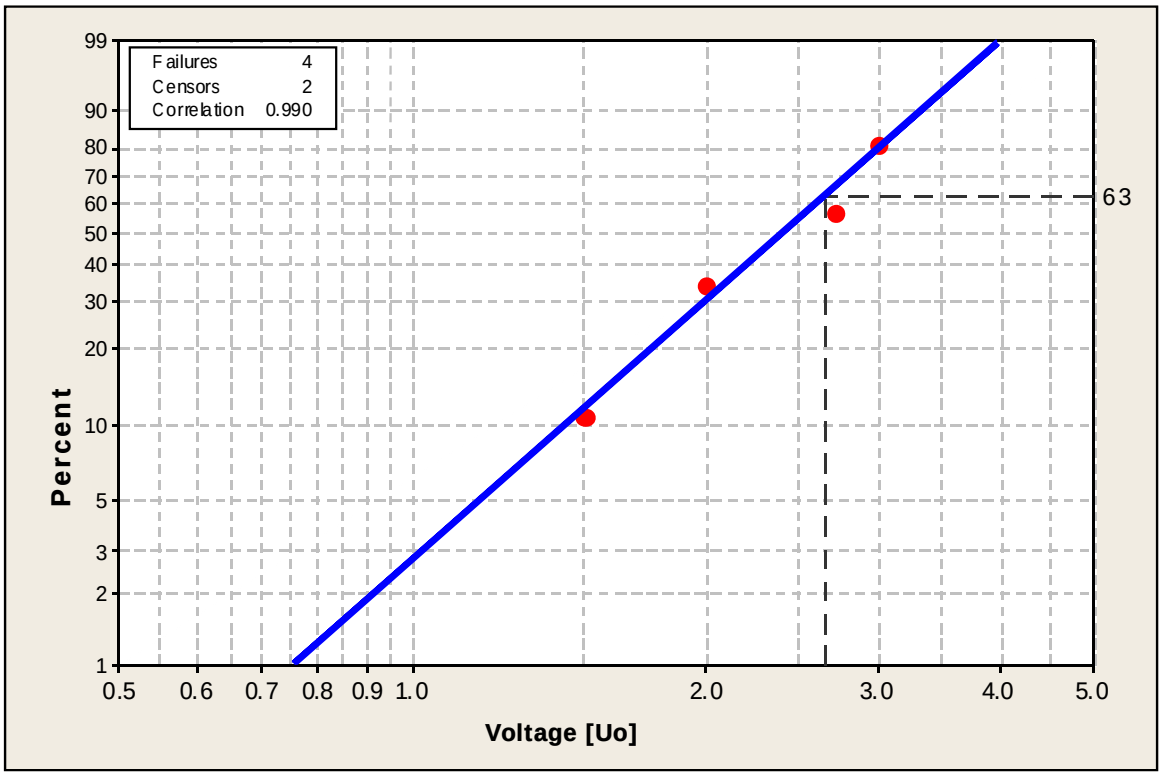

Figure 13: VLF Breakdown Voltage of Highly Aged XLPE Cables in Weibull Format

Prior to determining these breakdown strengths, all three of the dielectric loss features were measured. Thus after failure it was possible to examine which of these pre-mortem features best predicted the final breakdown strength outcome. The Performance Ranking approach involves identifying the best predictor of the breakdown strength using a Performance/Diagnostic Rank correlation plot as shown in Figure 14.

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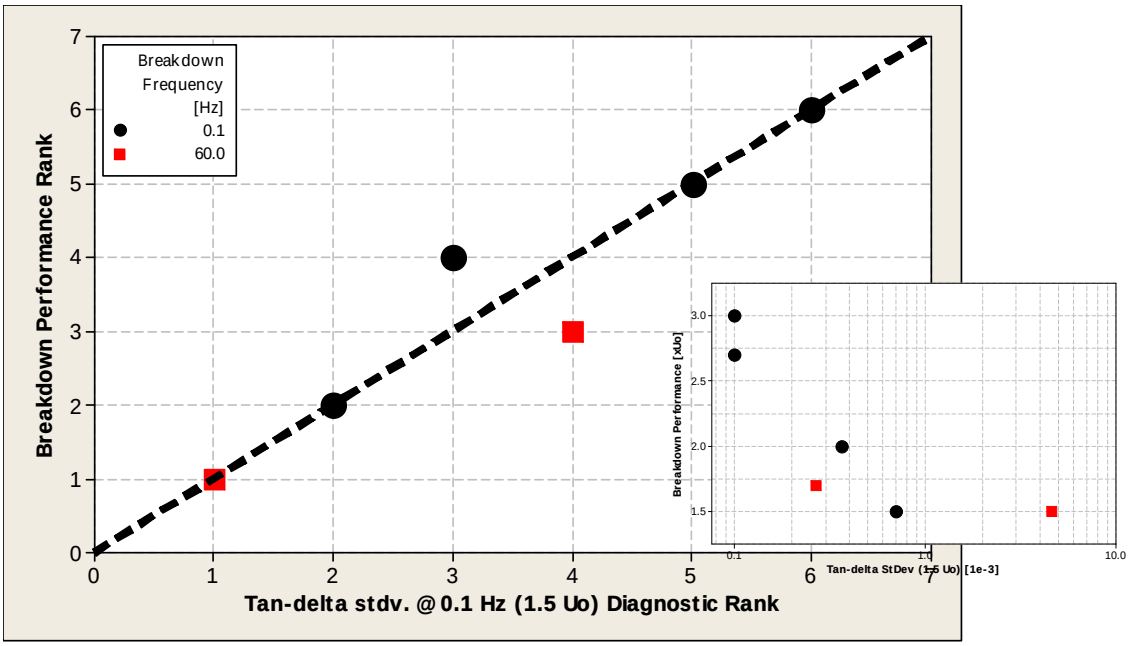

Figure 14: Correlation Between VLF Breakdown with Tan δ Stability (Standard Deviation) at 1.5 U_0 Rankings. Inset is the Data Correlation of VLF Breakdown with Stability (Standard Deviation)

The graphical results in Figure 14 may then be analyzed numerically using the Pearson Correlation Coefficient (Table 16).

Table 16: Performance and Diagnostic Rank Correlations

Tan δ Diagnostic Feature	Correlation Coefficient	*P*-Value
Mean Tan δ (1.5 U_0)	0.771	0.072
Tip Up (1.5 U_0 – 0.5 U_0)	0.771	0.072
Tan δ Stability (1.5 U_0)	0.943	0.005

Table 16 shows that the feature with the highest significance (i.e. 1 – *P*-Value) is Tan δ Stability. This feature quantifies how the measured Tan δ values change throughout the measurement period. The smaller this value, the greater the stability. Since a stable dielectric loss is indicative of a "good" dielectric, it makes sense that this would be a primary indicator of a cable system's condition. Analysis of all the available features indicates that an alternative hierarchy to the traditional Dielectric Loss/Tan δ approach in IEEE Std. 400™ – 2001 may be more appropriate. This hierarchy is as follows:

First Order Feature: Tan δ Stability – paper cables are in general more stable.

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Second Order Feature: Differential Tan δ or Tip Up – paper cables typically have negative tip ups whereas PE cables have positive values.

Third Order Feature: Dielectric Loss Tan δ – although overlapping the typical levels of loss are different for the insulation systems.

6.6.6 Mitigating the Risk of Failure on Test

In many cases, testing uses voltages that are higher than the operating voltage of the cable system. In these cases, there is a finite risk of failure for the elements under test. When such failures occur, the result is commonly termed a "Failure on Test" (FOT). The risk of FOT decreases by using test voltages close to or below the normal service voltage and by limiting the duration of the test voltage.

Figure 13 above shows the breakdown performance of aged XLPE cables. This analysis shows that the data fits a Weibull probability distribution and confirms that there are no "extra" failure modes for test voltages up to 3 U_0. This enables risk estimates to be made for various test voltages. IEEE Std. 400 – 2001 suggests the use of 2 U_0 for measuring Dielectric Loss and the Tip Up. As can be seen from Figure 13, this voltage has a risk of failure of approximately 30%.

On the other hand, the probability of failure could be reduced by 70% (30% probability down to 10 % probability) if the test voltage was reduced from 2 U_0 to 1.5 U_0. Of course, this is only useful if measurements at lower voltages provide the same level of information as measurements at higher voltages. This effect is studied in Figure 15 and Figure 16 using data correlation plots. The key finding is that both for Tan δ and Tip Up, the values are different at the different voltages. However, the *same rankings* occur. In other words, the lowest value at 2 U_0 is still the lowest value at 1.5 U_0. This shows that the lower (reduced risk) test voltages may be used without any loss in resolution. It is important to note that the criteria established using higher voltages should not be directly used for measurements made at lower voltages, but the correlation curves (the fitted line in Figure 15) provide a means to translate the criteria from one voltage to another.

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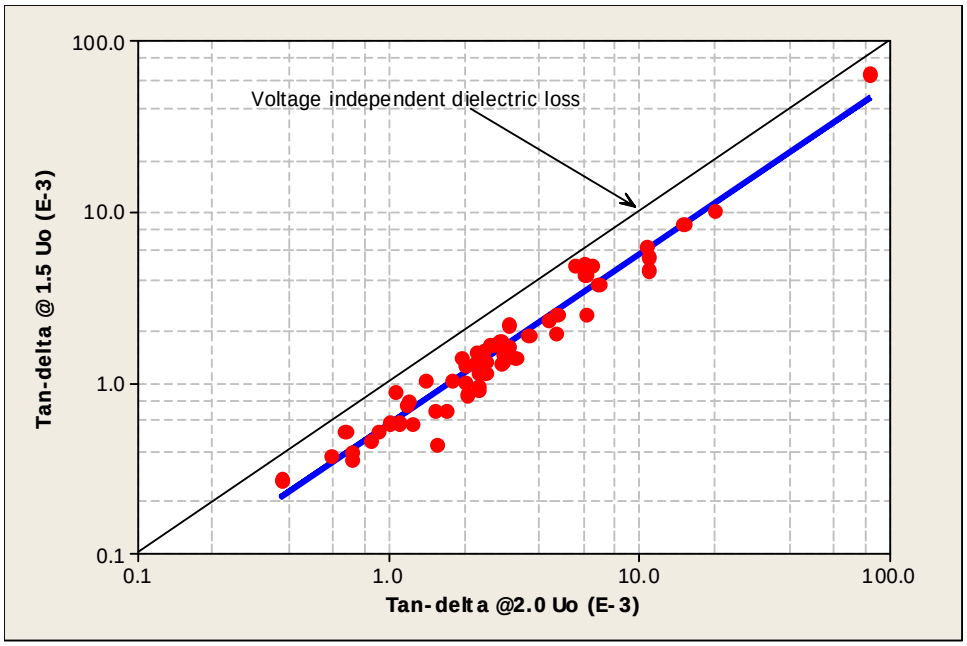

Figure 15: Correlation of Dielectric Loss Data Collected at Different VLF Test Voltages

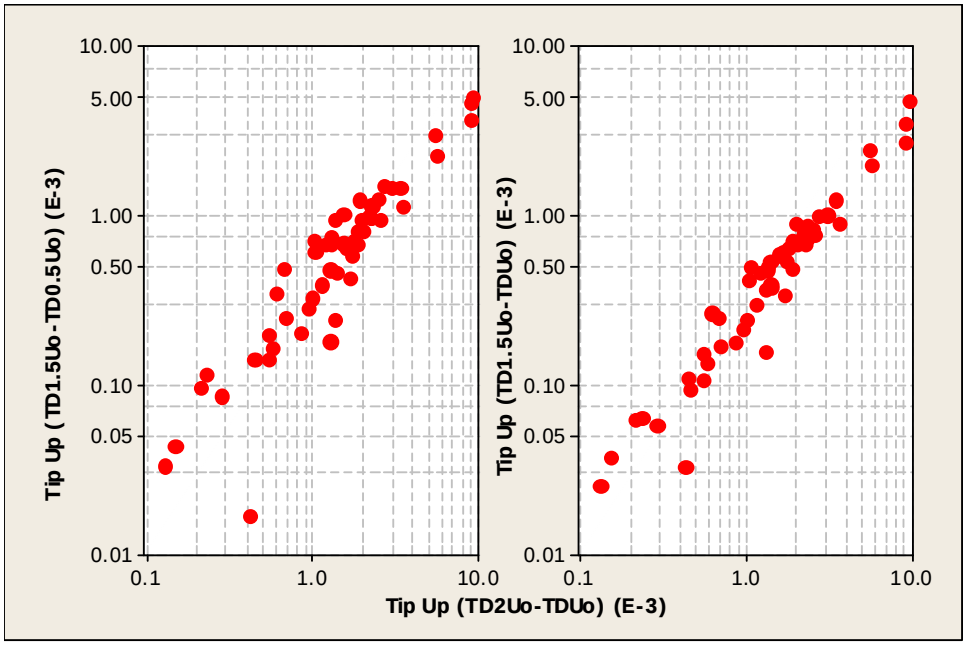

Figure 16: Correlation of Differential Loss (Tip Up) Data Collected at Different VLF Test Voltages

Since the same information can be obtained at lower risk, all *CDFI* measurements and analyses have been conducted by:

- Considering the Tip Up over a U_0 difference (the same as IEEE Std. 400 – 2001) but the interval being from 1.5 U_0 to 0.5 U_0 instead of 2 U_0 to U_0.
- Using the standard deviation of successive measurements at U_0 as the stability criteria

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- Using the mean of successive measurements at U_0 as the Tan δ value

The additional benefit of doing this is that the measurements are made at or below the voltages specified in IEEE Std. 400.2 – 2013 for simple VLF Withstand Tests. Naturally, it is sensible to make dielectric loss measurements at voltages that are equal to or below the voltage levels used for VLF Withstand tests. It also makes it more convenient, because it allows the tester to make Tan δ measurements while the VLF withstand test is underway.

6.6.7 Importance of Context

Sometimes testing is performed on an individual cable system in isolation from other, similar systems. When this is done, the utility has to judge the condition of the system by comparing the measured values to values outlined in documents such as IEEE Std. 400.2 – 2013. However, as discussed earlier, there is significant value in comparing the results to results on other, similar cable systems. In this case, the measured features (Stability, Tip Up, TuTu, and Tan δ) are considered in a hierarchical manner but the condition assessment levels are derived from comparisons with other local measurements rather than (or in addition to) external data sources such as IEEE Std. 400.2 – 2013. This approach appears in Figure 17 where data for adjacent subdivisions are segregated. Through inspection of these data, it is possible to select a subdivision (say Cambridge Highlands) and then identify the systems that have results that are noticeably different from the majority of the systems in that subdivision. These are likely the systems requiring the most urgent attention within that subdivision. However, this approach does not identify which systems need immediate attention.

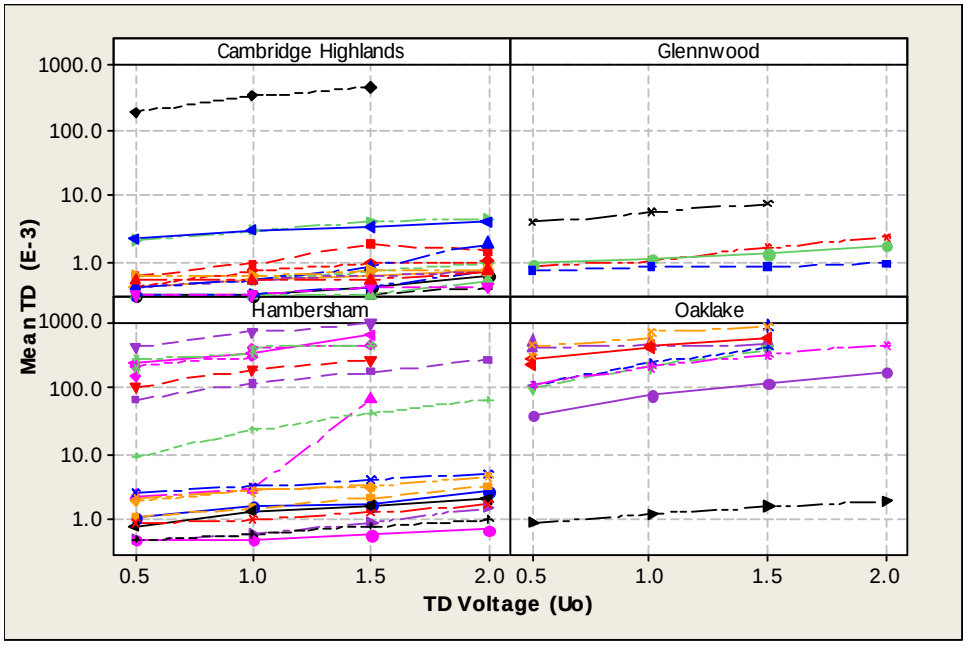

Figure 17: Dielectric Loss Data for Aged XLPE Cable Systems

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6.6.8 Usefulness of Length Analyses/Correlations

As noted earlier, Tan δ measurements provide the dielectric loss for the whole cable system, including the cable terminals and splices but cannot identify the source of the loss. This leaves the question: Does the loss measurement reflect the condition of the entire system, or does a small section have a high loss while the remainder has a low loss? To date, there does not appear to be a direct method of answering this question. However, comparing the measurement results with the physical characteristics of each cable system (such as the number of cable joints and the system lengths) it is possible to establish what may be causing a given system to have a high loss.

Simulations where cable systems are modeled as a series of parallel resistors and capacitors show that the dielectric loss of a system sometimes varies as a function of the system length when the loss measurement is affected by factors such as corroded neutral wires. The most convenient way to visualize this is in a log-log plot. Figure 18 shows typical field data that demonstrate how the condition of the neutrals can affect dielectric loss measurements. In general, Tan δ should be independent of the tested length except in the case of corroded neutrals where the Tan δ tends to increase with length. As Figure 18 illustrates, the Hambersham and Oaklake subdivisions display increasing Tan δ values with increasing circuit length. Such a trend is not readily visible in the Cambridge Highlands or Glennwood subdivisions.

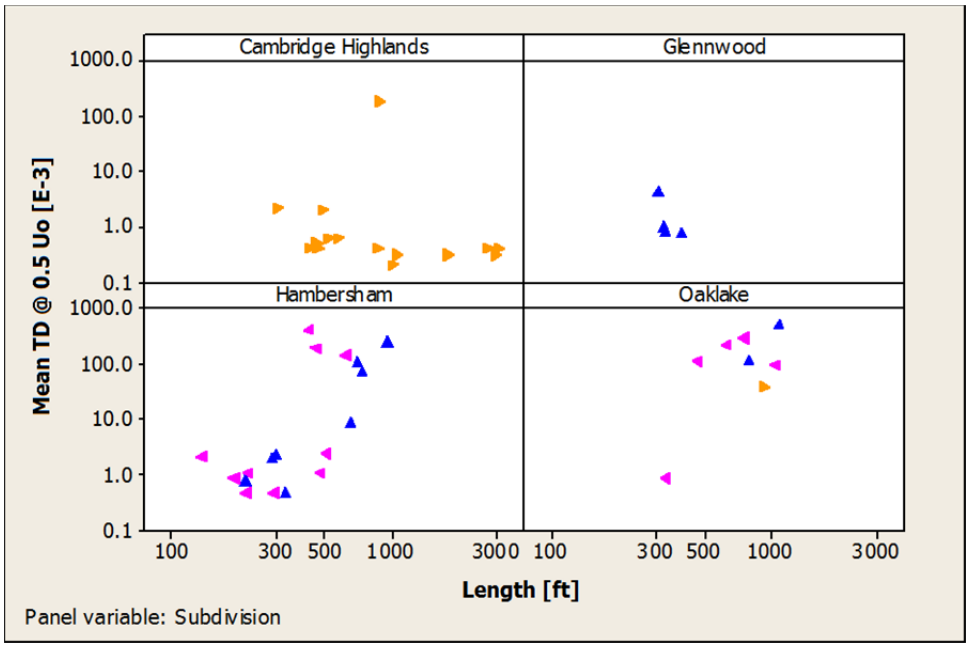

Figure 18: Dielectric Loss versus Length Representation for the Data shown in Figure 17

Similar observations apply to Figure 19. In this case, each system was first tested using Tan δ and then tested using a VLF Simple Withstand (see Chapter 9 for more information). Those systems that failed during the VLF Withstand show a length dependence as compared to those systems that went on to pass the VLF Withstand. Data are available for both filled and PE-based insulations.

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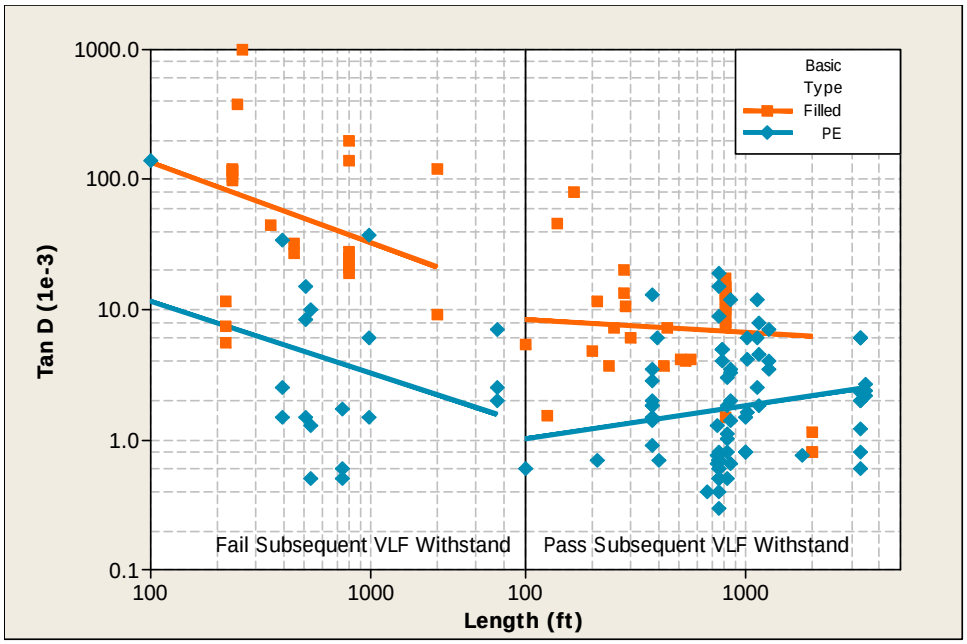

Figure 19: Dielectric Loss versus Length Segregated by Insulation Type (Filled and PE) with Performance in Subsequent VLF Withstand Tests

The forms of the curves shown in Figure 18 and Figure 19 may be interpreted using the descriptions in Table 17.

Table 17: Interpretation of the Slopes of the Dielectric Loss versus Length Graphs

Graph Form	Diagnosis	Example
Flat (Loss independent of length)	Uniform level of loss for all parts of the cable system.	Figure 18 (Cambridge Highlands)
Random (No clear length dependence)	No clear pattern of loss for the cable system population (see Figure 18 – Cambridge Highlands). Each system is different from all others.	Figure 19 (Cables pass subsequent VLF Withstand tests)
Upward Slope (Loss increases with length)	Neutral issues (the equivalent system is not a simple parallel representation of a resistor and a capacitor, but has a series resistance too). Either corroded neutrals or poor contact between the neutral and the insulation screen can cause this to occur.	Figure 18 (Hambersham)
Downward Slope (Loss decreases with length)	Isolated high loss portions (bad accessories or heavily water treed regions) within a large proportion of low loss cable can cause this to occur.	Figure 19 (Cables fail subsequent VLF Withstand tests)

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From this information, it is apparent that analyzing dielectric loss with respect to system length can yield useful information.

6.6.9 Expected Outcomes

The distribution of the dielectric loss data as a function of voltage source appears in Table 18. Figure 20 shows the individual lengths of cable systems tested using dielectric loss techniques.

Table 18: Distribution of Dielectric Loss Measurements by Source Type and Deployment

Source Type	Deployment	
	Laboratory [Conductor Miles]	Field [Conductor Miles]
60 Hz AC	0.3	--
Damped AC	--	--
VLF AC	1.5	770.8

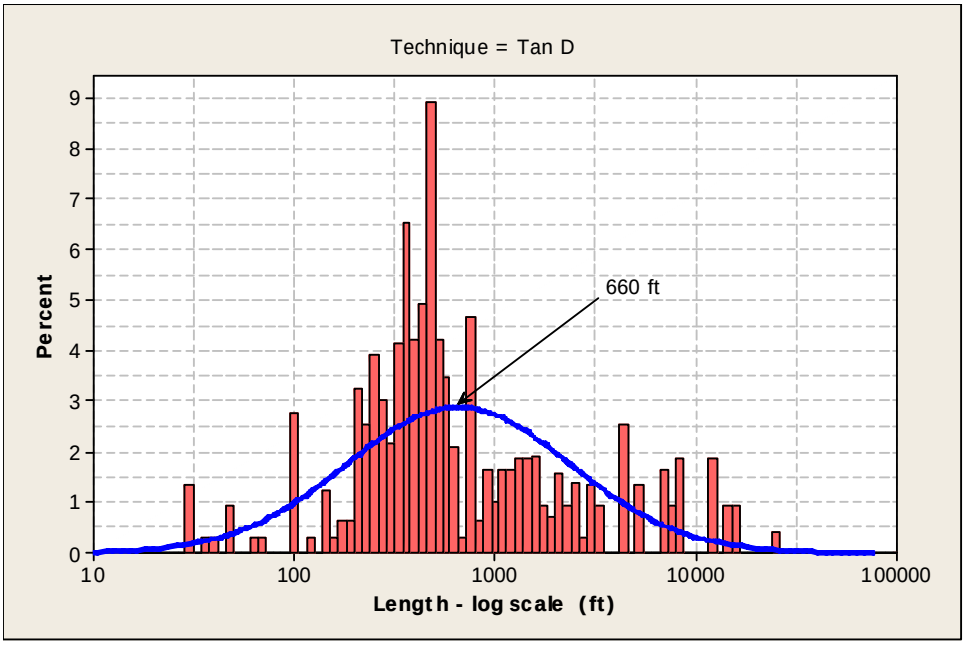

Figure 20: Cable System Lengths Tested with Dielectric Loss Techniques

The analysis of reported data is useful in a number of ways:

- It may be used to estimate potential testing scenario results.
- It places the results in context so that uncharacteristically high or low values are easily identifiable.

An analysis of all Tan δ field measurements gathered during the *CDFI* using a sinusoidal VLF (0.1 Hz) voltage source has established how the data correlate to the IEEE Std. 400 – 2001, IEEE Std. 400.2 – 2013, and *CDFI* Perspective performance requirements. The analysis results appear

in Figure 21 to Figure 23.

Figure 21 classifies the data according to IEEE Std. 400 – 2001, using Tan δ and Tip Up criteria as "either/or" requirements. Thus, a system with Tan δ of 1.5E-3 and a Tip Up of 2E-3 is classified as "Highly Degraded" based on the Tip Up whereas the Tan δ would suggest a classification of "Aged." Note that the standard does not have criteria for paper or filled systems.

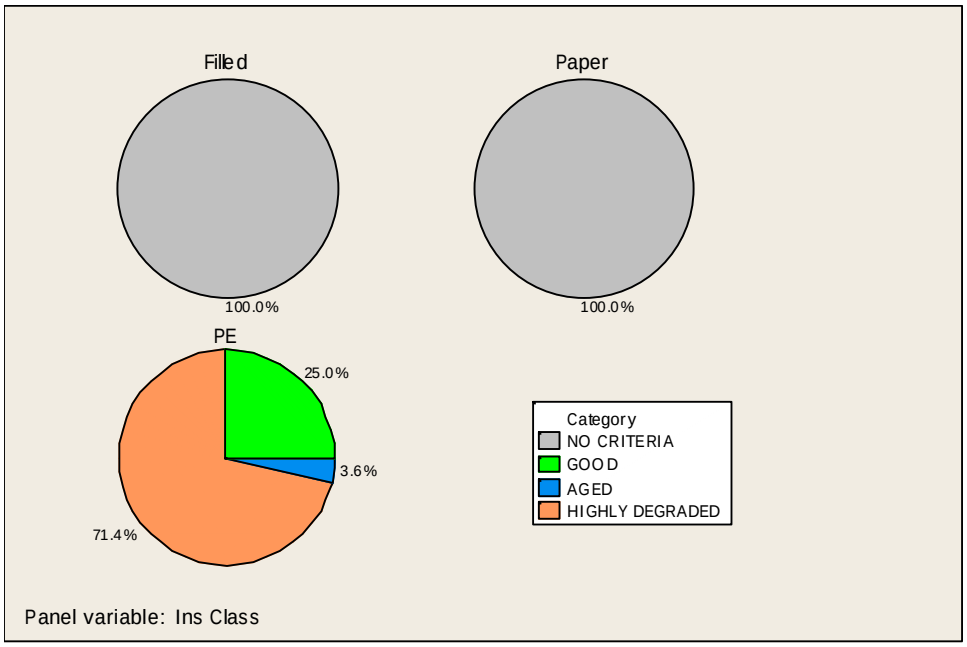

Figure 21: Distribution of Dielectric Loss Classifications Using Criteria Presented in IEEE Std. 400 – 2001

Figure 21 clearly shows the concerns with IEEE Std. 400™ – 2001 in that these levels classify more than 70 % of the systems as "Highly Degraded."

Figure 22 shows the same dielectric loss data used in Figure 21 but classified using the "atypical" approach developed in the *CDFI* for the Differential Tan δ and Tan δ, with the values derived from the analyses shown in Table 4 to Table 6. In this approach, filled and paper insulations may be addressed.

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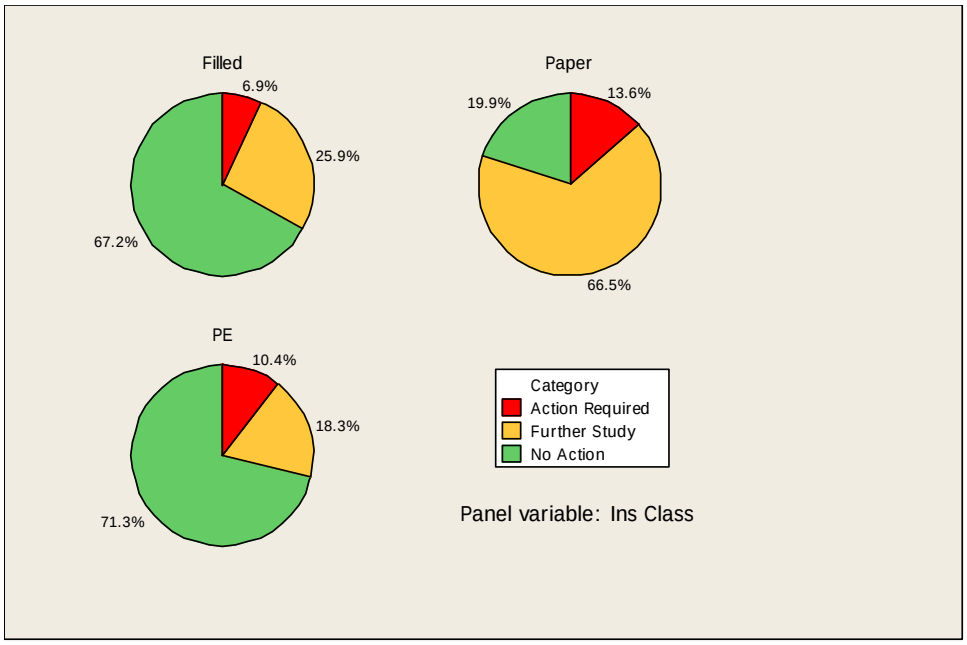

Figure 22: Distribution of Dielectric Loss Classifications Using Criteria Presented in the IEEE Std. 400.2 – 2013

Similarly, Figure 23 shows the same dielectric loss data used in Figure 21 and Figure 22 but classified using the latest criteria considered by the *CDFI* perspective with the diagnostic features and values shown in Table 12 to Table 14. In this approach, filled and paper insulations are addressed.

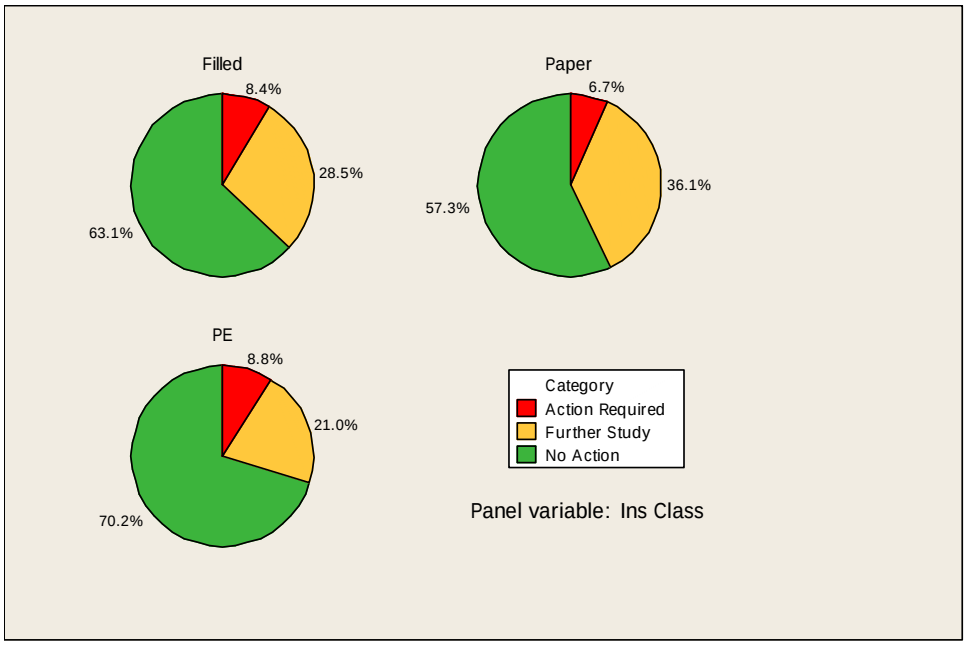

Figure 23: Distribution of Dielectric Loss Classifications Using Criteria Presented in the *CDFI* Perspective

As seen in Figure 22 and Figure 23, the distribution of dielectric loss classifications using the

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criteria presented in the IEEE Std. 400.2 – 2013 and the *CDFI* criteria is relatively similar for PE-based and filled insulation classes. However, for the Paper insulation class a considerable change is observed for those power cable systems that are classified as "No Action" and "Further Study Advised". These discrepancies may be due to the bigger dataset that has been considered for developing the latest *CDFI* criteria, 2013 compared to 2010. Therefore, this issue can be interpreted as an indication that the criteria for condition assessment in IEEE Std. 400.2-2013 for power cable systems with paper insulations may already be out of date.

Stepping back to Figure 22, it considers all the Tan δ data combined as one dataset. However, it is also useful to examine how different utility datasets distribute among the condition classes. Figure 24 shows the distribution for each insulation type and class for the "atypical" approach using the box and whisker format. Figure 24 allows a utility to determine how similar its measurements are to other utilities. Figure 25 gives the length-adjusted occurrence of the classes for the different datasets in Figure 24, also in box and whisker format. Not surprisingly, the distribution for each utility (shown by the individual data points) is different.

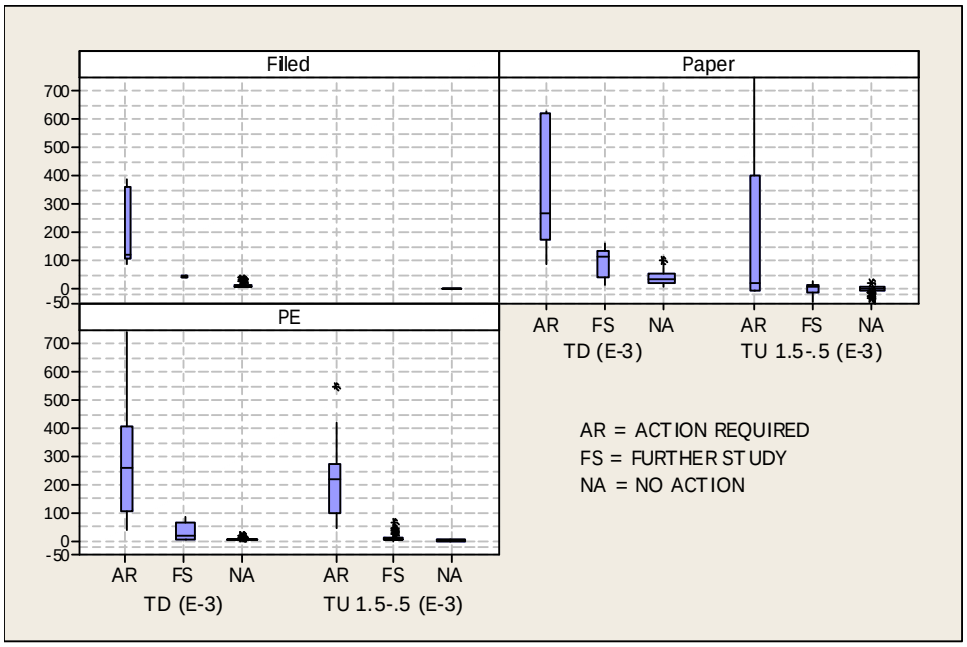

Figure 24: Tan δ and Differential Tan δ Data for the Dielectric Loss Classifications Based on Identifying "Atypical" Data (Figure 22)

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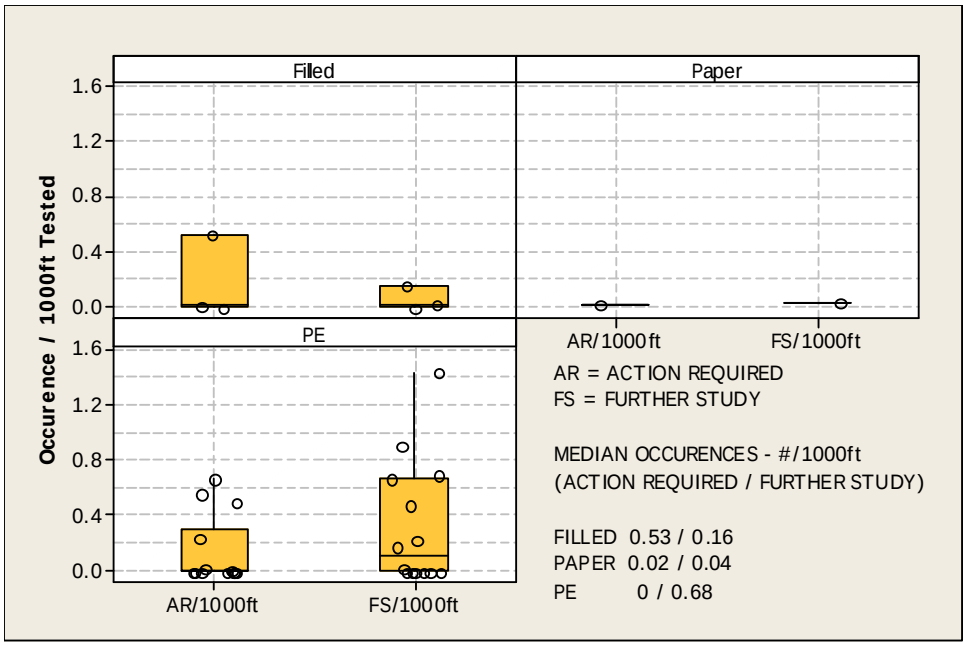

Figure 25: Occurrence of Dielectric Loss Classifications Based on "Atypical" Data

Figure 22 shows that using the "atypical" levels and multiple features results in a distribution much closer to what a utility might expect. Failure data are also available for these classifications and the usual Weibull time analysis of these data appears in Figure 26. These data result from measurements made by or supplied to the *CDFI*. These systems were left in service and their performance (measured by service failures) was tracked. The lower times correspond to the failures during the dielectric test (FOT). The quality of the fit is also worth noting since the distribution fits the available data well, which leads to several significant observations.

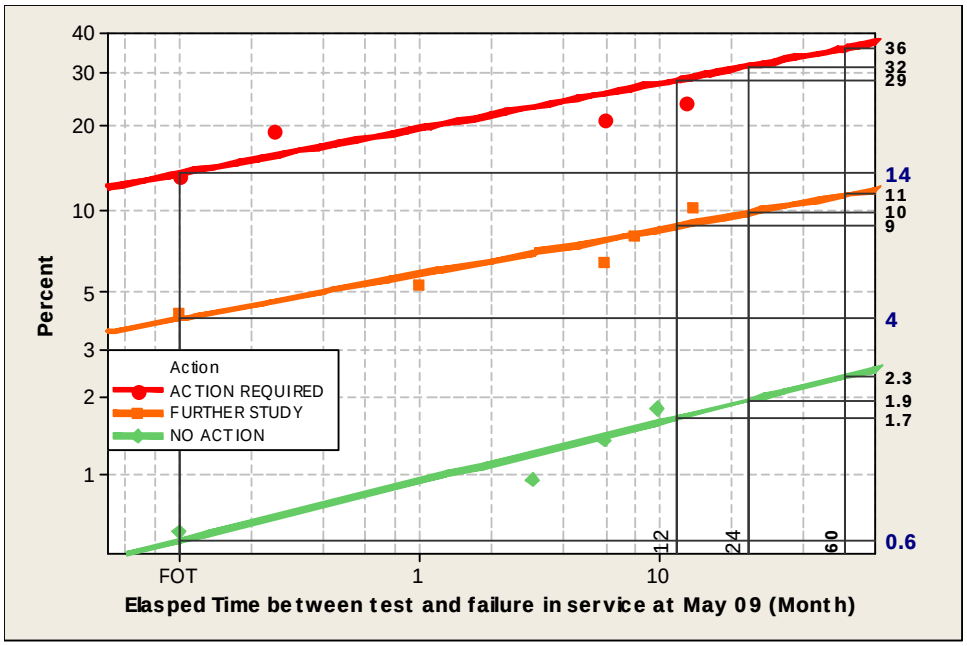

Figure 26: Diagnostic Performance Curves for Tan δ

These curves show that the likelihood of failure, if no actions are performed after testing, follow the classifications from the "atypical" approach reasonably closely (i.e. a system classed as "Action Required" has the highest probability of failure). Thus, these data show that there is a strong relationship between the cable system dielectric loss and subsequent service reliability. That is, an elevated Dielectric Loss feature (Tan δ, Tip Up, or Unstable Tan δ) indicates a higher risk of failure in service than cables with lower value Dielectric Loss features. As is the case with almost all diagnostics, even the most severe classification is not necessarily an immediate "death sentence." It clearly takes time for even the worst systems to fail. The vertical percentile lines in Figure 58 show the probabilities of failure for each condition assessment at selected times after test. Even after five years of service, only 36% of the worst systems failed. Note that the Stability, Tip Up, and Tan δ criteria were generated using only the measurement data, not the failure data. These criteria were then used to assess each of the systems for which both measurement data and failure data were available. The results of this analysis appear in Figure 26. An alternative approach to the data-directed methods employed above is to construct criteria that best relates the measurement data to the corresponding failure data.

One of the major issues with different diagnostic techniques and implementations is how to compare the different recommendation hierarchies. The Performance Curves in Figure 58 allow the conversion of any class designation into a probability of failure for any chosen time. For example, in the "atypical" approach for Tan δ, Table 19 shows how these data may be renamed.

Table 19: Diagnostic Class Renaming Example

Classification	Prob. of Failure within 2 Years [%]	Alternate Classification
No Action	2	Level 1
Further Study Advised	10	Level 5
Action Required	32	Level 16

In addition to the correlation between dielectric loss and service performance shown in Figure 26, similar and complementary evidence appears in Figure 27. In this figure, the performance of power cables installed in an industrial environment were first tested for dielectric loss and then subjected to a VLF (generally 0.1Hz sinusoidal) withstand test. These data are the same as those used for Figure 19 but appear here in a box and whisker format. These data show that for both the filled and unfilled (PE) cable cases, cable systems possessing elevated Tan δ (the Tip Up and Stability were not measured for these systems) had a much higher chance of failing the subsequent VLF test. Although it is difficult to correlate failures on withstand with service performance, it is clear that the cable systems with higher losses are electrically weaker and this normally correlates with shorter life.

Another conclusion from the research is (see Figure 27) is that filled and unfilled systems that have Tan δ > 20E-3 or 10E-3, respectively, have a much lower likelihood of passing a VLF withstand test.

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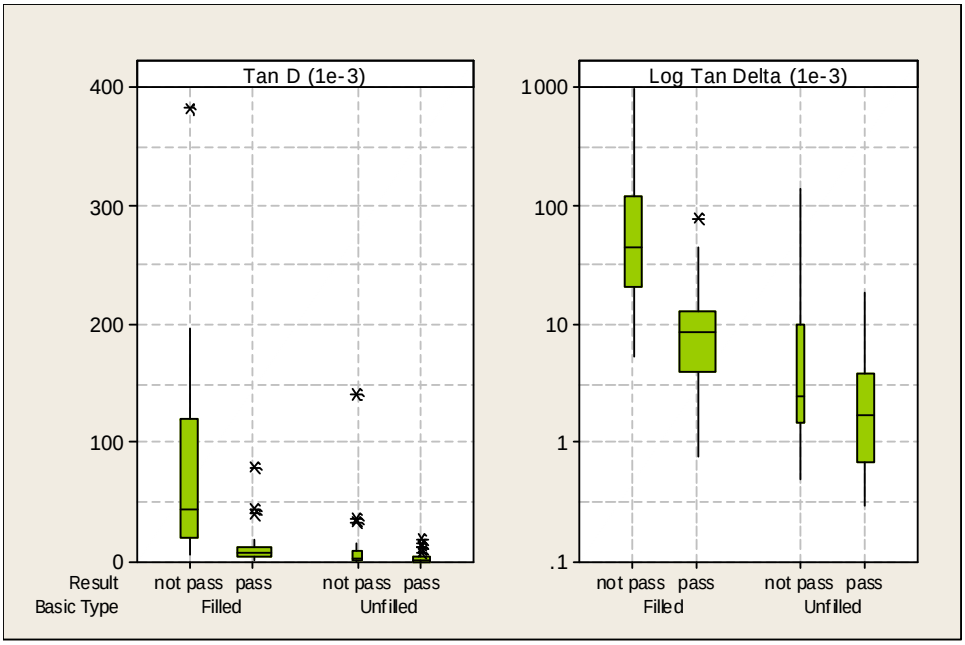

Figure 27: Relationship between VLF Withstand Performance and Dielectric Loss

The Diagnostic Performance Curves in Figure 26 and box and whisker plot in Figure 25 are very useful as they enable utilities to make an informed interpretation of the dielectric loss diagnostic data and assess what is likely to occur for different action scenarios. Table 20 demonstrates how a utility might use these collated research data to develop a scenario prior to the start of the testing and thereby be better prepared for any consequences. This scenario uses 14 miles of MV cable system with 80 systems. It is important to recognize that these data originate from the available field data and have generally followed the IEEE Std. 400 – 2001 $2U_0$ testing philosophy rather than the reduced risk approach described earlier. Thus, the estimated failures for systems after 5 years (26 %, 4 %, and 11 % for Filled, Paper, and PE, respectively) are likely to be high (conservative estimates) if the reduced-risk scheme is used.

Table 20: Example Scenario Evaluation

Insulation System	No Action / Further Study / Action Required [Cable Systems]	Predicted Failures		
		FOT	After 2 Years	After 5 Years
Filled	43 / 13 / 25	7	19	21
Paper	2 / 4 / 75	1	3	3
PE	1 / 55 / 25	3	7	9

6.6.10 Combined Assessment - Tan δ Principal Component Analysis (PCA)

Decision making based on Tan δ criteria is a topic of ongoing research and analysis. As discussed previously, the approach proposed in IEEE Std. 400.2 – 2013 to Tan δ criteria is to construct a three tier/diagnostic feature approach using three primary useful diagnostic features: Tan δ Stability (STD-time dependence), Tip Up (TU-voltage dependence), and Mean Tan δ (TD-

level of loss). Circuits were classified as "No Action Required", "Further Study Advised", or "Action Required" depending on the most severe assessment from these three Tan δ diagnostic features.

This is useful information, but at times it can be difficult to interpret. As an example, one possible result is that Stability and Tip Up could indicate "No Action Required" but the Mean Tan δ could indicate "Further Study Advised". In this case, it is not clear how to interpret the overall results. The interpretation becomes even more difficult when the fourth proposed diagnostic feature (TuTu – non-linear voltage dependence) is considered. Ideally, a method is needed to combine all four features to create a single "Health Index" that puts any set of measurements in context with the Tan δ database. The principal component analysis (PCA) method is one means of accomplishing this research goal.

In order to obtain a single "Health Index" from all four diagnostic features, the *CDFI* recently updated a variety of techniques and explored new approaches. From all techniques that have been explored, the PCA is the most attractive since it takes a given set of points in a high dimensional space and then reduces the dimensionality to a more manageable number. In other words, the PCA technique summarizes the data with several assumed independent variables to a smaller set of derived variables without sacrificing the potential for classification. In fact, the classification capability is enhanced by the PCA.

The technique provides a predictive model with guidance on how to interpret or "weigh" the primary measurement features. It also allows for a physical meaning to be ascribed to the resulting composite factors, i.e. the Principal Components. The PCA approach identifies linear combinations of factors and generates the principal components that better represent the data. The first component has or describes the largest portion of the variance, followed by the second, and then the third, and so on. The PCA redistributes the variance in such a way that the first k components explain as much as possible of the total variance of the data. It must be noted that the higher the variance the higher the potential for better classification.

Another important reason for choosing the PCA technique is that in many data analysis/mining scenarios, seemingly independent variables are highly correlated, which affects model accuracy and reliability. PCA is able to detect such correlations and then essentially exclude the redundant information.

To illustrate and easily understand the essentials of the PCA technique, Figure 14 shows a qualitative explanation of the technique. The circles represent a dataset in which there are two features (axes) and the variance within this dataset with respect to these features is represented by the area of the rectangle denoted as Area 1. The PCA method attempts to reduce the variance by generating new axes that are linear combinations of the available two features. This causes a rotation/translation of the original axes from F1-F2 to PC1-PC2. The new variance can then be thought of as the area of the rectangle represented by Area 2. By comparing the areas, it is clear that area 2 is smaller and, therefore, has less variance than the original configuration in Area 1. As mentioned above, this process can be used to reduce the dimension of a dataset to as few or as many principal components as are needed.

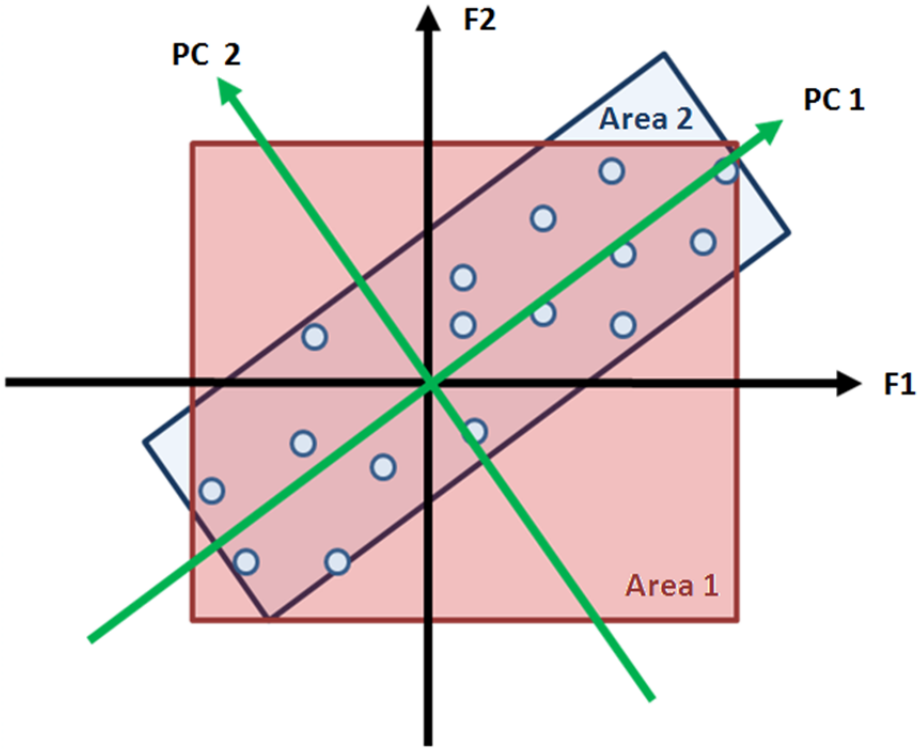

Figure 28: Graphical Interpretation of Principal Component Analysis (PCA)

The PCA technique has been applied to the PE Tan δ database and Figure 28 shows the transformation from the first two Tan δ diagnostic features (STD and TU) to the first two principal components (PC1 and PC2). As mentioned previously, the PCA reduces the dimensionality; however, this technique does not directly provide a single descriptor by itself, essentially it enables the constructions of simplified and appropriate feature maps that may enhance the classification potential of the diagnostic features when they are combined in the right manner; the principal components feature maps can then be used to provide a single condition assessment descriptor as it is shown later. The transformation can be observed in Figure 29 in which the application of the PCA technique clarifies the connection between PC1 and PC2 (right side of Figure 29) as compared to the original data, in this case STD and TU (left side of Figure 29).

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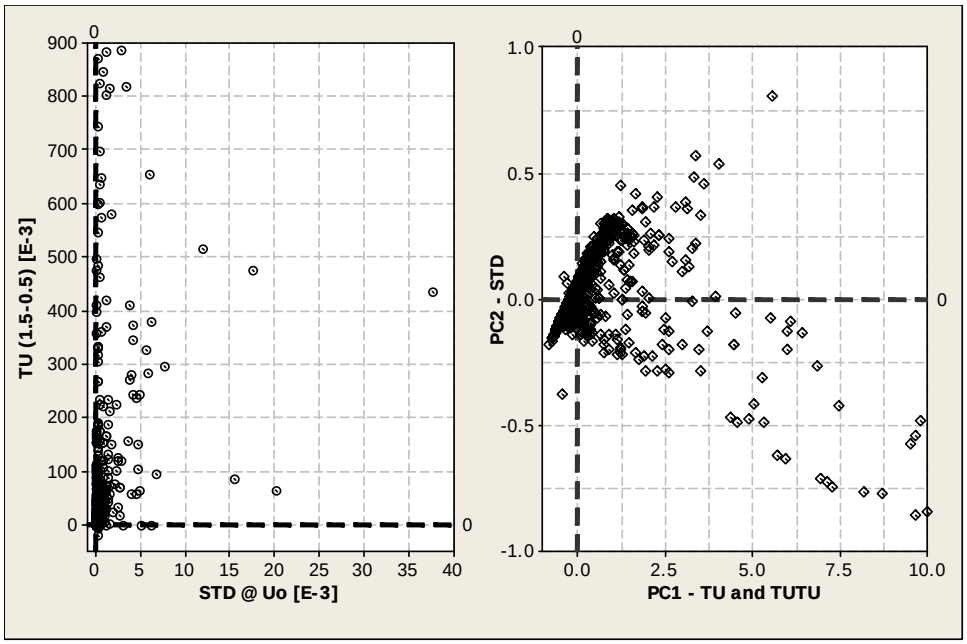

Figure 29: Scatter Plots of STD vs. TU (left) and PC1 vs. PC2 (right) – PE-based Insulations

Applying PCA to the PE Tan δ data yields the principal components shown in Table 21. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features included in each component. Results from Table 21 indicate that only three principal components are required to describe 97 % of the variance; therefore, this is the number of principal components considered here.

Table 21: PCA Variances and Component Composition for PE-based Insulations

Principal Component	Variance Described by Component [%]	Variance Described by Component Cumulative [%]	Tan δ Diagnostic Features
PC1	50	50	TU & TuTu (Voltage Dependence)
PC2	25	75	STD (Time Dependence)
PC3	22	97	TD (Level of Loss)
PC4	3	100	Not relevant since this component only describes 3% of the variability

Another important result from Table 21 is that PC1 describes 50 % of the variability and it is composed of TU and TuTu, features that consider the Tan δ voltage dependence. PC2 describes 25 % of the variability and it includes STD, and lastly, PC3 describes 22 % of the variability and it is mainly composed of TD. Also note that PC4 is not relevant since it only describes 3 % of the

variability of the data; therefore, this principal component is not taken into account in the analysis.

The main conclusion of the PCA research shown in Table 21 is that they also give an indication of the importance and relevance of the Tan δ diagnostic features; from the analysis the voltage dependence of measurements (TU and TuTu) is the most important factor followed by the time dependence (STD) and level of loss (TD) when the variability of the data is considered. These results should not be confused when compared with the results shown in *Phase I* of the *CDFI*. In *Phase I*, the importance and relevance of the features was determined using VLF breakdown correlations as compared to the PCA approach used in *Phase II*. In both cases the voltage dependence, time dependence, and level of loss were found to be independent diagnostic features; therefore, it can be assumed that they carry independent information. The overarching question is how to combine all diagnostic features in to a single indicator, which is discussed below.

The use of the PCA technique has allowed the development of a combined diagnostic feature scheme in which all independent features are considered together for an ultimate condition assessment. The combined diagnostic feature scheme is based on the computation of the PCA distance, i.e. given a set of principal components related to a set of measurements, how these components deviate from a known reference point. The PCA distance is computed using the principal components' values and a reference point that in this case corresponds to Tan δ measurements of a new cable system. Figure 30 shows the combined PCA distance of the three principal components for all the available data of PE insulated cable systems. In Figure 30, the percentage or rank position is given by the Y-axis values and, in practice, might conveniently be regarded as a "Health Index". The higher the rank position, the worse the cable system condition relative to all similar systems. The symbols in Figure 30 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 22. This table may be considered as an independent test of the research for the PCA Health Index.

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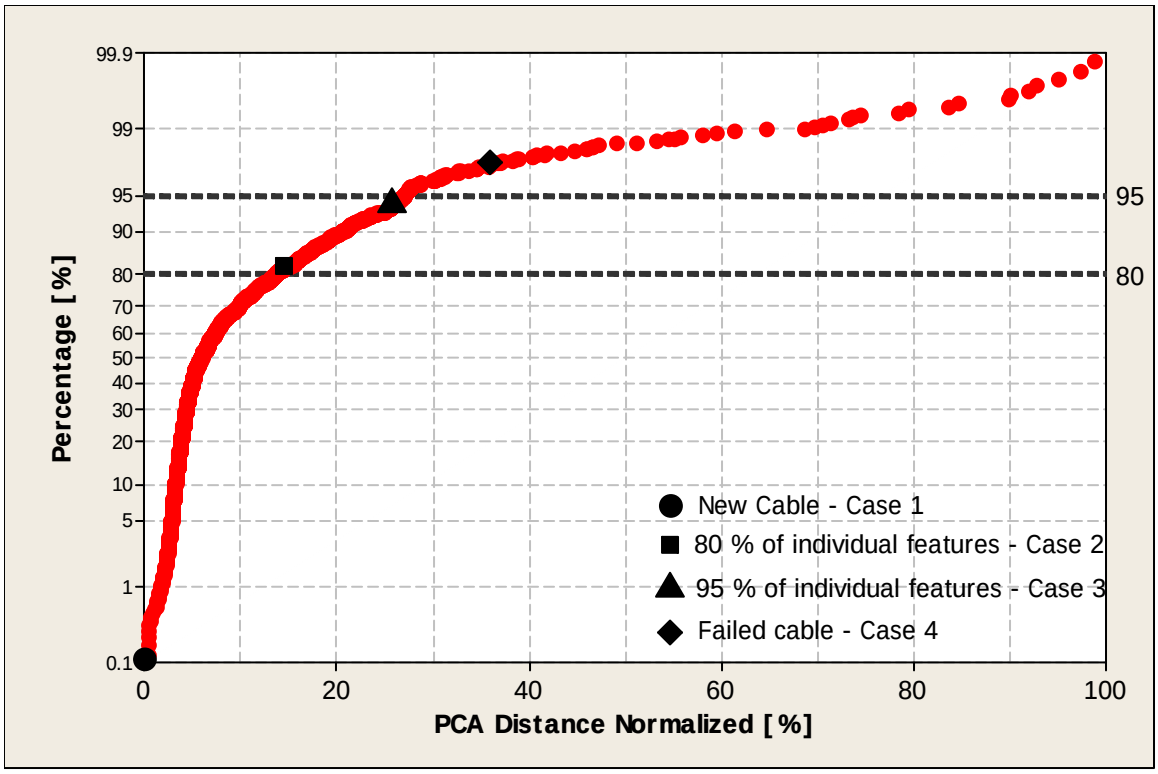

Figure 30: Empirical Cumulative Distribution for the Normalized PCA Distance for PE-based Cable Systems

Table 22: Test Cases for Tan δ Principal Component Analysis for PE-based Insulations

Case No.	Description	STD [E-3]	TU [E-3]	Tan δ [E-3]	TuTu [E-3]	Rank [%]
1	New Cable	0.00	0.00	0.10	0.00	0.10
2	Features at 80 % level	0.05	5.00	4.00	3.00	82.0
3	Features at 95 % level	0.50	80.00	50.00	58.00	93.9
4	Failed Cable*	3.60	247.00	316.00	17.00	97.6
5	Utility test 2007	0.00	0.80	2.80	0.00	79.0
6	Utility test 2010	0.00	1.80	6.00	0.60	84.5

* failure after 27 months from test date

In Table 22, the following examples are included:

- Case 1 represents that a new PE cable system lies at the 0.1st percentile. This translates to an extremely good "Health Index". Case 1 is represented in Figure 30 by the solid black circle symbol.
- Case 2 represents the situation in which all diagnostic features are at their respective 80 % levels (black square symbol in Figure 30). Note here that all the features at the 80 % level yield a "Health Index" of 82.0 %. Therefore, there is a good correlation between the feature

levels and the overall assessment considering all features together.

- Case 3 shows the situation in which all the diagnostic features are at the 95 % level (black triangle symbol in Figure 30), in this case the "Health Index" is 93.9%, Note again the good correlation between the features levels and the overall condition assessment.
- Case 4 is a real case and represents the poorest performer in a cable system that was tested in 2007 and failed in service 27 months later (black diamond symbol in Figure 30). The PCA indicates that back in 2007 the cable system was within the poorest 3% of all PE-based cable systems. This case is also represented.
- Case 5 and Case 6 are also real cases and represent a retest of a cable system after three (3) years of operation – Georgia Power: Wimbledon Woods (See field test data from previous quarterly reports).

In Table 22, note the change on the diagnostic features between Cases 5 and 6 after three years of operation shows this cable system went from "No Action Required" to "Further Study Advised". The "Health Index" changed from 79.0 % to 84.5 %, this represents a degradation in the rank position of about 2 % per year. Additionally, inspection of mid-range and lower ranks shows that, as might be expected, there is a degradation of rank position here as well, but the rate is much lower: approximately 0.3 % to 0.5 % per year. Information of this type is invaluable to an asset manager when deciding which cable systems need repair or replacement. In this case, an asset manager could prioritize within the "Action Required" and "Further Study Advised" classes. It is important to recognize that there is no capacity to ascribe a definite lifetime to the cable system but it can assist in prioritization.

The previous paragraphs have emphasized the usefulness of the PCA technique in creating an accurate condition assessment tool for PE-based cable insulations; however deriving the optimum PCA features to achieve improved classification is a topic that needs to be addressed for each cable insulation separately (PE-based insulations, Filled insulations, and PILC) since some rules cannot be used for all insulations. Appendix A presents the studies carried out for each type of cable insulation.

6.6.11 Analysis of Tan δ Diagnostic Features By Cluster Variable Analysis

The cluster variable analysis of all Tan δ diagnostic features has been performed for PE-based insulation. The cluster variable analysis is chosen because it provides another means of selecting a number of reduced features by taking into account the correlation between features rather than their variability used in the principal component analysis (PCA) approach. The next paragraphs describe the analysis.

As seen, one of the problems present when considering a large number of Tan δ diagnostic features is how to organize them into meaningful groups or clusters. In the case of the Tan δ diagnostic features the organization can be accomplished by performing a cluster variable analysis of the features. Its results are compared with the results from the PCA.

Cluster variable analysis is useful in this research because it identifies key variables that explain the principal dimensionality (not variability) of the data. It is used to classify the data into groups

when the groups are initially unknown. One important reason to cluster variables is to reduce their number; but more importantly, clustering variables is used in this research to understand the taxonomy and meaning of the Tan δ diagnostic features.

The analysis is an agglomerative hierarchical method that begins with a separate treatment of all features, each forming its own cluster. In the initial step, the two features closest together are joined. In the next step, either a third feature joins the first two (now considered as a stand-alone cluster), or to another feature is joined with a different cluster. This process continues until all clusters are joined into one. The complete procedure, from the initial cluster variable analysis to the final feature selection, is explained later in the section.

The agglomerative hierarchical method uses the distances between variables when forming the clusters. These distances are based on a single dimension that uses the absolute Pearson correlation coefficient between features. The correlation coefficient can be translated to a level of similarity between clusters. The level of similarity can be used as a tool to compare the relationship between features or clusters.

The similarity level between two features or clusters, e.g. features or clusters *i* and *j*, is given by:

$$S_{ij} = \frac{100(1 - d_{ij})}{d_{max}} \qquad \textbf{Equation 3}$$

where,

S_{ij}: Similarity level between features or clusters *i* and *j*,
d_{ij}: distance measure between features or clusters *i* and *j*, based on the absolute Pearson correlation coefficient,
d_{max}: Maximum distance between the initial set of features before starting the clustering procedure.

The interpretation of the level of similarity is quite straightforward. The level of similarity is a number that ranges from 0% to 100%. A similarity level approaching 100% indicates that the features or clusters under investigation are redundant, i.e. they carry essentially the same information. In other words, the features or clusters are highly correlated; thus, they contribute little to solving an eventual classification problem. In contrast, a level of similarity approaching 0% indicates that the features or clusters under investigation are complementary or uncorrelated. Thus, the likelihood of using these features or clusters in an eventual classification problem with good results is higher than using redundant features or clusters.

There are several algorithms available for the clustering of the Tan δ diagnostic features and each them may yield different results. However, here, the group average and the furthest neighbor methods are used in the cluster variable analysis of the Tan δ diagnostic features. Specifically, the group average method is used in the agglomerative procedure during clustering. The clustering process is as follows:

1. Initially each feature is declared a cluster and all distances between clusters are calculated.

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2. Two clusters with the smallest distance between them are fused together and declared to be a new cluster. This is the beginning of the agglomerative process.
3. All distances between clusters are again calculated and the agglomerative process continues until the number of clusters is one.
4. Once one cluster is left, the number of clusters to be considered for the final feature selection is determined by choosing a similarity level.

The results of the clustering procedure can be represented graphically in a tree-like plot, also known as a dendrogram plot. The dendrogram plot for the cluster variable analysis represents the features under analysis on the x-axis and the level of similarity between features and clusters on the y-axis. The clusters are represented by vertical and horizontal lines between the features.

Determining the number of clusters for the final feature selection can be termed as "cutting the dendrogram". Cutting the dendrogram is akin to drawing a line across the dendrogram to specify the final grouping at a particular similarity level. There is no pre-established procedure on choosing the similarity level for cutting the dendrogram. Results of the cluster variable analysis for the Tan δ features are shown in Figure 31.

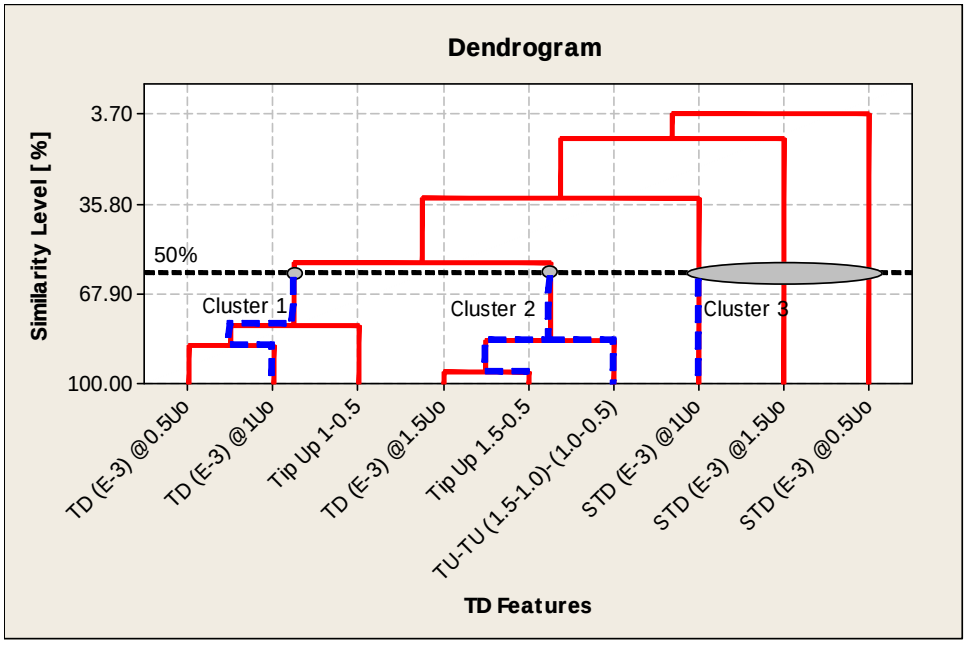

Figure 31: Research Dendrogram of the Cluster Variable Analysis of Tan δ Diagnostic Features

As seen in Figure 31, when a similarity level of 50% (typical value) is chosen to cut the dendrogram, five clusters are obtained. However, three clusters are considered in this case. Cluster 1 is composed of the features Tan δ at 0.5 U_0, Tan δ at U_0, and the Tip Up between U_0 and 0.5 U_0; cluster 2 is composed of the features Tan δ at 1.5 U_0, Tip Up between 1.5 U_0 and 0.5 U_0, and the TuTu; and cluster 3 is composed of all the standard deviations at all voltage levels.

Results of the cluster variable analysis in Figure 31 show that three of the four previously determined important diagnostics features using the PCA analysis group in different clusters.

These results are in accordance with the PCA analysis since they indicate that variability of the measurements, changes in Tan δ with voltage and absolute Tan δ values have to be considered separately in a scheme of reduced features.

The four important features obtained from the PCA analysis appear in Figure 31 by the blue-dashed lines. Note that the Tip Up between 1.5 U_0 and 0.5 U_0 and the TuTu are similar greater than approximately the 70% level; therefore, these two features can be thought of as carrying the same information. However, this is a topic of ongoing study and a more detailed analysis would be required to properly determine the differences between these two features. The primary conclusion of the cluster variable analysis is that their results are similar to those from the PCA analysis with respect to the type of features that should be considered for an improved condition assessment using a reduced number of Tan δ diagnostic features.

6.6.12 Value of Increasing Database Size

The Tan δ research work focuses on the application of statistical methods to the analysis of Tan δ data. When the statistical methods are used, then the question of how much date data are needed has to be addressed. These methods extract useful information from data; discovering relationships that have not previously been known. Additionally, by understanding and obeying statistical methods knowledge can be distinguished from speculation. Statistical methods are mathematical techniques that involve the following steps: (1) describing data, (2) gathering data, (3) organizing data, (4) analyzing data, and (5) interpreting data.

Therefore, the fundamental parts of any statistical analysis are the data, which can come in many forms. In this case, the data are sets of numeric values of the diagnostic features, a set of diagnostic features can be seen as a fingerprint for the related specific cable system. In general, as more data are available for analysis and interpretation, results tend to be more statistically significant and valid. The statistical confidence is an indication of the probability of a result not having occurred by chance. The adding of new data is a careful process since these data must be described, gathered, and organized using the same initial criteria. In other words, any additional data must be consistent with the original or previous datasets. This process is critical to the successful development of any criteria.

In this section the value of adding more data for statistical research was explored. To accomplish this, Tan δ stability data for PE-based cable systems were collected for a number of years. The data appear in Figure 32 by means of the probability distribution plots for two selected periods; all data collected to 2007 and all data collected to the end of 2011.

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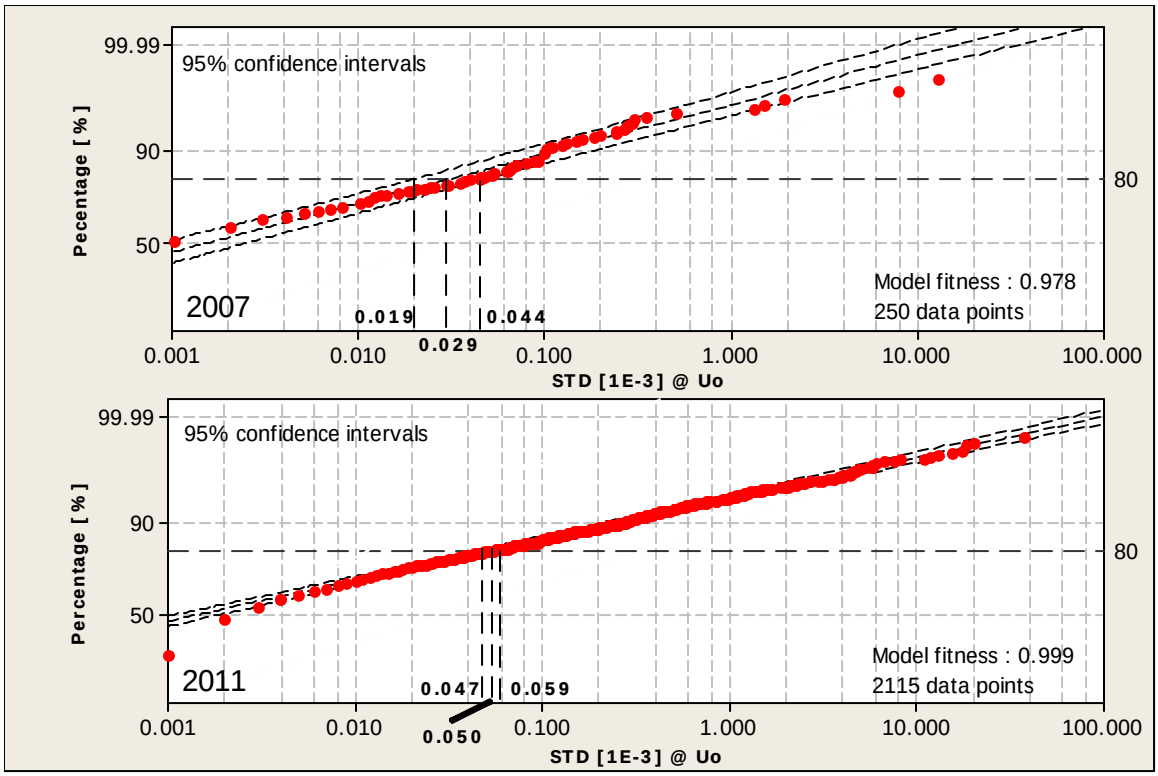

Figure 32: Comparison of 2007 (250 Data Points) and 2011 (2115 Data Points) Probability Distribution Plots for Tan δ Stability at U_0 Using Weibull Distributions and 95% Confidence Intervals

Figure 32 shows the comparison of the 2007 and 2011 probability distribution plots for the diagnostic feature Tan δ stability and U_0 using Weibull distribution parametric fits with 95% confidence intervals. The raw data are represented by the black dots, the Weibull fits and 95% confidence intervals by the dotted lines. The first case (top of Figure 32) considers the data collected up to 2007 and the second case (bottom of Figure 32) considers all the data collected up to the end of 2011, for comparison the two cases have the same scales and ranges on the two axes.

The 2007 dataset includes 250 data points while the 2011 dataset includes 2,115 data points. In relative terms, the 2007 dataset represents approximately 12% of the data in the 2011 dataset. The 2011 dataset is approximately 750% larger than the dataset from 2007. Table 23 shows a comparison of the 80th percentile estimates from the 2007 and 2011 Weibull curves in Figure 32.

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Table 23. Summary for Comparison of 2007 and 2011 Probability Distribution Plots for Tan δ Stability at U_0 Using Weibull Distributions and 95% Confidence Intervals		
	Case	
	Initial – 2007	***2011***
No. of data points	250	2,115
Model fitness index	0.978	0.999
Feature at 80% level [1E-3]	0.029	0.050
Lower 95% CI* [1E-3]	0.019	0.043
Upper 95% CI* [1E-3]	0.044	0.063
Range 95% CI* [1E-3]	0.025	0.020
Relative 95% CI* Range [%]	86	24

* CI: Confidence Interval

As seen in Table 23, adding more data to the analysis produces several clear benefits:

- The level for the feature is more statistically significant since the level for the 2011 case represents a greater population of cable systems; therefore, it can be inferred that the true estimated feature threshold for the whole universe of cable systems is closer to this value than the level obtained in the 2007 case.
- The population of systems tested through 2007 represents an incomplete sample set as multiple large gaps are present in the data (dataset jumps from 0.55 to 1.4). No gaps are visible in the 2011 dataset up to a stability of 9E-3.
- The width of confidence interval is significantly reduced in the 2011 dataset (by over 28%). This implies that that this estimate has a higher degree of certainty as compared to the 2007 dataset.
- The difference in the 80th percentiles estimates shows that the 2007 dataset was obtained from "healthier" cable systems than those that were tested through 2011. Applying the 2007 dataset estimate would have added 4% of the population to the "Further Study Advised" and "Action Required" classes.

Another important fact that must be noted is that in both cases the model fitness index is acceptable by being higher than 0.90; however, the model fitness index for the second case is better than the first case, which again shows the value of adding more data to the statistical analysis.

Similar statistical analyses can be realized for the other Tan δ diagnostic features; and in fact, they are presented in the next section in which the multimodal nature of the data is considered.

6.6.13 Tan δ Data Mode Analysis PE-based Insulations

The previous section has shown the value to the research of adding accurate data over time to the statistical analysis of the Tan δ diagnostic features. Specifically, it has been shown that as more data are available more precise threshold estimation and confidence intervals are realized.

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However, the preceding section has only shown the analysis for one of the Tan δ diagnostic features, i.e. the first tier that corresponds to the standard deviation of the Tan δ measurements at U_0. In this case, it has been shown that the Tan δ stability data are modeled with a high degree of confidence by a single Weibull distribution. However, for the other Tan δ diagnostic features a more detailed modeling analysis is required since they cannot be modeled by a single Weibull distribution.

When data can be modeled by a single Weibull distribution the probability distribution plot and the data itself form a straight line, as seen in Figure 33. A qualitative assessment of the accuracy of model fitting can be accomplished by observing how the model lines for the estimation and confidence intervals correlate with the data points. This qualitative assessment can be expressed quantitatively by the model fitness value; if the model fitness value is high (usually more than 0.90) then the model can be used to completely represent the statistical nature of the data.

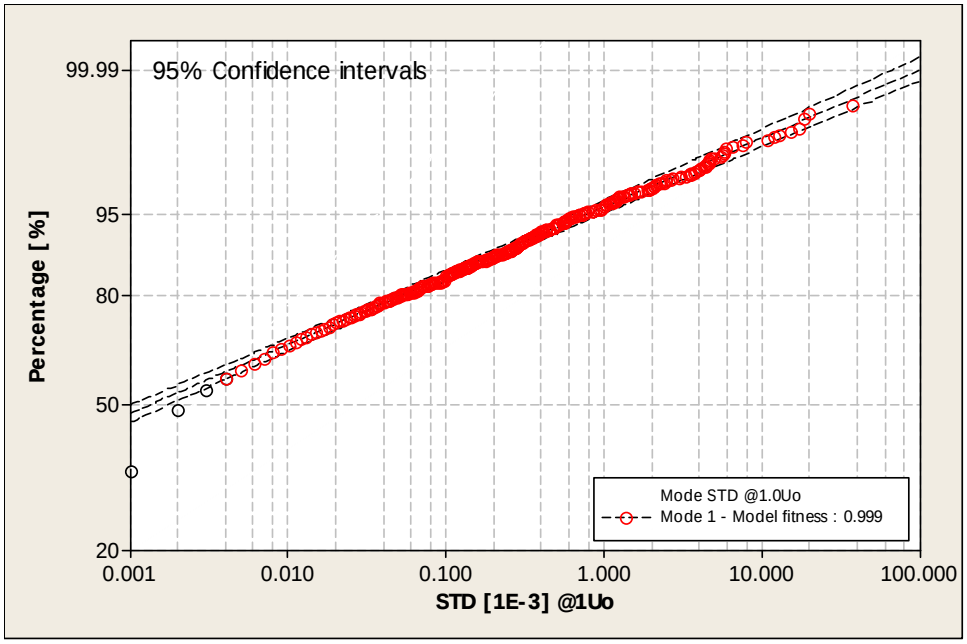

Figure 33: Probability Distribution Plot for Tan δ Stability at U_0 by Mode – PE Insulated Cable Systems

In some cases, the data cannot be represented by a single Weibull model. When this is the case, the data on a probability distribution plot do not lie on a single straight line; however, it can be modeled by several straight lines over specific ranges defined by limits on both axes of feature values and percentages. In this way, each line would represent the model for the data between the limits. Each separate model in the data is referred to as a mode; therefore, in a case in which the data can be represented by two straight lines, the data is said to have two modes.

Determining the number of modes and their limits is generally not a simple task. Usually heuristic techniques are applied to accomplish this goal. However, determining only the number of modes is a relatively easy task that is generally accomplished by performing a qualitative assessment of the probability distribution plot as the graphical representation enables the critical points to be readily identified. As an example, consider Figure 34 that represents the probability

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distribution plot of the second tier or diagnostic feature (i.e. Tip Up between $1.5U_0$ and $0.5U_0$). As seen in Figure 34, the data in this case can be represented by two straight lines or models that intersect around 50%; therefore, it is clear that the data have two modes. Moreover, Figure 35 shows the probability distribution plot of the third tier or diagnostic feature (i.e. Tan δ at U_0); as seen in the figure, this feature is also composed of at least two modes. The limit in this case is also approximately 50%.

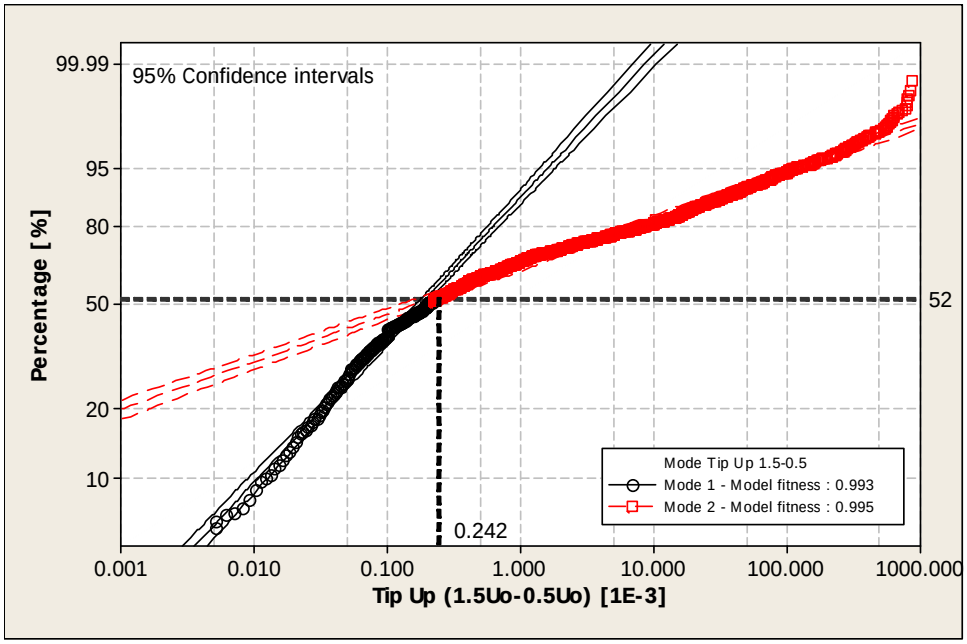

Figure 34: Probability Distribution Plot for Tip Up ($1.5U_0$-$0.5U_0$) by Mode – PE Insulated Cable Systems

Determining the limits between modes is not simple. In fact, there is no known established method to accomplish this. However, the limits are determined here by solving an optimization problem. Specifically, the limits between modes are determined by maximizing the model fitness for the two modes. In other words, the mode limits are determined in a way that the best model representation is accomplished for both modes. To find the limits in this way, an exhaustive search is performed around the possible values from the qualitative assessment; then, the limits that yield the best results are selected as the solution.

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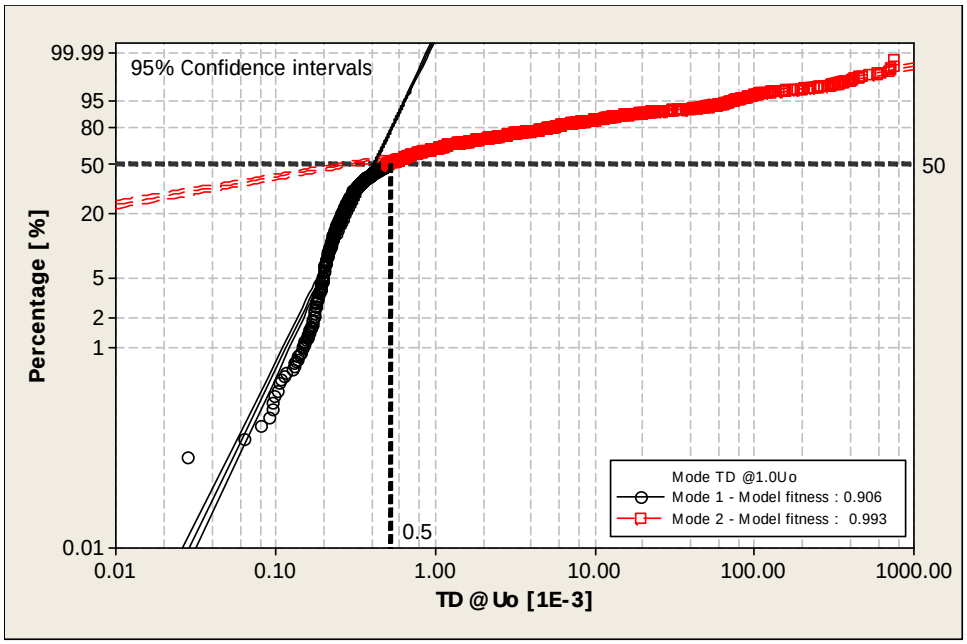

Figure 35: Probability Distribution Plot for Tan δ at U_0 by Mode

This procedure determined the mode limits for the second and third tiers or Tip Up between $1.5U_0$ and $0.5U_0$ and Tan δ at U_0. Results of the procedure appear in Figure 34 and Figure 35 respectively.

As observed in Figure 34 and Figure 35 both diagnostic features show two modes, the results of the analysis for determining the mode limits appear in Table 24 including the Tan δ Stability diagnostic features.

Table 24. Summary of Data Mode Analysis for Tan δ Features

Feature	No. Modes	Mode Limits [%] / [1E-3] (Y-axis/ X-axis)	Model Fitness Index
Tan δ Stability - STD (U_0)	1	-	0.999
Tip Up - TU ($1.5U_0$ & $0.5U_0$)	2	52/0.242	Mode 1: 0.993
			Mode 2: 0.995
Tan δ - TD (U_0)	2	50/0.5	Mode 1: 0.906
			Mode 2: 0.993

As seen in Table 24, the Tan δ stability at U_0 diagnostic feature is composed of only one mode whilst the Tip Up between $1.5U_0$ and $0.5U_0$ and Tan δ at U_0 are each composed of two modes. Note also that for all diagnostic features and modes the model fitness index is high which indicates that data are properly modeled when modes are considered. The most important use of mode analysis is that results can determine the 95% confidence intervals of the diagnostic features' thresholds presented in Table 25.

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Table 25: Criteria for Condition Assessment of PE-based Cable Systems – Collation of Research Data to December 2011					
Condition Assessment	**Tan δ Stability at U_0 [E-3]**		**Tip Up ($1.5U_0 – 0.5U_0$) [E-3]**		**Tan δ at U_0 [E-3]**
PE, HMWPE, XLPE, & WTRXLPE					
No Action Required	<0.05	and	<5	and	<4
Further Study Advised	0.05 to 0.5	or	5 to 80	Or	4 to 50
Action Required	>0.5		>80		>50

This is an important research contribution because generally assessment values are thought of as crisp thresholds when in fact they are results of statistical analyses of data and therefore they always contain a level of confidence related to them. The level of confidence is determined and clarified here by using the mode analysis to properly model the data. The 95% confidence interval limits for Tan δ features thresholds from Table 25 appear in Table 26 considering the two levels of 80% and 95% of condition assessment.

Table 26. Modal Analysis Results for the 80% and 95% Confidence Interval Limits for Tan δ Diagnostic Feature Thresholds Shown in Table 25.						
Diagnostic Feature	**95% Confidence Interval Limits [E-3]**					
	80% Level			**95% Level**		
	Value (Table 25)	**Lower Limit**	**Upper Limit**	**Value (Table 25)**	**Lower Limit**	**Upper Limit**
Tan δ Stability - STD (U_0)	0.050	0.047	0.059	0.50	0.41	0.61
Tip Up - TU ($1.5U_0$ & $0.5U_0$)	5.00	4.14	6.04	80.00	64.53	99.17
Tan δ - TD (U_0)	4.00	3.45	4.64	50.00	42.34	59.00

Table 26 shows the modal analysis results for the 80% and 95% confidence interval limits for Tan δ diagnostic feature thresholds shown in Table 25. As an example, if the diagnostic feature of Tan δ stability at U_0 is chosen at the 80% level, the threshold value is 0.05 (see Table 25) and there is a 95% probability that this threshold is between the range of 0.047 and 0.059. Therefore, care must be taken when the threshold values are used as they are a range rather than individual values. In practice, when diagnostic features are close to or at these threshold values, additional cable system information must be considered to determine a condition assessment. If, for example, the condition assessment falls between "No Action Required" and "Further Study Advised", those actions specified by a "Further Study Advised" condition could be performed to more clearly determine a valid condition assessment.

6.6.14 High Voltage Systems Sub Protocol

The majority of VLF portable diagnostic equipment is designed for testing MV cable systems up to 35 kV. However, newer VLF technology has allowed for testing voltages up to 90 kV. Therefore, voltage restrictions for VLF testing of HV power cable systems have disappeared; however, the main issue is to reduce the testing time and risk of failure during the test by maintaining significant diagnostic features for condition assessment.

The *CDFI* has also explored diagnostic tests on 46 kV (XLPE) and 69 kV (XLPE) HV cable systems as well as subsea cables (XLPE and Paper). In both cases, it is desirable from the utility perspective to keep test voltage levels at or below operating voltage. In the case of subsea cables, the critical and costly nature of these systems makes it unlikely that a utility would want to stress these systems above normal operating voltage. As a result, *CDFI* proposes to utilize a reduced voltage protocol for making Tan δ measurements on these types of cable systems.

The standard approach used in the *CDFI* for medium voltage cable systems is shown in Figure 36. Several measurements are made at each voltage using a 0.1 Hz VLF source with a maximum voltage of 1.5 U_0 for a Tan δ Ramp test and 2.2 U_0 for a Monitored Withstand.

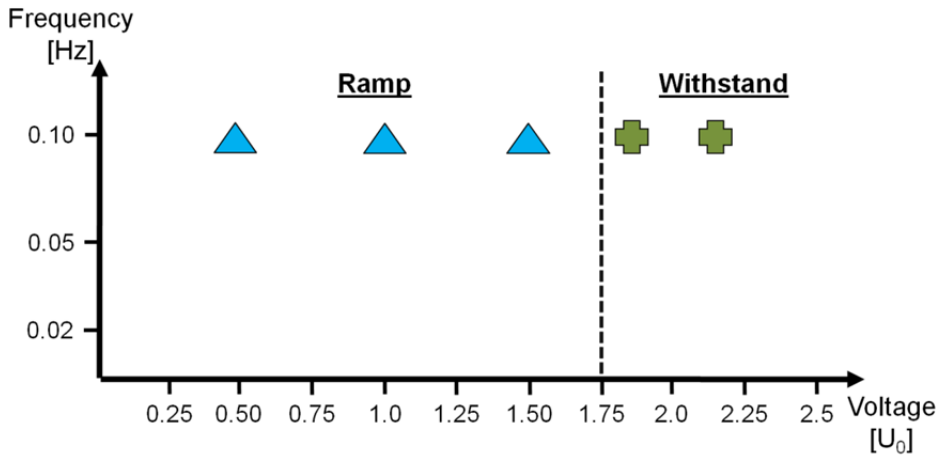

Figure 36: Medium Voltage Tan δ Protocol and Withstand Voltage Levels

In the case of HV and subsea cable systems, tests conducted as part of the *CDFI* perspective consider lower voltages (all test voltages less than or equal to U_0) as well as multiple frequencies. The protocol appears in Figure 37.

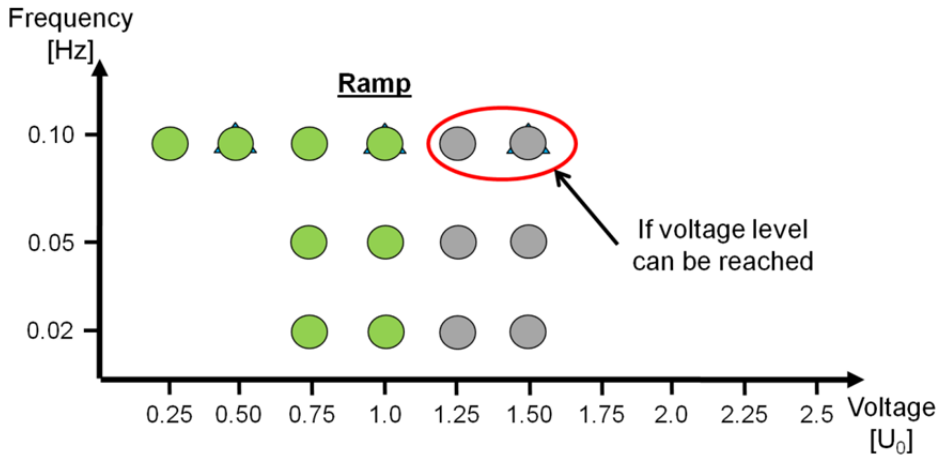

Figure 37: High Voltage/Subsea Tan δ Protocol

The additional voltage steps in the HV/subsea protocol allow gaining a better understanding of the linearity of the voltage dependency. The protocol in Figure 37 also makes use of the variable frequency capability of VLF units to test at frequencies as low as 0.02 Hz. This is otherwise known as Frequency-Domain Spectroscopy (FDS). Past work with IREQ and their Time-Domain Spectroscopy (TDS) unit has shown that additional information can be obtained using a variable frequency approach.

The following diagnostic features can be used in the assessment:

- Tan δ Stability at U_0 and 0.1 Hz,
- Tip Up/Differential Tan δ between U_0 and 0.5 U_0 at 0.1 Hz,
- Tip Up of the Tip Up on Tan δ between 0.25 U_0 and 0.5 U_0, 0.5 U_0 and 0.75 U_0, 0.75 U_0 and U_0 at 0.1 Hz,
- Tan δ Stability at U_0 and 0.02 Hz,
- Frequency Stability – Mean Tan δ at 0.02 Hz, Mean Tan δ at 0.05 Hz, and Mean δ at 0.1 Hz.

An example of Tan δ measurements from research on a 69 kV cable system shows the value of the added voltage steps. Figure 38 shows the Tan δ for this three phase system considering the MV protocol and limiting the voltage to U_0 (as requested by the utility). Also, three phases have some voltage dependence but since measurements were only made at two voltage levels there is no way to examine the non-linear nature of the voltage dependence.

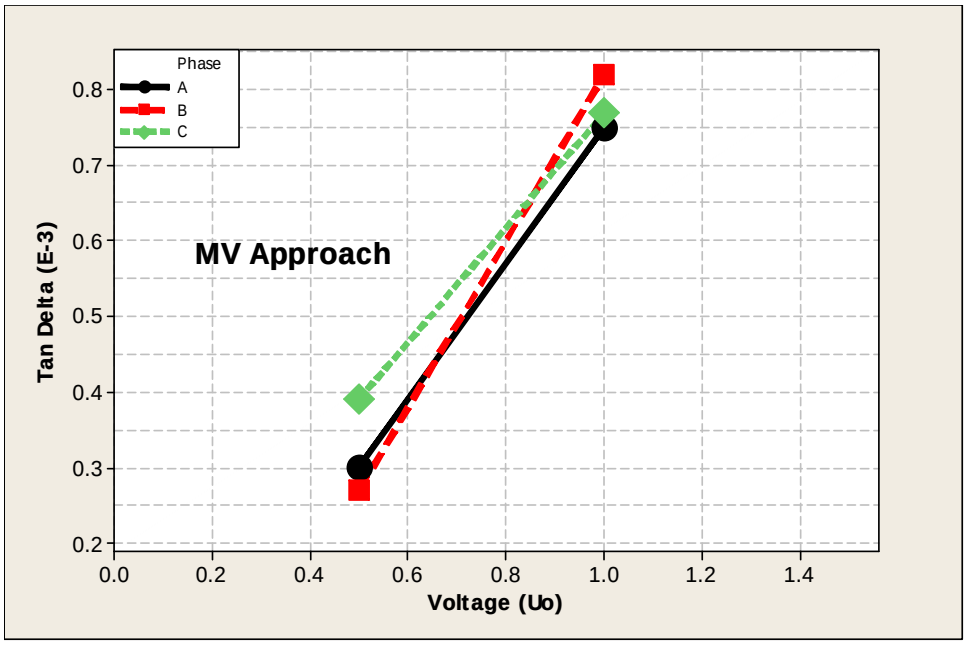

Figure 38: Medium Voltage Tan δ Approach on a 69 kV Cable System

Figure 39 shows the same three phase system tested according to the HV/subsea protocol. Clearly, the voltage dependence is non-linear and different for each phase.

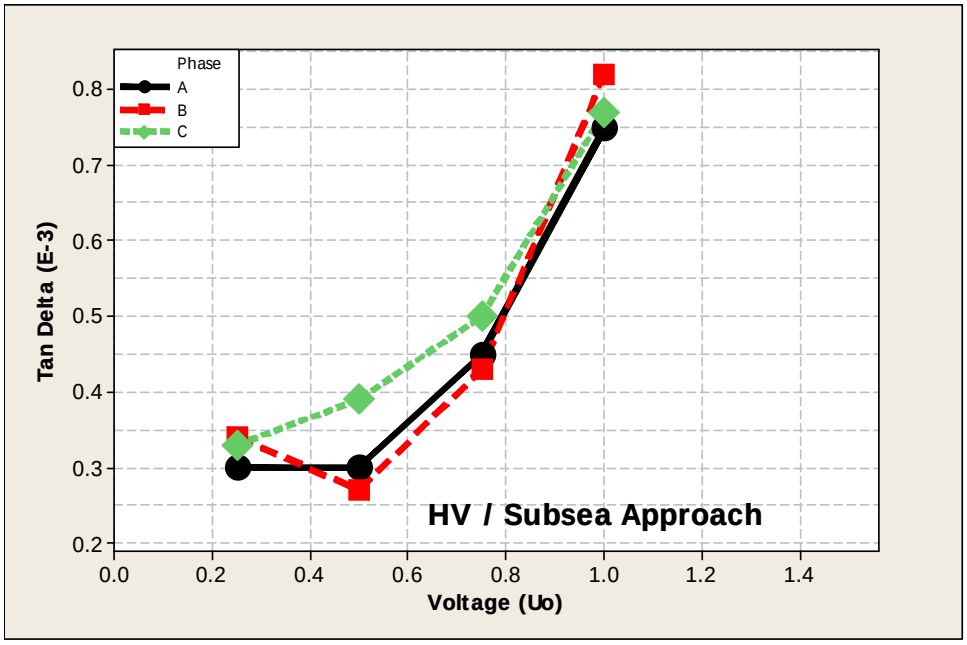

Figure 39: HV/Subsea Tan δ Approach on a 69 kV Cable System

The frequency dependence of the Tan δ, Tip Up, and Stability are also valuable as shown in the sample test of Figure 40. This figure shows the Tip Up – Tan δ map for four systems with measurements made at 0.1 Hz and 0.02 Hz. The Tan δ increases at a lower frequency as expected, but the Tip Up for Cable 3 and Cable 4 increased at 0.02 Hz. These Tip Ups were identical at 0.1 Hz.

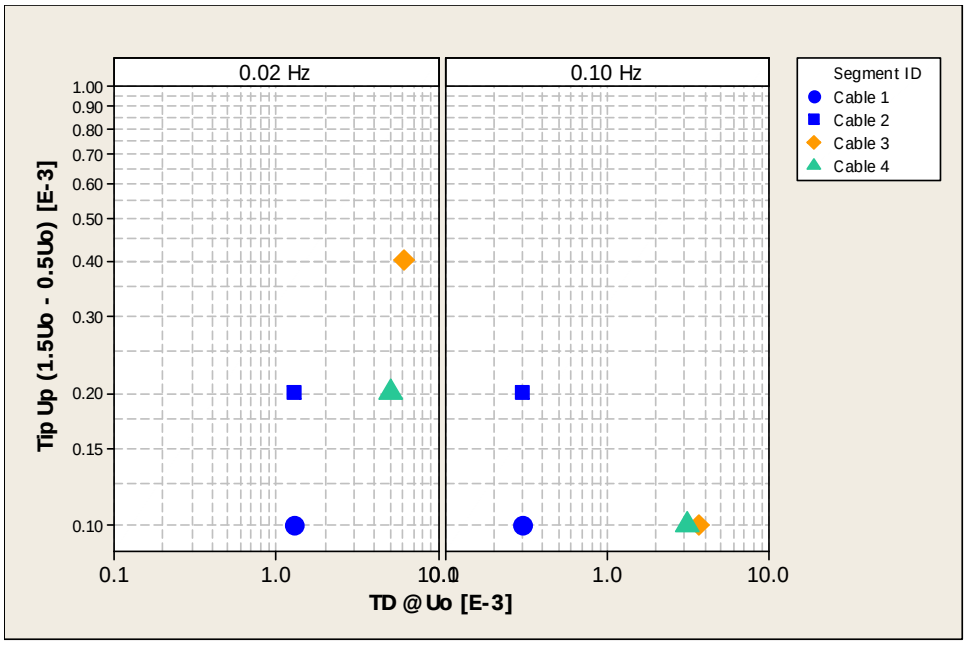

Figure 40: Sample Frequency Domain Spectroscopy Data for Four Circuits – 0.02 Hz (Left) and 0.1 Hz (Right)

This additional information will be useful as greater numbers of HV and subsea cable systems are tested. As more data are collected, the development of assessment criteria is possible by establishing threshold values to segregate between the different condition assessment classes.

6.6.15 Retests of PE-based Insulations

Most texts on Tan δ testing note the benefits of comparing previous measurements. One of the goals of field tests performed in *CDFI Phase II* is to revisit systems that were originally tested as part of *CDFI Phase I* to establish what changes in condition these systems experienced over the intervening years. These tests were conducted with the goal of understanding the outcomes of diagnostic tests. Thus, the sections were not remediated but were left in service to establish their service performance. Thus, if the criteria had been followed in 2007, service failures would have been prevented.

Several such retests have been completed and the data have been collated together to give a sense of the level of change that systems experienced. Table 27 contains a summary of the test results for the 70 systems that were retested as part of *CDFI Phase II*.

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Table 27: Summary of VLF Tan δ Retest Results

		TO					
		1-3 Years Between Tests			3-5 Years Between Tests		
		No Action Required	Further Study	Action Required	No Action Required	Further Study	Action Required
FROM	No Action Required	18	1	0	13	0	0
	Further Study	11	2	1	3	7	1
	Action Required	2	1	1	0	0	9
	TOTAL	37			33		

Several observations result from the data in Table 27:

- Cable systems with good performance remained good (97%),
- Several cable systems assessed as "Further Study" improved in performance (56%) as a result of utility actions.
- 44% of "Further Study" systems remained the same or degraded further.

6.6.16 Age Lines

The condition assessment using VLF Tan δ in conjunction with the power cable system age allow for estimating the evolution of the condition assessment over time; in other words, a quantitative estimation of how the power cable systems are changing assessment classes with time can be accomplished. This information is of extreme importance because if the power system age is known, then a prognosis can then be made on how it will transition between condition assessment classes in the future. This increases the importance of knowledge-based supported decision making for asset management of power cable systems.

Particularly, field tests at Snopud, Duke Energy, and WE Energies have provided, in addition to VLF Tan δ test data, the installation year for each of the tested systems. It is, therefore, possible to consider these data to expand the research to develop the concept of Tan δ age lines. The Tan δ provide an estimation of what percent of cable systems are in each condition assessment class as time evolves. This analysis has only been performed for PE-based insulations. Figure 41 shows two age lines for Tan δ measurements, specifically:

- "Further Study Advised or Worse" – It is necessary to combine the "Further Study

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Advised" and "Action Required" classes in order for the data censoring to work out properly. As a result, the percentage of "Further Study Advised" systems is the difference between the "Further Study Advised and Worse" curve and the "Action Required" curve.

- "Action Required" – The age line for systems classified as "Action Required".

Furthermore, the assigned assessment class was determined using the *CDFI*-PCA assessment tool discussed earlier.

Figure 41: Tan δ Age Lines – "Further Study Advised & Worse" and "Action Required"

As Figure 41 shows, the percentage of systems assessed as "Action Required" increases with age. Table 28 shows how the 30-year prediction compares to the 40-year prediction.

Table 28: Comparison of 30 and 40 Year Tan δ Assessments

Assessment Class	Age	
	30 Years [%]	40 Years [%]
No Action Required	70.2	23.0
Further Study	24.3	21.9
Action Required	4.5	55.1

Figure 41 provides the utility with useful planning information that can establish which areas should be tested. It also provides guidance as to how systems in the "No Action Required" class transition to "Further Study Advised" and, eventually, to "Action Required". This is important as the utility must continue to manage its cable system long after the initial round of testing is

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completed.

6.6.17 Feeder Assessments

It is becoming increasingly common for utilities to test three phase systems as part of their VLF Tan δ diagnostic programs. The criteria provided to date by the *CDFI* only presents guidance at the individual power cable system or "Phase" level and do not expressly discuss how the three phases can be considered as a single feeder section or in other words a "Feeder" level assessment. The most obvious approach used for adapting the current criteria is to simply take the worst recommendation/assessment and apply this to the entire feeder section; i.e. the overall condition assessment at the "Feeder" level would be the worst case from the condition assessment at the "Phase" level.

As an example, a feeder with two phases assessed at the "Phase" level as "No Action Required" while the third phase is "Action Required" would yield a "Feeder" level assessment of "Action Required." However, this ultimately leads to a higher than expected percentage of "Action Required" and "Further Study Advised" when one considers feeder sections. Therefore criteria for assessment at the '"Feeder" level based on the same approach developed within the *CDFI* for Tan δ that identifies critical dielectric feature levels that separate "usual" from "unusual" feeders is required.

To properly assess these feeder sections, it is necessary to develop a different set of criteria that not only addresses the percentile issue above but also considers the potential phase-to-phase differences. The following features are suggested for the *CDFI* for condition assessment at the "Feeder" level:

- Maximum Phase Tan δ Stability – The highest Tan δ stability of all three measured at U_0.
- Tan δ Range for Three Phases – The difference between the highest Tan δ at U_0 and the lowest Tan δ at U_0.
- Poorest Phase Tip Up – The highest Tip Up measured in any one of the three phases.
- Poorest Phase TuTu – The highest Tip Up of the Tip Up (TuTu) measured in any one of the phases.
- Maximum Phase Mean Tan δ – The highest mean Tan δ measured on any one of the three phases at U_0.

The same approach used to develop the current *CDFI* Tan δ criteria at the "Phase" level could be employed to identify the critical levels for "Further Study Advised" and "Action Required." It will be necessary to increase the percentiles from the 80^{th} and 95^{th} percentiles in order to obtain a class distribution that is in line with the intended 80/15/5 ("No Action Required"/"Further Study Advised"/"Action Required") that has been used in the past to separate "usual" from "unusual" feeders. The new percentiles can be obtained using probability theory and, for ease of analysis, the assumption is made that the features are statistically independent. This assumption is likely rather weak for the Tip Up and TuTu and the Maximum Phase Tan δ and Tan δ Range but it does allow for a straightforward and relatively simple solution. This appears in Equation 4 for the class "Action Required".

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$$\binom{5}{1}P(AR)\left(1-P(AR)\right)^4+\binom{5}{2}P(AR)^2\left(1-P(AR)\right)^3 + \binom{5}{3}P(AR)^3\left(1-P(AR)\right)^2 + \binom{5}{4}P(AR)^4\left(1-P(AR)\right)+P(AR)^5=0.05 \quad \textbf{Equation 4}$$

where,

P(AR): Probability of "Action Required,"
$\binom{x}{y}$: "x choose y" = $\frac{x!}{(x-y)!y!}$.

Equation 4can then be solved numerically to yield a probability of "Action Required" of 0.01. This in turn implies that the new "Action Required" percentile should be set to the 99th percentile. The "No Action Required" percentile can be similarly calculated to yield the 96th percentile. The remaining 3% between 96% and 99% would then correspond to the "Further Study Advised" class.

Similar equations can be derived and solved to yield the appropriate percentiles for different numbers of features. The general form for the probability calculation for "No Action Required" and "Action Required" using a set of independent features correspond to Equation 5 and Equation 6, respectively.

$$P(NA)^n=0.80 \quad \textbf{Equation 5}$$

where,

P(NA): Probability of "No Action Required" (can be thought of as the dividing point between "No Action Required" and "Further Study Advised."

$$\sum_{i=1}^{n}\binom{n}{i}P(AR)^i(1-P(AR))^{n-i}=0.05 \quad \textbf{Equation 6}$$

The challenge with the above equations is selecting features that are truly independent. Additional work is needed in this area. However, the equations have been applied to the *CDFI* paper insulation (PILC) database and criteria for condition assessment at the "Feeder" level have been developed from this research, these criteria appear in Table 29.

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Table 29: VLF Tan δ Criteria for PILC Cable Systems at "Feeder" Level from *CDFI* Research **FEEDER ASSESSMENT** **These criteria CANNOT be used unless data are available for all five features ***			
Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Max Phase Stability for TD_{U_0} (standard deviation)	< 1.2	1.2 to 2.3	> 2.3
	and	or	
Tan δ Range for Three Phases (Max Mean TD_{Uo} –Min Mean TD_{Uo})	< 30	30 to 50	> 50
Poorest Phase Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-45 to 24	-57 to -45 or 24 to 30	< -57 or > 30
	and	or	
Poorest Phase TuTu $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	< 16	16 to 23	> 23
	and	or	
Max Phase Mean TD_{U0}	< 170	170 to 210	> 210

* If all five features are not available, use the worst condition assessment at the "Phase" level as the assessment for the "Feeder" level.

In the assessment scheme shown in Table 29, the condition of a cable system is assessed as: "No Action Required", "Further Study Advised", and "Action Required". Once a circuit is assessed as "Further Study Advised" or "Action Required", additional work is needed to restore the feeder to reliable operation.

In the case of a "Further Study Advised" assessment, the following actions are recommended:

- Review data for a rogue measurement in the sequence – most common in the first acquisition,
- Re-clean terminations and repeat measurements,
- Compare measurements with previous tests or other results from other phases of the circuit,
- Place on "watch list",
- Confirm type of PILC circuit – belted or H-type. Belted cables use higher loss oils and are, generally speaking, older than H-type designs. Belted designs would likely produce increases in Tip Up, TuTu, and Mean Tan δ.

- Investigate condition of oil-filled switches used for sectionalizing or disconnecting transformers – a comparison of the phases could identify unusual switch behavior. Also, an analysis of Tan δ as a function of the number of switches in each circuit would be useful for determining whether or not the switches have a significant effect on Tan δ,
- Disconnect all cable terminations from switchgear and retest (if practical for the specific switch gear involved), or
- Consider feeder to feeder comparisons.

The recommended actions for circuits assessed as "Action Required" are the same as the actions for "Further Study Advised" with the following additions:

- Conduct IEEE Std. 400.2 – 2013 Monitored Withstand test for 60 min,
- Retest in near future, or
- Place on "watch list" and consider remedial actions (replacement or repair) for the feeder.

There are some circumstances where the precise cable design (e.g., shielded or belted, conducting or non-conducting shield), system composition, insulation material, or vintage is known. Therefore, in these cases the database would allow for the development of "cable system specific" criteria to provide better discrimination. A case study illustrating these circumstances follows.

The *CDFI* has had the opportunity to compare "Phase" and "Feeder" condition assessments using the different available criteria for a utility feeder PILC database. Specifically, since 2010, the utility has maintained an underground cable system diagnostic program for its PILC feeder circuits. One of the primary diagnostics used in this program is VLF Tan δ. In total, 72 feeder circuits of 6.9 kV (U_0) were tested with a total of 213 phase tests completed. This includes tests from 2010 through March 2012.

Using the utility VLF Tan δ results in and the criteria presented in Table 6, Table 14, and Table 29, it is useful to construct a summary table that shows how the feeder *CDFI* customized criteria compare to the phase IEEE and *CDFI* criteria. Table 30 contains this summary.

Table 30: Summary of the Utility Specific Condition Assessments for Each of the Available Criteria Sets

Criteria	Assessment Class Distribution		
	No Action Required	**Further Study Advised**	**Action Required**
Assessment at "Phase" Level [%]			
IEEE Std. 400.2 – 2013 (Table 6)	47	43	10
CDFI Perspective – (Table 14)	51	37	12
Assessment at "Feeder" Level [%]			
Feeder IEEE Std. 400.2 – 2013	39	39	22
Feeder *CDFI* Perspective	37	45	18
Feeder *CDFI* Perspective (Table 29)	82	4	14

The comparison between assessments at the feeder level using the different criteria appear graphically in Figure 42.

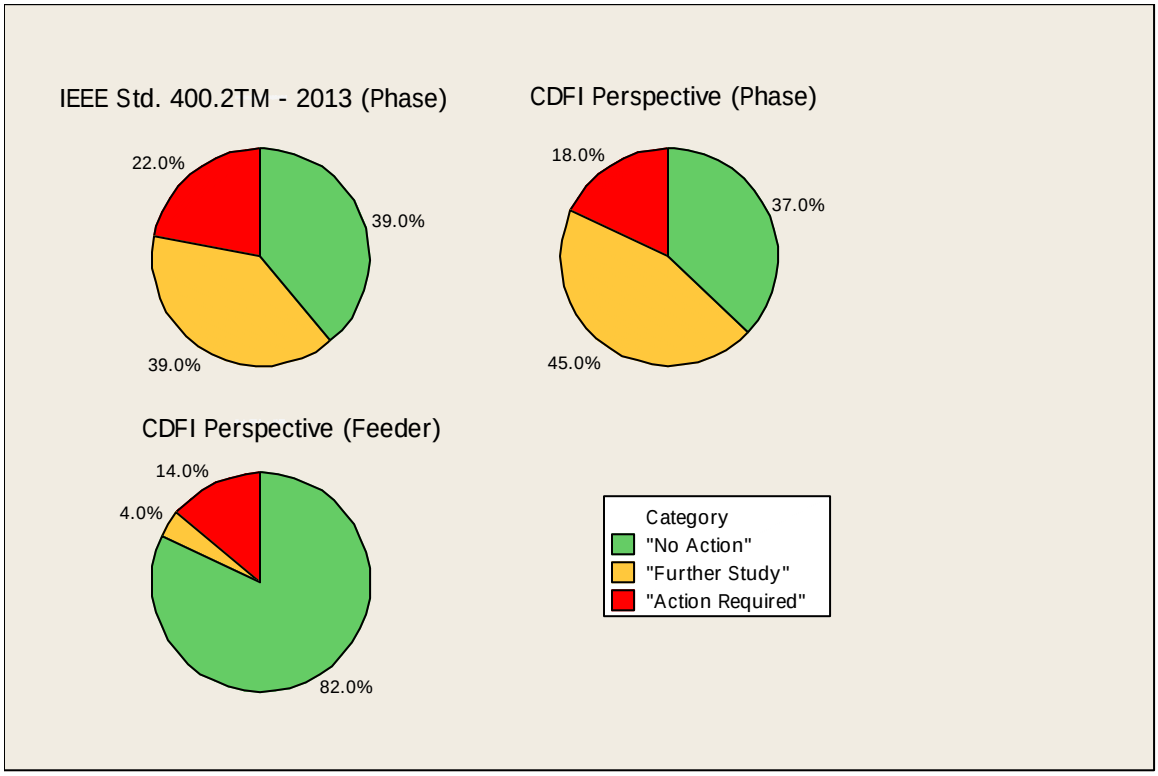

Figure 42: Comparison of Utility Condition Assessments at the "Feeder" level for each of the Available Criteria Sets

As seen in Table 30 and Figure 42, using VLF Tan δ Criteria for PILC Cable Systems at the "Feeder" Level, the overall assessments for the "Feeder" level are distributed between classes much closer to expectations (85%/15%/5%). Thus, these criteria could be used in place of either the IEEE or *CDFI* criteria for assessment at the "Feeder Level" of PILC power cable systems.

6.6.18 Cable Injection

The *CDFI Phase II* has deployed VLF Tan δ measurements on power cable systems recently injected for cable rejuvenation; more importantly, compared those measurements with the ones of cable systems planned or rejected for cable rejuvenation in the same subdivisions. The diagnostic field tests were performed on Duke Energy URD type underground cable systems located in Ohio and Indiana, 7.2 kV XLPE unjacketed (15 kV cable design). Five subdivisions were tested. The cable systems in the Ohio subdivisions have been injected using the un-sustained (low pressure) technology while the cable systems in the Indiana subdivisions have been injected using the sustained (high pressure) technology. The field tests performed in Ohio and Indiana are the first experience within the *CDFI* to test injected cable systems and compare results with non-injected systems. All of these systems have seen similar operating field conditions.

At the time of testing, there were two injection technologies used by Duke Energy to rejuvenate their XLPE cable systems. The technologies were the un-sustained and sustained methods; specifically, the un-sustained method was used in Ohio and the sustained method was used in Indiana. One *CDFI* objective is to determine how rejuvenation might affect Tan δ values. This knowledge will enhance the assessment of rejuvenated cable systems over their extended service life. In addition, all of the generated information will be relevant to other utilities that now perform, or plan to perform, cable injection on a regular basis.

The two injection technologies are different but share the same underlying physical mechanisms and chemical principles:

- All terminations are replaced.
- All (sustained) or many (un-sustained) splices are replaced.
- Water is expelled from the conductor by the injection fluid.
- Remnant water between the conductor strands, insulation, and water trees reacts with the silicone based fluid and is chemically bonded to the injection fluid.
- Oligomerization (a chemical process that converts monomers to a finite degree of polymerization) reactions occur with the water and the extended (not crosslinked) molecules diffuse more slowly (maximizing retention).
- The exclusion and binding of the water with the injection fluid is postulated to retard the growth of further water tree areas inside the bulk cable insulation, this is a topic of ongoing study.
- Special (hydraulic) splices and terminations are used.
- After injection, cable system reliabilities are reported to be improved, this improvement can be due to:
    1. Replacement of all poorly performing (aged) terminations.
    2. Replacement of many poorly performing (aged) splices.
    3. Improved moisture barriers for the new splices and cable conductor.
    4. Reduced rates of tree growth within the bulk cable insulation.

Independent of the injection technology used, the integrity of the neutral is checked before injection. If the neutral is degraded by more than 50%, the cable system is rejected. Neutral integrity is assessed by the technology provider using the TDR and Ohm-Check techniques.

Injection may also not be possible if there are more than two splices and/or the fluid cannot be pushed through the system. The fluid reaction times are typically between 21 days and 6 months for the unsustained and sustained technologies respectively; but times also depend upon temperature, moisture content, and reaction fluid technology. All tested power cable systems have completely reacted before testing.

Therefore, this section presents an analysis on how cable injection affects the Tan δ measurements represented here by four Tan δ diagnostic features. Given the limited number of Tan δ measurements made on injected cable systems it is not yet clear how the injection process influences Tan δ. In fact, the complex nature of the injection process makes it difficult to predict how injection affects the dielectric characteristics of the insulation. As shown before, the PE-

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based *CDFI*-PCA tool was used to determine the overall assessment of cable systems (i.e. "No Action Required", "Further Study Advised", or "Action Required"). While this is the best criteria available to date, this approach may not be the most suitable assessment method for injected cable systems as the insulation now includes other compounds not found in new PE-based insulations. Therefore, it is useful instead to directly compare the raw measurement data.

Figure 43 shows the box plots of each Tan δ diagnostic feature by injection and injection technology. Remember that only one injection technology was used in any particular subdivision. It is, therefore, best to compare each injection technology with its corresponding group under "No Injection" as this represents the subdivisions in the same state.

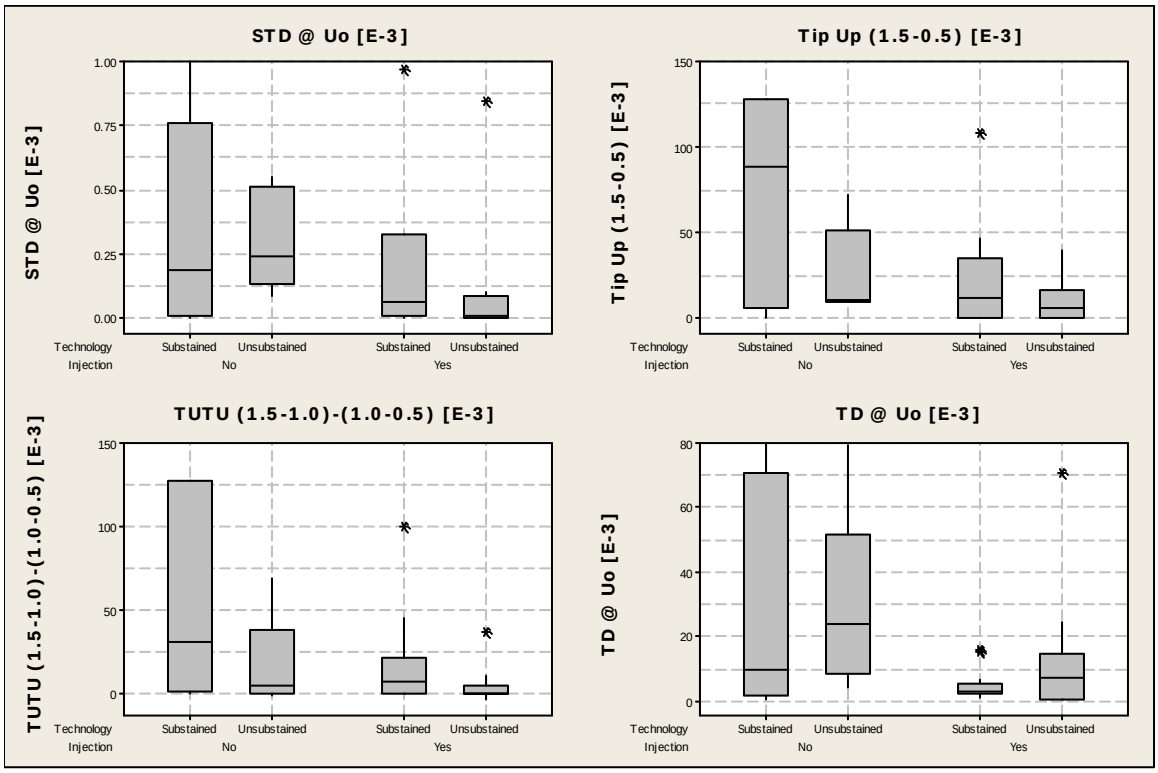

Figure 43: Tan δ Diagnostic Features by Injection Technology

Figure 43 illustrates that in general (and independent of the injection technology), all diagnostic features have narrower ranges and lower magnitudes on the injected systems. In other words, the test results indicate that these systems are in overall better condition than those that were not injected.

When comparing injection technologies, Figure 43 gives an indication that the un-sustained injection method has lower ranges and magnitudes for Stability, Tip Up, and TuTu than the sustained (high pressure) method. The cables injected using the sustained method, on the other hand, display lower Tan δ at U_0. However, it is important to emphasize that this observation is only valid for the cases studied herein; thus, these results cannot be generalized. The results are in general systemic; however, a similar conclusion might be expected.

Thus, the field experience reported has identified the following advantages of the cable injection:

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- Accessories are replaced, which minimizes the likelihood of their causing near-term future failures.
- Cable system neutral condition is evaluated; only systems with 50% of remaining neutral or better are injected.
- Water is pushed out of the conductor and replaced by the injection fluid which over time polymerizes and acts as a conductor blocking agent.
- Injection fluid diffuses through the insulation and reacts with the water in the aged water-tree regions; however, this has not yet been confirmed by the *CDFI*.
- According to the system operators, injection overall has helped on improving system reliability; however, the mechanisms of how this is accomplished have not yet been assessed.

6.6.19 Effect of Splices

There has been ongoing debate within IEEE-PES-ICC and other organizations as to the effect of accessories on the Tan δ measurement. It is, therefore, useful to examine the Tan δ as functions of the number of splices. It has been suggested that terminations and splices could have a significant effect on the measured Tan δ values. The accessories themselves could overly influence the measurement, and this has generally been observed for the two following cases:

- The insulation losses for a certain type of accessory (e.g. resistive field grading accessories) are higher than the cable insulation losses.
- Traditional accessory types that have reached highly degraded condition and thus their insulation losses are higher than the cable insulation losses.

Therefore, when performing Tan δ measurements, if possible, the number of accessories, types, and conditions should be considered in order to evaluate their effects on the Tan δ value of the cable system. It is important to recall that for field testing applications, the focus on deploying diagnostics is to assess the condition of the power cable system as a whole; i.e. cable plus accessories. Thus in this scenario, if Tan δ measurements indicate an "Action Required" and it is due to a highly degraded accessory, then the application of Tan δ is considered successful.

During *CDFI Phase II*, Tan δ field test data have been collected to help understand the effect of the number of splices on Tan δ measurements. The data have been obtained from two testing sites:

- The first site is an aged URD with power cable system of 7.2 kV U_0, XLPE, unjacketed, and 15 kV cable design.
- The second site is a new feeder type power cable system of 20 kV U_0, jacketed, and 35 kV cable design.

Results for the Tan δ magnitude at U_0 as a function of number of splices for the first and second sites appear in Figure 44 and Figure 45, respectively.

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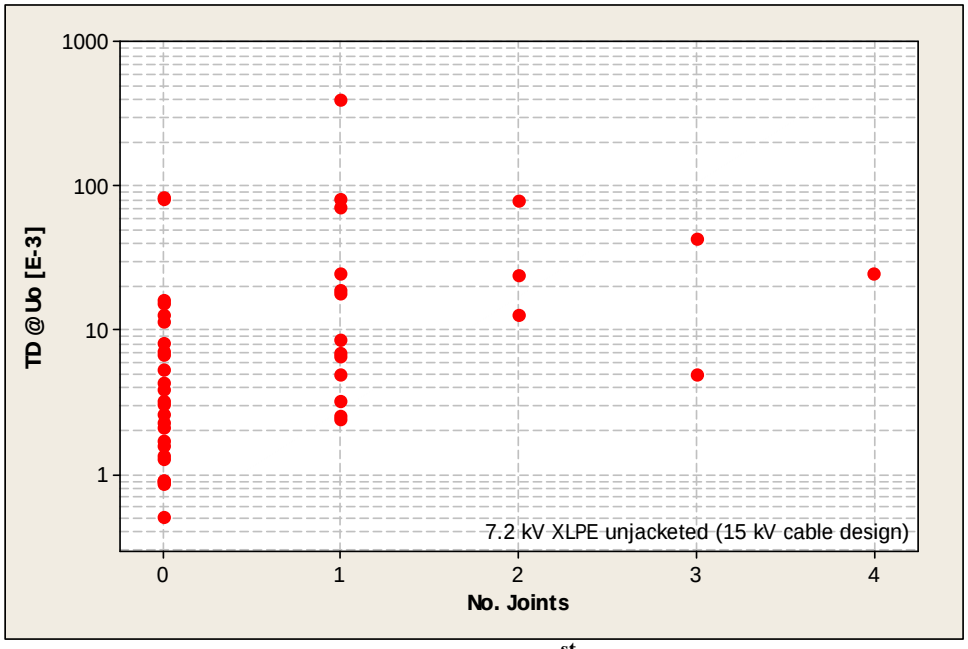

Figure 44: Tan δ versus Number of Joints (1st Site) for an Aged XLPE System

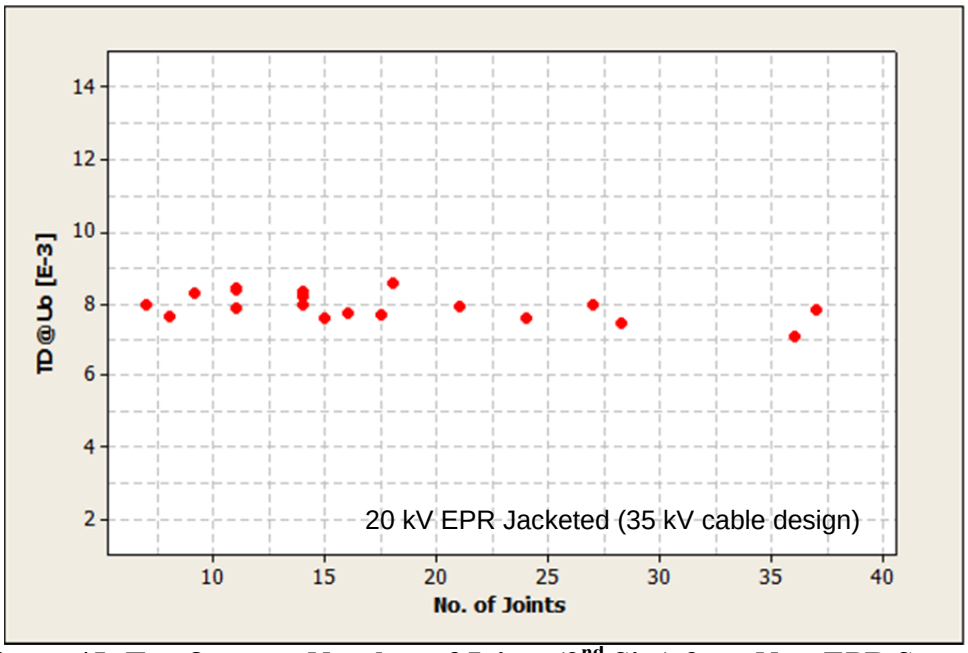

Figure 45: Tan δ versus Number of Joints (2nd Site) for a New EPR System

As the figures illustrate, there is no discernible change in the Tan δ with increases in the number of joints. Moreover, as mentioned before, it is sometimes conjectured that higher Tan δ magnitudes are due to the presence of splices; however, this is not supported by the data.

6.6.20 Hybrid Circuits

As power cable systems age, degrade, and eventually fail, it is common that newer power cable

system technologies are introduced; these situations are commonly described as a hybrid power cable system. The most common hybrid system configurations are Paper/Filled or Paper/PE-based or Paper/Filled/PE-based. In addition, they typically have more splices, some of which have different kinds of weaknesses located at different junctures along the power cable system.

These situations present a dilemma for selection of diagnostics as it is unclear which of the power cable diagnostic technologies is most appropriate. For example, DC hipots have been used effectively for the commissioning of paper power cable systems; however, they have been proven to be detrimental to PE cables. Thus condition-based maintenance strategies in such networks require a combination of diagnostic technologies and differentiated interpretation of tests over time.

In other words, the numerous parameters of the hybrid arrangement limit the application of single indicator evaluation and decision models. Still, it is possible to pinpoint weak cable sections with a multi indicator approach and a differentiated analysis; for example, the application of VLF Tan δ together with PD (Partial Discharge). A more thorough description of the application of combined diagnostics is explained later in the handbook.

Based on many years of practical field experience, experts support the definition of individual evaluation criteria. Pinpointing of degraded cable sections or joint locations is easily attainable if PD activity can be measured. Moisture ingress prone cable sections can be identified by knowing the power cable system cable details over its entire length. Moisture ingress in splices is also a major cause of degradation and system faults. Moisture ingress prone cables can be identified with VLF testing. Water tree aging can be understood from the behavior of the VLF Tan δ stability trend as well as the response of TD over several voltage steps.

In Hybrid cables, a PILC section in good condition shows natural losses that are much higher compared to the Tan δ of a highly serviced, aged XLPE section. Accordingly, the Tan δ result of a hybrid cable system needs to be carefully considered as highly serviced, aged cables may not be recognized. The maintenance VLF withstand test according to IEEE 400.2 is an important tool to confirm that no hidden weaknesses are present.

Often the Tan δ is highly influenced by moisture ingress into splices. In general, the Tan δ stability and the Tan δ trend are clear indicators of moisture ingress in splices. In general, if there is moisture ingress in the splices, the Tan δ might indicate:

- Moderate to highly fluctuating values throughout each voltage level.
- Decreasing Tan δ values throughout each step voltage level, this is due to small amounts of moisture in either a splice or termination that vaporizes during voltage application.
- Strongly increasing Tan δ values throughout each voltage level, which can be due to tracking inside the splice or termination.

Thus, the analysis of the Tan δ time variability using the standard deviation appears to be the only parameter allowing identification of degradation in hybrid power cable systems.

Nevertheless, a progressive increase of Tan δ values over time for sequential tests indicates the

presence of gradually increasing degradation. Thus, in order to recognize this trend, records must be maintained over time, typically several years. In this case, through experience and heuristic knowledge, when the Tan δ measurements exceed historically established thresholds of magnitude and stability for a particular hybrid system configuration, consequence, and voltage levels, the cable system might have degraded to a point requiring replacement. On the other hand, if the Tan δ is below the established thresholds, then additional tests could determine whether the system insulation is perhaps defective.

In conclusion, higher insulation losses over time and increases in instability as functions of testing voltage are indicators that the insulation of a hybrid power cable system may be approaching failure. Therefore, even for complex situations, experience shows that knowing how to use diagnostic testing results makes it possible to develop a testing strategy focused on diagnostic parameters that have not yet been defined in the standards.

6.7 Outstanding Issues

6.7.1 Criteria Based on Local and Global Data

The criteria for VLF Tan δ as well as those developed for other diagnostic techniques are intended, by the nature of this project, to be industry-wide criteria that include test results from as many utilities as possible. This provides a global perspective on each diagnostic technique. This perspective does not distinguish between the variety of system designs, environmental conditions, and installation practices used by the utilities supplying the data. The result is a large dataset that represents the experience of many utilities. At present, data are segregated by insulation class only. Unfortunately, there are cases where this approach may not generate criteria that are ideal for an individual utility. Indeed, this is specifically recognized in IEEE Std. 400.2 – 2013 where a local perspective is advocated. This is due to the many factors that can contribute to system aging such as the manufacturer, vintage, cable/accessory design, operating environment, and operating conditions. In such cases, it is necessary to generate local criteria that are based solely on an individual utility's test data.

The process of developing local criteria is the same as that used to determine global criteria within *CDFI* (see previous quarterly reports and the *CDFI Phase I* final report for more information). The challenge is having enough data from the specific utility to facilitate this process. As a consequence, local criteria cannot be developed unless significant effort has already been expended in testing. A utility just starting a diagnostic program must rely on the global criteria until they can generate enough data for local criteria to be determined.

6.7.2 Very Low Frequency (VLF) and Power Frequency

The *CDFI* has shown that VLF Tan δ measurements provide much information about the insulation condition of power cable systems. However, the condition assessment can also be accomplished by performing Tan δ measurements at a power frequency of 60 Hz; in fact,

measurements at a specific power frequency are commonly used in laboratory approval tests (here the frequency can range from between 49 Hz to 61 Hz according to the standards). However, for field testing applications, the deployment of Tan δ at 60 Hz has several challenges to overcome. To test a power cable system with 60 Hz power requires a power supply of high reactive power capacity. This requires bigger, more expensive, and difficult to handle test equipment. Thus, it is nearly impossible to test a power cable system of several thousand feet with a 60 Hz power supply. , It takes 600 times less reactive power to test a typical VLF cable system at a frequency of 0.1 Hz than it does at 60 Hz.

Furthermore, the magnitude of Tan δ numbers increases as the frequency decreases, making measurement easier. However, the changes on Tan δ with frequency are not proportional to the frequency change; they are the result of complex physical processes that occur inside the bulk insulation and depend on various factors that include insulation parameters (not strictly constant with frequency), temperature, moisture content, operating conditions, aging process, system design, and voltage. Thus, Tan δ measurements at 60 Hz cannot be directly compared with those at 0.1 Hz; however, a correlation between the measurements at the different frequencies can be established. The relation between Tan δ measurements at the different frequencies has been and still is a topic of ongoing study, analysis, and discussion inside the power cable system community.

Figure 46 shows the correlation between Tan δ measurements (U_0) at 60 Hz and 0.1 Hz. The data encompass tested cable of extruded insulations including PE-based and EPR in the laboratory. Service aged, accelerated aged, and new cable conditions are considered here for the Tan δ correlation.

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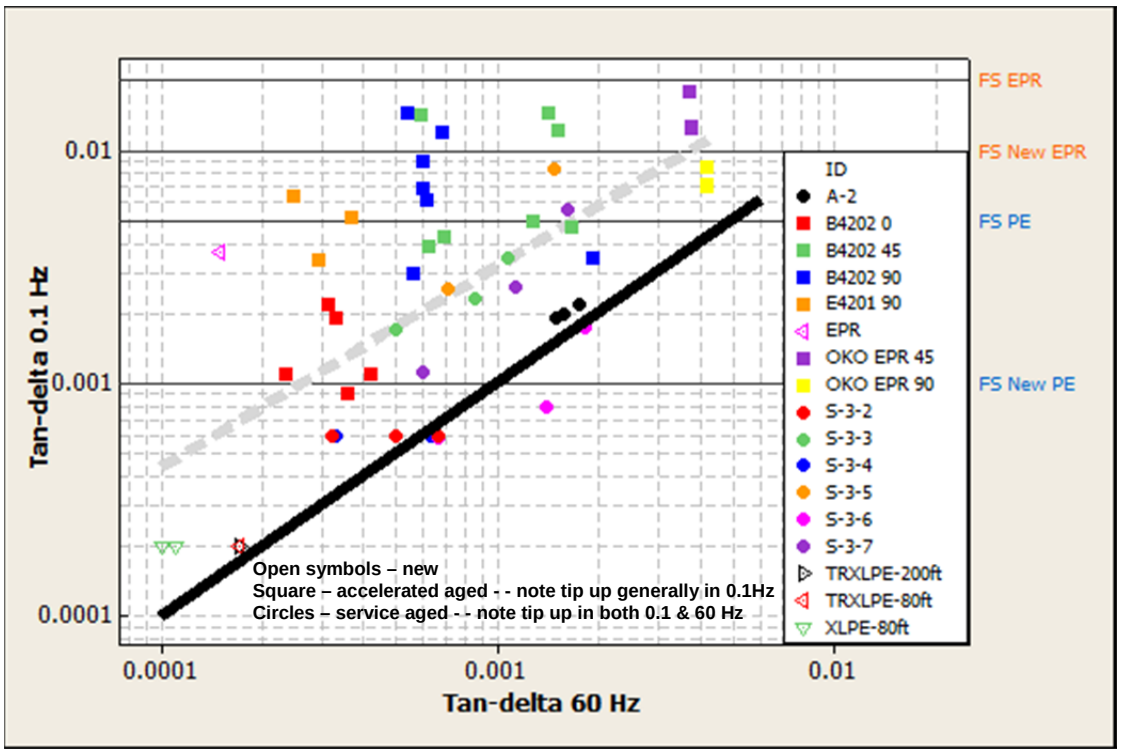

Figure 46: Correlation between Tan δ (@ U_0) at 60 Hz and 0.1 Hz (Horizontal Lines Represent the Limits for "Further Study Advised" for Aged and New PE-based and Filled Cable Systems (See Table 7, Table 8, Table 12, and Table 13)

Figure 46 clearly shows that there is not a perfect 1:1 correlation (represented by the black line) between Tan δ measurements at 60 Hz and 0.1 Hz. Nevertheless, there is some correlation represented by the gray line that could be useful in translating diagnostic criteria from one frequency to the other. The actual correlation between measurements is represented by the gray dashed line. Moreover, Tan δ values at 0.1 Hz are generally larger than those at 60 Hz because of the greater sensitivity of 0.1 Hz Tan δ measurements as compared to 60 Hz.

6.8 References

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10. A. Jonscher, *Dielectric Relaxation in Solids*, Chelsea Dielectrics Press, 1983.

6.9 Relevant Standards

- IEEE Std. 400 – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*
- IEEE Std. 400 – 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.1 – 2007: *IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage*
- IEEE Std. 400.2 – 2004: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)*
- IEEE Std. 400.2 – 2013: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)*

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6.10 Appendix

Section 6.6.10 described the overall approach used by the research to produce a "Health Index" assessment from the Principal Components of PE cable systems. The following section provides the fine details of the PCA procedures for the three main insulation classes. The general approaches are the same for each; however, the ultimate outcome will be colored by the level of physical understanding and data fidelity.

At this point, it is important to recognize that the PCA approach adopted here is not an anonymous statistical procedure as might be applied in a neural network (artificial intelligence) solution. In this case, the selection of features and interpretation of the PC distances ultimately depends upon an understanding of the physics of the measurements and the degradation. Consequently the outcomes will evolve as that understanding improves. This is particularly true for the PILC analyses described later.

6.10.1 Principal Component Analysis for PE-based Insulations

The Tan δ features considered in this study were:

- **Stability of Tan δ (STD)**: stability measured by the standard deviation for sequential measurements made at U_0, where U_0 is the phase-to-ground system operating voltage
- **Tip Up (TU):** differential Tan δ between $1.5U_0$ and $0.5U_0$
- **Tan δ (TD):** mean Tan δ measured at U_0
- **Differential Tip Up (TuTu):** the difference of Tip Ups over a $0.5\ U_0$ span

The values for the features above correspond to Tan δ measurements for PE-based insulation cables (PE, XLPE, WTR-XLPE) contained in the database. This database includes 2,507 Tan δ tests. In this dataset, 2,008 of the tests have all the required measurements present. These field measurements were collected from May 2006 until June 2013 in 39 areas, from 10 different utilities.

Several combinations of the Tan δ features defined above were tested using PCA. The objective was to find the combination that would better classify the condition of a cable system as compared with the total population of the database. The combinations included various functions of the Tan δ features as: linear terms, quadratic terms, compounded terms (multiplication of two features), and logarithmic function (for better scaling a particular feature). In each combination, a PCA was carried out and the resulting principal components were combined to create a single "Health Index", mathematically called the PC-distance.

This PC-distance corresponds to the Euclidean distance from a pre-defined origin in the three dimensional space spanned by the orthonormal base of the first three principal components (components that explain the largest portion of the variance). In this case, the pre-defined origin corresponded to Tan δ values of a new PE-based insulation cable, thus the smaller the magnitude of the PC-distance, the more similar the condition is to a new cable while larger values imply increasingly deteriorated condition.

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Once the PC-distances were calculated for all 2,008 tests, a ranking scheme was defined to assess the condition of the cables: all samples with PC-distance above the 80th percentile were classified as "Further Study Advised" and all results above the 95th percentile were declared as "Action Required".

In order to test the accuracy of the classification scheme for each combination of Tan δ features a test set with known cable conditions was used:

- New cable: expected to fall in the low percentile area (origin),
- Cable with individual features at 80% level: expected to classify around the 80th percentile,
- Cable with individual features at 95% level: expected to classify around the 95th percentile,
- Cable failure: expected to classify at the 95th percentile or above,
- Four cables with increasingly degraded condition: expected to classify around 80th percentile with increased percentile for each sample,

The values of the Tan δ features for each sample in the test set appear in Table 31. Table 32 shows the 12 combinations of Tan δ features that were evaluated. Among those combinations, only three of them were able to perform an acceptable classification of the test samples in Table 31.

Table 31: Tan δ features for PE-based insulation cables

Sample	STD	TU	TD	TuTu
New cable	0	0	0.1	0
Cable with individual features at 80%	0.05	5	4	0
Cable with individual features at 95%	0.5	80	50	60
Failed cable	3.6	247	315	17
Consecutive degradation of cable, Stage 1	0	0.8	2.8	0
Consecutive degradation of cable, Stage 2	0	1.2	5.4	-0.2
Consecutive degradation of cable, Stage 3	0	1.8	6	0.6
Consecutive degradation of cable, Stage 4	0.9	58	48.7	21.6

The difference in the classification results for the three combinations was negligible. In all of them:

- A new cable is classified as the 0th percentile,
- A cable with individual features at the 80% level is classified as the 82nd percentile,
- A cable with individual features at the 95 % is level classified as the 94th percentile,
- The cable failure classified at the 98th percentile,
- The four cables with increasingly degraded condition are classified as being in the 79 th, 83 rd, 84 th, and 93 rd percentiles.

The results are categorized as Correct (the test cases were ranked in the correct order AND gave the correct percentile) or Incorrect (the test cases were NOT ranked in the correct order NOR gave the correct percentile) Therefore, additional criteria were required for choosing the final combination of features. The cumulative variance was taken into consideration as well as the

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coefficients associated with each principal component. Analysis of the coefficients showed that one of the combinations was able to decouple the effects of the stability of Tan δ (STD) and the Tan δ (TD) itself in an optimal fashion.

This combination considered: (i) a quadratic term for the stability of Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a logarithmic function for the Tan δ (log (TD)), and (iv) a linear term for the differential Tip Up (TuTu).

Table 33 shows the coefficients for the principal components of the selected combination of features described above. When looking at the values in Table 33, it was possible to determine that

- the first principal component (PC1) mainly contained the information of the Tip Up and the differential Tip Up (the largest coefficients in that column (0.68 and 0.64 respectively) are associated to these features),
- the second principal component, PC2 enclosed the information of the stability of Tan δ (coefficient equal to 0.99),
- the third principal component (PC3) primarily held the contribution of the Tan δ (coefficient equal to 0.91).

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Table 32: Combination of Features for PE-based Insulation Cable Systems												
Features										**Classification of Test Set**	**Cumulative Variance**	**Rank of Test Set (percentiles)**
STD	**TU**	**TD**	**TuTu**	**log(TD)**	**STD^2**	**TD^2**	**log(TD)^2**	**STD·TD**	**STD·log(TD)**			
☑	☑	☑	☑							Incorrect	-	-
☑	☑	☑	☑					☑		Incorrect	-	-
	☑		☑					☑		Incorrect	-	-
☑	☑		☑	☑						**Correct**	97.8%	[0.05, 82, 94, 98, 79, 83, 84, 94]
☑	☑		☑	☑					☑	**Correct**	88.6%	[0.05, 82, 94, 98, 78, 83, 84, 93]
	☑		☑						☑	Incorrect	-	-
	☑	☑	☑		☑					Incorrect	-	-
☑	☑		☑			☑				Incorrect	-	-
	☑		☑		☑	☑				Incorrect	-	-
	☑		☑	☑	☑					**Correct *Optimal***	97.5%	[0.05, 82, 94, 98, 79, 83, 84, 93]
☑	☑		☑				☑			Incorrect	-	-
	☑		☑		☑		☑			Incorrect	-	-

☐ Basic Tan δ features ☐ Additional Tan δ feature (this report) ☐ Experimental Tan δ features

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Table 33: Coefficients for Best Combination of Features for PE-based Insulations from *CDFI* Research

Contact NEETRAC if wishing to implement the Health Index algorithm

Feature	PC1	PC2	PC3
STD^2	0.03	**0.99**	-0.14
TU	**0.68**	-0.02	-0.12
Log(TD)	0.36	0.1	**0.91**
TuTu	**0.64**	0.09	0.37

The combination of Tan δ features detailed above have both an acceptable cumulative variance of 97.5% and principal component's coefficients that allow for each principal component to have a physical meaning (PC1 being Tip Ups, PC2 being Stability of Tan δ, and PC3 being Tan δ). It was for these reasons it was selected for the final implementation of a PCA condition assessment tool for PE-based insulation cables.

6.10.2 Principal Component Analysis for Filled Insulations

A study similar to the one presented for PE-based insulations was conducted for the case of filled-based insulation cables. Experience has shown that sometimes it is difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect /missing records, obliterated or obscured markings on the cable jacket, indistinct coloring, etc. For this reason, several types of filled insulations are included: EPR (black EPR, mineral filled EPR), Kerite, and Vulkene®.

The Tan δ features considered in this study were the same as in the previous case: Stability of Tan δ (STD), Tip Up (TU), Tan δ (TD), and Differential Tip Up (TuTu).

The values for these features correspond to Tan δ measurements for filled insulation cables contained in the most recent database. This database includes 463 samples, 273 of them having field measurements for all four features noted above. These field measurements were collected from May 2006 until June 2012 in nine utilities.

Analogous to the PE-based insulations case, several combinations of the Tan δ features defined above were tested using PCA. The objective was to find the combination that would better classify the condition of a cable as compared with the total population contained in the database.

In order to test the accuracy of the classification scheme for each combination of Tan δ features, the test set defined below was used:

- Cable with individual features at 80% level considering the full database of 463 tests: expected to classify around the 80th percentile,
- Cable with individual features at 95% level considering the full database of 463 tests: expected to classify around the 95th percentile,
- Cable with individual features at 80% level considering a subset of the database of 273

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tests: expected to classify around the 80th percentile,

- Cable with individual features at 95% level considering a subset of the database of 273 tests: expected to classify around the 95th percentile.

The values of the Tan δ features for each sample in the test set appear in Table 34.

Table 34: Tan δ features of Test Set for Filled insulation cables

Sample	STD	TU	TD	TuTu
Cable with individual features at 80%, full database – 471 data	0.35	10	35	1
Cable with individual features at 95%, full database – 471 data	1.5	180	120	100
Cable with individual features at 80%, subset of database – 273 (all features reported)	0.2	10	28	1
Cable with individual features at 95%, subset of database database – 273 (all features reported)	2.8	215	103	100

Table 35 shows the twelve combinations of Tan δ features that were evaluated. For these combinations, the PC-distance was calculated with respect to the point defined by the first quartile of the data (the definition of a new cable was not used in this case because there are several distinct types of insulation in this group).

Among those combinations, only three were able to perform an acceptable classification of the test samples in Table 34. The difference in the classification results for the three combinations was negligible: cables with individual features at 80%, for both the full database and a subset of it, classified as 82nd percentile and cables with individual features at 95% classified between the 95th and the 98th percentile (full database and subset of the database respectively).

Additional criteria were considered for choosing the final combination of features: the cumulative variance and the coefficients associated with each principal component. There were no distinctive differences between the combinations for neither of them, for the filled insulation case, was not possible to separate the interdependences of the stability of Tan δ and the Tan δ.

Since none of the combinations are shown to be better than the others, the final combination of Tan δ features was chosen to be the same as for the PE insulated cables: (i) a quadratic term for the stability of Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a logarithmic function for the Tan δ (log (TD)), and (iv) a linear term for the differential Tip Up (TuTu).

However, the analysis for the different combinations should be repeated once more data have been gathered and/or a better test set can be defined with filled insulation cables of known condition.

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Table 35: Combination of Features for Filled Insulation Cable Systems

Features										Classification of Test Set	Cumulative Variance	Rank of Test Set (percentiles)
STD	TU	TD	TuTu	log(TD)	STD^2	TD^2	$log(TD)^2$	STD·TD	STD·log(TD)			
☑	☑	☑	☑							Incorrect	-	-
☑	☑	☑	☑					☑		Incorrect	-	-
	☑		☑					☑		Incorrect	-	-
☑	☑		☑	☑						**Correct**	96.6%	[82, 95, 82, 98]
☑	☑		☑	☑					☑	**Correct**	97.15%	[82, 95, 82, 98]
	☑		☑						☑	Incorrect	-	-
	☑	☑	☑		☑					Incorrect	-	-
☑	☑		☑			☑				Incorrect	-	-
	☑		☑		☑	☑				Incorrect	-	-
	☑		☑	☑	☑					**Correct *Selected***	96.3%	[82, 95, 82, 98]
☑	☑		☑				☑			Incorrect	-	-
	☑		☑		☑		☑			Incorrect	-	-

☐ Basic Tan δ features ☐ Additional Tan δ feature ☐ Experimental Tan δ features

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6.10.3 Principal Component Analysis for Paper Insulations

A PCA study was also carried out in the case of PILC cables. This case the research was much more complex than the previously presented for PE-based insulations and filled insulations, because:

- PILC data exhibit both positive and negative Tip Ups,
- There is not a good physical understanding (in terms of origin and direction of degradation) of the physical meaning behind PILC Tan δ data,
- There has been considerable material and design evolution over the life cycle of PILC cables and,
- Most PILC cables in underground systems are 3-core cables.

No comprehensive or relevant studies have been found in literature to understand the physical phenomena involved in having a positive or negative Tip Up, or in characterizing the degradation of a cable by the change in the Tan δ value over different voltage levels. Empirical evidence seemed to indicate that having higher values of Tan δ (either positive or negative) imply a worse cable condition, but there was no indication on how to compare the assessment of a cable with a positive Tip Up versus one with a negative Tip Up of equal magnitude.

Considering this lack of information, it was decided to carry out independent PCA studies for the positive and negative Tip Ups. In addition, having 3-core cables added the differences between phases as an additional variable for cable assessment.

PCA study with basic features for PILC insulations

The basic Tan δ features considered in the study were: Stability of Tan δ (STD), Tip Up (TU), Tan δ (TD), and Differential Tip Up (TuTu). The values for these features correspond to Tan δ measurements for PILC cables contained in most recent database as of July 2012. This database includes 562 samples, 190 of them having field measurements for all four features above.

Further analysis of the available data indicated that only 16 samples out of 190 had a positive Tip Up, therefore the PCA analysis was carried out using the 174 samples with negative Tip Ups. These negative values were multiplied by a factor of -1 in the PCA, in order to preserve the criteria of larger numbers meaning worse cable condition.

Analogous to the PE-based and filled insulations cases, several combinations of the Tan δ basic features were tested using PCA. The objective was to find the combination that would better classify the condition of a cable as compared with the total population of the database.

In order to test the accuracy of the classification scheme for each combination of Tan δ features the test set defined below was used:

- New cable: expected to fall in the low percentile area (origin),
- Cable with individual features at 80% level considering the full database of 562 samples: expected to classify around the 80th percentile,

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- Cable with individual features at 95% level considering the full database of 562 samples: expected to classify around the 95th percentile,
- Cable with individual features at 80% level considering a subset of the database of 174 samples: expected to classify around the 80th percentile,
- Cable with individual features at 95% level considering a subset of the database of 174 samples: expected to classify around the 95th percentile.

The values of the Tan δ features for each sample in the test set appear in Table 36.

Table 36: Tan δ features of Test Set for PILC cables

Sample	STD	TU	TD	TuTu
New Cable	0	2	16	0
Cable with individual features at 80%, full database – 562 data	0.1	35	90	8
Cable with individual features at 95%, full database – 562 data	0.4	50	200	20
Cable with individual features at 80%, subset of database – 190 having all features	0.2	28	94	8
Cable with individual features at 95%, subset of database database – 190 having all features	0.3	40	152	20

Table 37 shows the twelve combinations of Tan δ features that were evaluated. All combinations classified the test set similarly, with three of them performing slightly better. A common problem for the classification was to have the percentiles too polarized at the upper end:

- Cables with individual features at 80%, both full database and subset, classified below the 80th percentile,
- Cables with individual features at 95%, both full database and subset, classified well above 95th percentile.

The first part, misclassification at 80th percentile, implies the application of a non-conservative criterion to the single "Health Index" defined by the PC-distance, i.e. a cable with all individual features at 80 % of their corresponding values will classify as a healthy cable. On the other hand, having an extreme classification at the 95th percentile region implies that the granularity for degraded cables is nonexistent; therefore, there is no possibility of prioritizing cables classified in the "Action Required" category.

Among the combinations, three provided an acceptable classification of the test set in Table 36. The misclassification error for these three combinations was small: cables with individual features at 80%, for both the full database and a subset of it, classified as 78-80th percentile and cables with individual features at 95% classified between the 95th and the 100th percentile (subset of the database and full database respectively). In these cases, the misclassification can be explained by the relatively small size of the PILC database (174 samples as compared to 273 of filled insulation and 2008 of PE-based insulation).

By looking at the results in Table 37, the combination of (i) a quadratic term for the stability of

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Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a quadratic term for the logarithm of Tan δ ($log(TD)^2$), and (iv) a linear term for the differential Tip Up (TuTu), seemed to have a better classification performance. However, the analysis for the different combinations should be repeated when more data have been gathered on PILC cables.

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Table 37: Combination of Features for PILC cables												
Features										Classification of Test Set	Cumulative Variance	Rank of Test Set (percentiles)
STD	TU	TD	TuTu	log(TD)	STD^2	TD^2	$log(TD)^2$	STD·TD	STD·log(TD)			
☑	☑	☑	☑							Polarized	-	-
☑	☑	☑	☑					☑		Polarized	-	-
	☑		☑					☑		Polarized	-	-
☑	☑		☑	☑						Polarized	-	-
☑	☑		☑	☑					☑	Polarized	-	-
	☑		☑						☑	Polarized	-	-
	☑	☑	☑		☑					**Correct**	94.5%	[3, 78, 100, 77, 96]
☑	☑		☑			☑				Polarized	-	-
	☑		☑		☑	☑				**Correct**	94.1%	[1, 78, 100, 77, 95]
	☑		☑	☑	☑					Polarized	-	-
☑	☑		☑				☑			Polarized	-	-
	☑		☑		☑		☑			**Correct *Selected***	94.1%	[2, 80, 100, 78, 96]

☐ Basic Tan δ features ☐ Additional Tan δ feature ☐ Experimental Tan δ features

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PCA Study with Additional Features for PILC Insulations

The analysis in the previous section included the same features as in the case of the PE-based insulation and Filled insulation cables. Three additional PCA studies were carried out to enhance the previous analysis so the additional complexities of PILC cables could be taken into account. The topics explored were:

- Use of the differences between the Tan δ (TD) values of the three phases as condition assessment features,
- Use of the geographical location of the cable as a condition assessment feature – this is believed to be a practical alias for the age/design information of the cable system,
- Use of both, differences in phases and location as condition assessment features.

To be able to have a larger dataset, the set of the basic features was reduced to only three features: Stability of Tan δ (STD), Tip Up (TU), and Tan δ (TD). In this way, it was possible to identify 55 samples having information on all three basic features plus location.

In order to represent the information provided by the differences between the 3 phases of a cable, a single feature was selected to be added to the existing basic features: the variable "Range", which is defined as the difference between the maximum and the minimum Tan δ value among the three phases in a cable:

$$Range = Max_{a,b,c}\ (Tan\ \delta@1U_0) - Min_{a,b,c}\ (Tan\ \delta@1U_0)$$

Example: if Tan $\delta_{phase\ a}$ = 3, Tan $\delta_{phase\ b}$ = 2, and Tan $\delta_{phase\ c}$ = 10, then the Range = 10-2 = 8

The calculations of the Ranges between the three phases of all cables samples provided the results in Table 38.

Table 38: Statistical Values for Differences Between PILC

Minimum Range among 55 samples	0.4
Maximum Range among 55 samples	50.3
Average Range among 55 samples	8.4
Standard Deviation of Range among 55 samples	9.2

In addition to the values presented in Table 38, it was possible to define the following rules based on the empirical distribution presented in Figure 47:

- "Further Study Advised" for Range feature: all Range values above 10 (80th percentile),
- "Action Required" for Range feature: all Range values above 20 (95th percentile).

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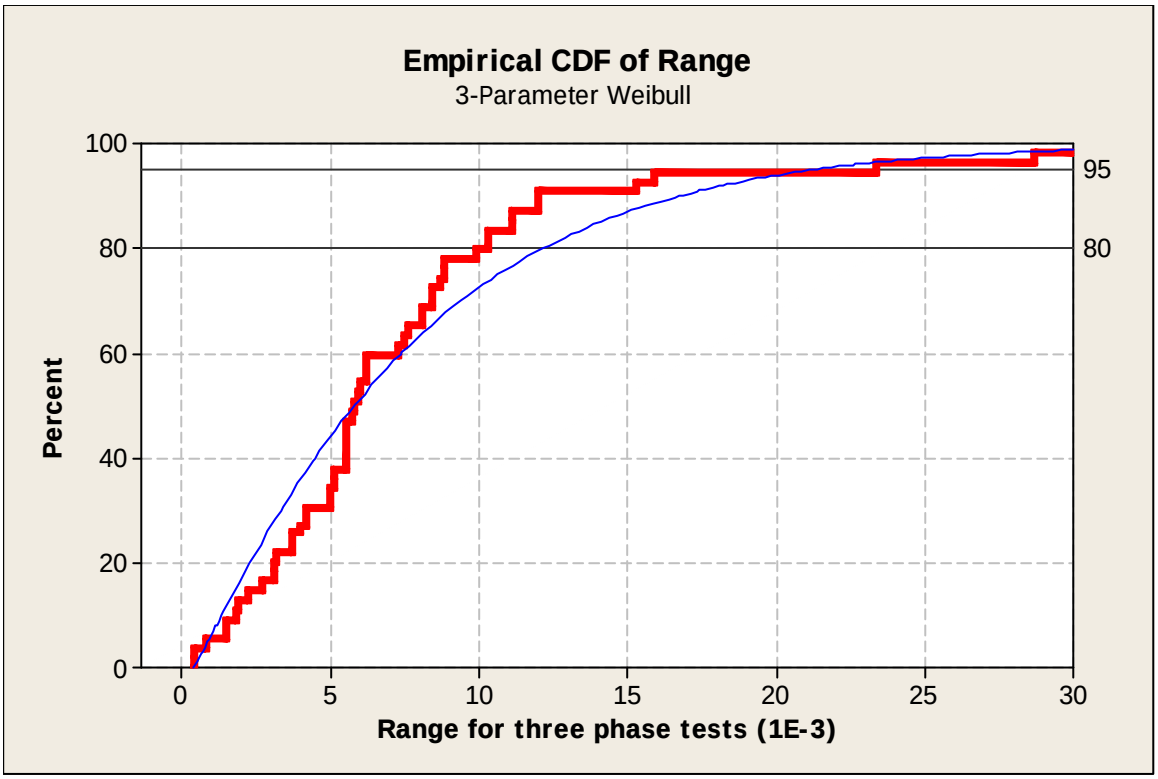

Figure 47: Empirical CDF of Differences in Tan δ for 3 Core Cables (PILC Insulations)

In the case of the location, by analyzing the data in the database, it was possible to determine three distinct geographical areas, and the average of Stability of Tan δ (STD) and Tan δ (TD), was computed for each one (Table 39). The average of Tan δ was chosen to be used as the location mark.

Table 39: Average Values for Tan δ (TD) and Tan δ Stability (STD)

Area	Average TD [1E-3]	Average STD [1E-3]
Location 1	159.1	0.8
Location 2	64.7	0.1
Location 3	83.2	0.3

Study 1: Research Using Basic Tan δ features and Range feature

The PCA results for the first study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD), and Range. The idea was to test how the classification of a given cable changed as a result of having larger differences with respect to the other two phases of the same cable. The test set used in this study appears in Table 40.

Table 40 shows that five cable conditions were tested and then re-tested with a different value for the Range feature: the values for the Range features were selected to represent a sample below the 80th percentile (Range = 5), between the 80th and the 95th percentile (Range = 15), and above the

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95th percentile (Range = 35).

Table 40: Tan δ and Range Features of PILC Test Set				
Sample	**STD**	**TU**	**TD**	**Range**
New Cable	0	2	16	[5,15,35]
Cable with individual features at 80%, full database	0.1	35	90	[5,15,35]
Cable with individual features at 95%, full database	0.4	50	200	[5,15,35]
Cable with individual features at 80%, subset of database	0.2	28	94	[5,15,35]
Cable with individual features at 95%, subset of database	0.3	40	152	[5,15,35]

Table 41 shows the obtained results.

Table 41: PCA Research Results for Study with Basic Tan δ and Range Features			
Sample	**No Action Required** **Range = 5**	**Further Study (80th percentile)** **Range = 15**	**Action Required (95th percentile)** **Range = 35**
New Cable	**4**	23	87 Concerning too high
Cable with individual features at 80%, full database	73 Improve with TuTu	**82**	94
Cable with individual features at 95%, full database	96	97	**99**
Cable with individual features at 80%, subset of database	76 Improve with TuTu	**84**	95
Cable with individual features at 95%, subset of database	91	93	**98**

Results shown in Table 41 indicate that for each of the five samples, the condition of the given cable progressively deteriorates, as the difference between phases is greater. As an illustration, consider a cable with individual features at 95% of the full database, progressively classified as the 96th, 97th, and 99th percentiles. However, this effect is overdone when the sample is a new cable (percentile changes from the 4th to the 87th percentile).

This indicates that the Range feature has promise for classification use, yet a better understanding of the effect of the differences between phases has to be acquired before it is acceptable as an assessment feature (i.e. it is necessary to determine whether a new cable having a large difference with respect to the other phases is really subjected to a higher probability of failure).

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Study 2: Basic Tan δ Features and Location feature

The PCA research results for the second study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD)), and Location (via a Location alias). The purpose of the test was to determine whether the association of a given sample with a geographical cluster could improve the classification. The following test set was used:

Table 42: Tan δ and Location Features of Test Set for PILC cables

Sample	STD	TU	TD	Location Alias
New Cable	0	2	16	65
Cable with individual features at 80%, full database	0.1	35	90	85
Cable with individual features at 95%, full database	0.4	50	200	160
Cable with individual features at 80%, subset of database	0.2	28	94	85
Cable with individual features at 95%, subset of database	0.3	40	152	160

The cable samples in Table 42 were tested with and without the location feature. Table 43 shows the obtained results.

Table 43: PCA Results of Study with Basic Tan δ and Location Features

Sample	Without Location Alias	With Location Alias
New Cable	39	21
Cable with individual features at 80%, full database	78	67
Cable with individual features at 95%, full database	100	100
Cable with individual features at 80%, subset of database	84	79
Cable with individual features at 95%, subset of database	95	98

The comparison of the research results in Table 43 indicated that the use of the Location alias feature did not improve the classification of the test samples.

Study 3: Basic Tan δ features, Location and Range features

The PCA results for the last study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD)), Location, and Range. The following test set was used:

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Table 44: Tan δ features, Location and Range Features of Test Set for PILC cables					
Sample	**STD**	**TU**	**TD**	**Loc. Alias**	**Range**
New Cable	0	2	16	65	[5,15,35]
Cable with individual features at 80%, full database	0.1	35	90	85	[5,15,35]
Cable with individual features at 95%, full database	0.4	50	200	160	[5,15,35]
Cable with individual features at 80%, subset of database	0.2	28	94	85	[5,15,35]
Cable with individual features at 95%, subset of database	0.3	40	152	160	[5,15,35]

Table 45 shows the obtained results.

Table 45: PCA Study Results for Basic Tan δ, Location, and Range Features			
Sample	**No Action Required** **Range = 5**	**Further Study** **(80th percentile)** **Range = 15**	**Action Required** **(95th percentile)** **Range = 35**
New Cable	**21**	30	82
Cable with individual features at 80%, full database	59	**72**	91
Cable with individual features at 95%, full database	96	97	**100**
Cable with individual features at 80%, subset of database	61	**79**	94
Cable with individual features at 95%, subset of database	93	94	**98**

The comparison of the results in Table 41, Table 43, and Table 45 indicate that the combined use of the Location and Range features improve the classification of the test samples as compared with the case of only using the Location feature; however, this improvement is insufficient to surpass the results obtained by using only the Range feature.

In summary, for the additional features explored in this section, the most promising is the Range feature which takes into account the differences between the 3 phases of a 3-core cable. The use of this feature requires further investigation once more data can be compiled. Possible choices for including this variable as an assessment feature include: (i) replicate the analysis presented above, (ii) expand the PCA analysis to consider all three phases at the same time (10 dimension PCA), or (iii) utilize the Range feature as a separate condition assessment tool.

CHAPTER 7

Medium Voltage Cable System Partial Discharge

Joshua Perkel & Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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7.0 MEDIUM VOLTAGE CABLE SYSTEM PARTIAL DISCHARGE

A large amount of research published over the past 10 to 20 years investigates the phenomenon of partial discharges (PD) in cable systems. Much of this work is meaningful in that it shows how partial discharge testing can be applied to discover and sometimes locate certain types of defects within these systems. Interestingly, the study of partial discharge in cables is largely empirical due to the complexity of the phenomenon [1-25]. In *CDFI Phase II*, NEETRAC explored the complex issues associated with making partial discharge measurements on cable systems and provides a review of what NEETRAC was able to learn about the advantages and disadvantages of this diagnostic technology.

PD measurements are quite different from tan δ (dielectric loss) measurements. Tan δ measurements provide straightforward values that can be readily repeated and analyzed and the measurement method or operator typically does not come into play. On the other hand, the output from a PD measurement is very much a function of the technique/approach used to make the measurement. The output must be highly synthesized and the results provided, particularly for field tests, which are highly customized. This chapter provides a broad overview of the issues associated with making PD measurements on MV cable systems with a primary focus on field measurements though the topic must also be discussed in context with laboratory measurements.

7.1 Test Scope

Partial Discharge diagnostic technologies detect localized "void-type" defects in cables and/or accessories. Voids in this context can be,

- Quasi-spherical (most often due to manufacturing process problems);
- Dendritic (often due to aging processes that lead to the development of electrical trees resulting from enhanced voltage stresses);
- Interfacial (due to the delamination of components, or a loose fit between the cable and an accessory);
- Irregular (mechanical damage either before or after installation).

It should be noted that cable systems with metallic shields that become ungrounded due to mechanical damage, corrosion or improper ground connections can also experience electrical discharges that may be detected using partial discharge diagnostics, though this is not the primary purpose for deploying this diagnostic technique.

Partial Discharge can occur in all cable system types, although the usefulness of PD diagnostics may be limited when performed on discharge resistant cables (as defined in ICEA S-94-649 and S-97-682) or on fluid impregnated paper insulated cables (PILC or MIND). These cables, which have some resistance to electrical discharges, can experience partial discharges even at operating voltage. However, this is typically not considered a problem because of their discharge resistant characteristics. Mixed (hybrid) cable systems containing both discharge-free and discharge-resistant cable designs can be especially challenging to test using partial discharge diagnostics.

All discharge-free cable and many pre-molded cable accessories are PD tested at the factory prior to shipping. As such, they should be PD free as defined in the appropriate IEC, ICEA, and IEEE standards when received by the customer. Any PD detected in service is likely due to problems caused by installation (new) or defects that develop over time (aged). However, it is important to be aware that there are no industry recognized testing procedures or discharge limits for PD tests conducted on complete cable systems installed in the field.

Consequently, although appealing, there are some limitations to PD testing in the field. They are as follows:

- Factory and field test procedures are very different.
- In factory tests, components are tested separately (cable, terminations, and joints), while field tests *de facto* involve the complete cable system.
- Different field test environments impose a number of complications such as significant background electrical noise or very long lengths that must be addressed to yield acceptable results.
- Interaction among and impact on PD signals by different cable system components are not completely understood.
- Different PD measurement technologies/approaches generally cannot be correlated.
- PD is often intermittent. It may be present one day and absent the next.

While there are significant complications, PD testing can be useful, but the results are very often not definitive.

7.2 How it Works

During the application of a high voltage on a cable system, sensors pick up electrical discharges that may be from the cable system or external to the system. If conditions are right at a void location, a partial discharge (i.e. a discharge across the void) occurs. The PD measurement equipment detects transient millivolt or microampere level signals generated at the discharge site that travel through the cable to the detection equipment. The exact shape and bandwidth of these pulses depends on the discharge source, frequency response of the cable system, and frequency response of the measurement equipment and the distance between the PD source and the signal detector. Each of these factors alters the shape of the original PD pulse. The PD pulses themselves must then be separated from ambient noise signals. Available PD instruments are classified by bandwidth as they can have bandwidths of hundreds of kilohertz (narrow band and wide band according to IEC 60270 – 2000) to up to 100 MHz (ultra-wide bandwidth (UWB)).

Figure 1 shows the commonly used equivalent circuit to describe PD measurements. The capacitances (C) are identified by the subscripts *a*, *b,* and *c*. C_a represents the capacitance of an element of power cable that does not contain a defect. C_b and C_c represent an element of cable that contains a void defect, where C_c is the capacitance of the void and C_b represents the remnant cable element capacitance. S_g is the spark gap that represents the discharging defect/void.

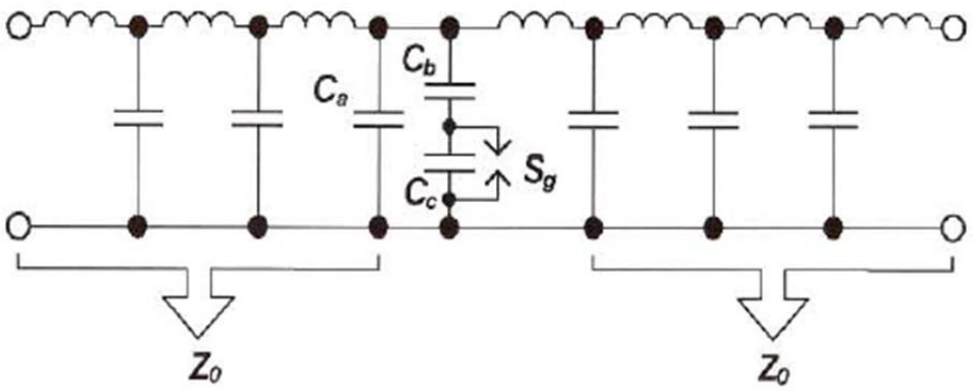

Figure 1: Equivalent Circuit for Power Cable PD [16]

As shown in Figure 1 the capacitances C_b and C_c, and thus the charge generated in the measurement circuit, will depend upon the radial position of the void within the cable. This is because the capacitances depend upon the relative amount of insulation on either side of the defect.

Although outside the scope of this project, a brief discussion on the physics of discharges in voids is included to help users better understand the complexity of this test. PD is a Townsend discharge in a small cavity (a gas ionization process where, initially, a small number of free electrons, accelerated by a sufficiently strong electric field, results in electrical conduction through a gas by avalanche multiplication). The stress at which the discharge initiates (V_{PD}) is described by Paschen's Law, where the critical parameter is the product of the void size [diameter d] and the internal pressure [p]; β and χ are constants related to the gas within the void.

$$V_{PD} = \frac{\beta \cdot p \cdot d}{\chi + \ln(p \cdot d)} \qquad \textbf{Equation 1}$$

The Paschen Equation identifies a number of fundamental issues that the cable system engineer using PD testing must understand, including:

- Discharges only occur in gaps – PD testing can only find voids, not contaminants unless they subsequently debond from the insulation, thus leaving a void.
- Voids need to satisfy three further conditions to discharge:
  - They must not be completely filled with a liquid;
  - If they are gas filled, then the gas must be at a low enough pressure for the discharge initiation stress to be at or below the test stress (See Figure 2);
  - They must be large enough; small voids require higher initiation stresses (Figure 2).

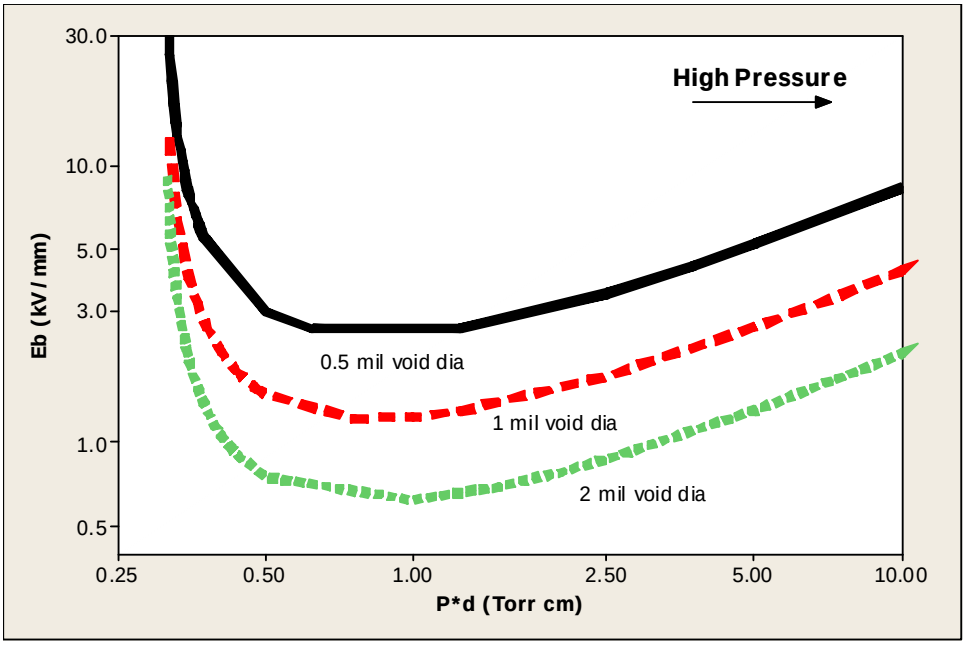

Figure 2: Theoretical Paschen Curves for Air-Filled Voids (Selected Void Sizes)

When measuring PD, three prerequisites must be satisfied during the measurement period:

- The voids must be in a state that allows them to discharge.
- The voltage must be high enough to initiate the discharge (inception voltage).
- The PD signal must reach the detector in a suitably unattenuated, undispersed state to be recognizable as PD signals with respect to the background noise.

Addressing the first point, PD is a stochastic (probabilistic) process. It may or may not be present at a void depending on all the parameters and conditions described above. Thus if no PD is detected, it can mean either that no voids are present or that a void is present but that that conditions are not right for it to discharge. This is significant for short measurement times and the risk of "false negative" results should be recognized.

A number of technical articles have described instances where PD pulses (at most a few nanoseconds wide) spread and reduce in magnitude as they propagate away from the PD source as a result of high frequency attenuation in the cable due to dispersion (frequency-dependence of the propagation velocity) [16]. The loss of high frequency energy from the PD pulse reduces its magnitude and distorts its shape. This can make it difficult to acquire the PD pulses and accurately identify the source and type of the PD.

7.3 How it is applied

PD testing can be performed online and offline [11]. Online techniques typically employ high frequency current transformers (CTs) or capacitively coupled voltage sensors to detect transient signals from discharges.

Offline voltage sources can be,

- 30 – 300 Hz AC: Equipment typically consists of an excitation transformer connected in series or parallel with a variable inductance reactor. The equipment is heavy and requires a truck or van.
- 0.01 – 1 Hz (nominal) AC offline Very Low Frequency (VLF): Equipment is relatively light and portable but may act as an additional source of noise. Both sinusoidal and cosine-rectangular waveforms can be used.
- Damped AC (DAC): Equipment is relatively light and portable. The applied voltage is a highly damped sine wave with a frequency range of 30-500 Hz, though frequency varies with cable length and can, in some cases, be tuned with an external element (capacitor).

Field PD results may be reported in terms of,

- Customized indicators (mV or mV·s);
- Scaled charge magnitude (pC) at a given test voltage level;
- Extinction voltage (voltage at which the discharge extinguishes as the voltage is lowered);
- Inception voltage (voltage magnitude at which discharge initiates as the voltage is increased);
- Number of pulses per unit time;
- Frequency content of the PD pulses;
- Phase relationship of the PD pulses to the applied voltage (Phase-Resolved PD Pattern);
- Estimated PD source location(s).

PD measurements are influenced by the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type of insulation material (EPR, XLPE, PILC, etc.), ambient electrical noise, and many other factors discussed earlier. Therefore, accurate interpretation of the PD data requires sound knowledge of temporal (time dependency) PD behavior. Although simplistic PD measurements (discharge magnitude in pC and PD inception voltage) are commonly employed in diagnostic assessments, the true impact of partial discharge on cable system performance is difficult to predict. This happens because different PD techniques/approaches yield different PD measurements, though some PD diagnostic providers claim to have developed proprietary means for interpreting PD measurements to predict cable system performance. Studies performed in the *CDFI* show that a low PD inception voltage or a high picocoulomb value does not necessarily indicate that a cable system will soon fail.

As discussed in the *CDFI* Perspective, the connection between a measured discharge and its impact on the cable system requires many laboratory and field tests to create a database of PD characteristics that indicate “bad” PD and “tolerable” PD. This form of PD testing could enable utility engineers to create their own criteria for evaluating the condition of a cable system. To date, the *CDFI* has not been able to gather a database large enough to establish a correlation between a given PD measurement and cable system performance. However, analyses on a number of PD field test results containing PD based recommendations (*Act* or *Not Act*) are used to establish preliminary accuracy assessments for online and offline PD diagnostic techniques.

The stochastic nature of PD measurements can create considerable variability in the measurements over time and between identical cable systems operating under similar conditions. The best way to overcome this issue is by performing periodic PD tests as part of a power cable testing and replacement program. If data from such tests are analyzed carefully, periodic PD measurements could potentially be correlated, over time, with cable system performance.

Most offline techniques apply a voltage of 1.5 to 2.5 U_0, where U_0 is the operating phase-to-ground RMS voltage of the circuit. The application of high voltages for a long period (cycles or time) may cause some level of further degradation of an aged cable system. This can potentially occur when performing any diagnostic test requiring the application of voltage above the operating voltage. See a more detailed discussion in Chapter 2. The precise degree of degradation will depend on the voltage level, frequency, and time of application. Thus, when undertaking elevated voltage PD measurements (or any other elevated voltage test), a utility should consider that a failure might occur and resources may be needed to make repairs. The section on expected outcomes in the *CDFI* Perspective provides insight on the likelihood of failure on test.

The advantages and disadvantages of different approaches to PD testing appear in Table 1 and Table 2 as a function of voltage source used to perform the test. Table 3 shows the overall advantages, disadvantages, and open issues for PD testing.

Table 1: Advantages and Disadvantages of Online PD Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
60 Hz AC Voltage Supplied by Utility System (De-energizing not needed)	• No non-system energization equipment is required. • Testing waveshape and frequency is the same as the service voltage. • The cable circuit is not de-energized as part of the test. • It is relatively easy to monitor over an extended period (10 to 60 minutes or longer) so that PD sites are more likely to discharge and be detectable. • Test is performed while the cable system is at normal operating temperature.	• Cannot detect PD that would occur at voltages above normal operating voltage. • Sensitivity assessment typically not possible. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Detailed assessments are not available for several days to weeks. • Sensors generally must be applied at every cable accessory (either sequentially or simultaneously) and at each end of the tested cable system. • In most approaches, PD sites in cable are not specifically located. They are only identified as occurring between two sensors or at a sensor on an accessory. However, changes in frequency spectra can be used to infer proximity to sensors. • In some approaches, results are reported as levels - the specific meaning of each level is difficult to interpret. • Cannot be combined with other diagnostic tests.

Table 2: Advantages and Disadvantages of Offline PD Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
30 – 300 Hz AC Power Frequency	• Testing waveshape and frequency are close to the operating and factory test voltages. • Sensitivity assessment can establish the lowest detectable PD level. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured.	• Equipment is large, heavy, and expensive. • Application of elevated voltage (> U_0) may cause further degradation. • Short (less than a minute) data acquisition time may not capture some PD. • Results are reported in diagnostic levels, charge, and voltages which specific meaning may be difficult to interpret.
0.01 – 1 Hz AC Very Low Frequency (VLF) Sinusoidal & Cosine-Rectangular Voltage	• Equipment is small and easy to handle. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured.	• Application of elevated voltage (> U_0) may cause further degradation. • Short data acquisition time (few cycles) may not allow PD to occur. • Does not replicate operating voltage waveshape or frequency. • PD behavior is not well understood at these frequencies. • Difficulty syncing with voltage waveform when phase-resolved data is needed. • Special filtering and/or gating needed for VLF generators
Damped AC (DAC) (30 Hz to 500 Hz)	• Can measure PD inception and extinction voltages (PDEV) in same shot. • Voltage source and PD acquisition are integrated in a single unit. • Straightforward to use.	• Only the first voltage cycle is controlled. • Does not replicate operating voltage waveshape or frequency. • Comparisons between circuits are difficult because the applied voltage frequency and decay rate vary as a function of the circuit impedance characteristics. • PD behavior is not well understood when using decaying voltage waveform. • Difficult to define consistent PD test process. • Few cycles during which to detect PD.

Table 3: Overall Advantages and Disadvantages of PD Measurement Techniques	
Advantages	• Identifies single or multiple localized void-type defects. • Applicable for all cable types. • If PD test interpretation indicates that cable circuit is PD-free then there is a high probability that the circuit will not fail within the next several years. • Offline techniques allow for the detection of PD at voltages above U_0. • Can detect electrical trees, interface tracking, voids. • Basic results available at end of test. • Test can be stopped if "unacceptable PD" is observed.
Open Issues	• It is unknown whether cycles or time at elevated voltage is the critical parameter in determining the risk of damage to the cable system. • PD results on cable systems are not directly comparable to the factory test results on individual components. • Different providers perform PD measurements using different measurement methods, sensors, measurement frequencies, bandwidth, metrics, and sensitivity assessment. Results from different PD providers/equipment are difficult/impossible to compare with each other. • Interpretation of PD signals is very challenging (i.e. the test results can be provided as "Good/Bad", "Acceptable/Unacceptable", "Pass/Not Pass", "Defer/Repair/Replace", "1/2/3/4/5", etc.). • Locating and characterizing PD sources can be difficult because of noise, attenuation, dispersion, cable accessories, and cable system complexity. • Not clear which PD features provide information on the severity (i.e. whether or not the defect will lead to failure). • Results for hybrid circuits are difficult to interpret. • Neutral corrosion (wire or tape) can lead to false negatives (i.e. absence of PD). • Voltage exposure (impact of voltage and time on cable system) caused by elevated 60 Hz AC, DAC, and VLF has not been established.
Disadvantages	• Cannot detect all possible cable system defects – only those that discharge and are detected by the measurement equipment. • Does not directly detect water trees. • Does not assess global degradation (high density of defects such as water trees or contaminants distributed over a significant portion of the system length). • No uniform Pass / Not Pass criteria established for field testing. • Only a small percentage of PD sites detected actually fail in service.

7.3.1 Partial Discharge Sensors

Two groups of sensors are used for PD measurements, they are as follows:

- **Sensors for PD detection:** transducer that responds to an input PD quantity by generating a functionally related output usually in the form of a mechanical or electrical signal.

- **Sensors for PD synchronization:** transducer that detects the energizing high voltage and provides a low voltage electrical signal to synchronize the incoming PD signals with the ac waveform.

Partial discharge measurements are most commonly performed using both sensor types.

A variety of PD detection sensors are available:

- **Capacitive:** The PD signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well. Because it connects with the high voltage terminal, the sensor must be able to withstand test voltages.
- **Inductive:** The PD signal is detected through the induction principle most commonly in the form of a high frequency current transformer (HFCT). This type of sensor can also be used for online and offline application. In addition, as no connection is required with the high voltage terminal, the use of inductive sensors is practical and easier to deploy than high voltage capacitive sensors.
- **Piezoelectric:** Partial discharges generate micro mechanical surges that then propagate through the cable system and may be detectable. In this case, the sensor is deformed by the wave and the deformation generates an electrical signal.
- **Acoustic:** Similar to the piezoelectric sensor, the acoustic sensor detects the sonic wave that propagates through the surrounding air/soil and converts this to an electrical signal.

Although all four types of PD sensors are applicable, the more commonly used are capacitive and inductive sensors. The reasoning behind this is that detection via electrical measurement (either voltage or current) is the most direct means of quantifying PD. Consequently, electrical measurement is also the only means of providing some estimation of the PD magnitude. The piezoelectric and acoustic sensors can only provide an indication that PD is present and, generally, the sensor must be located near the discharge site to be effective. This in itself causes accessibility issues and limits applicability to terminations, riser cable sections, and accessories in vaults/manholes. On the other hand, piezoelectric and acoustic sensors may also be combined with capacitive and inductive sensors to improve PD source location.

Table 4 provides pictures of all the different types of sensors for PD detection (typical images sourced from the Internet).

Table 4: Different Types of Sensors for PD Detection	
Type	**Illustrative Image**
Capacitive – Capacitive Coupler PD and Synch signals	
Capacitive – Direct Coupler PD signal	
Inductive – High Frequency Current Transformer (HFCT) PD signal	
Piezoelectric	
Acoustic	

Two voltage synchronization sensor types are available:

- **Capacitive:** The synchronization signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both PD detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well. Because it connects with the high voltage terminal, the sensor must be able to withstand test voltages.
- **Inductive:** The PD synchronization signal is obtained by the sensor through the induction principle. The most common inductive device is the Rogowski coil. The Rogowski coil

detects the current flowing in the cable system and generates a corresponding voltage signal. It is necessary, therefore, to adjust the signal phase from the Rogowski coil to account for the phase difference between the current and energizing voltage to provide the correct voltage reference. This type of sensor can be used for online and offline applications.

Table 5 shows examples of all the different types of sensors for PD synchronization (typical images sourced from the Internet).

Table 5: Different Types of PD Sensors for Synchronization

Type	Example
Capacitive – Capacitive Coupler PD and Synch signals	
Inductive – Rogowski Coil Synch signal	

Voltage synchronization can also be accomplished using an external signal if available. For example, the energizing voltage source may include a low voltage output that could be used as a synchronization signal. In the case of online measurements, some PD instruments can use an internal synchronization signal generated from its ac source. However, care must be taken when using this approach because the phase difference between the external synchronization signal and the PD test voltage must be properly determined to accomplish meaningful PD measurements.

7.3.2 Partial Discharge Source Location

Before conducting PD measurements in the field, the location of the cable system splices should be determined so that PD signals originating from accessories can be distinguished from those coming from the cable. The splice locations can be determined by the principle of Time-Domain Reflectometry (TDR) presented in Chapter 2.

In most cases, the TDR is performed off-line for terminal and distributed measurements; however, for online PD measurements, the same TDR technique may be employed with the exception that the TDR pulse is injected into the energized cable system using a high frequency current transformer (HFCT).

Upon identifying the splice locations, the PD source location can be performed. There are two approaches used:

- location using PD data in the time-domain;
- location using PD data in the frequency-domain.

In both approaches, PD instrument bandwidth on the order of several megahertz is necessary to provide a reasonably precise location along the conductor length.

The following sections elaborate on each of the PD source location approaches.

7.3.2.1 Source Location in Time-Domain

This approach utilizes the same principle as TDR and appears in Figure 3.

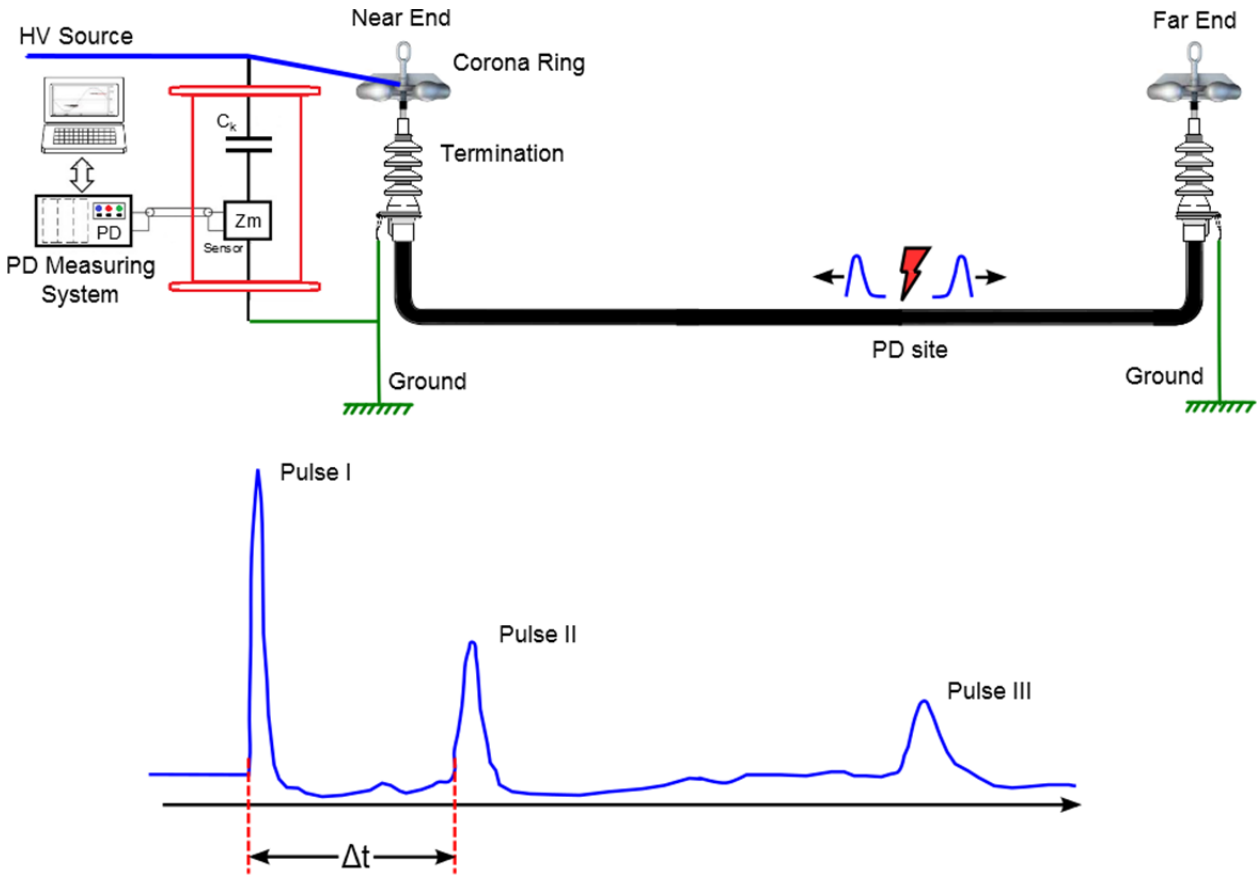

Figure 3: Illustration of PD Location in Time Domain

As shown in Figure 3, the energizing voltage and the PD detection equipment are located at the near end of the cable system. A discharge event occurring at a source located somewhere within the cable system generates a pulse that then splits into two pulses that travel in opposite directions along the circuit. The PD pulse travelling directly to the near end is acquired first as Pulse I. As time passes, the pulse travelling towards the far end is completely reflected at the far end back to the near end where it is acquired as Pulse II. Pulse II is more attenuated and dispersed than Pulse I because of its longer path through the cable system. Using the difference between the arrival times of Pulse I and Pulse II (Δt), the total length of the circuit and the speed of propagation, the location of the PD source along the conductor length can be estimated.

Additional reflections may be recorded. Pulse III in Figure 3 represents the round trip (near-far-near ends) Pulse I takes through the cable system after reflecting off the near end.

This method is applicable in cases where multiple synchronized sensors are deployed along the circuit. In this scenario, the PD source location is determined by analyzing the arrival times of the pulses at each sensor. This is particularly useful on branched and extremely long cable systems and it assumes accessibility to the locations of interest where the PD sensors (usually HFCTs) are to be deployed.

7.3.2.2 Source Location in Frequency-Domain

PD source location using frequency domain data can be performed for both offline and online approaches. This method uses the calculated frequency components of the PD pulse and that the energy signature of a PD pulse as a function of its frequency components is highly correlated to the distance from the PD source. The calculated energy is higher at sensor locations near the PD site. By examining the energy signatures measured at each sensor location, an approximate PD source location can be determined.

Two factors can influence the accuracy of this technique:

- Distance between two consecutive sensors – shorter distance between sensors improves accuracy because changes in PD pulse energy versus distance can be better estimated.
- PD sensor frequency range – greater bandwidths result in improved accuracies because a wider frequency range is used to estimate the energy and thus its changes with distance can be better observed.

A less commonly used method of location than the time-domain approach, frequency-domain source location has not been verified within *CDFI*.

7.3.3 Laboratory and Field Testing

Partial discharge tests are generally classified into two categories: laboratory and field tests. Each category has different objectives and issues. The categories are determined by the location at which

tests are performed. Each of the categories covers different test types. The relationship between test types and the test categories appears in Table 6.

Table 6: Relationship between Test Types and Test Categories for PD Measurements		
	Laboratory	**Field (On site)**
Test Type	• Routine • Qualification • Sample	• Commissioning • Maintenance

To better explain Table 6, each test type is detailed below.

- In the laboratory category:
    - **Laboratory Testing:** Tests conducted on new or aged accessories and cable together as a cable system to study the interactions between them from a research perspective. The research is commonly focused on investigating design issues and/or estimation of the aging and degradation mechanisms that a cable system as a whole experiences during its service life.
    - **Factory Testing:** Tests carried out on new accessories (typically premolded types) or cable to verify that they comply with industry standards. Tests are performed routinely as part of the production line.
    - **Qualification Testing:** Industry standard tests completed to ensure the effectiveness of the manufacturing processes, equipment, and procedures used to produce cable system components for field use.

- In the field (on site) category:
    - **Commissioning:** Tests deployed to check the integrity of the individual components (cable and accessories), their interfaces, and the cable system as a whole including damage that may have occurred during installation and/or workmanship issues.
    - **Maintenance:** Tests intended to detect deterioration and to verify the serviceability of cable systems in service for some time.

The deployment conditions for laboratory and field PD test categories are different; the goal of each test type differs from one another and more importantly, the factors that influence PD measurements for each of them vary significantly. Utility engineers should have a basic understanding of each PD test type. Therefore, Table 7 provides a comparison of the important factors associated with laboratory and field PD tests.

Table 7: Overall Comparison of Laboratory and Field PD Tests
Laboratory Tests
• Cable and/or accessories tested together as a short cable system. • Focused on investigating design issues and aging and degradation mechanisms. • Focused on new systems. • Performed under controlled conditions of noise, grounding, temperature, accessibility, etc. • Short systems allow for lumped equivalent circuit modeling. • Conventional (as defined within IEC 60270) and non-conventional (ultra-wide bandwidth) measurements can be deployed. • Does not replicate operating environment. • Presence of PD on new systems above an accepted threshold can indicate problems with the cable, accessories, or interface between the two.
Factory Tests
• Only for new cables and accessories. Each is tested separately. • Focused on identifying cable system components that comply with industry standards for maximum discharge magnitude. • Performed under controlled conditions of noise, grounding, temperature, accessibility, etc. • Long cable runs are modeled by a lumped equivalent circuit. • Only conventional measurements are deployed. • Performed routinely as part of the production line. • Does not replicate operating environment. • PD magnitudes that exceed requirements cause components to be examined more thoroughly.
Commissioning Tests
• Complete cable system that is tested prior to beginning its service life. • Focused on PD detection and PD source location. • Electrical noise, grounding, temperature, accessibility are not readily controllable. • Long systems require distributed impedance circuit modeling. • Attenuation, dispersion and reflections cause PD signal degradation that affects the measurements. • Conventional and Non-conventional measurements can be deployed. • Presence of PD could indicate design, after-laying, and/or workmanship issues. • Rarely deployed at MV except for some utility specific conditions. • Generally performed at test voltages above normal operating voltage.
Maintenance Tests
• Complete cable system that is tested at some point during its service life. • Focused on detecting and localizing PD sources with some assessment of severity. • Done under uncontrolled test conditions of noise, grounding, temperature, accessibility, etc. • Long systems require distributed impedance equivalent circuit modeling. • Attenuation, dispersion and reflections cause signal degradation affecting measurements. • Conventional and Non-conventional measurements can be deployed. • Presence of PD could indicate design, degradation, or installation issues.

As factory and laboratory testing are familiar to many engineers involved in cable system diagnosis the tendency has been to try and transfer criteria for factory and laboratory tests to field testing. However, these criteria cannot be directly applied to field tests as the underlying assumptions used in factory and laboratory tests are no longer valid due to the large differences in the lengths involved - see section 7.6.2 for a detailed discussion of the issues associated with length and measurement bandwidth.

7.4 Success Criteria

As mentioned above, PD results may be reported in a number of ways. However, many providers of PD testing services prefer not to supply detailed PD data. They suggest that interpretation of the test results requires analysis of charges, voltages, pulse shapes, pulse frequencies, etc. that is best undertaken by the provider. Instead, they process the data to classify the tested cable circuit. In principle, there are two main classes: Pass – no action required and Not Pass – some type of action required. The Not Pass class is often subdivided into finer classes such as "Monitor" or "Repair When Convenient". Providing the results in the form of classes or rankings provides the customer with a straightforward interpretation of a very complex measurement. However, note that,

- The classification rules are typically proprietary and cannot be compared between PD providers.
- The classification rules often evolve with time.
- The original data may not be readily available for re-analyses or comparison with subsequent test data.

With limited guidance regarding acceptable versus unacceptable PD results, some have suggested using factory test standards as a basis for providing PD results. The basic logic is that if a cable system can meet the current factory test standards for individual new components then it is most likely in good condition. Unfortunately, this only provides guidance for cable systems that are "good" – it says nothing about those cable systems that do not meet the current factory standards. Are the circuits that do not meet these standards really "bad" or are they just "not new"?

There is an additional complication as the factory test standards have changed over time. As a result, an aged cable system could be expected to meet a more stringent test standard than was in effect when the cable system was manufactured. Figure 4 gives the evolution of the maximum permitted factory test PD levels defined in AEIC cable specifications [18] for discharge-free extruded cable only. This figure is helpful in that it shows the level of PD that a cable could possibly have as a function of year of manufacture. To use this information effectively, the cable age must be known. An example can best illustrate this point. The presence today of 20 pC of discharge at 2 U_0 in a discharge-free cable manufactured in 1975 does not imply that discharge is developing in a worsening void defect or that an electrical tree is growing. That may have simply been the condition of the cable in 1975. However, 20 pC of discharge at 2 U_0 would be of concern for cables installed in the last 20 years. To help deal with these issues, it is useful to have the basic test data provided in addition to classification information to identify trends over time.

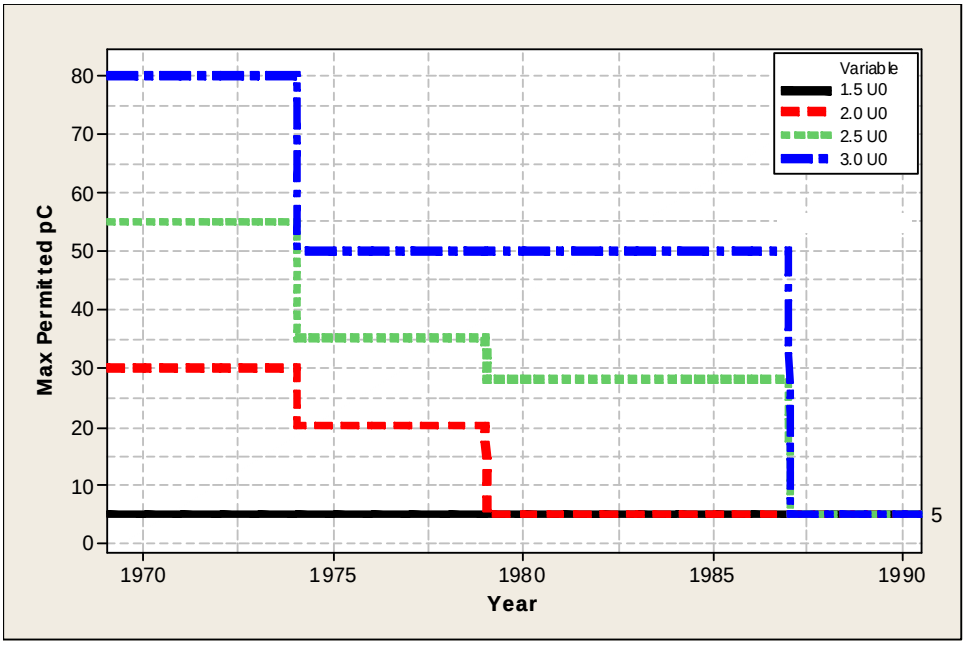

Figure 4: Maximum Permitted Factory Test PD Levels for Discharge-Free Extruded Cable Only (Accessories Excluded and Conventional IEC Std. 60270 – 2000 Style) [18]

The only success criteria for accessory component PD tests in US standards are in IEEE Std. 48 for cable terminations, IEEE Std. 386 for separable connectors (elbows/bushings), and IEEE Std. 404 for cable joints. Note that results for cold shrink and heat shrink accessories that are tested in the factory are not applicable after they are installed.

It is important to note that the PD criteria in these cable and accessory standards and specifications are,

- for design and production tests of new, individual components;
- used as one of a suite of electrical and non-electrical tests;
- Do not address in-service PD tests.

In some cases, partial discharge is allowed, depending on the specific standard/specification, the year of the specification, the type of product, and the test voltage. Partial discharge service providers in the USA do not make their criteria publically available.

7.5 Estimated Accuracy

To estimate the accuracy for the various implementations of PD technologies it is necessary to define common criteria applicable to all technologies. The adopted definitions are:

- "Pass" – Cable System is defined by the PD Providers as either free of partial discharge activity or any measured PD is considered benign. The means by which the providers make this determination is typically proprietary.

- "Not Pass" – Cable System is defined by the PD Providers as containing partial discharge activity that requires utility action or presents a quantifiable risk to reliability. The means by which the providers make this determination (including the level of risk) is typically proprietary.

The resulting accuracies for PD technologies based on results from multiple data sets from tests performed in the field appear in Table 8. The analyzed datasets include data using Online (U_0) and Offline (1 – 2.5 U_0), using VLF and 60 Hz excitation voltages. At this time, no Damped ac (DAC) PD data have been provided to *CDFI*.

Figure 5 shows all of the available PD accuracy data in a graphical form. Of all the PD datasets analyzed thus far, the Pass accuracy is generally much higher than the Not Pass accuracy. Note that these accuracies use time horizons of 1 to 11 years depending on when the tests took place. This table combines PD Offline techniques with PD Online techniques, as data are too limited for each of these techniques to develop separate tables.

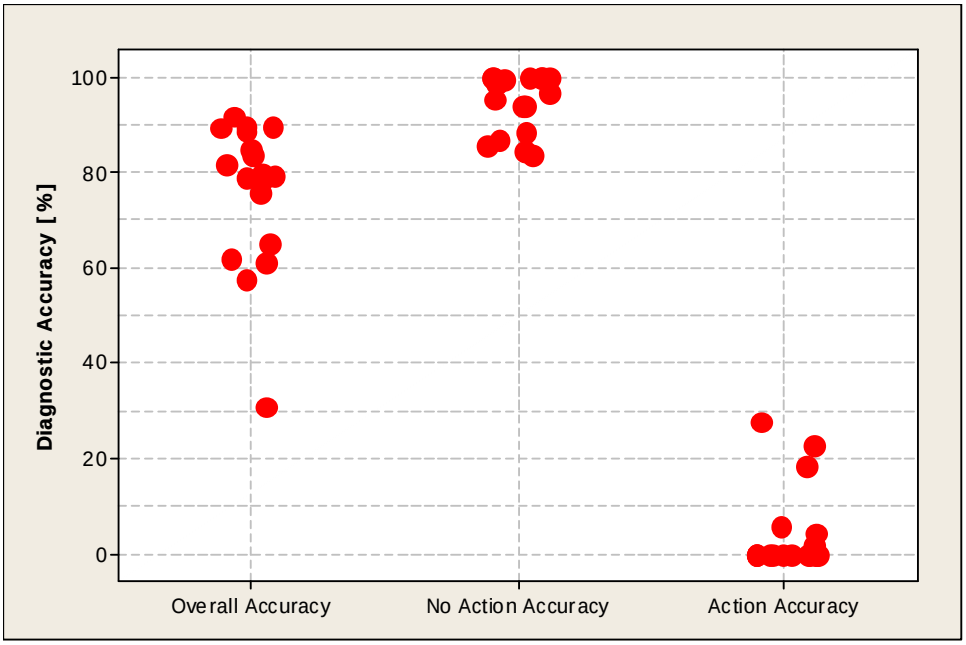

Figure 5: Estimated PD Accuracies for each Available Data Set

The high Pass accuracy (94% to 98%) implies that those systems diagnosed as Pass have a very high probability of not failing for several years. If one assumes a Pass accuracy of 95%, then one system in 20 will fail and 19 will not fail within the time horizon. On the other hand, the low Not Pass accuracy indicates that systems diagnosed as Not Pass also have a high probability of not failing for several years. Alternatively, on average, fewer than 1 in 20 Not Pass systems actually go on to fail within several years of testing.

Combining the condition-specific accuracies and weighting them according to the relative population sizes yields the overall accuracy. This accuracy represents a weighted average that is, as expected, lower than the Pass group accuracy yet much higher than the Not Pass accuracy simply

because the Pass group tends to be a much larger population. As a result, the Pass group accuracy is more influential in the overall accuracy calculation.

Table 8: Summary of Accuracies for Partial Discharge Techniques			
Accuracy Type	**Partial Discharge**		
		Raw	**Weighted**
Overall Accuracy (%)	Upper Quartile	89.2	85.0
	Median	79.8	79.5
	Lower Quartile	64.5	79.0
	Number of Data Sets	18	18
	Length (miles)	669	669
"Pass" Accuracy (%)	Upper Quartile	100	99.1
	Median	98.1	94.0
	Lower Quartile	88.1	88.4
	Number of Data Sets	18	18
	Length (miles)	669	669
"Not Pass" Accuracy (%)	Upper Quartile	4.9	23.0
	Median	0.1	6.0
	Lower Quartile	0.1	0.1
	Number of Data Sets	18	18
	Length (miles)	669	669
Time Span (years)		1998 – 2009	
Cable Systems		Extruded Feeder, Extruded URD, Hybrid Feeder	

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7.6 *CDFI* Perspective

Partial discharge is useful for cable diagnosis because it is able to provide a localized assessment of specific aspects of cable system condition. However, PD tests cannot identify the presence of all defects that can affect the life of a cable system: PD tests are classically focused on "void-type" defects.

At MV, PD technologies are generally deployed on aged assets/systems that have been in service for a number of years. The goal is to diagnose the system health while providing information on the likelihood of future service failures. Medium voltage PD technologies strive to provide a judgment of the severity of any detected signals under the theory that shorter remaining life is associated with more severe signals and hence defects. The basic assumption is - the largest PD signals come from the most severe defects; the most severe defects limit the remaining life; hence, the largest PD signals indicate the shortest remaining life. However, care must be taken when interpreting the PD measurements and the reported classifications that result as the correlation between the PD measurements and remaining life is, to date, weak.

One of the main goals of this section is to help users understand field PD measurement techniques on MV cable systems. The issues are many and diverse; however, during *CDFI Phases I* and *II* the crucial characteristics and limitations of PD measurements were identified, and are as follows:

1. PD is generally measured on aged assets, i.e. the focus is on maintenance testing. See Section 7.6.4.
2. Field measurements cannot be correlated to laboratory / factory test results. See Sections 7.6.1, 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.8, 7.6.12, and 7.6.13.
3. PD magnitude does not provide a direct link to estimates of deterioration or likelihood of failure. See Sections 7.6.1, 7.6.4, 7.6.6, 7.6.9, 7.6.10, and 7.6.13.
4. Tests, analysis, and reporting are orientated towards obtaining a diagnosis from a single test (trending or comparison with an identifiable benchmark are rare). See Section 7.6.10.
5. Results from different PD technologies cannot be compared. See Sections 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.7, 7.6.8, 7.6.10, 7.6.11, and 7.6.13.
6. Complicated test data are commonly processed and reported/recorded as classification data (Thus re-analysis/reconsideration by a user is not possible; only coarse trending (across class boundaries but not within a particular class) is possible by a user). See Section 7.6.10.
7. Measurements and analysis techniques are proprietary, detailed information is not available. See Sections 7.6.2, 7.6.3, 7.6.5, and 7.6.11.
8. Measurements are mostly made from one end of the system (terminal measurements). See Section 7.6.3.
9. Noise and PD signal deterioration are unavoidable and may limit effective PD detection in practice. See Section 7.6.1, 7.6.6, and 7.6.12.
10. Measurement variability is unknown and likely affects making comparisons using criteria and between repeated tests. See Section 7.6.14.

Because of the issues and limitations listed above, the information in this chapter provides the user with an increased awareness of PD measurements on MV cable systems rather than a detailed explanation of how to conduct tests or analyze data.

During *CDFI Phases I* and *II*, many laboratory and field PD tests on MV cable systems were conducted in conjunction with analyses of a number of MV PD data sets. These tests and analyses enabled the development of the perspective presented below. The *CDFI* perspective relies on knowledge gained from the following specific hands-on activities:

- Gather and analyze experience (NEETRAC and others) with PD testing of MV cable systems, with respect to test methods, equipment, and results– primarily in the form of maintenance tests.
- Conduct laboratory tests to assess and support field test processes and procedures.
- Recommend practices to enhance field PD measurements (calibration, sensitivity, and range checks).
- Provide general guidelines for PD test procedures on site (voltage levels, measuring time, measuring conditions, and pass criteria).
- Understand the impact of generally acceptable requirements on the value that field PD testing on MV systems might bring.

It is useful to begin with a discussion of the frequency content of PD signals as this drives the measurement/detection philosophies and challenges.

7.6.1 PD Signal Characteristics and Behavior In Cable Systems

A PD current signal or pulse constitutes a displacement of electrons and positively charged ions parallel to the direction of the local electrical field. For a "void-type" defect inside the bulk dielectric insulation of a cable system, the PD current generates a time varying electro-magnetic field which permeates the bulk dielectric insulation and induces current flows on both the conductor and the metallic shield of the cable system [17].

Partial discharge pulses can be described in terms of their shapes. The typical parameters of a PD pulse are its amplitude and width. The amplitude is defined as the peak amplitude of the PD pulse; in other words, it is the maximum magnitude that the PD pulse reaches independently of its shape. On the other hand, the pulse width is generally defined as the difference in time between those points in the PD pulse that have amplitude equal to 50% of the peak amplitude. The amplitude and width of a PD pulse appear in Figure 6.

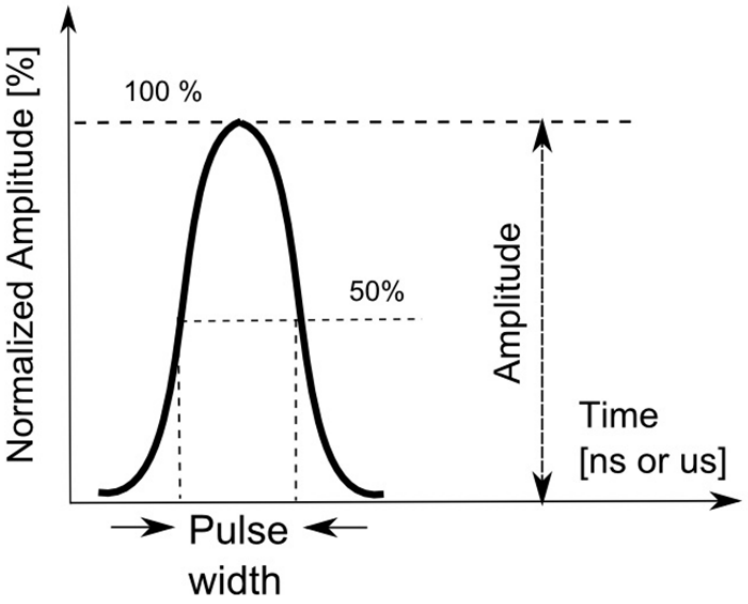

Figure 6: Typical Parameters of PD Pulse

The time-domain waveform of a PD pulse occurring within a cable system depends on the nature of the "void-type" defect and its location. However, the typical pulse width is on the order of fractions to tens of nanoseconds. Therefore, the frequency content of an actual PD pulse (at the discharge site) would be on the order of tens to several hundreds of megahertz [17]. The magnitude of the induced current depends on the strength and direction of the electromagnetic field generated by the discharge itself at the conductor and metallic shield. Thus, the magnitude of the induced PD signal on both conductors also depends upon the location of the "void-type" defect relative to the insulation and conductor screens.

7.6.1.1 Pulse Propagation

Partial discharge pulses are electromagnetic waves that propagate along the cable system. According to Maxwell's Equations, the propagation velocity is a constant and is the product of the frequency (*f*) and wavelength (λ) as shown below:

$$v = f\lambda$$

Where:

v is the speed of light within the cable system as defined by the permittivity and permeability of the insulation:

$$v_{insulation} = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}}$$

$\varepsilon_0 \approx 8.854$ E-12 F/m

$\mu_0 = 4\pi$ E-7 H/m

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In the case of PE-based insulation materials, ε_r is 2.3 and μ_r is 1. Thus, the propagation velocity inside polyethylene material is 1.98E8 m/s. Consequently, a 1 MHz (1 us) pulse would have a wavelength of 198 m while a 1 GHz (1 ns) pulse is 0.2 m in length. The wavelength represents the physical space within the material that the pulse occupies. Cable systems include other characteristics such as insulation wall thickness, conductor size, etc., that further reduce the propagation velocity.

A cable system component can affect a pulse when it is similar in size to the pulse wavelength. A splice is unlikely to change the shape of a 1 μs duration pulse since the pulse is much longer than the splice length. As Chapter 2 described, TDR pulses tend to be less than 100 ns in duration so that they are able to respond when they encounter cable accessories.

Unfortunately, cable systems cause a number of changes in the characteristics of propagating pulses. Suffice it to say, as the pulse propagates, its high frequency components degrade faster than those in the lower frequency bands do. As an illustration, simulation results of the relationship between the PD pulse bandwidth and propagation distance from the discharge site appear in Figure 7. These simulation results use a 15 kV 1/0 XLPE cable system with a 175 mil insulation wall.

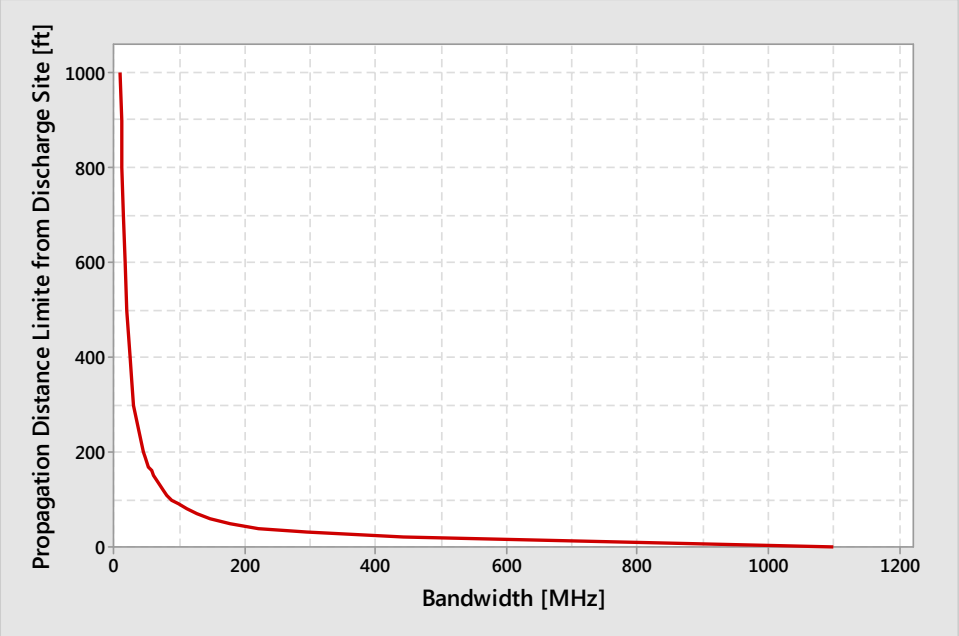

Figure 7: PD Pulse Bandwidth and Propagation Distance from Discharge Site – Linear Scale

As shown in Figure 7, the bandwidth of the propagating pulse decreases rapidly as the pulse moves away from the discharge site; as the propagation distance increases, the bandwidth seems to reach an asymptote. However, to better visualize the bandwidth behavior over all frequencies, the bandwidth axis in Figure 7 may be transformed into a logarithmic scale as shown in Figure 8. The frequency ranges for practical field measurements (yellow rectangle) and IEC 60270 (green rectangle) are included for reference in Figure 8.

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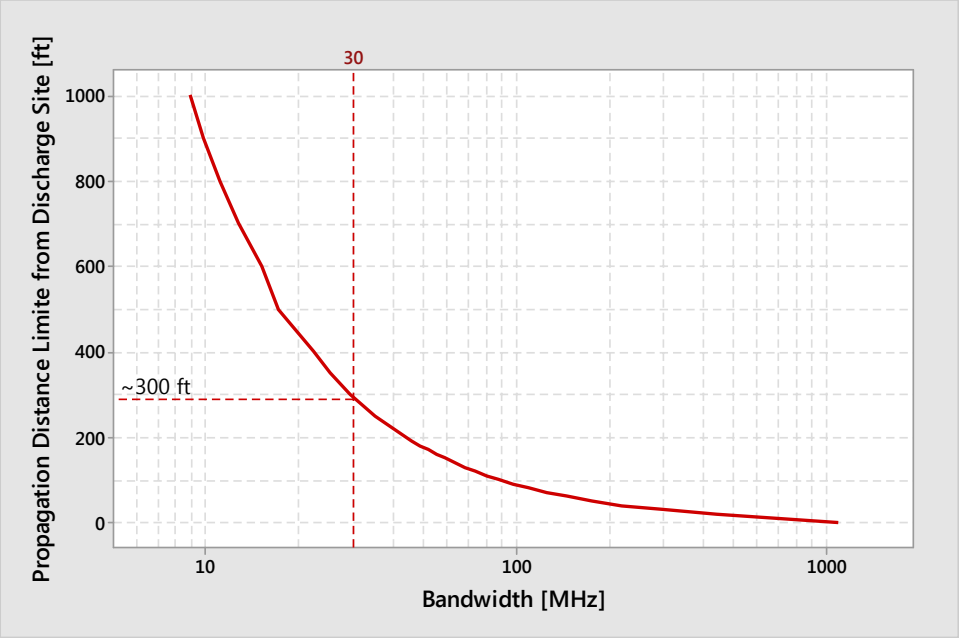

Figure 8: PD Pulse Bandwidth and Propagation Distance from Discharge Site

The most important interpretation of Figure 7 and Figure 8 is that they clearly show that the bandwidth of a PD pulse propagating along the cable system becomes limited as the PD pulse moves farther away from the discharge source. As an example, a typical MV cable system length of 300 ft, the bandwidth of the propagating pulse becomes limited to approximately 30 MHz.

7.6.1.2 Attenuation and Dispersion

As mentioned above, PD pulses distort as they propagate away from their sources. The distortion is caused by several types of cable system losses which are frequency dependent. The longer the cable system, the greater the distortion [17]. The examples in Figure 7 and Figure 8 show that attenuation can eliminate frequencies present in the original PD pulse once the pulse has traveled short distances from the source location. The physical processes that characterize the changes are well known and defined: skin effect, dielectric loss, reflection, and radiation [17]. These physical processes can be represented by two major sources of PD pulse distortion: attenuation and dispersion.

As PD pulses travel along a cable system, the system behaves as a "lossy" transmission line. The various physical sources for these losses can be categorized into two primary mechanisms:

1. loss of energy (attenuation); and
2. different propagation velocities for different frequencies (dispersion).

In addition, spurious pulses will appear resulting from reflections of PD pulses at the system ends and at splice locations. Detailed information on attenuation and dispersion follow.

Attenuation: Energy lost as a function of the distance traveled by the pulse and its frequency

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spectrum. In a cable system, attenuation is due to losses in the bulk insulation and propagation through the resistance of the conductor, neutral, and semiconductive screens. Normally, attenuation increases with frequency. Energy losses may be quite high for frequencies on the order of a few megahertz. As a consequence, fast PD pulses can only travel limited distances (because of their high frequency components) before they are attenuated to a level at which they may be hidden by the induced background noise. Figure 9 shows the relationship between attenuation per unit length and PD pulse width for a 300 ft cable system of 33 kV, 630 mm^2 conductor, XLPE cable. Figure 9 shows that faster pulses experience higher attenuation levels as compared to slower/wider pulses.

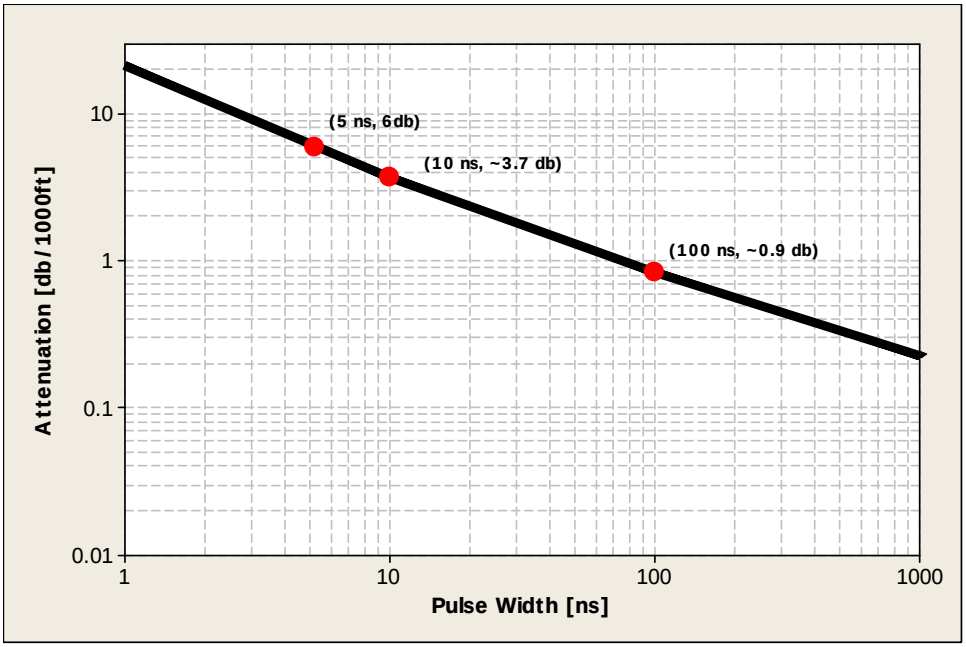


Figure 9: Calculated Attenuation as a Function of PD Pulse Width for 300 ft of 33 kV, 630 mm^2, XLPE Cable

The attenuation per unit length provides useful information regarding how far a PD pulse could theoretically travel through a cable system before being attenuated by a specified amount. For example, by analyzing the attenuation function shown in Figure 9, several observations follow:

- A 5 ns PD pulse has an attenuation of 6 dB/1,000 ft; consequently, the pulse only travels 1,000 ft before losing 50% of its initial amplitude.
- A 10 ns PD pulse has an attenuation of approximately 3.5 dB/1,000 ft; consequently, the pulse travels 1,700 ft before losing 50% of its initial amplitude.
- A 100 ns PD pulse has an attenuation of approximately 0.9 dB/1,000 ft; consequently, the pulse travels 6,700 ft before losing 50% of its initial amplitude.

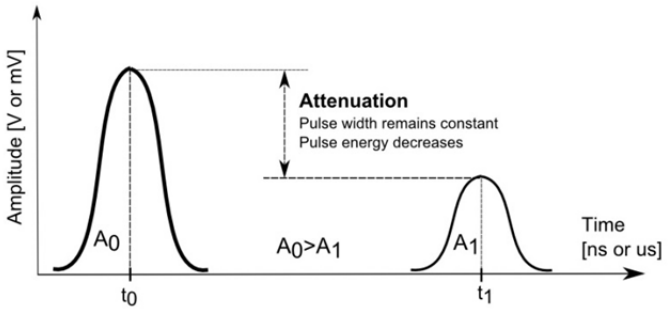
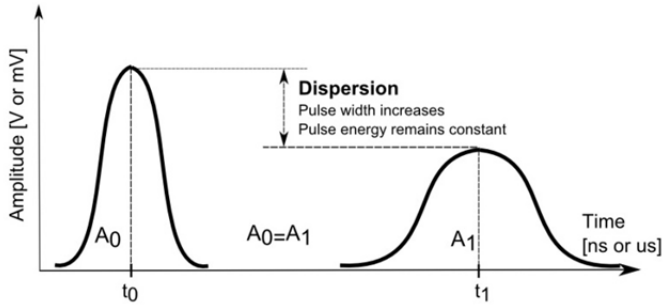
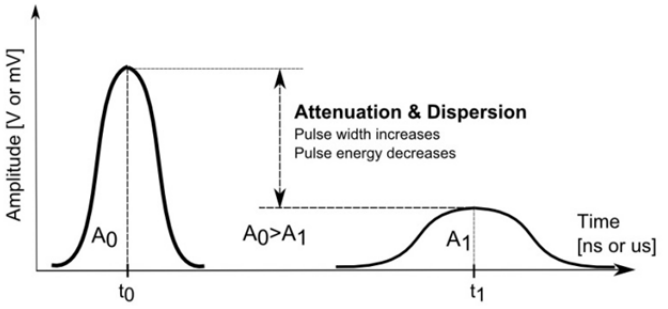
Even though the attenuation information is useful; generally, it cannot be considered alone. PD pulse distortion is always due to both attenuation and dispersion.

Dispersion: The velocity of a pulse through a medium generally depends on the frequency and wavelength of that pulse. As a result, different pulses will travel at different velocities and different components of a pulse will travel at different velocities as well. Since a PD pulse is composed of

different frequency components, these components travel at different velocities along the cable system. This difference causes the distortion known as dispersion. The distortion can be seen as a phase shift of each of the individual frequency components of the PD pulse and generally results in lower amplitude, longer duration pulses as compared to pulse shapes at their sources. Dispersion distorts PD pulses without loss of energy.

As a rule of thumb, it can be understood that attenuation causes the loss of frequency content of the PD pulses while they are distorted and spread out in time due to the dispersion effect. Table 9 presents the cases on how a PD pulse is distorted by attenuation, dispersion, and both.

Table 9: Attenuation and Dispersion of PD Pulses

Observations	Case
Attenuation: • Reduced amplitude • Constant pulse width • Reduced energy	
Dispersion: • Reduced amplitude • Increased pulse width • Constant energy	
Attenuation & Dispersion: • Reduced amplitude • Increased pulse width • Reduced energy	

Both attenuation and dispersion of PD pulses have been observed through research in the laboratory. The observation is possible by injecting a fast voltage pulse into a non-aged 25 kV WTRXLPE cable. The pulse travels approximately 2,300 ft and its initial and final traces at the near and far ends, respectively, are shown in Figure 10 and rescaled for comparison in Figure 11.

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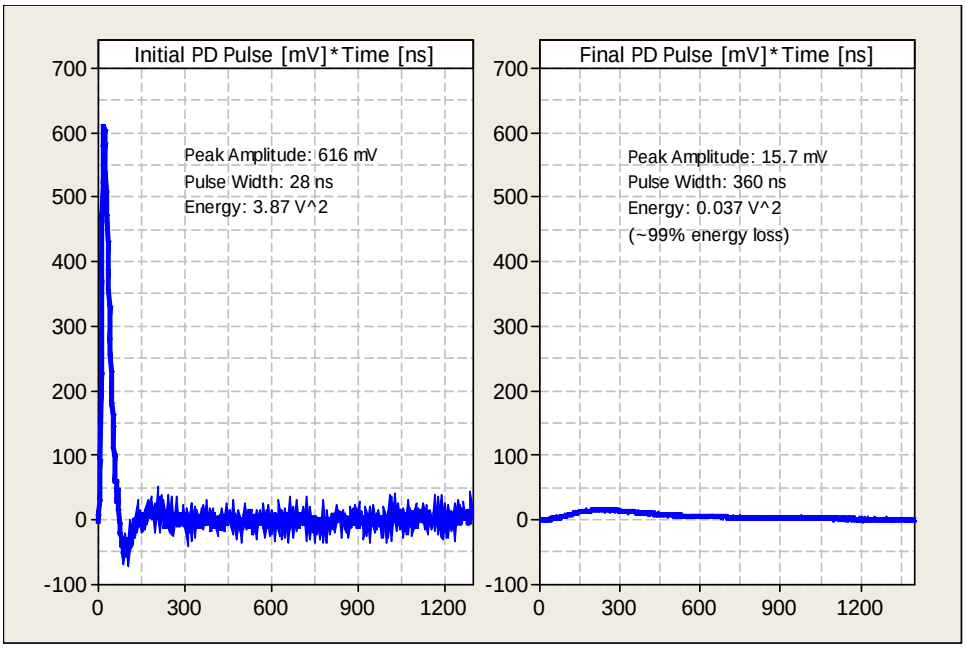

Figure 10: Laboratory Recorded Initial and Final Traces (Equal Axis Scales) of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

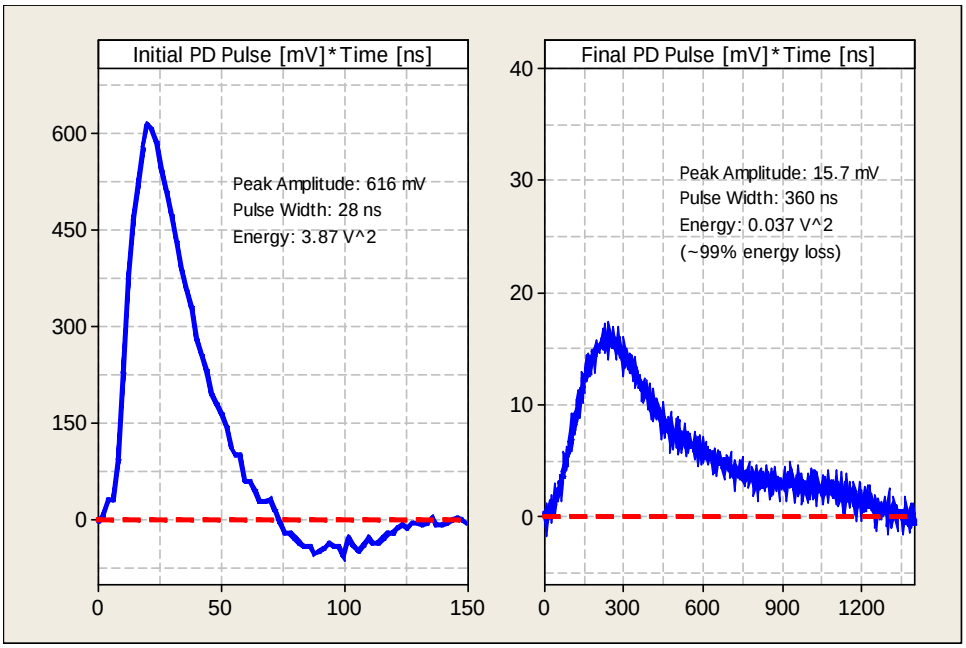

Figure 11: Laboratory Recorded Initial and Final Rescaled Traces of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

As seen in Figure 11, the attenuation and dispersion phenomena greatly affect the pulse shape parameters; specifically, observe that the peak amplitude decreases from 616 mV to 15.7 mV, which represents a reduction in amplitude of approximately 30 dB over the 2,300 ft of cable length. Similarly, the pulse width increases from 28 ns to 360 ns. Regarding the change in energy, the initial pulse shows an initial energy of 3.87 V^2 while the final pulse has 0.037 V^2 of energy which represents an energy loss of 99%.

7.6.1.3 Reflections From Cable System Structural Elements

In addition to deterioration from attenuation and dispersion, PD signals are further degraded by the cable system structure (i.e. number of cable sections and accessories that compose the system). This results from characteristic impedance changes between cable sections and accessories that cause portions of the pulses to be reflected. These impedance mismatches occur at all transitions between cable and splices and between cable and terminations/elbows.

To illustrate the effect of reflections, two different cable system structures appear in Figure 12 and Figure 13. The system in Figure 12 is the least complex system possible in the field: one cable length and two terminations. The second system, shown in Figure 13, adds a splice to the system shown in Figure 12. Both of these systems occur frequently in utility URD systems.

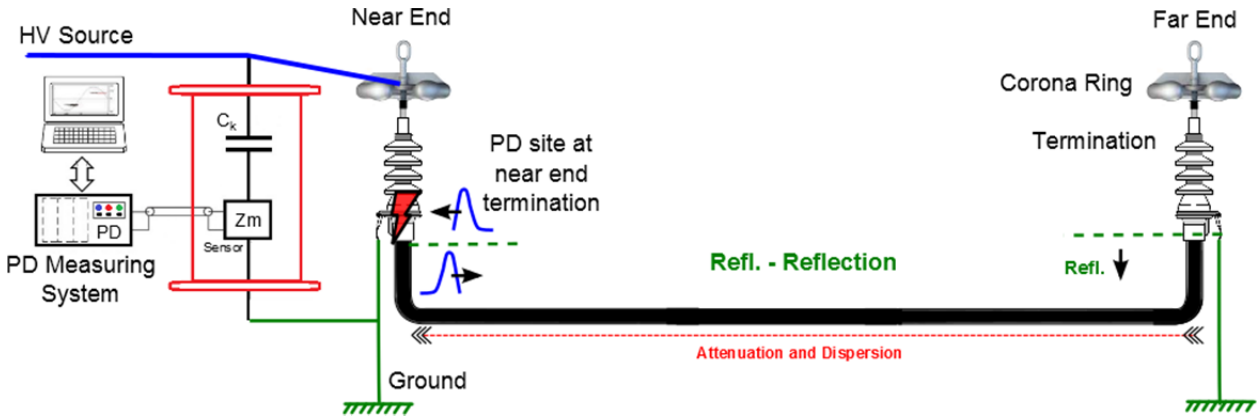

Figure 12: Illustration of PD Signal Degradation by Attenuation and Dispersion

In Figure 12, PD signal degradation results only from attenuation and dispersion (ignoring reflections off the far end termination) of PD pulses traveling from their source site along the cable system length to the detection equipment.

The signal degradation that occurs in Figure 13, on the other hand, includes attenuation, dispersion, and reflection of the PD pulse at the splice. The mismatch in characteristic impedance between the splice and cable does not allow all the PD pulse energy to transfer from one side of the splice to the other as a portion is reflected. Thus, additional signal degradation occurs and more energy is lost.

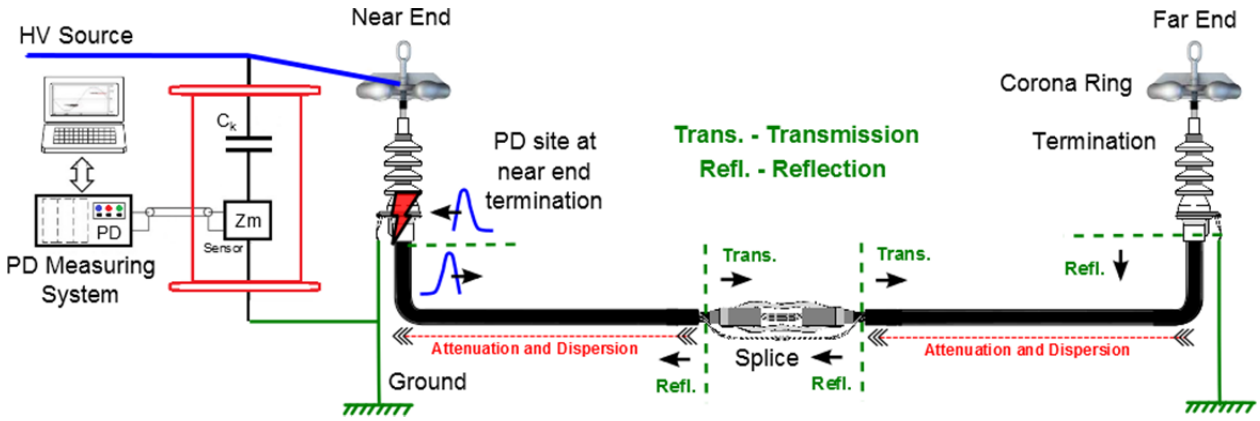

Figure 13: Illustration of PD Signal Degradation by Attenuation, Dispersion, and Cable System Complexity (Structure)

Figure 14 shows the resulting TDR trace for a PD pulse generated at the near end termination for the systems shown in Figure 12 and Figure 13. In both cases, the most important feature to consider is the amplitude of the far end reflection with respect to the initial PD pulse amplitude at the near end termination; the difference between these two amplitudes can be used to quantify and compare the signal degradation.

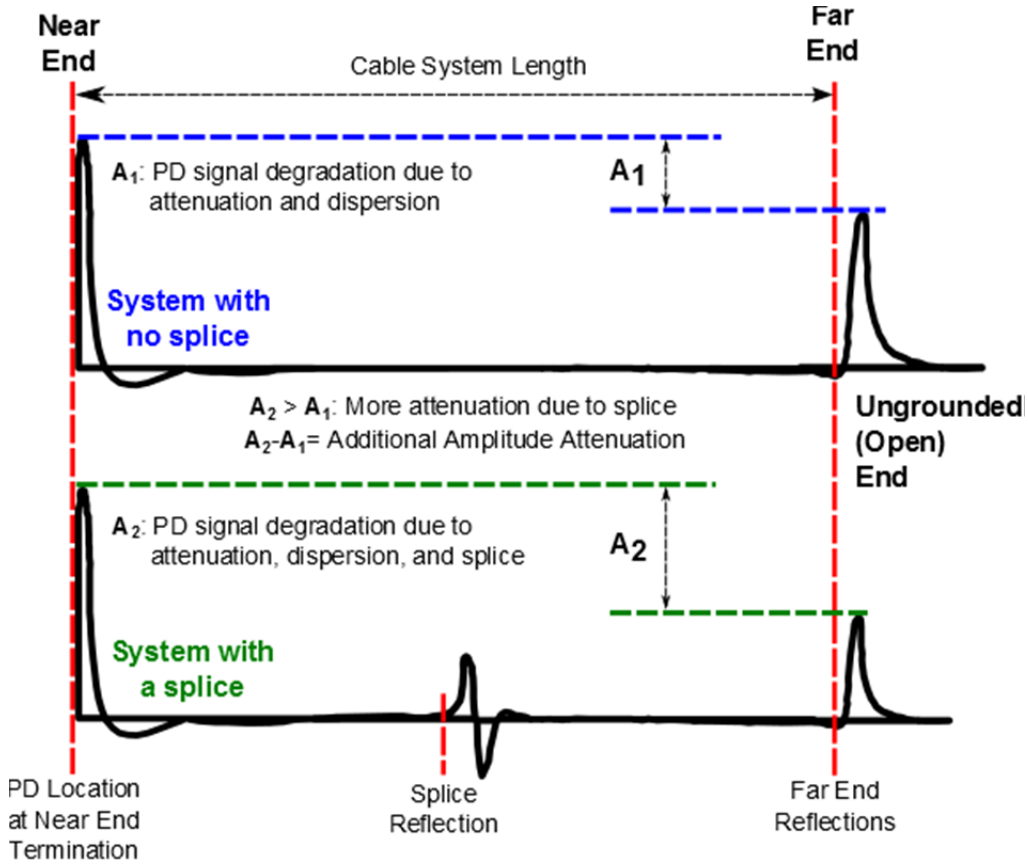

Figure 14: Impact of Cable System Complexity on Additional PD Signals Deterioration

As shown in Figure 14, signal degradation for the cable system with no splices (Figure 12) and for the cable system with a splice (Figure 13) are quantified by A_1 and A_2, respectively. The signal degradation is worse for the system with the splice as compared to the system with cable and terminations only. Assuming that both systems have the same length, type of cable, and that the splice length is negligible when compared with the total system length, then the signal deterioration from attenuation and dispersion can also be assumed equal on both systems. Therefore, the difference between A_1 and A_2 is the result of the splice.

Users unfamiliar with this issue may tend to think that a good way around this would be to characterize, in some consistent way, the interactions between characteristic impedances of all different cable system components. While this approach may work, its application is only possible if all the information about cable and components is known. Unfortunately, in field applications the exact circuit composition is generally unknown.

Ultimately, the system composition has a significant effect on the resulting pulse shapes and amplitudes so care must be taken when making assessments based on these features.

7.6.2 Conventional And Non-Conventional PD Measurements

Presently, PD measurements are categorized into Conventional and Non-Conventional approaches. The categorization is done with respect to the frequency bandwidth of the measurement equipment used to detect and quantify the PD activity. The frequency bandwidth is typically defined by users from recommendations given by IEC 60270; specifically this document refers to the NB (narrow-band), WB (wide-band), and UWB (ultra-wide-band) bandwidths. Table 10 shows the recommendations for each of these bandwidths within IEC 60270.

Table 10: Recommended Frequency Bandwidths According to IEC 60270

System Type	Frequency Requirements [kHz]	Observations
Wide Band – WB	$30 \leq f_1 \leq 100$ $f_2 \leq 500$ $100 \leq \Delta f \leq 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \leq \Delta f \leq 30$ $50 \leq f_m \leq 1{,}000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

Conventional and Non-conventional measurement approaches relate to the bandwidths as follows:

- **Conventional PD Measurement:** Measurement methodology outlined in IEC 60270 and makes use of either NB or WB bandwidths. Results are typically reported in terms of charge magnitude (pC).

- **Non-Conventional PD measurement:** Measurement methodology that utilizes UWB equipment that is outside the scope of IEC 60270. Results can take a variety of formats but are not provided as charge magnitude. UWB is understood to be 1 MHz to 200 MHz and above. The lack of standard recommendations has consequentially led to a diverse group of commercially available equipment from multiple manufacturers and service providers.

A comparison between Conventional and Non-Conventional PD measurements categories, considering a set of important topics, appears in Table 11.

Table 11: Comparison between Conventional and Non-Conventional PD Measurement Approaches

Topic	Category	
	Conventional	**Non-Conventional**
Typical Deployments	Factory Field Laboratory	Field Laboratory
Standards/Guides	• Factory – IEC 60885-3 • Laboratory – IEC 60270	IEEE Std. 400.3
Typical Approach for Measurements	Single-ended terminal measurement	
Sensor	Coupling Capacitor	Coupling Capacitor HFCT LFCT
Typical Cable or Cable System Length	• Factory – Less than 3,000 ft (~1,000 m) • Field – 50 ft to 10,000 ft (16 m to 3,300 m) with average of 300 ft (100 m) • Laboratory – Less than 300 ft (~100 m)	50 ft to 10,000 ft (16 m to 3,300 m) Average of 300 ft (100 m)
Metric for Reporting on PD Magnitude	Scaled charge – apparent charge by quasi integration (usually in pC)	Multi-featured – amplitude of pulse in mV or area under pulse waveform (mV·s)
Measurement System Bandwidth	• Factory – f_2 [§] < 500 kHz • Laboratory – f_2 [§] < 1 MHz • Narrow band (NB) – Δf [£] =[9 kHz, 30 kHz] with f_2 [§] < 1 MHz • Wide band (WB) – Δf [£] =[100 kHz, 400 kHz] with f_2 [§] < 500 kHz	1 MHz to 200 MHz (manufacturer dependent)
Calibration	• Factory – Injection of known charge at one end or ends bonded together, injector must comply with IEC 60885-3	Not Applicable

Table 11: Comparison between Conventional and Non-Conventional PD Measurement Approaches		
Topic	**Category**	
	Conventional	**Non-Conventional**
	• Laboratory – Injection of known charge only at the near end, injector must comply with IEC 60270 • Field – Injection of known signal for establishing sensitivity and charge scaling	
Scale Factor	Not Applicable	Used in some cases
Sensitivity Check	• Factory – Capacitive sensors are assumed to have a negligible effect • Laboratory – Capacitive sensors are assumed to have a negligible effect if test set-up conforms to IEC Std. 60270	Resolve minimum amplitude that can be detected
Performance Check	Included in the calibration procedure	Included in the sensitivity check
Range Check	Not required as it is assumed that if the requirements of the standards are met, all PD signals can be measured at the ends	Generally ignored
Background Noise	< 5 pC	No established criteria
Loss of Charge	• Factory – Loss is assumed to be insignificant • Laboratory – Conservation of charge is assumed	Not relevant
§: f_2 – upper limit frequency and f_1 – lower limit frequency £: Δf – bandwidth (BW), $\Delta f = f_2 - f_1$		

7.6.2.1 Cable System Modeling

Partial discharge signals at their sources can include frequency components in excess of 1 GHz. In Conventional PD measurements, the calibration and interpretation procedures are based on a simplified lumped capacitive model of the cable system as shown in Figure 15. This is generally a reasonable model assumption since the low frequencies considered by the NB and WB bandwidths have wavelengths longer than the typical tested cable system lengths. Longer lengths may be achieved with lower frequencies. Unfortunately, the electrical noise tends to be high at lower frequencies and with longer cable system lengths.

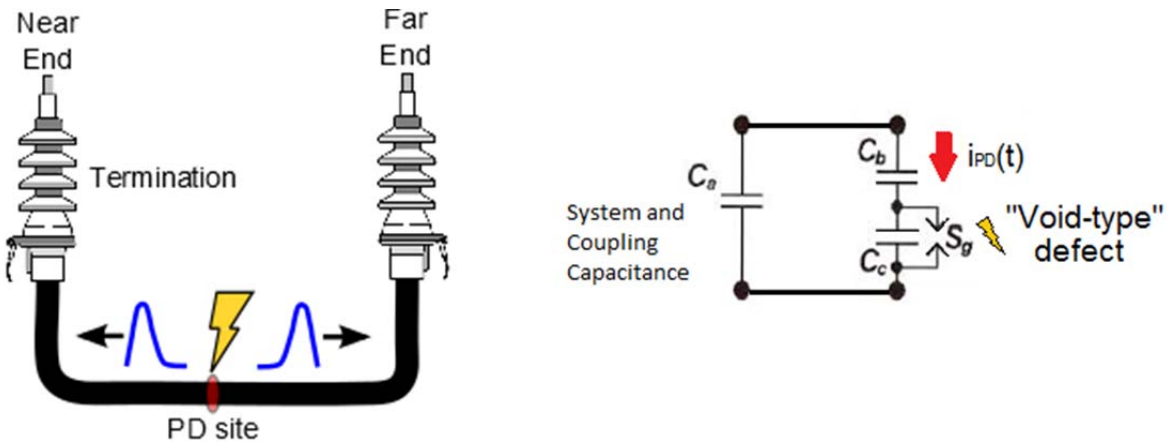

Figure 15: Lumped Capacitive Model

The narrow bandwidths (NB and WB) discussed in IEC essentially define a scaled charge (voltage measurement rescaled to picocoulombs using a calibrator) for PD magnitude. The IEC 60270 approach leads to detection systems that are relatively insensitive to variations in the PD pulse wave shape and duration, so long as the PD pulse is fast relative to the detection equipment. Thus, conventional PD measurements are insensitive to high frequency attenuation, dispersion, and other signal deterioration factors caused by the cable system structure and internal configuration as previously discussed. The primary disadvantage of low bandwidths and long cable systems is that multiple pulses can be captured at the same time resulting in an error in the estimated charge magnitude. A further complication is that the location function of a PD system requires a travelling pulse to perform the localization. In these cases, the cable system must be modeled as distributed impedance and not as a lumped capacitance.

In recent years, users have tended to move away from the conventions of IEC 60270 to avail themselves of more advanced electronics, digital signal processing, and lower noise levels to perform the diagnosis using higher frequency measurements; i.e. measurements in the non-conventional category.

As mentioned earlier, the non-conventional category tends to make use of UWB bandwidths, with upper frequency responses in excess of 200 MHz, depending on the equipment manufacturer. These high frequencies, by definition, have shorter wavelengths and so they become comparable in size to the cable system and even the components within that cable system. Thus, the non-conventional category is based on the more general distributed impedance model that appears in Figure 16.

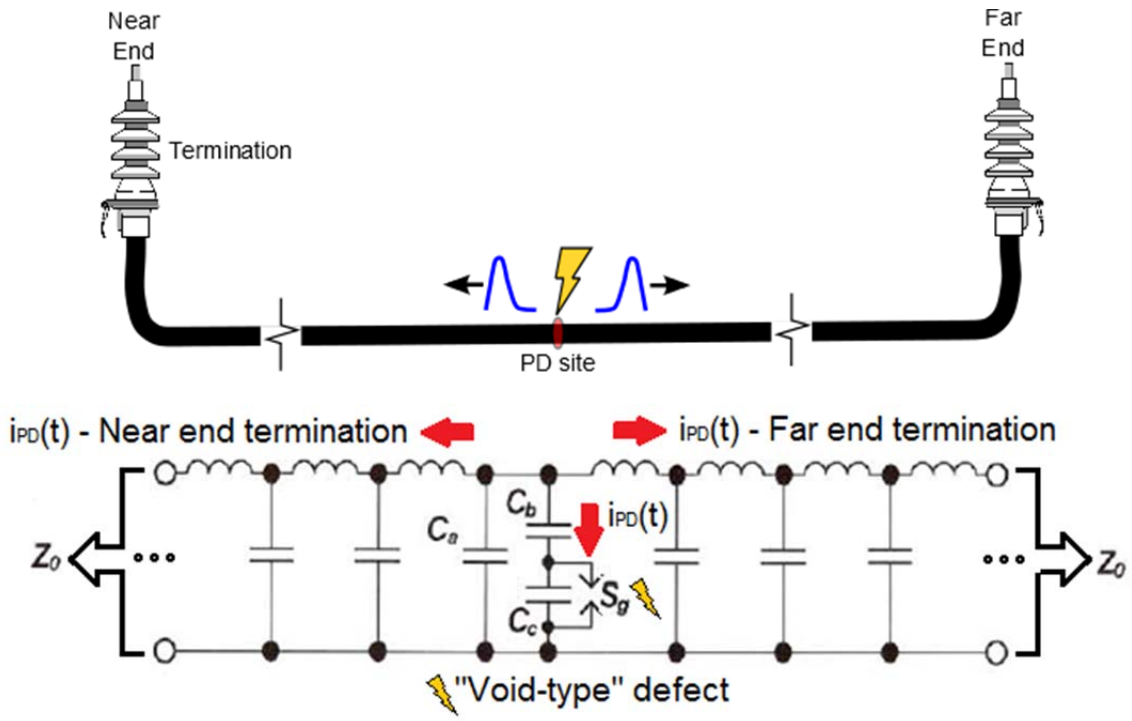

Figure 16: Distributed Impedance Model for Long Cable Systems

There is a complicated relationship between conventional and non-conventional PD measurements, measurement bandwidth, cable system length, and modeling. The following sections attempt to unravel some of this complexity.

7.6.2.2 The "Bandwidth-Length" Relationship

The challenge of which cable system model to use is may be addressed by considering frequency wavelengths and comparing them with the cable system length. Well established guidelines from signal theory exist for demarcating the boundary between lumped and distributed modeling. This threshold is illustrated in Figure 17.

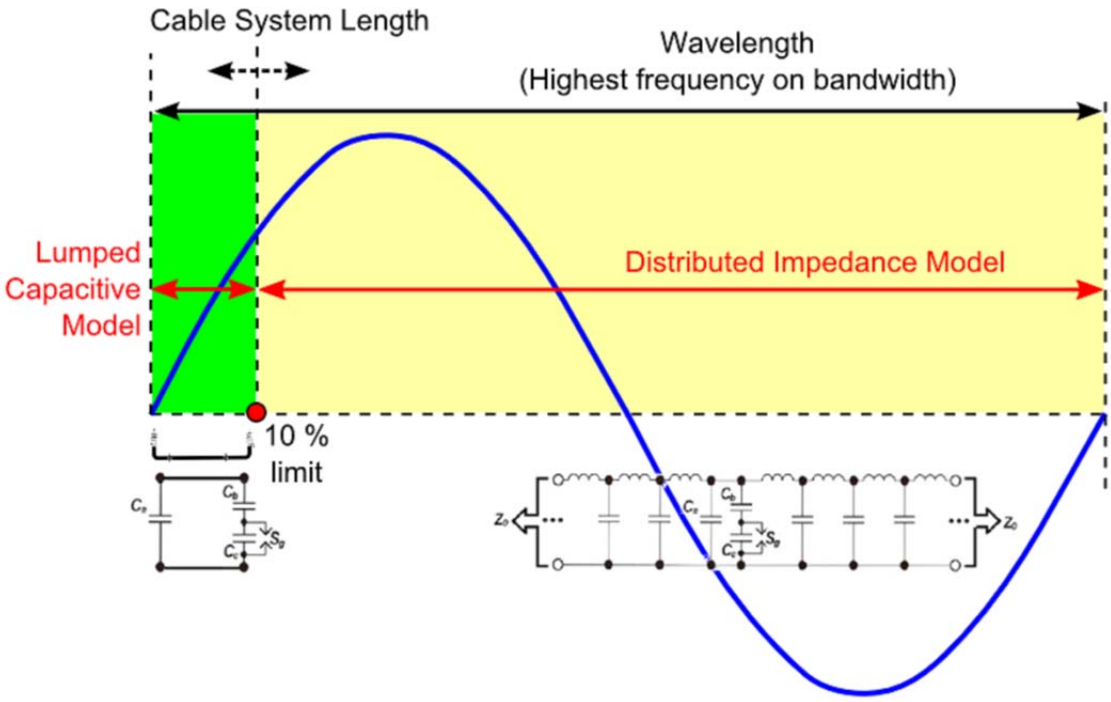

Figure 17: Illustration of Criteria for Lumped or Distributed Modeling

As seen in Figure 17, the accepted criterion indicates that if the cable system length is less than 10% of the wavelength corresponding to the highest frequency under evaluation (i.e. the shortest wavelength) then the cable system model may be simplified to the lumped capacitance approach. On the other hand, cable systems which are longer than this threshold may only be modeled using the distributed impedance approach. Note that the distributed impedance approach is valid for any cable system length.

IEC 60270 limits the bandwidth so that cable systems can be tested using the lumped capacitance approach. The recommended frequency bands shown earlier are repeated here for convenience in Table 12. An illustration appears in Figure 18.

Table 12: Recommended Frequency Bandwidths According to IEC 60270

System Type	Frequency Requirements [kHz]	Observations
Wide Band – WB	$30 \leq f_1 \leq 100$ $f_2 \leq 500$ $100 \leq \Delta f \leq 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \leq \Delta f \leq 30$ $50 \leq f_m \leq 1{,}000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

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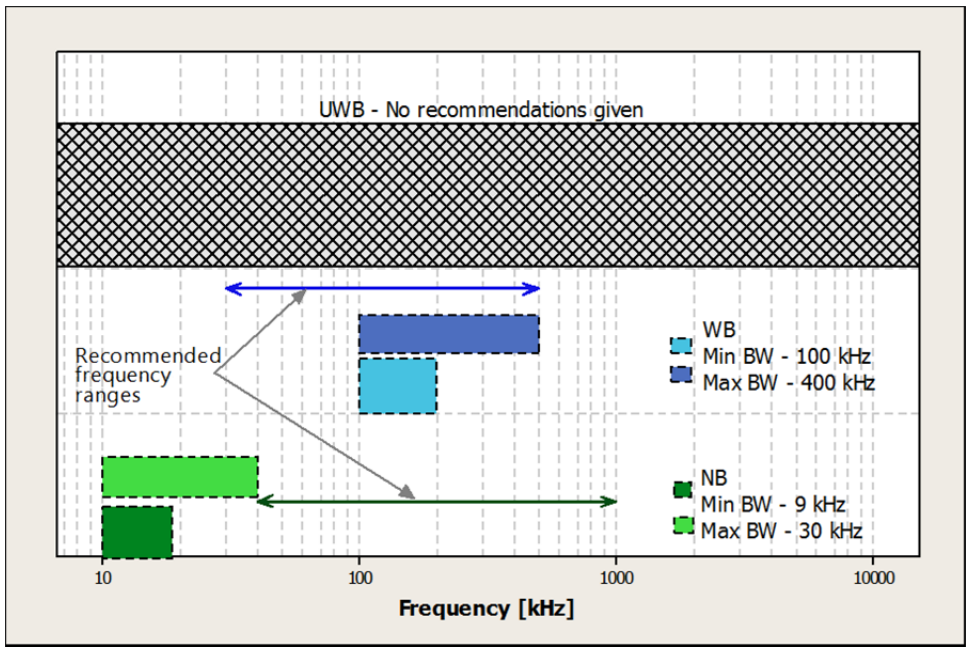

Figure 18: Illustration of Frequency Recommendations According to IEC 60270

The "10%" wavelength guideline can then be applied to the recommendations shown in Table 12 and Figure 18 and a "map" may be constructed for the appropriate modeling conditions (see Figure 19).

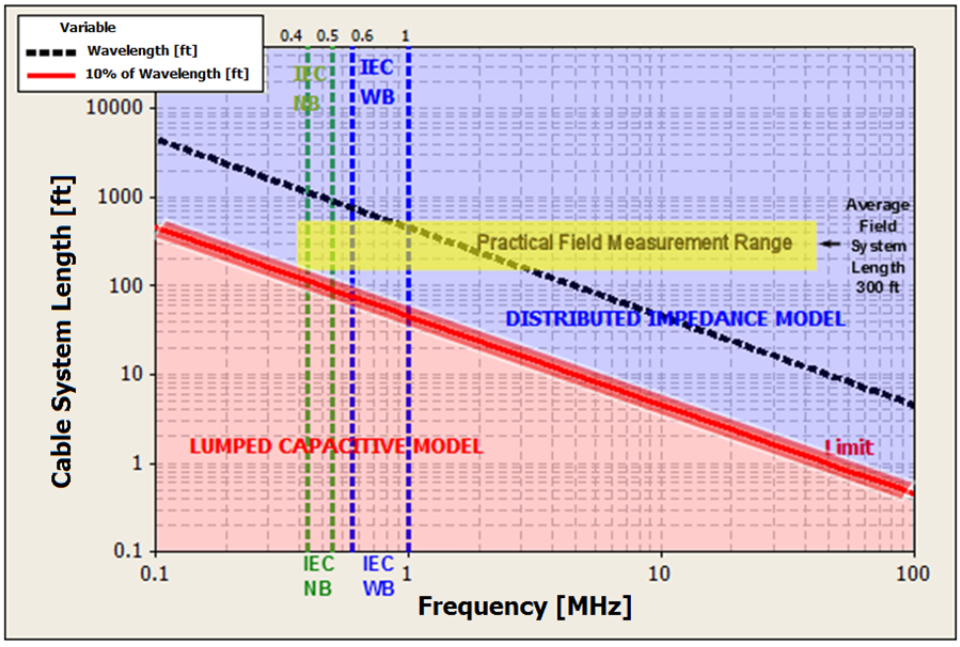

Figure 19: Relationship between PD Measurements Highest Frequency on Bandwidth and Applicability of the Cable system Modeling Categories (Figure 15 and Figure 16).

In Figure 19, the red line represents the recommended maximum cable system length (i.e. 10% of the frequency wavelength) and the black line represents a full frequency wavelength. In this analysis, the signal propagation speed required to compute the wavelength is assumed to be 50% the

speed of light. This speed value corresponds to the average of most real PE-based insulation cable designs. Note that this is less than the theoretical value for pure polyethylene.

Figure 19 can be interpreted as follows:

- Within the frequency and bandwidth range specified by IEC 60270, the assumption that the cable system predominantly behaves like a lumped capacitance is likely to be valid for lengths less than 40 ft (as high as 100 ft if using narrow bandwidth). For these lengths, calibration of the measured PD magnitude is a valid concept.
- A cable system with a length exceeding 500 ft is more likely to behave as distributed impedance and should be tested as such for all practically deployed PD measurements. In this case, the assumptions that are made in IEC 60270 for system modeling and calibration are no longer valid.

In addition, Figure 19 serves to demonstrate the reason why it is impossible to directly compare measured PD magnitude data between factory (Conventional) PD tests and field PD tests. Although other PD metrics (e.g. PDIV, PDEV, pulse repetition rate, etc.) may still be estimated for cable systems with lengths and frequencies in the blue region in Figure 19, calibration per IEC 60270 is no longer valid. The practical field measurement range in terms of frequency and cable system length is represented in Figure 19 by the yellow box centered at 300 ft, which is the average length of MV cable systems in the field. This indicates that most field test lengths fall outside of the region where a lumped parameter is applicable.

7.6.3 Measurement Approaches

The underlying principles of PD measurements are common to all approaches to PD detection. However, there are many ways to detect and quantify these discharge signals. This large number of approaches makes comparisons between test results from different PD diagnostic technologies so difficult that utilities should refrain from making comparisons.

7.6.3.1 Energizing Cable Systems In The Field

There are two basic approaches for energizing cable systems for PD measurement:

Online
This approach uses PD signals captured under operating conditions of voltage and temperature. There are at least four different methods of online technology each of which takes a different approach to quantification and interpretation of the test results.

The ability to test without disconnecting the system is often cited as an advantage. However, no less effort is required as some form of sensor needs to be attached at multiple locations along the cable system. This may be much easier for conduit systems than for direct buried systems. This entails risks, including safety risks for line crews.

In one form of this approach, the technique cannot pinpoint discharge locations between sensors. Discharges that are active only above operating voltage go undetected. The inability to locate discharges distant from the sensor may not be a serious handicap as many utilities replace cable sections or accessories rather than repair a specific location. In these cases, the ability to locate PD within a few feet is insignificant.

Providers' different approaches make it difficult to compare quantitative measurements. Most of the online data reported within the *CDFI* has come from one service provider/technology, which provides the results in the form of numerical ranking.

Offline
This approach uses PD signals captured at voltages that are typically above operating voltages. When adopting this method, there might be some risk to the cable system from elevated voltage, but the risk to personnel and the customer are minimal. The ability to conduct a sensitivity assessment (i.e. assessment of the measurement system's ability to detect low magnitude signals), locate discharges, and probe for defects that discharge only above operating voltages are seen as advantageous. When making these measurements, defects that are prevalent at operating temperatures may be missed. The stochastic nature of PD can mean that the defects are inactive during the short times typically employed for the measurements.

The approaches to interpretation of offline PD are complex and fluid. However, all approaches typically employ procedures that should maximize the measurement sensitivity. Unfortunately, sensitivity assessments in the field are complex and conducted in many different ways. Practical comparisons of the quantitative measurements made by the different approaches are difficult and generally impossible to make.

Most of the data reported within the *CDFI* has come from two excitation technologies: 60 Hz AC and 0.1 Hz VLF AC.

7.6.3.2 Capturing PD Signals

Data acquisition systems are the interface between the sensors and computers. Through the data acquisition systems, the signal data that comes to the sensors is converted from its physical form into an analog electrical signal that the acquisition system transforms into a digital form to be processed and analyzed by computers. The signal is then run through a series of algorithms and results can be sent to other computers to be presented to the user. For PD measurements, there are two main data acquisition philosophies:

- Triggered Instruments
- Continuous Acquisition Instruments.

A description of each of the PD measurement philosophies follows.

Triggered Instruments

The first instrument type is commonly known as "triggered" instruments. The decision by a PD measurement as to whether to record a signal or not is determined by, as its name states, an amplitude trigger. In other words, the instrument records a signal whose instantaneous amplitude exceeds a user selected value. Once the trigger level is reached, the instrument records the signal for a preset length of time. The instrument typically maintains a "pre-trigger" buffer that allows for the portions of signals that occur before the trigger level is reached to be captured as well. To assist in demonstrating the concept, its illustration in time domain appears in Figure 20.

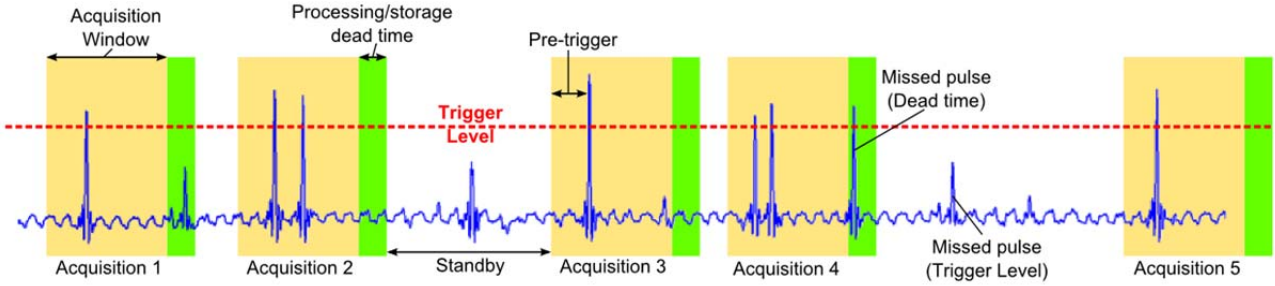

Figure 20: Time Domain Illustration for Trigger Level Based PD Measurement Philosophy

In Figure 20, the set trigger level is represented by the red dashed line and the incoming signal (waveform) by the blue solid line. With these settings, only five pulses reach the trigger level and thus only five acquisition windows are recorded. In each acquisition window, there is a pre-trigger time (time before triggering instant) and a processing/storage dead time (time after the acquisition window has ended). The pre-triggering time is used to capture the waveform before the trigger instant while the processing/storage dead time is time required to run the acquired data through a series of algorithms that characterize and store the acquired signals to memory. After an acquisition window and its corresponding dead time, the acquisition system goes to standby mode waiting on the next pulse to reach the trigger level and thus repeat the process.

Also, as noted in Figure 20, two reasons explain whyt some pulses are missed:

- **Pulses that do not meet the trigger level:** The missed pulses that do not meet the trigger level can be captured by decreasing the trigger level to an adequate value. The *CDFI* perspective considers that the best practice is to have the trigger level just above the average background noise level; in this case, all pulses having a higher peak amplitude than the average background noise level are captured and more importantly, the acquisition system would not get continuously triggered ("stuck") on the noise.
- **Pulses that meet the trigger level but come during the processing/storage dead time:** There is no clear solution for handling missed pulses that meet the trigger level but occur during the processing/storage dead time. However, concerns have abated as continuing improvements in computer processing and communication times have reduced the significance of dead times.

As mentioned earlier, after data acquisition, it must be stored to memory and analyzed. The typical analysis and storage process scenario (i.e. data processing) for a trigger level based PD instrument appears in Figure 21. The synchronization signal in Figure 21 provides information about the phase of the test voltage.

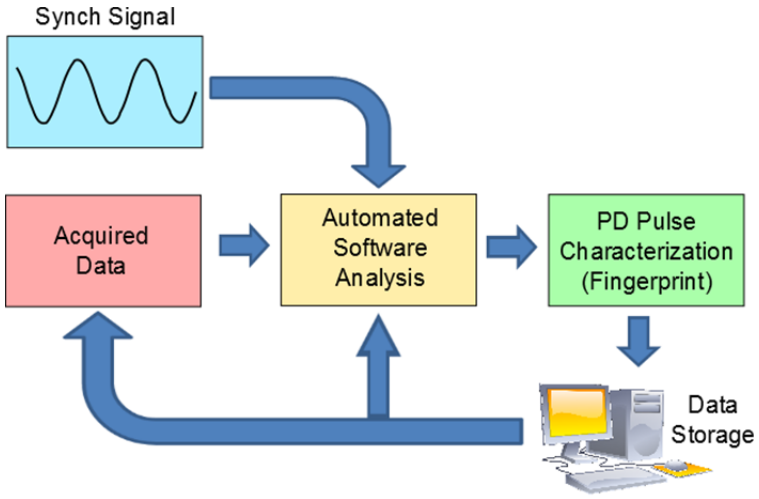

Figure 21: Data Processing Scenario for Trigger Level-based PD Measurement Philosophy

As seen in Figure 21, the acquired PD and synchronization signals are automatically analyzed by software providing a basic characterization or fingerprint of the acquired pulse. After the automated analysis, all the information can then be communicated and stored to memory in a remote computer. The remote computer generally serves as the operator interface. Based on the information, the operator may take control actions on the acquired data or automated software analysis process, adapting the acquisition system to his/her needs.

Continuous Acquisition Based PD Measurement

The second philosophy is the continuous acquisition based PD measurement. In this case, the measurement is based on a single acquisition window in which all signals that come from the sensor are continuously acquired. The start and end times for the acquisition window define the acquisition

time and are not trigger driven; they are selected by the operator of the PD measuring equipment. Typical predefined acquisition times are one cycle of the test voltage (typically 50 or 60 Hz). It is also possible to have alternative operator specified acquisition times. Figure 22 illustrates the concept of continuous acquisition based PD measurement. In this figure the blue solid line represents the incoming signal.

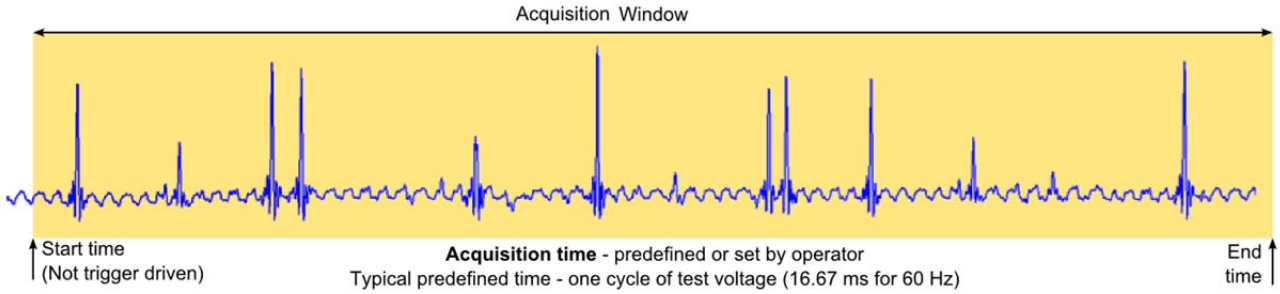

Figure 22: Time Domain Illustration for Continuous Acquisition-based PD Measurement Philosophy

Because of its nature, no pre-triggering or dead time issues exist for the continuous acquisition based PD measurement philosophy. The extraction, analysis, and characterization (i.e. data processing) of the PD signals are generally performed offline, i.e. after all the data are acquired over a range of test conditions. A typical data processing scenario for this approach appears in Figure 23. As before, the synchronization signal in Figure 23 provides information about the phase of the test voltage.

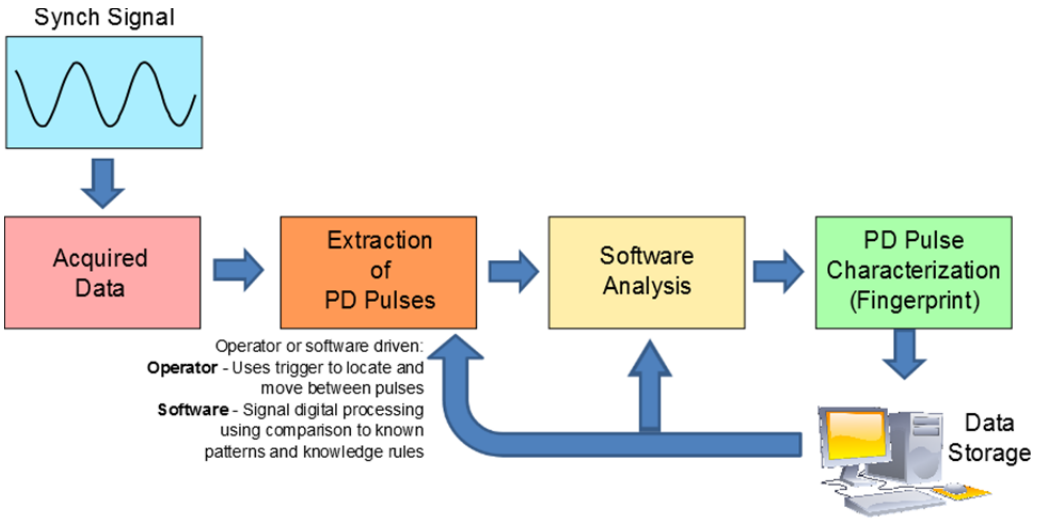

Figure 23: Typical Data Processing Scenario for Continuous Acquisition-based PD Measurement Philosophy

In Figure 23, the extraction of PD pulses can be operator or software driven. When the operator extracts the PD pulses, he/she uses experience and knowledge rules to recognize PD pulses. The operator can use a variety of software tools to extract PD pulses of interest.

Once the PD pulses have been extracted from the raw data, the analysis, characterization, and storage of data is accomplished in a similar manner as the trigger level based instruments.

7.6.3.3 Locating Sensors And Quantifying PD Signals

The two PD instrument types described above can be used for acquiring PD signals at a number of cable system locations including one or both terminations as well as any accessible splice location. This yields three primary deployment types,

- **Single-ended Terminal Measurement:** PD measurements are performed with a PD sensor located at one of the cable ends (typically designated as the "near" end) – see Figure 24.
- **Dual-ended Terminal Measurement:** PD measurements are performed simultaneously at both cable ends (near and far ends) – see Figure 25.
- **Distributed Measurement:** PD measurements are performed with sensors located at terminations and splices, the measurements can be done sequentially or simultaneously. When a PD sensor is moved from splice to splice and PD measurements are made sequentially, the deployment is often termed "splice" or "joint hopping" – see Figure 26.

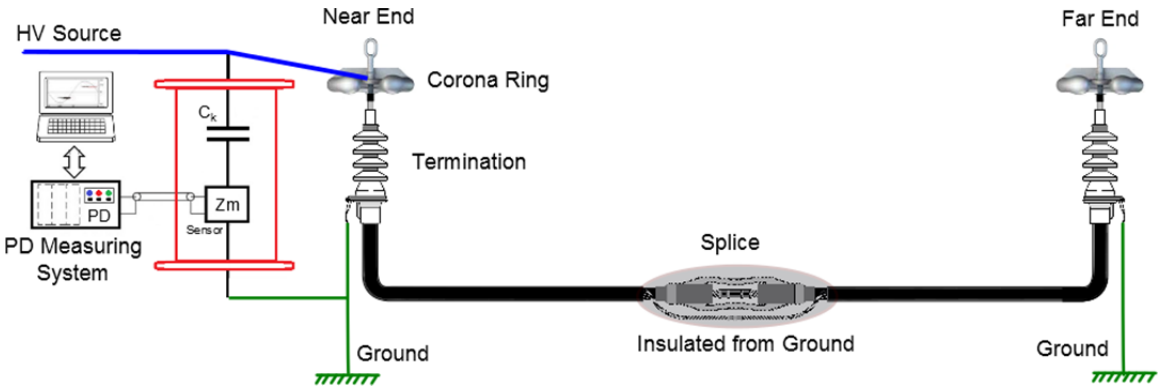

Figure 24: Single-ended Terminal Measurement

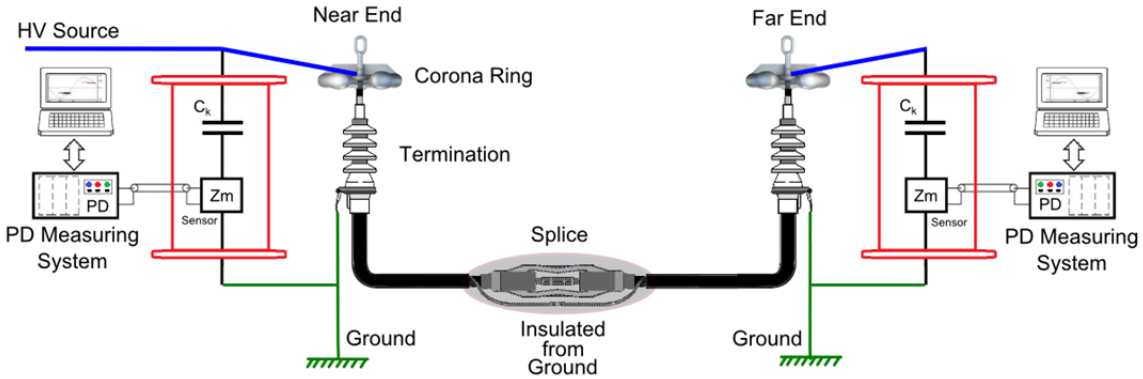

Figure 25: Dual-ended Sequential Terminal Measurement

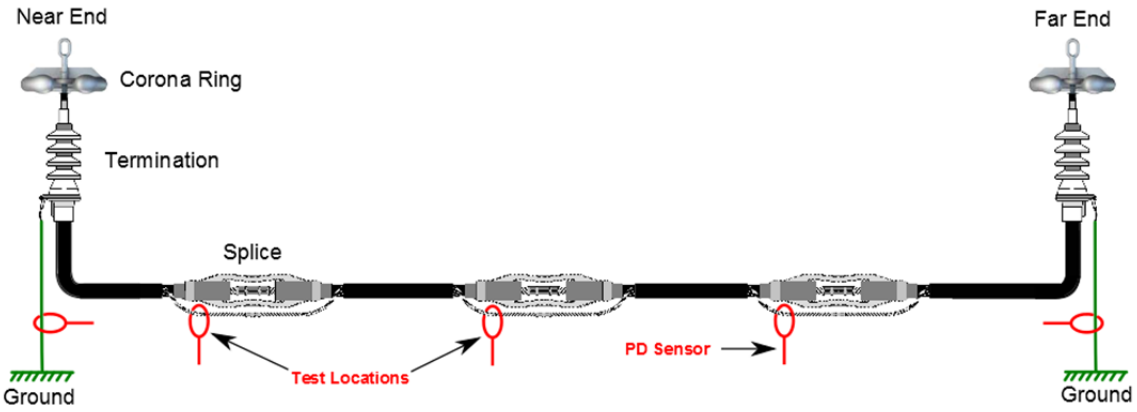

Figure 26: Illustration of PD Distributed Measurement on MV Power Cable Systems

The measurement approaches shown above can use different methods to estimate the size of the discharge. The following two methods are typically used:

- **Scaled Charge (pC):** The apparent charge, expressed in pC, can be estimated using a pre-derived scale factor or integration of PD current waveforms (as captured by the sensor-acquisition equipment). This method is related to the wide-band and narrow-band test setups presented on the IEC 60270 – 2000 and IEC 60885 – 1988. In addition to the PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.
- **Multi Featured (mV):** PD magnitude is estimated from measurement results using any relevant/convenient metric – typically, PD magnitudes are referenced to the peak magnitude of PD waveforms (as captured by the sensor-acquisition equipment) in millivolts. Other metrics such as the area under the pulse curve in mV-µs could also be used. This method is related to the ultra-wide-band test described on the IEC Std. 60270 – 2000. In addition to the PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.

Table 13 shows the relationship between the voltage source type and the measurement approaches for on-site PD testing of MV cable systems.

Table 13: Source Type Usage for On-site PD Testing of MV Cable Systems			
Source Type	**Approach to Measurement**	**Scaled Charge**	**Multi-Featured**
Power Frequency ac (30 – 300 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	Yes
Very Low Frequency ac (≤ 0.1 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	No
Damped ac Voltage (20 Hz to 1 kHz)	Terminal (Single and Dual-ended)	Yes	No
	Distributed	No	No

Regardless of the voltage source type, there are several issues to consider:

- Time and test voltage magnitude above U_0.
- PD diagnostic features (e.g. PD magnitude, PDIV, PDEV, or PD Patterns) cannot be compared either between voltage source types or measurement approaches.

In the previous measuring scheme, Table 14 outlines the four different field approaches to PD measurement and their relevant features.

Table 14: Overview of Field PD Measurement Approaches [26]				
Test Category	**Terminal Scaled Charge**	**Terminal Multi-Feature**	**Distributed Scaled Charge**	**Distributed Multi-Feature**
Location of Measurement	Single or Dual-ended		Distributed PD Measurement with sensors at accessories (splices and/or terminations)	
Sensor	Any internal or external sensor (capacitive or inductive)			
Typical Power Cable System Length	• <5,000 ft from each terminal sensor used. • No joints or few straight metal clad joints. • Limited by cable system propagation characteristics maximum lengths often lower due to attenuation and dispersion effects – see Range Check.		Any length	
Upper Cut-off Frequency	< 1MHz Typically	< 30MHz Typically	< 1MHz Typically	< 750MHz Typically
	Or any other specified bandwidth within allowed range			
Calibration	• Any well documented form of either classic calibration or double sensors. • Calibration voltage pulse with a rise time typically 10 times faster than circuit response – see Calibration.		Not applicable.	
Scale Factor	Not applicable		• Any well documented form of either double sensor methods and/or sensitivity by construction. • Includes evaluation of wave propagation in the cable adjacent to sensors.	
Sensitivity Check	• Required across the frequency range of the bandwidth of the measurement. • Includes evaluation of wave propagation in the cable adjacent to sensors – see Sensitivity Check.			
Performance Check	Required to check PD System Operability – see Range Check			
Range Check	Required to establish the length that a PD pulse can travel down a cable at selected levels of amplitude and dispersion – see Range Check			
Noise	Noise mitigation is essential		Noise mitigation may not be essential due to sensor location at accessories and propagation (filter) characteristics of cable	
Loss of charge	Loss assumed to be small enough not to perturb measurement	Recognizes loss of charge/current, especially at bonding of cable systems	Recognizes loss of charge/current, especially at bonding of cable systems	
Reporting on PD magnitude	Apparent charge by suitable (typically digital) integration technique. Any suitable metric (pC, mV, i_{PD})		Induced apparent charge by suitable integration technique (typically digital).	Any suitable metric (pC, mV, i_{PD})
Location	Location by time of flight from terminals		Location by sensor position and time of flight	

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7.6.4 Commissioning and Maintenance Tests

During *CDFI Phases I* and *II*, the utility participants were asked to provide locations where the various diagnostic technologies could be deployed in a field setting. A number of utilities volunteered for this opportunity and a number of sites were chosen for PD testing. Both commissioning tests on new systems and maintenance or condition-assessment tests on aged systems were performed. Table 15 summarizes the PD tests completed during the *CDFI*.

Table 15: PD Field Tests Performed During *CDFI Phase II*

Utility	Date	Length [ft]	Voltage Source Types	Test Type
Hydro Quebec	April 2011	35,000	VLF	Maintenance
Duke Energy	June 2011	5,700	VLF	Maintenance
Alabama Power	July 2011	9,000	VLF Online Damped AC	Maintenance
Alabama Power	August 2011	60,000	VLF Damped AC	Maintenance
Industrial Plant	December 2011	9,300	Damped AC	Maintenance
Georgia Power	December 2011	11,700	VLF	Maintenance
AEP	February 2012	7,900	VLF	Maintenance
Snopud/EPRI	March 2012	12,400	VLF	Maintenance
Hydro Quebec	March 2012	35,400	VLF Damped AC	Maintenance
Georgia Power	March 2012	16,500	VLF	Maintenance
We Energies	November 2012	31,000	60 Hz VLF Damped AC	Maintenance
Ameren	April 2013	79,100	Damped AC	Commissioning
Georgia Power	April 2013	5,000	VLF Damped AC	Maintenance
Ameren	August 2013	14,000	Damped AC	Commissioning
Snopud/EPRI	February 2014	38,400	VLF Damped AC	Maintenance
Duke Energy Franklin	March 2014	4,600	VLF Damped AC	Maintenance.
Duke Energy	March 2014	2,800	VLF Damped AC	Maintenance.
Duke Energy	March 2014	13,200	VLF Damped AC	Maintenance
Maximum Length Tested: 457,602 ft or 87 mi or 139 km in over a 41-month period (Actual Tested Cable System Length is a Subset of Total)				

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The results shown in Table 15 consider a time span of 41 months that started in April 2011 and ended in March 2014, a significant total length of 457,602 ft (87 mi or 139 km) of cable systems have been tested using different PD source types and this approach to measurement deployment. The PD sources were made available by the diagnostic testing providers, most of whom were participants in the *CDFI*. The PD source types include online PD and VLF, Damped AC, and 60 Hz for off-line PD. More importantly, Table 15 also shows the type of test deployed; i.e. maintenance or commissioning tests. Additional tests are known to have been completed by utilities not directly involved in *CDFI*. These tests are included in Figure 27.

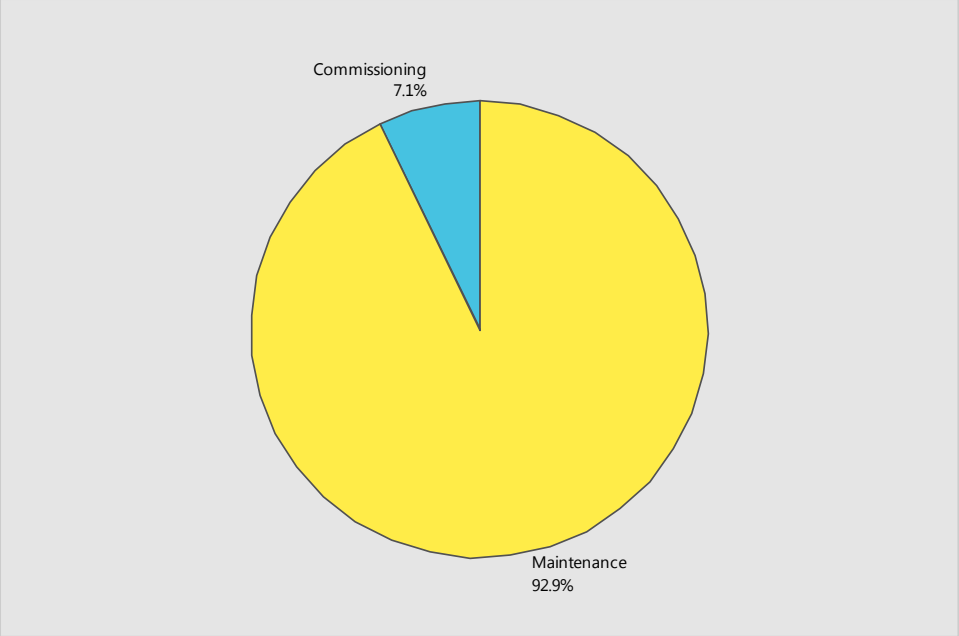

Figure 27: Distribution of PD Tests for MV Cable System between Commissioning and Maintenance Tests

Based on Figure 27, it is straightforward to conclude that MV PD field measurements are mainly used in the maintenance mode.

7.6.5 Calibration Principles

In the context of cable system PD measurements, the term "calibration" is strictly defined as the process presented in IEC 60270 for relating measurement data to charge magnitudes. Originally, the calibration process was developed for laboratory use; the goal was to develop a practical framework that enabled results between laboratories to be compared. However, there are a number of explicit conditions that must be fulfilled in the field for calibration to be meaningful.

7.6.5.1 IEC 60270 Calibration Method

The calibration of PD measuring systems serves to verify that the measuring system is able to measure a predetermined PD magnitude in picocoulomb correctly. Calibration is performed for the complete test configuration including,

- Cable system under test;
- Coupling capacitor; and
- Measurement hardware.

Each cable system tested requires calibration unless tests are conducted on a group of similar cable systems. In this case, "similar" means the same cable type, length, and terminations.

Calibrating a PD measuring system is done by repetitively injecting a short duration current pulse of known charge magnitude (known current and integration time) into one or both terminals of the cable system under test (with all required measuring and source equipment connected). The resulting configuration puts the pulse injector in parallel with the coupling capacitor and high voltage source as shown in Figure 28.

The pulse injection uses a calibrator (pulse injector) designed and calibrated to provide a consistent known charge magnitude. IEC 62070 specifies a number of requirements for the calibrator device. Unfortunately, no specific requirements for the pulse wave shape (i.e. amplitude and pulse width) are included.

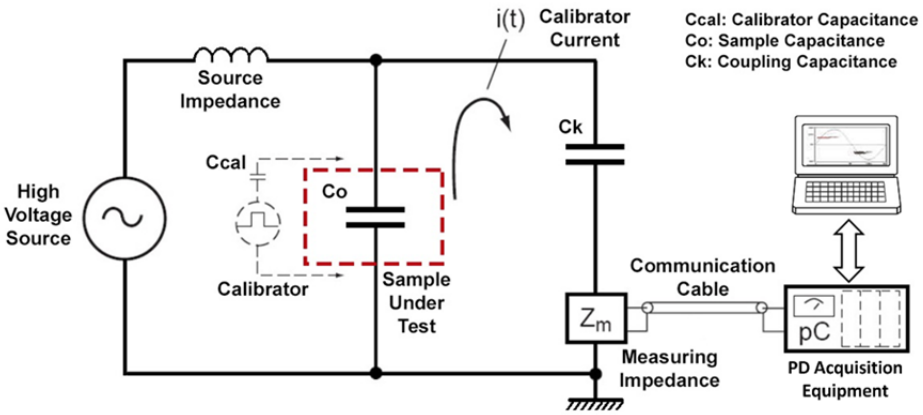

Figure 28: Calibration Test Set-up for PD Measurements

The standard PD measuring test method presented in the IEC 60270 is the coupling capacitor method (i.e. independent of the type of electrical sensor used (capacitive or inductive) the presence of the coupling capacitor is always required). Figure 28 illustrates the reasoning behind this. As PD pulses contain high frequency components, these frequency components do not flow through the high voltage source as it is largely inductive and represents high impedance. The coupling capacitor provides a low impedance path for these frequencies allowing the PD current pulses to be measured by the sensor (Z_m – measuring impedance).

In this method, the charges of PD pulses are usually determined from peak magnitudes of pulses in the PD detector. Peaks of pulses as seen by the PD detector depend on the capacitances of the sample under test and the measuring circuit (coupling capacitance). When the detected PD pulses are compared with the calibration pulses, the charges of PD pulses can be estimated.

The PD calibrator needs to comply with standard requirements and so its characteristics are checked periodically. IEC 60270 regulates the specification to estimate the calibrator performance, and this specification and others related to the calibration procedure appear in Table 16. This standard specification regulates the type test, routine test, performance test, and performance check of the PD calibrator. Charge, rise time, and pulse repetition rate must be measured and calibrated in these tests, except for the performance check.

Table 16: IEC 60270 Requirements for PD Calibrators

Attribute	Requirement	Comments
Calibrator Charge (q_0)	Tolerance ±5% of set charge and ≤ 1 pC	Clause 7.2.3 whichever is greater
Pulse Rise Time (tr)	Tolerance ±10% of set time and ≤ 60 ns	Clause 7.2.3 tr – 10% to 90% of peak value
Pulse Repetition Rate (**N**)	Tolerance ±1% of set rate	Clause 7.2.3
Linearity of Calibrator	Tolerance ±5% or ±1 pC	Clause 6.3 whichever is greater
PD Measured Metric (Scaled Charge)	50% to 200% of Calibration	Clause 5.2
Calibrator Capacitance (C_{cal})	≤ 0.1 Sample Capacitance (C_0)	Clause 5.2
Coupling Capacitor (C_k)	Always to be present	Regardless sensor type (capacitive or inductive)
Recalibration Sample Capacitance (C_0)	In the range of ± 10% of C_0 allowed	No recalibration required for similar cable systems Clause 5.2

7.6.5.2 Pulse Injectors

Pulse injectors (otherwise known as calibrators) are used in the calibration procedure described above. As Table 16 shows, the waveform the pulse injector generates is not defined and so the bandwidth of the pulse is equally ill defined. It is, therefore, difficult to reconcile the "calibration" aspect of these devices with the recommended bandwidths for PD instruments when the pulses used in calibration are not specified.

The issue is important because the signal deterioration of high frequency components of PD pulses travelling through a cable system is significant. Pulse injectors themselves are believed to produce pulses that resemble actual PD pulses and so should have quite wide bandwidths. The relationship between the injected pulses and the bandwidth can be analyzed by comparing the power spectrum density functions of the pulses with the recommended bandwidths. A study was conducted with three different pulse injectors to determine what differences exist between devices and their effect on the results a PD instrument would report had these injectors been used for calibration.

The pulse injectors used in this research appear in Figure 29.

Figure 29: Commercially Available Pulse Injectors

Figure 30 shows a comparison between pulse waveforms of the different injectors for a setting of 100 pC and into an impedance of 50 Ω. The value of 50 Ω is selected because cable characteristic impedances are usually near this value.

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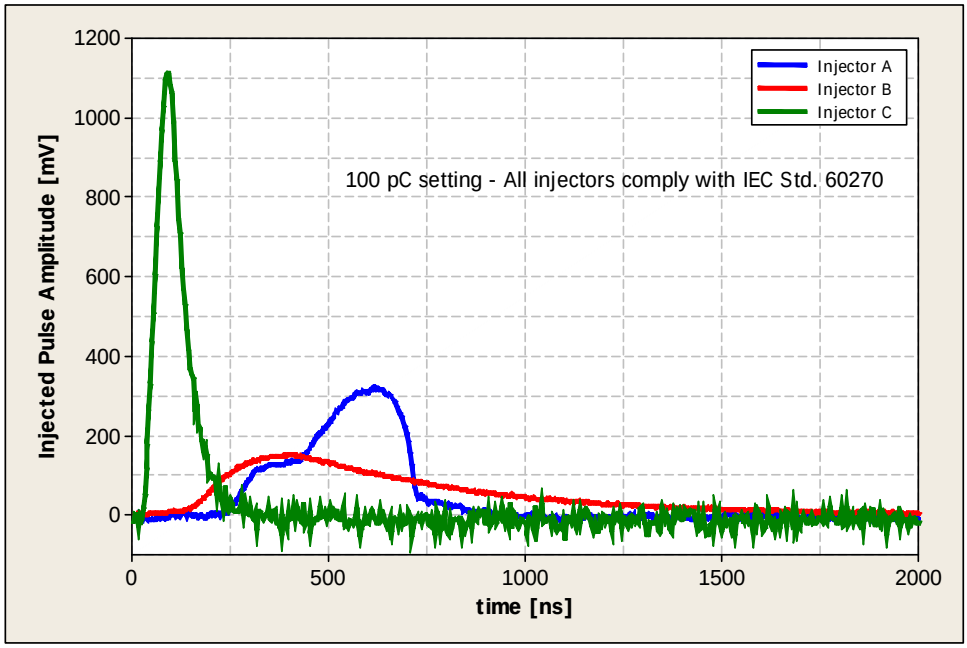

Figure 30: Comparison Between Pulse Injectors – 100 pC Setting into a 50 Ω Impedance

As seen in Figure 30, the waveforms between pulse injectors are different; however, they should be compared in terms of their charge setting, which can be estimated by the area under the pulse. This comparison appears in Figure 31.

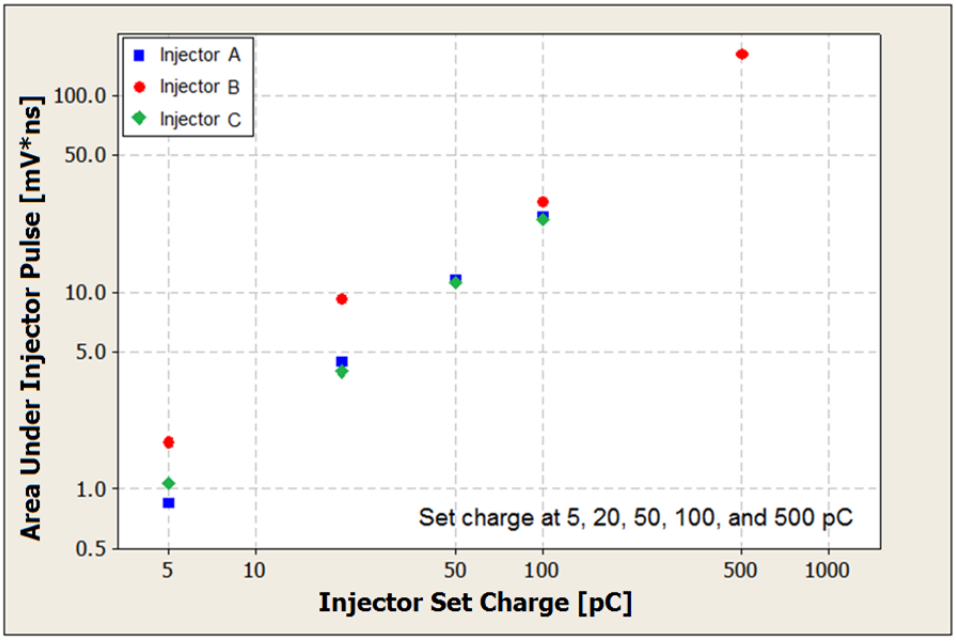

Figure 31: Comparison of Calculated and Actual Charge Settings for Different Injectors

As seen in Figure 31, there is a linear correlation between the charge setting and the area under the pulse for all three injectors. However, the difference between pulse waveform shapes is significant even though they produce similar charge magnitudes. Considerable differences are apparent

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between the injected pulse waveforms in Figure 30. These differences do not impose limitations on the applicability of pulse injectors because all of them comply with the required scale charge magnitude and other IEC 60270 requirements. However, differences in pulse waveforms directly translate to different frequency spectra. The comparison of these spectra appears in Figure 32.

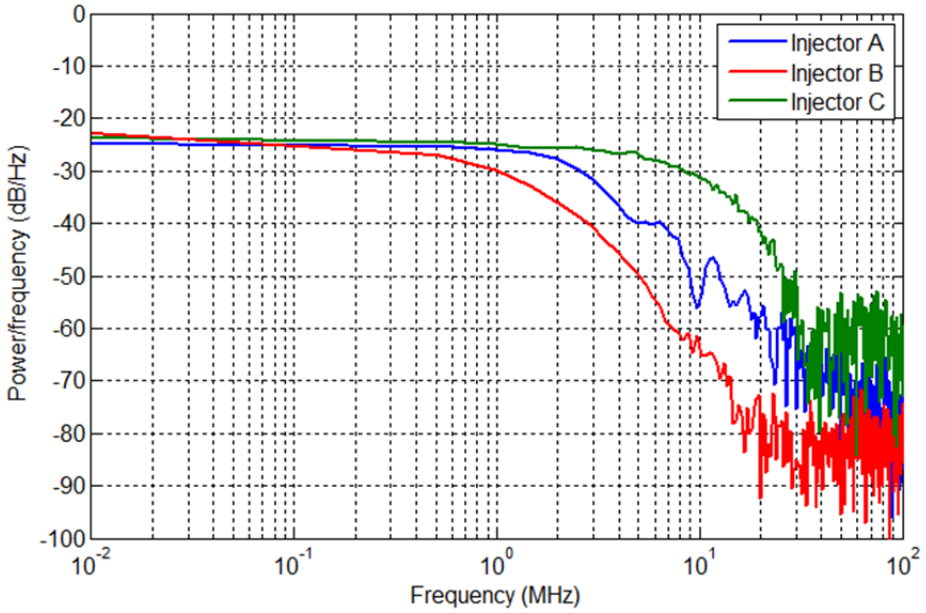

Figure 32: Power Spectral Density of Different Injector Pulses

As shown in Figure 32, at low frequencies (<300 kHz) all three pulses have virtually the same spectrum. This is expected since the zero frequency component of the spectrum is directly related to the area under the pulse in time domain and thus the charge setting. However, significant differences are observed between spectra at high frequencies (>1 MHz). For example, the fastest pulse (Injector C) has higher frequency content as compared with the slowest pulse (Injector B) which has the lowest frequency content. Figure 32 also indicates that at high frequencies the pulse from Injector A lies between Injector B and Injector C. This leads to two observations,

- At low frequencies and for the same charge setting, all injector pulses and, thus, devices can be assumed identical as long as they comply with IEC requirements.
- At high frequencies and for the same charge setting, all injector pulses and, thus, devices behave differently. Therefore, injected pulse waveform is very important and should be considered if measurements are to be deployed in this frequency range.

While the above two observations are clearly shown in Figure 32, it is still difficult to define the boundary that should be used for distinguishing the low and the high frequency ranges. This can be overcome by considering the approach adopted in filter design. When designing different filters (low, high, and band pass) the 3 dB-point criterion often defines the frequency threshold value relative to the maximum value of the power spectrum density function. The 3 dB-point corresponds to the frequency where the power spectrum density function is half its maximum value. The 3 dB-point criterion has been applied to the power spectrum density functions of Figure 32 and the results appear in Figure 33.

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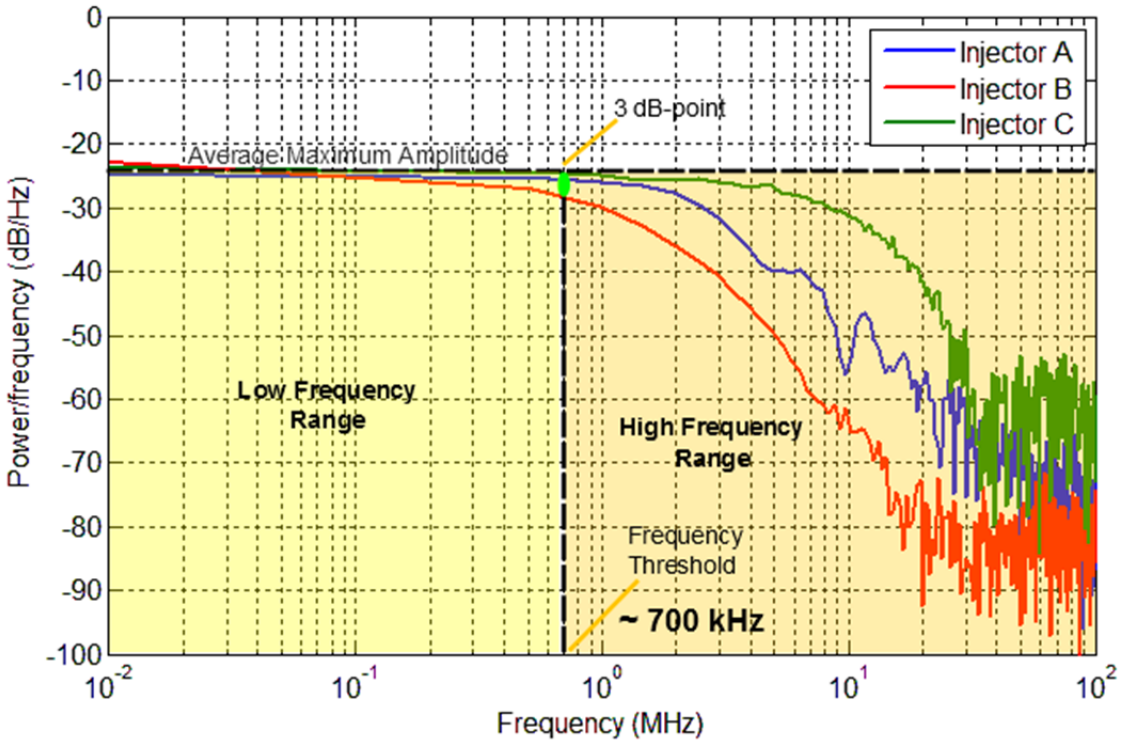

Figure 33: 3 dB-point Criterion to Determine Frequency Threshold

As seen in Figure 33, the threshold for differentiating the low and the high frequency ranges is approximately 700 kHz.

Once the threshold frequency between the low and the high frequency ranges has been established, a comparison between IEC Std. 60270 – 2000 bandwidth requirements and the power spectrum density functions, of the different injector pulses corresponding to Figure 30, is shown in Figure 34.

Considering the frequency threshold level of 700 kHz, then the narrow-band (NB) and wide-band (WB) allowed bandwidths fall in the low frequency range of the spectral density function of the injector pulses; therefore, it can be concluded that if NB or WB frequency ranges as specified by IEC Std. 60270 – 2000 are used for PD measurements, then there are no issues or limitations regarding the waveform of the injector pulses. Under this scenario, different injectors may be used and results can be compared in terms of scale charge through the calibration procedure as specified by the standard.

In contrast, the ultra-wide-band (UWB) as seen in Figure 34 could consider frequencies that are below and above the threshold level of 700 kHz; therefore, the injector pulse results using different injectors cannot be compared. Under these conditions the energy of the injected pulse is an extra factor to consider e.g., the energy of the pulse from Injector C has more energy when compared to the pulse from Injector B. The bigger energy of Injector C comes from the fact that its power spectrum density function has higher frequency components; the energy of the injector pulse is related to the area under the curve of its power spectrum density function.

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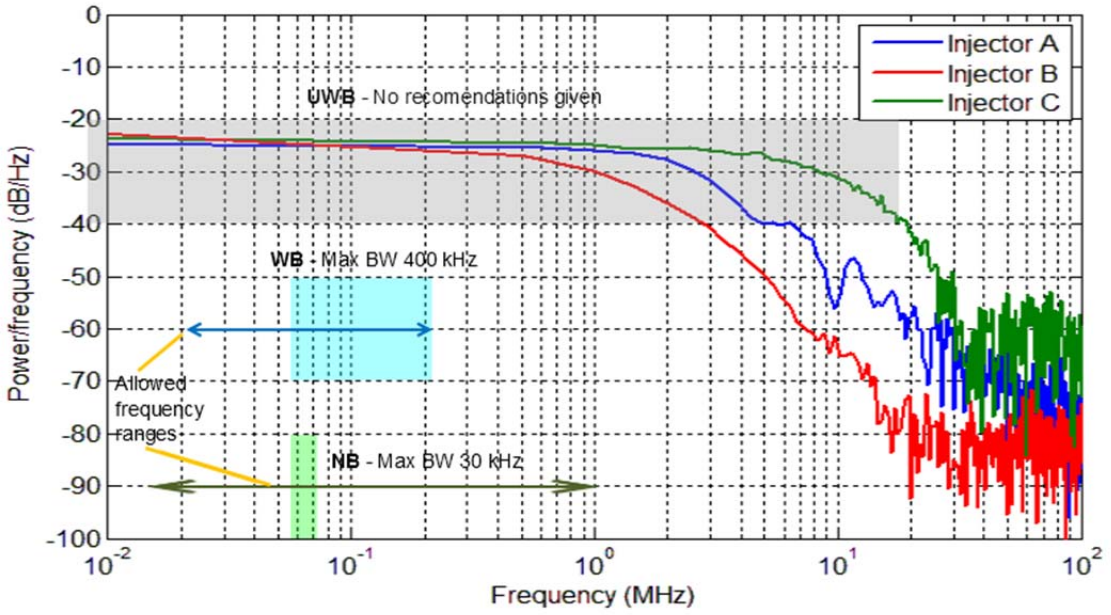

Figure 34: Comparison between IEC Std. 60270 – 2000 Bandwidth Requirements and the Power Spectral Density Function of Different Injector Pulses Corresponding to Figure 30

All issues and limitations described here that emerge when using UWB could be diminished by defining the characteristics of pulse injectors such that they produce the same standardized waveform.

7.6.6 Performance Assessment

The current thinking for field PD measurements is that performance checks should be made before the actual PD test to provide a measure of the "goodness" of the test. In declaring cable systems to be PD free, it important to understand the detection limitations for the particular circuit, equipment, and noise environment at the time the measurement was performed.

Two performance checks have been proposed:

- Sensitivity Check; and
- Range Check.

These checks are covered in the following sections.

7.6.6.1 Sensitivity Check

The sensitivity of a measuring system is defined as the capacity it has to respond to changes in the variable that it is measuring. The sensitivity is an absolute quantity and can be also understood as the smallest absolute amount of change in the measured variable that can be detected by the

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measuring equipment. The main goal of this check is to establish the smallest pulse amplitude and width that can be detected from the injection location (either near end, far end, or both) by the PD measuring system.

In the context of cable systems, the sensitivity check is a complex topic to handle and characterize, which is due to all the factors that can affect the sensitivity of a PD measuring system. These factors directly affect the amplitude of PD pulses:

- Background noise;
- Type and performance of PD sensors;
- Grounding practices; and
- Frequency response of PD measuring system.

The sensitivity check tries to establish the relationship between the amplitude of "PD-like" injected pulses (A_i) and the amplitude of the resulting measured pulses (A_m) as detected by the measuring equipment. This is illustrated in Figure 35. Measurements that will be made according to IEC are performed in terms of charge while UWB measurements are made in terms of voltage.

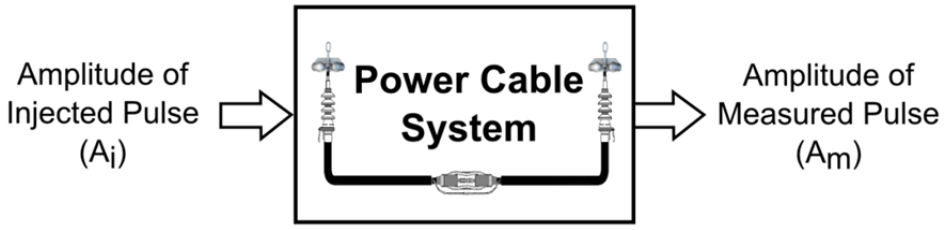

Figure 35: Sensitivity Check of PD Measurements on MV Power Cable Systems

The concept of the sensitivity check is illustrated in Figure 36. The pulse injection can be performed from either end of the cable system. However, it is useful to start at the near end first as the minimum pulse width and amplitude for the near end will be lower than would be observed from the far end. The benefit of this approach is that the user is able to confirm the PD detection equipment and associated connections are installed/operating correctly.

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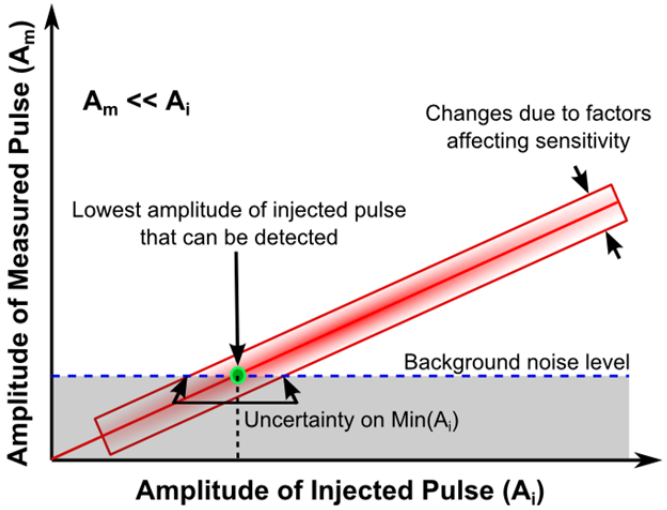

Figure 36: Sensitivity Check Concept (Near or Far End Injection)

There are fundamentally two ways of approaching the Sensitivity Check:

- For a given pulse width, the lowest amplitude of the injected "PD-like" pulse is determined. The injection starts with the highest possible amplitude and is reduced until the measured pulse amplitude falls beneath the background noise level. This amplitude and the fixed pulse width represent the sensitivity of the PD measuring system under these particular test conditions.
- For a given pulse amplitude, the narrowest pulse width of the injected "PD-like" pulse is determined. The injection starts with the widest possible pulse and the width is then decreased until the measured pulse amplitude falls beneath the background noise level. This value and the pulse width represent the sensitivity of the PD measuring system under these particular test conditions.

In addition, Figure 36 depicts a linear relationship between A_i and A_m. Under ideal conditions, this would be the case. However, the linearity is influenced by a multitude of factors and interactions that are beyond the scope of this document. Suffice it to say, there is inherent uncertainty in the min(A_i), i.e. tests performed at different times may give different sensitivity check results.

There are several ways to deploy the sensitivity check for laboratory and field PD measurements, including terminal (single-ended and double-ended) and distributed measurements. The details of the sensor placement and connections for the various options appear in Table 17.

Care must be taken when interpreting the approaches to Sensitivity Check in comparison to the PD approaches to measurements. The approaches to Sensitivity Check consider only the relationship between the "PD-like" pulse injection location and one PD sensor at a time. If more than one PD sensor is used simultaneously during the test (e.g. for dual-ended or distributed deployment), then the sensitivity check should be performed from the injection location to each of the PD measuring systems present in the cable system during the simultaneous acquisitions of the PD signals by using the approaches presented in Table 17.

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Table 17: Illustration of the Approaches for Sensitivity Check Deployment for PD Measurements on MV Power Cable Systems

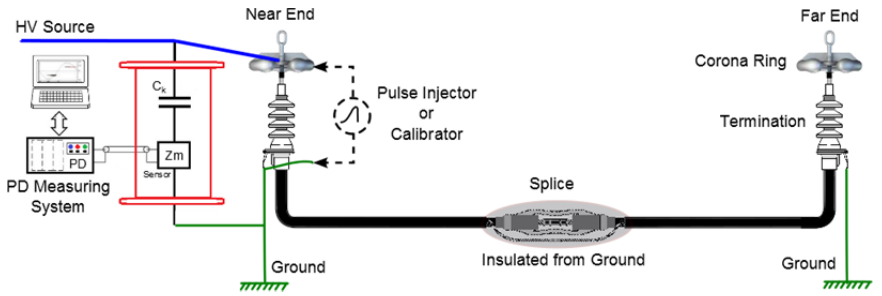
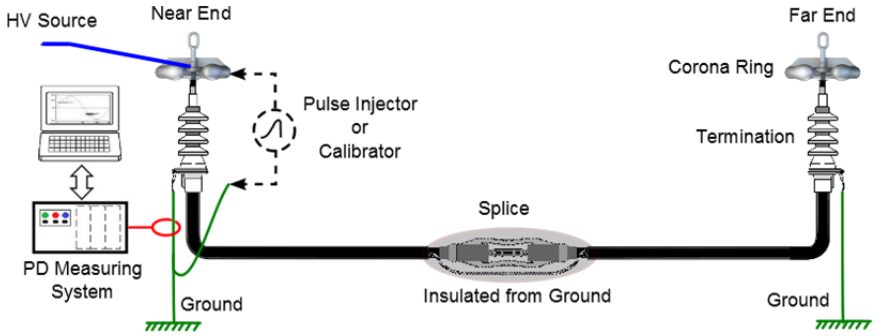
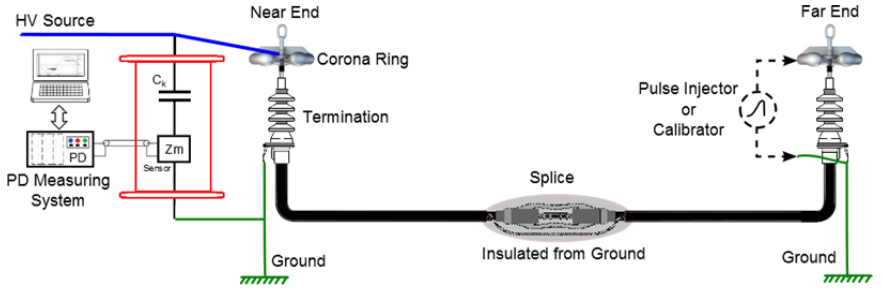
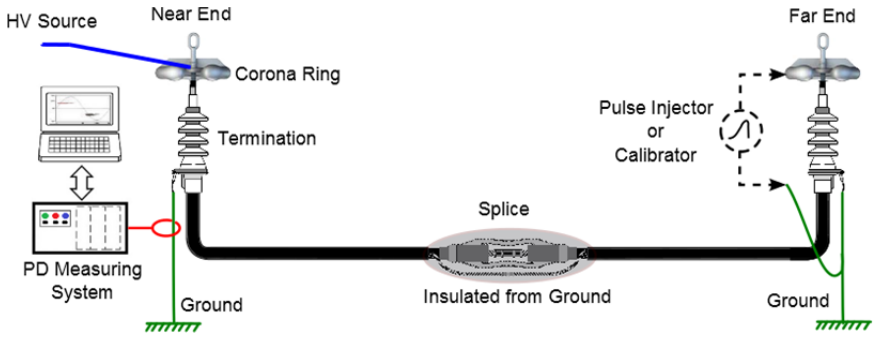
Deployment	
Injector and PD Measuring Equipment Located at the Same End with Coupling Capacitor	
	• Not affected by attenuation or dispersion • Capacitive or inductive sensors • Highest sensitivity
Injector and PD Measuring Equipment Located at the Same End without Coupling Capacitor	
	• Inductive sensor • Not affected by attenuation or dispersion • Reduced sensitivity (enhanced noise rejection)
Injector and PD Measuring Equipment Located at Different Ends with Coupling Capacitor	
	• Attenuation and dispersion effects observed • Capacitive or inductive sensors • Quantifies ability to detect PD from far-end
Injector and PD Measuring Equipment Located at Different Ends without Coupling Capacitor	
	• Inductive sensor only • Attenuation and dispersion effects observed • Reduced sensitivity (enhanced noise rejection)

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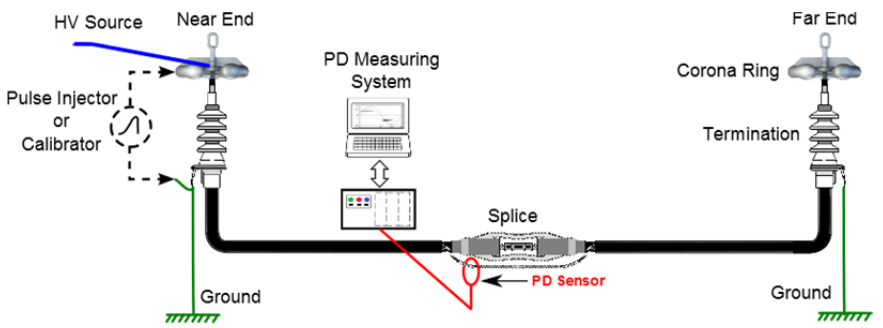
Table 17: Illustration of the Approaches for Sensitivity Check Deployment for PD Measurements on MV Power Cable Systems

Deployment	
Injector Located at One End and PD Measuring System Located at a Splice	
	• Distributed measurement • Inductive sensor • Attenuation and dispersion effects observed • May require injection from both ends if splice is not centrally located

As mentioned above, the presence of the coupling capacitor is always advisable to ensure a low impedance path for the PD current to flow and thus increase the sensitivity. However, there are situations in which it is not possible to use a coupling capacitor. In such cases, the sensitivity check could still be performed as shown in Table 17 using an inductive PD sensor. Unfortunately, the expected sensitivity would not be as high as those approaches that use a coupling capacitor.

7.6.6.2 Range Check

As mentioned above, as PD pulses propagate from a source or sources towards the cable system ends, they are subjected to attenuation and dispersion that then degrade the signal that could be detected. This affects the sensitivity of PD measurements. In particular, the peak amplitude and energy of the traveling PD pulses decrease with the increasing travel length. As a consequence of this length effect, the sensitivity changes as a result of the relative positions of the PD source(s) and sensors. So for short cable systems, PD activity may be readily detected by a terminal measurement using capacitive or inductive sensors. For long cable systems, the attenuation, dispersion, and other factors affecting the sensitivity may degrade the signal to the point where pulses occurring at the far end would no longer be detectable. Range check is a procedure that establishes the distance that a "PD-like" pulse can travel along a cable system and still be measured. Similar to the Sensitivity Check, the Range Check is accomplished by injecting "PD-like" pulses into the cable system from either end. The concept of range check appears in Figure 37.

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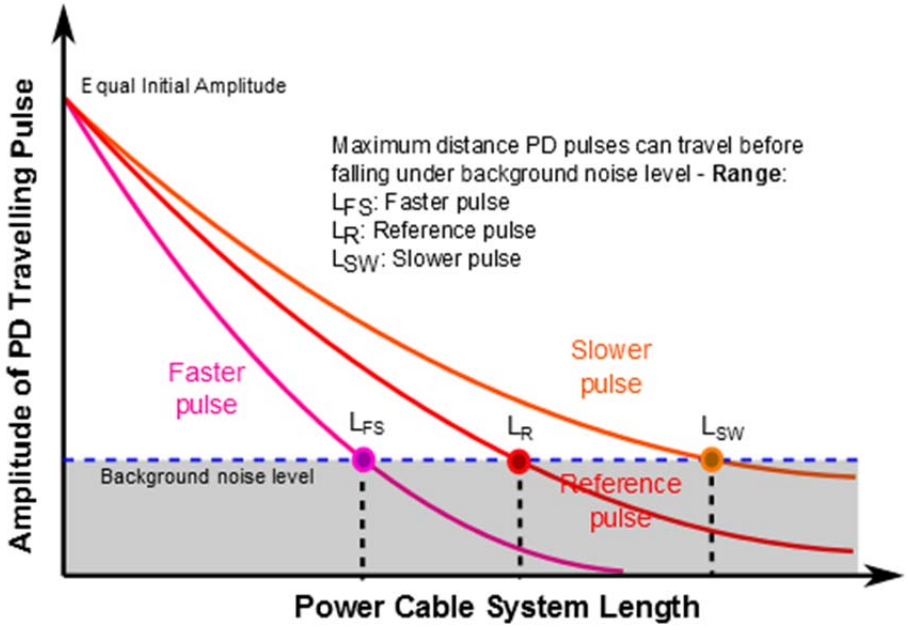

Figure 37: Range Check Concept for MV Cable Systems

Figure 37 illustrates how the peak amplitude of a PD pulse changes as it travels along the cable system. Initially, three PD pulses with the same peak amplitude are considered, the difference between them is their width with the "Faster Pulse" having a narrower width than the "Reference Pulse" and with the "Slower Pulse" having a wider width than the "Reference Pulse". The dashed blue line represents the background noise level. If the peak amplitude of the traveling PD pulse drops below this value then it is assumed that the pulse cannot be detected. Under this scenario, it is observed in Figure 37 that the "Faster Pulse", "Reference Pulse", and "Slower Pulse" are able to travel distances L_{FS}, L_R, and L_{SW}, respectively. The distances L_{FS}, L_R, and L_{SW} represent the "ranges" that their respective PD pulses can travel down the cable system and still be detected. It is also important to note that the faster the pulse, the shorter the range and *vice versa*.

The comparison between pulses in Figure 37 is possible because all the PD pulses were assumed to have the same initial peak amplitude. This assumption is rarely true (if ever) for commercially available pulse injectors. Therefore, care is required when comparing range check results for different pulses/pulse injectors on the same cable system. In the ideal case, the peak amplitude and width of the injected pulses could be adjusted to different values thus allowing the Range Check to be performed over a range of different conditions. However, in reality, conventional calibrators or portable TDR units are used as sources for the "PD-like" pulses. Unfortunately, these devices are limited in their flexibility as they generally only allow changes of one of the pulse parameters. For example, PD calibrators utilize a fixed pulse shape where only the initial amplitude (charge magnitude setting) may be adjusted by the user. TDR units, on the other hand, generally only allow the alteration of the pulse width. The ideal "PD-like" pulse injector should have the option of independently setting the amplitude, pulse width, and its characteristic input/output impedance. The typical connection of a pulse injector appears in Figure 38.

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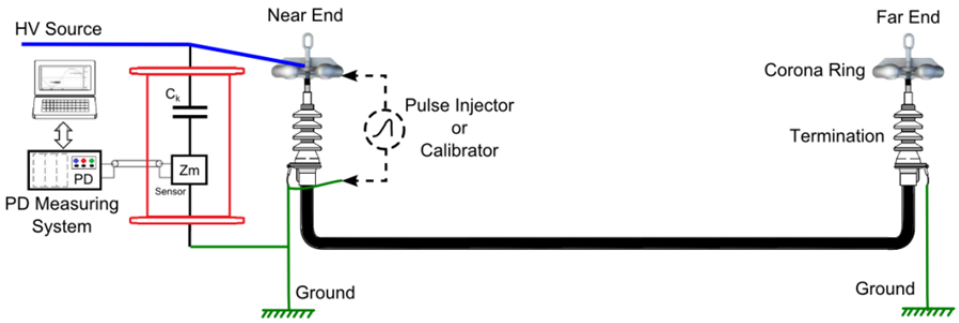

Figure 38: Typical Test Setup for Range Check Procedure

The Range Check procedure begins by injecting a "PD-like" of known width and amplitude into a power cable system as shown in Figure 38. The PD acquisition system should be able to provide the TDR trace of the injected "PD-like" pulse as its travels through the cable system. An illustration of this TDR trace for a power cable system without splices appears in Figure 39.

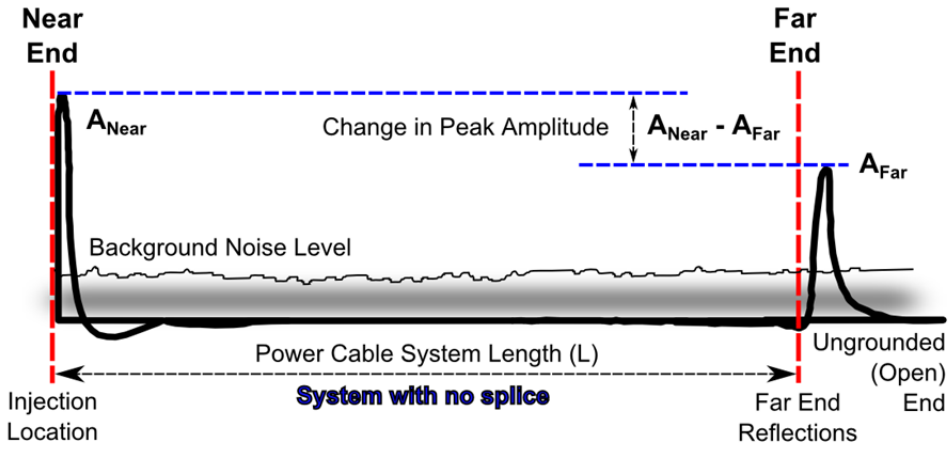

Figure 39: Illustration of Range Check Trace for a Cable System without Splices

The text below describes the Range Check procedure for a power cable system with no splices. In this example this procedure is conducted on a 34 ft long XLPE, 15 kV, 1/0, jacketed cable system for demonstration.

1. Use the following established pulse time widths: 5 ns, 10 ns, 20 ns and 30 ns. If these exact pulse time width numbers cannot be met, use approximate values. For faster pulses, if necessary, adjust the amplitude of the injected pulse at the near end until a good reflection from the far end above the background noise level is observed on the TDR trace (as shown in Figure 39). Each TDR trace represents the cable system response to the different pulse widths – see example traces in Figure 40.

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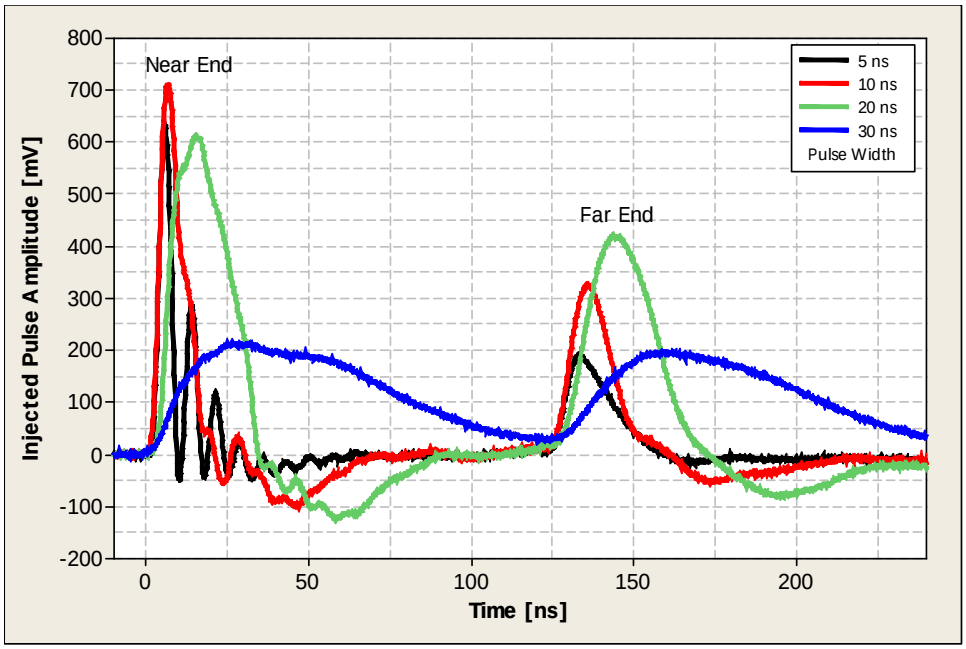

Figure 40: Example Range Check Traces

2. For each of the traces, identify and quantify the peak amplitudes of the injected pulses at the near end and far end reflection and compute the change in amplitude per unit length according to:

$$\Delta A = \frac{1}{2L} \ln\left(\frac{A_{Near}}{A_{Far}}\right) \qquad \textbf{Equation 2}$$

Where,
ΔA: Change in peak pulse amplitude per unit length in [ft^{-1}],
L: Cable system length in [ft],
A_{Near}: Peak amplitude of the injected "PD-like" pulse at the near end in [mV],
A_{Far}: Peak amplitude of the reflected pulse corresponding to the far end in [mV].

Figure 41 shows the normalized (to initial peak value) Range Check traces for the traces shown in Figure 40.

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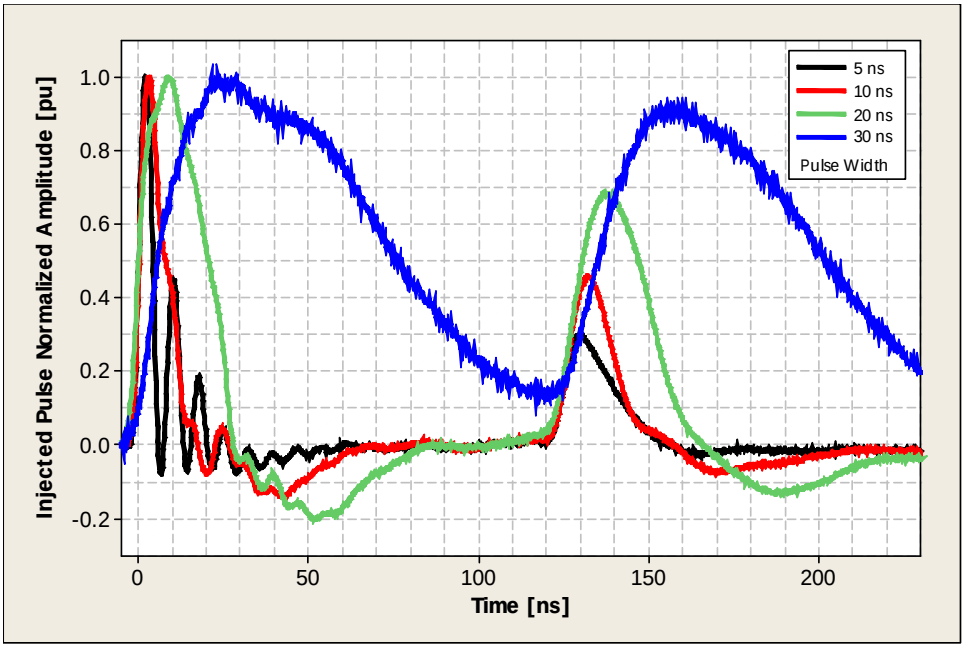

Figure 41: Normalized (to Initial Peak) Range Check Traces

- Estimate distance needed to attenuate each initial peak to the measured noise floor (wider pulses will yield longer distances) using (3).

$$Range\ Check|_{Amplitude}^{Pulse\ Width} = \frac{1}{\Delta A}\ln\left(\frac{Amplitude}{A_{Noise}}\right) \qquad \textbf{Equation 3}$$

Where,

Range Check: Distance, for a given pulse width and amplitude, that a PD pulse can travel along the cable system and still be detectable above the background noise level in [ft],

Amplitude: Peak amplitude of a PD pulse at its source location in [mV],

A_{Noise}: Estimated metric for the amplitude of the background noise level in [mV].

Figure 42 shows the resulting distance calculations for the 5 ns, 10 ns, 20 ns, and 30 ns pulses used in this example. The background noise for these measurements was 2 mV and so the 30 ns pulse would be able to travel 4,000 ft before the return pulse would too low to distinguish above the noise floor. The 5 ns pulse, on the other hand, can only travel 264 ft before it is lost in the noise.

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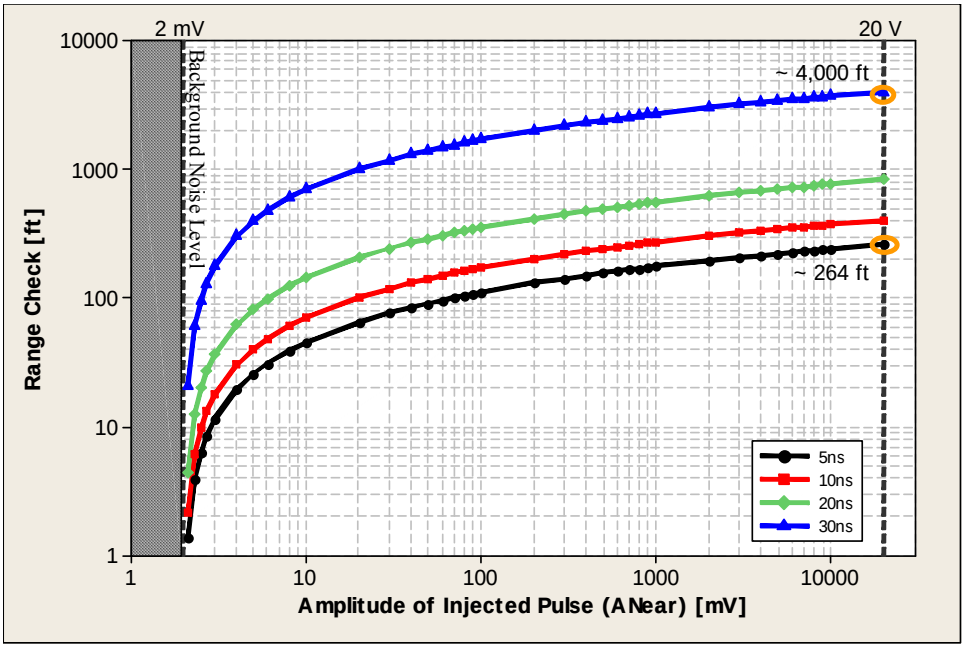


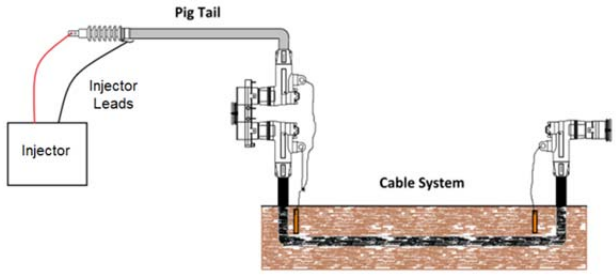
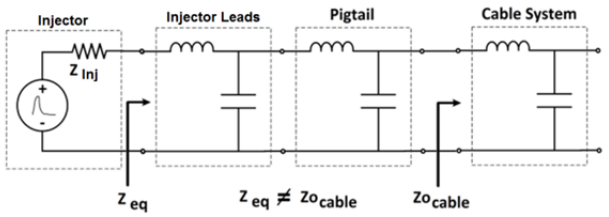
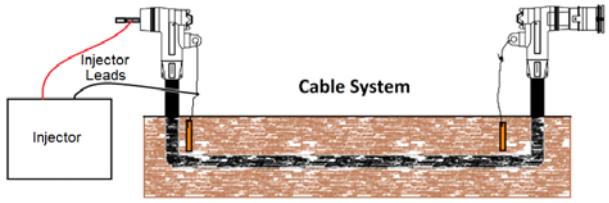
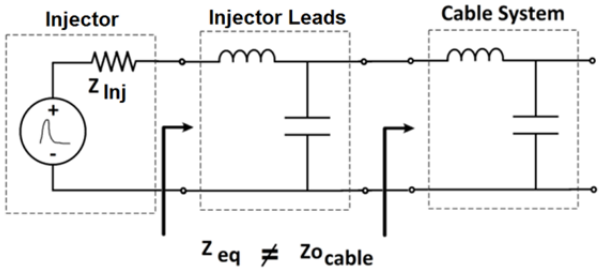
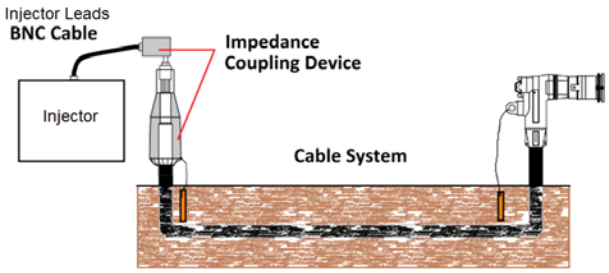
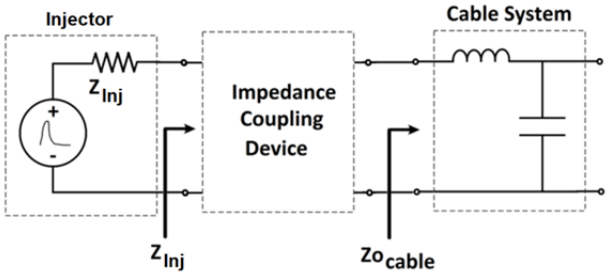
Figure 42: Results for Range Check Example

In summary, the Range Check procedure described above can estimate the distance that a "PD-like" pulse, of known characteristics, could travel along a cable system and still be distinguishable above the noise floor. This method, while imperfect, does provide enhanced information on the attenuation, dispersion, and other factors that cause PD signals to deteriorate as they travel to the detection equipment. The information can then be used to evaluate whether a PD signal, coming for a particular site of the cable system, can be successfully detected at the location of the measuring equipment location and thus determining whether distributed PD measurements should be deployed or not.

7.6.7 Practices For "PD-like" Pulse Injection

Pulse injection units are not built to connect directly onto the various cable system sizes in use on utility systems. The injectors utilize a set of test leads for making the actual connection which have a difference characteristic from that of the cable system. The resulting impedance mismatch causes a reflection at the transition point from the connection leads to the cable system. The severity of this reflection is determined by the degree of mismatch. This reduces the energy the pulse injector is able to transfer into the cable system and can limit the user's ability to perform Sensitivity or Range Checks on longer length systems.

Table 18 shows the known practices for "PD-like" pulse injection, the typical deployment and equivalent circuit showing the transition points and characteristic impedance changes are also presented.

Table 18: Known Practices for "PD-like" Pulse Injection	
Typical Deployment	**Equivalent Circuit**
Multiple Impedance Mismatches – No Correction	
	
Single Impedance Mismatch – No Correction	
	
Single Impedance Mismatch – Impedance Coupling Device	
	

As Table 18 shows, the three primary means of pulse injection include at least one impedance mismatch and may or may not utilize an impedance coupling device (ICD). The ICD can utilize geometric grading, a resistive matching circuit, or a combination of both. Use of an ICD can allow a pulse injector to be used on longer length cable systems than would have otherwise been possible. The least efficient method utilizes a "pig tail" to connect the pulse injector to the cable system while the most efficient method makes a direct connection to the cable system via an ICD. The latter method may require the user to remove the existing termination or elbow to install the ICD.

It is important to mention that in most cases a perfect impedance coupling is not possible nor is it needed. In most MV cable systems, a high level of matching is unnecessary to successfully complete both Sensitivity and Range Checks. This is more of an issue on longer length systems or those that exhibit high dielectric loss.

7.6.8 Grounding Effects

The main goal of grounding is to provide a low impedance path for fault current to return so that protective equipment can detect the fault and act accordingly. This protects users from equipment that could become energized if the fault were not interrupted. Within the context of PD measurements, the cable system grounding has a large effect on how PD signals propagate within the system. Systems with a single grounding point (some HV and EHV installations) allow PD detection equipment to capture more signals as there is but one path to ground. Multiple grounds allow signals to exit the cable system where there may not be detection equipment set up. This is primarily an issue in the field where cable systems are often grounded in at least two locations (such as MV cable systems). Laboratory tests can utilize the single ground approach and are thus better able to capture the PD pulses that might occur in a cable system in the field.

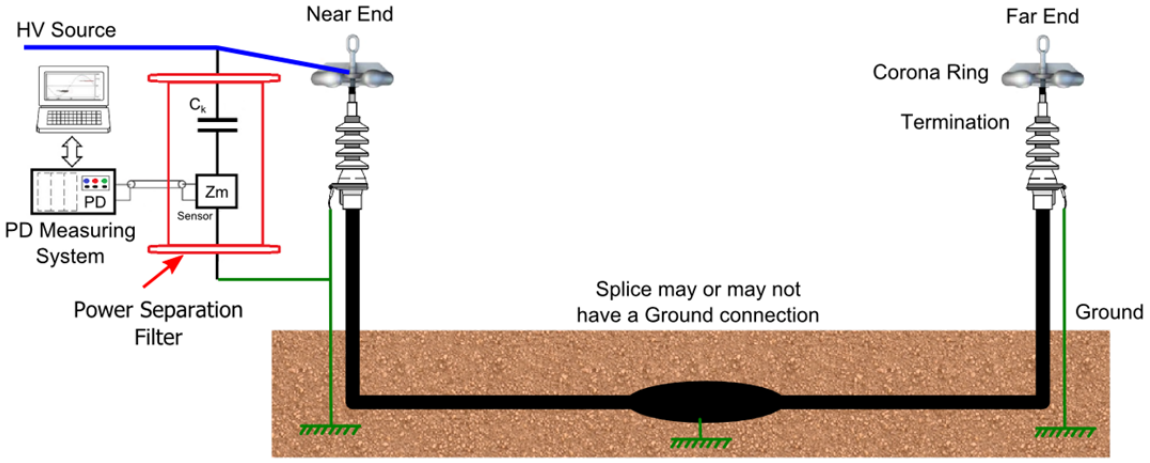
Grounding affects the signals that are able to flow through the sensors and so sensor placement is a key component to the effect grounding has on PD measurements. Three primary sensor configurations are considered:

- **Capacitive Divider with Built-In Sensor:** This configuration considers the coupling capacitor and the sensor together in the same unit. The PD signal may be detected using either a capacitive or an inductive (HFCT) sensor.
- **Coupling Capacitor and Sensor:** This configuration considers the coupling capacitor and sensor as separate units; typically, the sensor is an HFCT that can be coupled to the grounding connection of the coupling capacitor or the grounding connection of the cable system under test.
- **Standalone Sensor:** This configuration only considers the presence of the sensor because there are situations in which the use of a coupling capacitor is not possible. Typically, the sensor is a HFCT coupled to the grounding connection of the cable system under test at the near end.

The various sensor connections and their field and laboratory deployments appear in Table 19 through Table 21.

Table 19: Capacitive Divider with Built-In Sensor Connections

Field Deployment



Laboratory Deployment

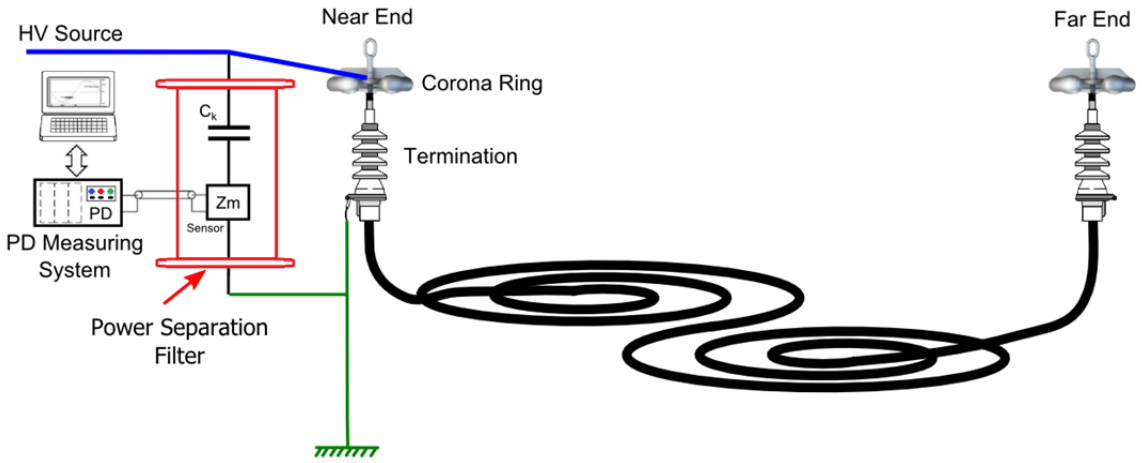
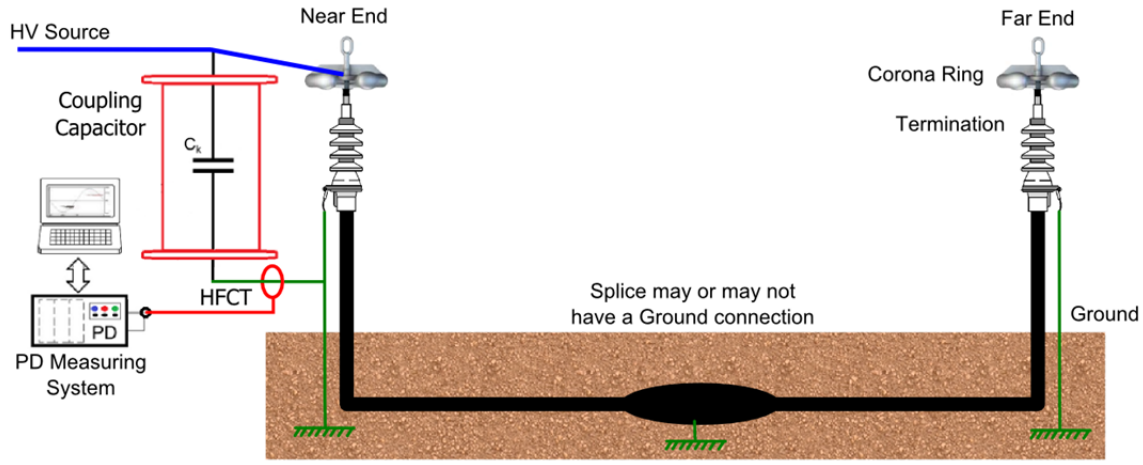


Table 20: Capacitive Divider with Separate Sensor Connections

Field Deployment



Laboratory Deployment

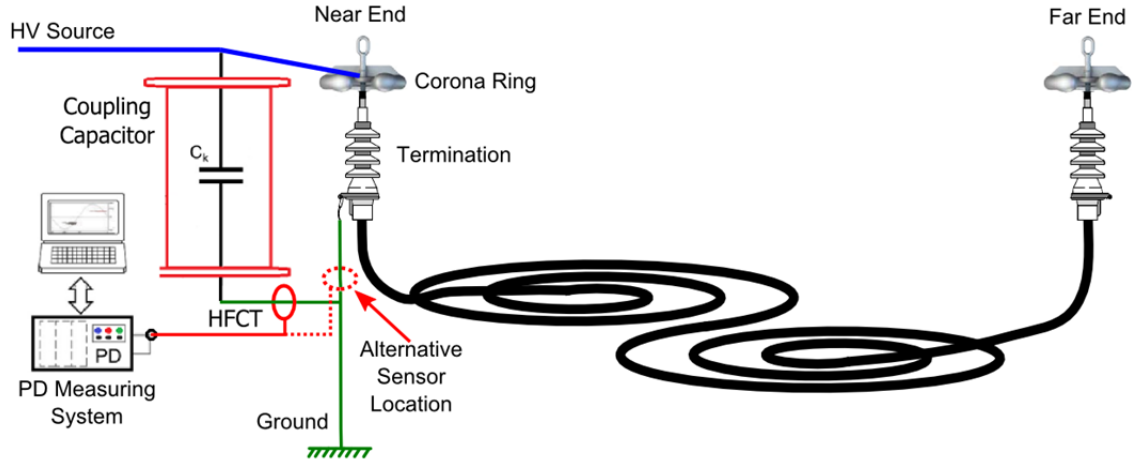
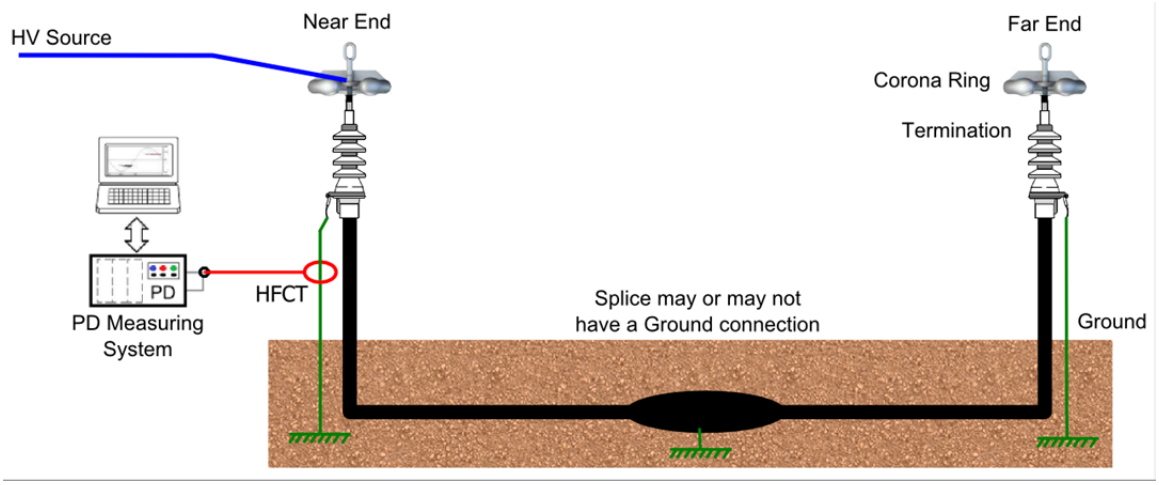
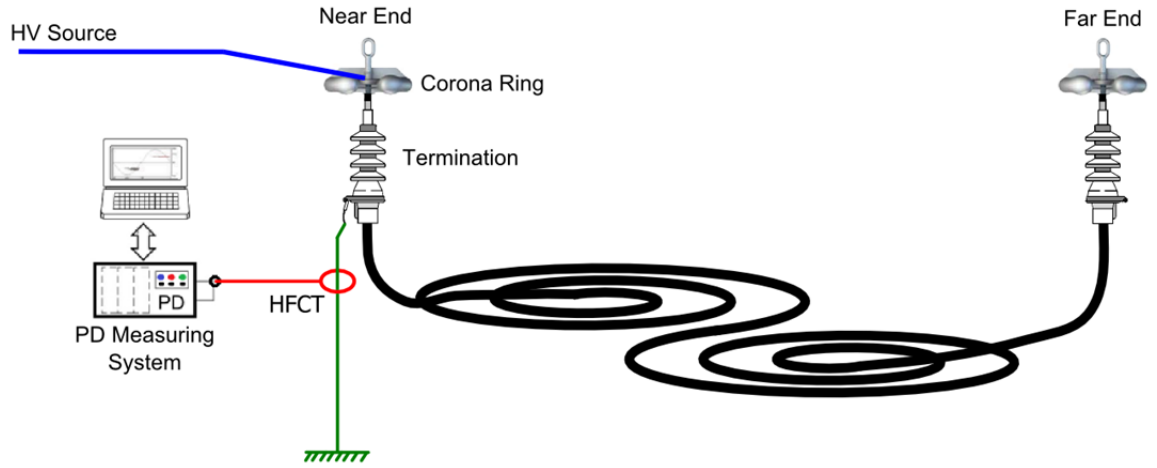


Table 21: Standalone Sensor Connections

Laboratory Deployment



Field Deployment



It is important to note than each of the field connection examples utilize a more complicated grounding arrangement than those employed under laboratory conditions. Care is necessary when trying to employ laboratory techniques and guidance in field situations.

7.6.9 PD Inception Voltage And Magnitude For Classification

Traditionally, the magnitude and inception voltage of PD signals were used to determine whether discharge sites would cause a failure in service. Analytical work on pilot studies have shown that, even if advanced classification tools are used, PD magnitude and inception voltage cannot be used to accurately identify the defects that cause cables or accessories to fail.

The objective of any classifier used in this fashion is to correctly predict a cable system's performance based solely on the available diagnostic feature data. This amounts to assigning a

"Pass" or "Not Pass" assessment to each tested cable system. The most critical performance metric for any classifier is the success rate of its classification, in other words, whether it correctly assesses each cable system. There are fundamentally two forms of success rates for classifiers:

- **Overall Success Rate** – For a complete set of cable systems, this success rate is based on the percentage of the systems that performed as predicted by the classifier (i.e. the number of "Good" systems that did not fail plus the number of "Bad" circuits that did fail) when tested using a training dataset.
- **Group Success Rate** – For each group ("Pass" and "Not Pass"), this success rate is based on the percentage of the systems that perform as predicted by the classifier, but separated by the assessment class. In other words, what percentage of "Pass" systems did not fail and what percentage of "Not Pass" did fail. These tend to be very different figures.

Because of the above definitions, three classifier success rates must be considered in examining a technique's performance with different diagnostic features. It is important to understand, however, that different classification techniques are more efficient in emphasizing elements of the diagnostic features. Unfortunately, classifiers are only successful if the diagnostic features they use are the right ones to make the classification. For example, one cannot use the sound of a car engine to classify the color of its body. Engine sound simply has little or no connection to the color of the car. This analogy is also true in classification using diagnostic features.

Figure 43 shows an example of the accuracies of one classifier, k-Nearest Neighbor (k-NN), when used with PD magnitude and inception voltage data to classify sites as those that will fail ("Not Pass") and those that will not ("Pass"). This classifier has one adjustable parameter that might improve the classification success rate: the number of neighbors to use in the classification. The objective is to choose the number of neighbors (neighborhood size) that achieves the best balance between the group success rates. In this example, 13 neighbors represent the best balance between the two groups.

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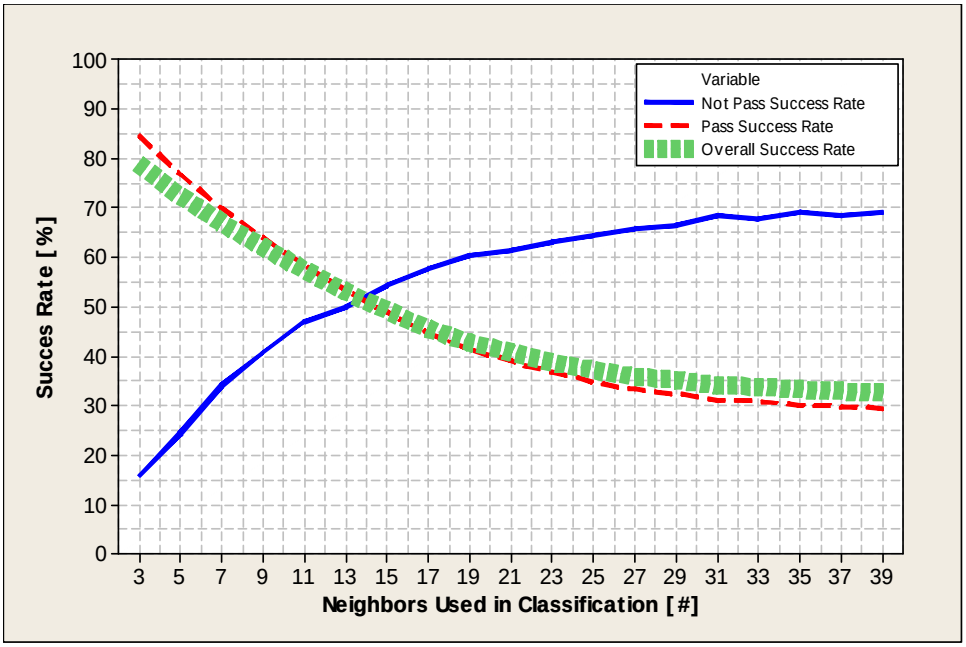

Figure 43: k-NN Success Rates for Different Sized Neighborhoods

For 13 neighbors, the overall success rate for this classifier is only 52%. This implies that PD magnitude and inception voltage are unsuitable for classification since the accuracy is only slightly better than flipping a coin.

The k-NN analysis raises a number of rarely addressed issues:

- What are the appropriate diagnostic features to use for classification? (If not PD magnitude and inception voltage, then what?)
- How many diagnostic features are required?
- What is the best way to use these features?

These questions are addressed for both laboratory and field measurements in the *CDFI*. The approach was to use a multivariate clustering algorithm that combines similar variables into groups or clusters. These clusters indicate, in principle, the number of features required and what features might be chosen. Figure 44 shows the analysis of laboratory data that initially contains 56 different PD diagnostic features. The goal of this graph is to identify how dissimilar different features are – the more dissimilar the better, since dissimilar features provide unique information on the PD signal. Lower values of similarity indicate high dissimilarity (Figure 44). Successive use of clustering reduces the original 56 features down to 15.

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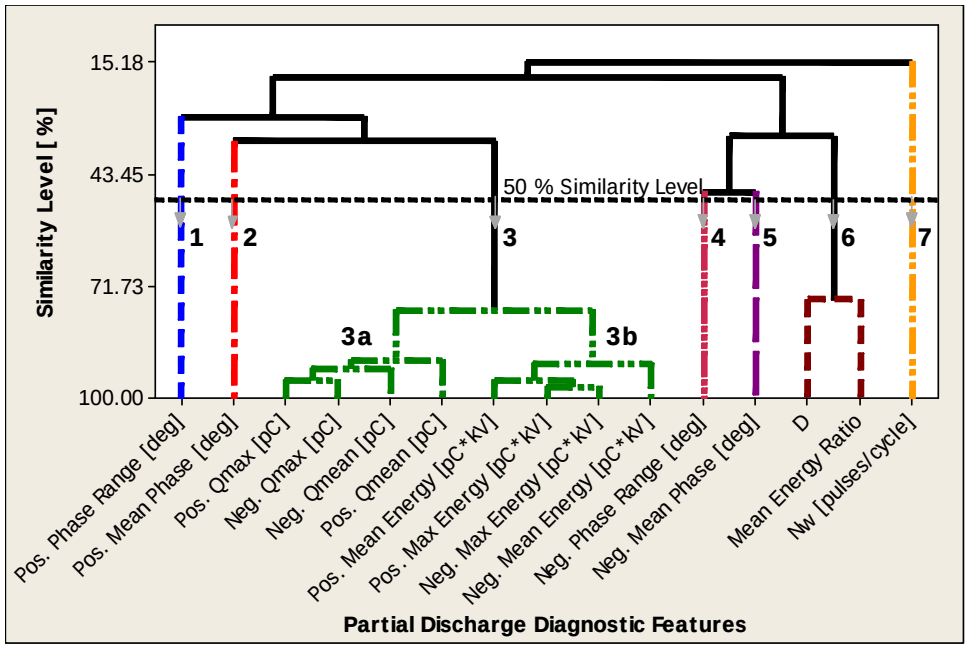

Figure 44: Dendrogram Representation of PD Features

These remaining 15 features naturally arrange themselves into 7 clusters. Clusters 1, 2, and 7 each have a single member while Cluster 3, for example, contains 8 features. This means that a single diagnostic feature from within Cluster 3 can represent the information contained in all the features in Cluster 3. This is important since adding more features from Cluster 3 will not improve the classifier's ability to make the classification, as these additional features do not contain additional information.

Table 22 shows the resulting seven clusters and the features contained within each cluster. In theory, these features could be used for classification.

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Table 22: Feature Clusters Based on Dendrogram		
Cluster [#]	**Feature [#]**	**Feature Name**
1	1	Positive Phase Range [deg]
2	2	Positive Mean Phase [deg]
3	3	Positive Qmax [pC]
	4	Negative Qmax [pC]
	5	Negative Qmean [pC]
	6	Positive Qmean [pC]
	7	Positive Mean Energy [pC*V]
	8	Positive Max Energy [pC*V]
	9	Negative Max Energy [pC*V]
	10	Negative Mean Energy [pC*V]
4	11	Negative Phase Range [deg]
5	12	Negative Mean Phase [deg]
6	13	D - Symmetry Factor
	14	Mean Energy Ratio
7	15	Nw [pulses/cycle]

As mentioned above, the key to any classification problem is to choose the right features. The dendrogram approach shown in Figure 44 represents one approach to solving this problem.

7.6.10 Reporting and Interpretation

It is widely acknowledged that signal interpretation and classification are major challenges in field testing. PD tests on new cables or accessories in the factory are made on,

- one device at a time with known characteristics;
- inside shielded rooms where ambient electrical noise is minimized;
- with special laboratory type terminations and grounding arrangements; and
- no component to component interfaces.

Interpretation of the PD data is relatively straightforward in these cases as there should be no PD present. PD tests in the field, on the other hand, are made on circuits with,

- multiple unknown aged components (with possibly different factory PD requirements);
- standard cable system field grounding; and
- located in unique ambient noise environments.

The signals of interest must first be captured and then separated from the extraneous noise. This separation process is challenging as the cable system acts as an antenna for all types of electrical noise. Interpreting the PD signals (if present) is also a challenge because the circuit under test is

often a hybrid mix of cable types and cable accessories that are of different vintages with different amounts of aging. Thus, PD measurements in the field are generally more difficult to interpret than factory or laboratory measurements.

The basic goals of PD interpretation are to,

- distinguish true PD signals from background noise;
- establish that the PD signals are located within the devices being tested; and
- confirm whether the PD poses a risk to the cable system.

Partial discharge data are reported in a variety of forms. They may be a simple report of one PD parameter such as PD magnitude as a function of applied voltage or may include an analysis of multiple parameters that are embedded in PD signals (e.g. phase, density, inception voltage, etc.). Some practitioners believe that a detailed analysis provides little benefit to the customer. They benefit most by indicating that PD is present, often by quoting a discharge magnitude (pC) and/or an inception voltage and an approximate location. Others consider that the traditional PD metrics are insufficient indicators and have developed customized and, thus, proprietary indicators. Both approaches are effective; however, they each have advantages and disadvantages.

Traditional Indicators (PD magnitude and inception voltage)

The advantages of this approach are:

- This type of data is familiar and available from providers.
- Performance criteria based on these indicators may be uniformly established and updated as new performance information becomes available.

The disadvantages of this approach are:

- Although familiar underlying assumptions are well understood, misinterpretations of PD data can occur.
- PD magnitude and inception voltage are generally insufficient to classify accurately the severity of the discharge. In fact, highly detailed analyses within the *CDFI* show this is the case (Figure 43 and Figure 44).
- Traditional parameters do not provide the user with actionable information.
- Without an indication of severity, it is impossible to know if the presence of PD is a problem.
- PD magnitude is highly dependent on calibration and service providers have not standardized calibration procedures.

Customized Indicators (recommended actions or level codes)

The advantages of this approach are:

- They have the potential to consider more information in their classification of discharges than magnitude and inception voltage alone.
- The more detailed analysis of the PD has the potential to highlight the impact of the discharge on performance.
- The recommended actions or level codes derived from the detailed analysis provide a user with actionable information.

The disadvantages of this approach are:

- It is difficult to verify that the more detailed classification is accurate as the algorithms and knowledge used to make the classifications are proprietary.
- When classes are updated, it is difficult to establish the relationship between the old and new classes. This is particularly challenging when the number of classification levels change.
- Level indicators are essentially ranks (e.g. “1, 2, or 3,” “a, b, or c,” or “replace, repair, or OK”) and, thus, do not convey the relative differences between levels. In other words, we can say (a) is more severe than (b) but not by how much.

7.6.11 Expected Outcomes

During the *CDFI*, several PD data sets were collected and analyzed from both lab and field PD tests. The distribution of the data between lab and field data appears in Table 23. Figure 45 shows the individual lengths of cable systems tested using PD measurement techniques.

Table 23: PD Measurement Lengths		
Technique	**Laboratory [Conductor miles]**	**Field [Conductor miles]**
PD Offline	2	490
PD Online	-	262

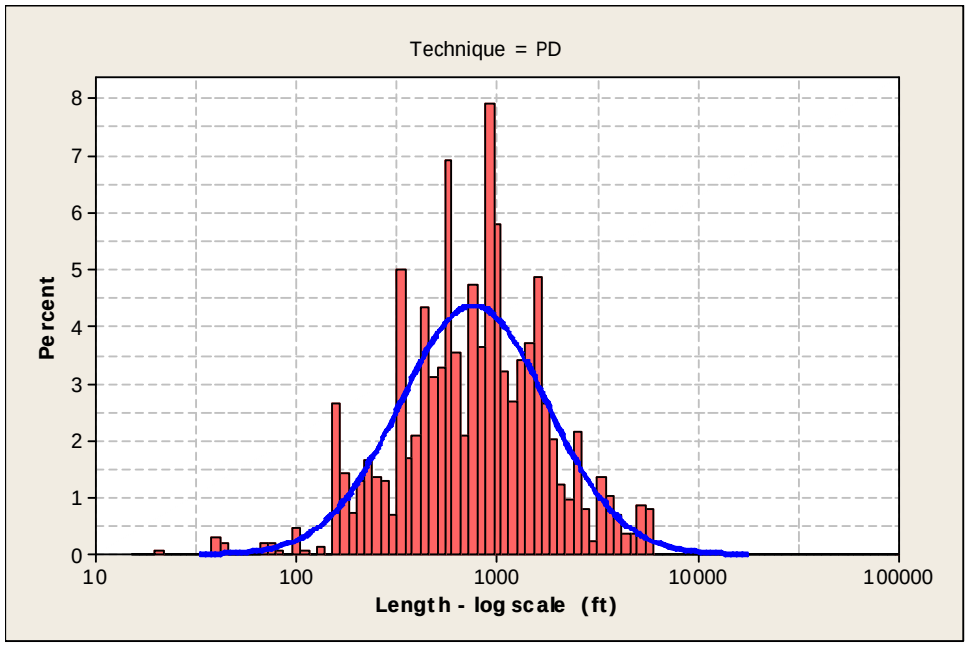

Figure 45: Tested Cable System Lengths – PD

Analyzing the reported data is useful in two ways:

- to estimate potential scenarios that would result from the use of different PD measurement techniques; and
- to establish trends and to identify uncharacteristically high or low test results.

Analyses were compiled for field data from the two main PD approaches:

- online – one of four techniques were analyzed;
- offline – two of four techniques were analyzed.

The use of customized indicators in some of the offline and online measurement techniques makes it difficult to compare results. However, they are useful in analyzing general outcomes/scenarios.

Offline

Figure 46 shows how all of the Offline PD data analyzed in the *CDFI* are distributed as a whole among the custom indicators. For example, 62.2% of the total populations of systems tested were classified as "Defer" by the diagnostic provider. The data are from one Offline PD technique. The diagnostic provider has verified that the custom indicators have evolved over time, but the extremes appear to be consistent ("Replace" and "Defer"). The "Repair" category consolidates a number of generational steps (indicators).

Figure 47 shows how the individual data sets are distributed among the custom indicators (used in Figure 46): each solid symbol represents a single dataset. For example, for the "Replace" indicators one data set had 25% its tested circuits classified as "Replace" while another data set had only 2.5% of circuits classified as "Replace".

Figure 48 shows how all of the detected PD site data analyzed in the *CDFI* were distributed as a whole among the cable system components. As an example, approximately 39% of the PD sites were found in the cable portions of the tested circuits.

Figure 49 shows how detected PD sites from the individual data sets were distributed among the cable system components: each solid symbol represents a single dataset. As an illustration, this figures shows that 5% – 44% of all PD sites identified within a particular dataset were located in splices.

Figure 50 relates the occurrence of PD sites to the length of the cable system tested: based on the mean and median, respectively, we would expect 19 and 8 PD sites per 10,000 ft of system tested.

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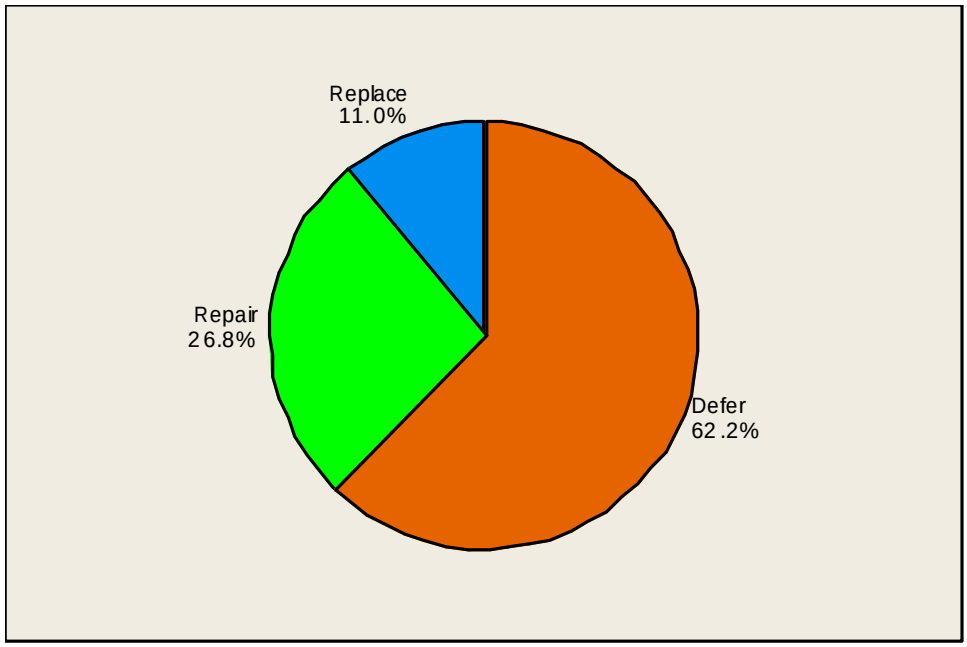

Figure 46: Split between Action Classes – Offline

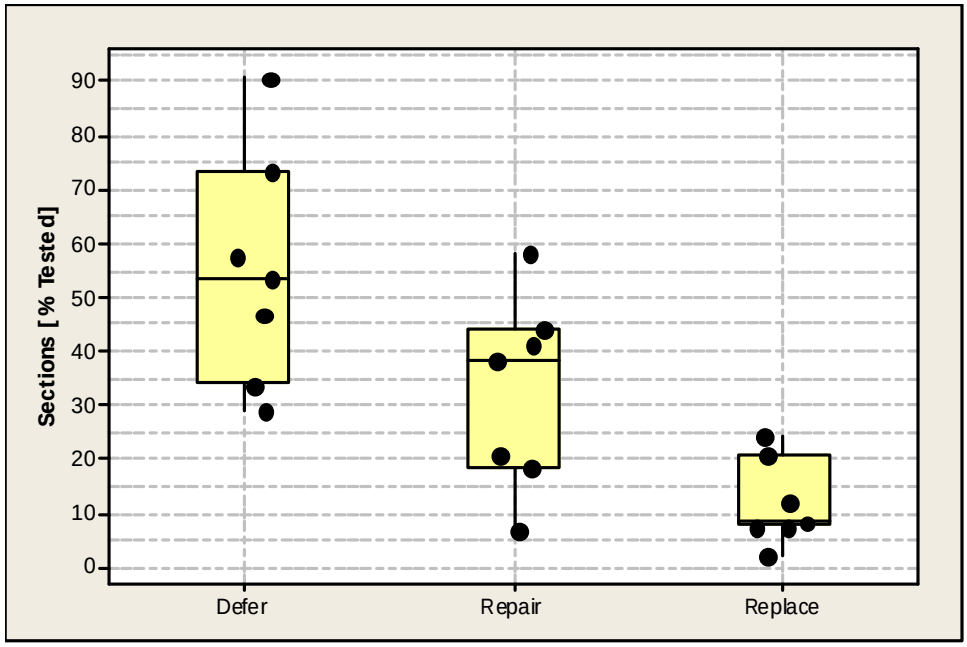

Figure 47: Range within Classes - Offline

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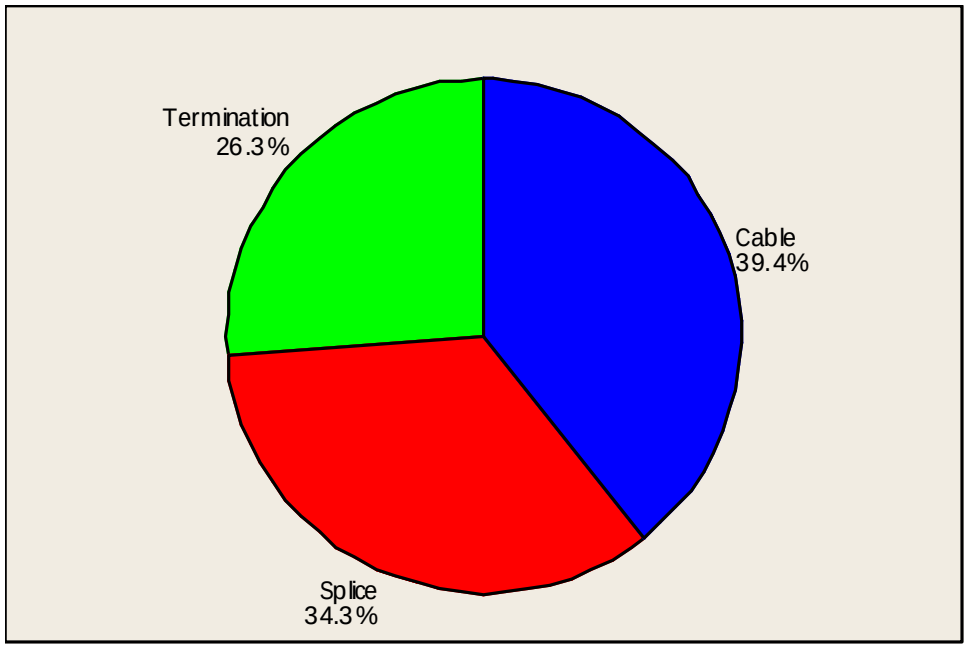

Figure 48: Split between PD Sources – Offline

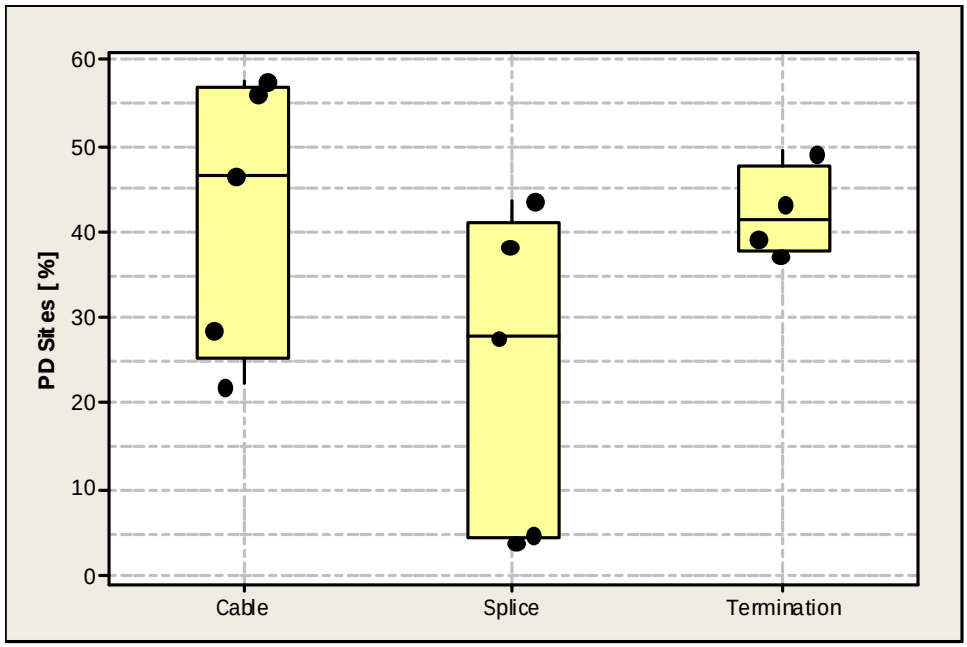

Figure 49: Range within PD Sources – Offline

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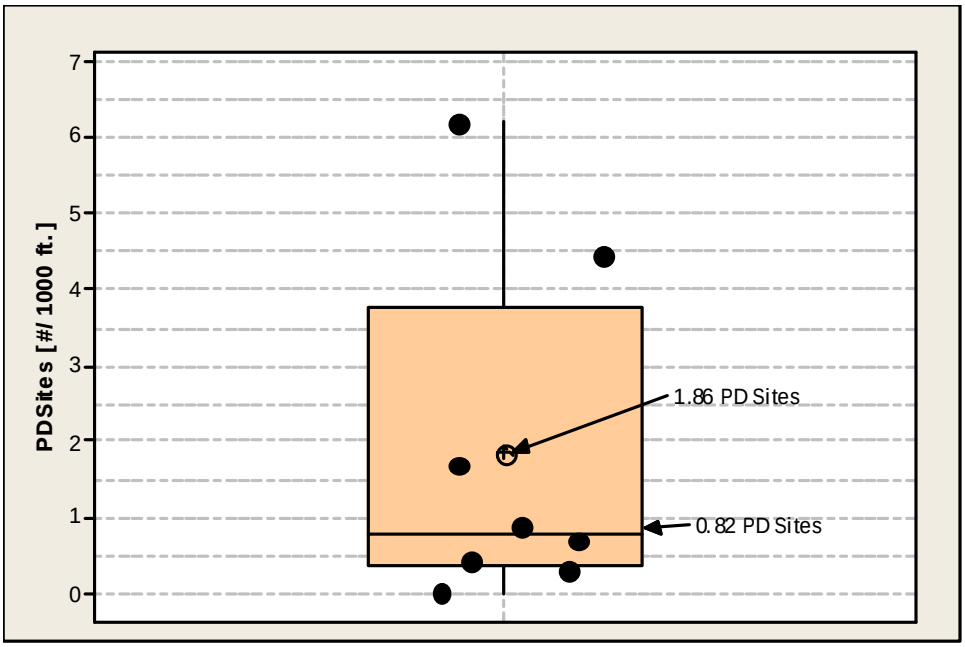

Figure 50: Range of PD Occurrence per 1,000 ft - Offline

Online

Figure 51 shows how all of the Online PD data analyzed in the *CDFI* are distributed as a whole among the custom indicators. The data are from a single method of the Online PD technique. The diagnostic provider has reported that the custom indicators have not evolved over time. For example, 62.2% of accessories and 68% of cable sections tested are classified as Level 2 by the diagnostic provider.

Figure 52 shows how the individual data sets are distributed among the custom indicators (used in Figure 51): each solid symbol represents the dispersion for a single dataset. For example, the individual datasets indicate that 45% – 90% of tested accessories were classified as Level 2.

Figure 53 shows how all of the Level 4 and Level 5 (indicating presence of PD) data analyzed in the *CDFI* were distributed as a whole among the cable system components. This technology embodiment does not permit the separation of joints and terminations, thus the data only pertain to accessories.

Figure 54 shows how the Level 4 and Level 5 data from the individual data sets were distributed among the cable system components: each solid symbol represents the dispersion for a single dataset. For example, 0% – 80% of tested cable sections within a particular dataset were classified as Level 4 or Level 5 by the diagnostic provider.

Figure 55 relates the occurrence of Level 4 and Level 5 to the length of cable system tested, these data are segregated for cables and accessories as well as the grouped approach for all - based on the median we would expect 1 PD site per 4,000 ft of system tested.

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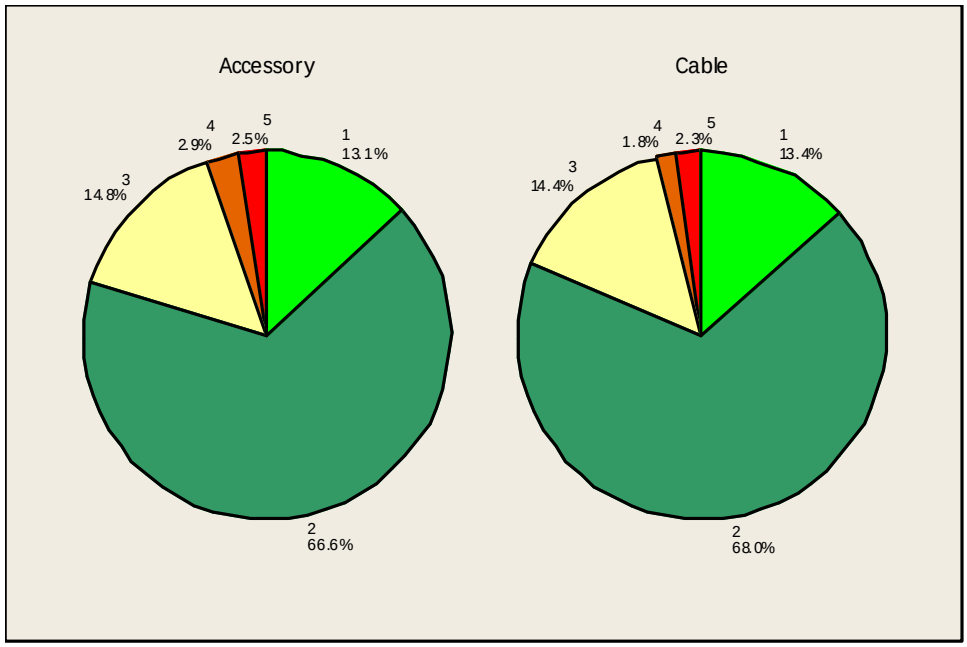

Figure 51: Split between Assessment Classes – Online

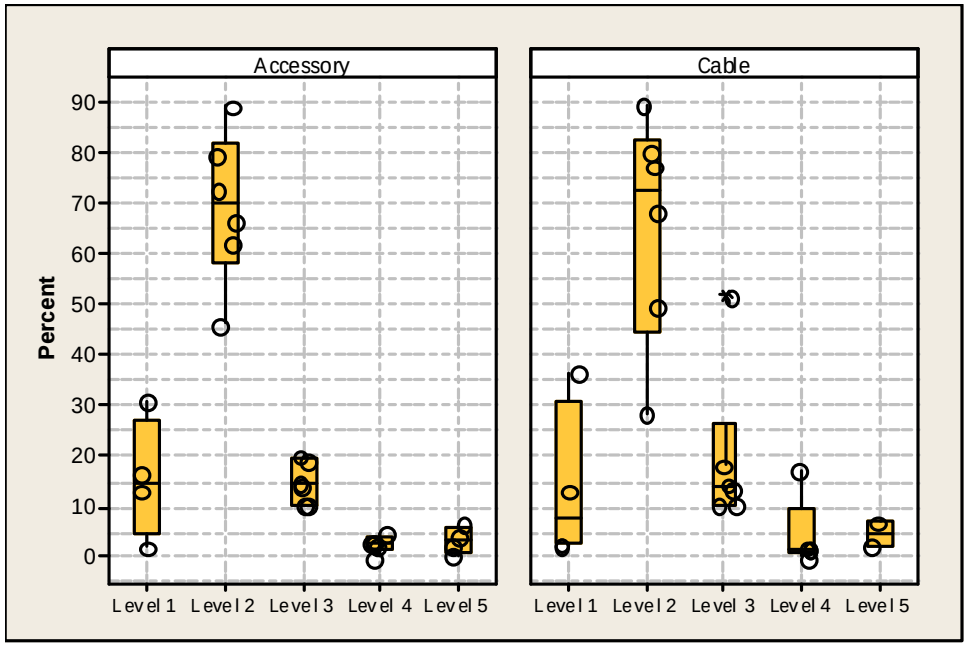

Figure 52: Range within Classes - Online

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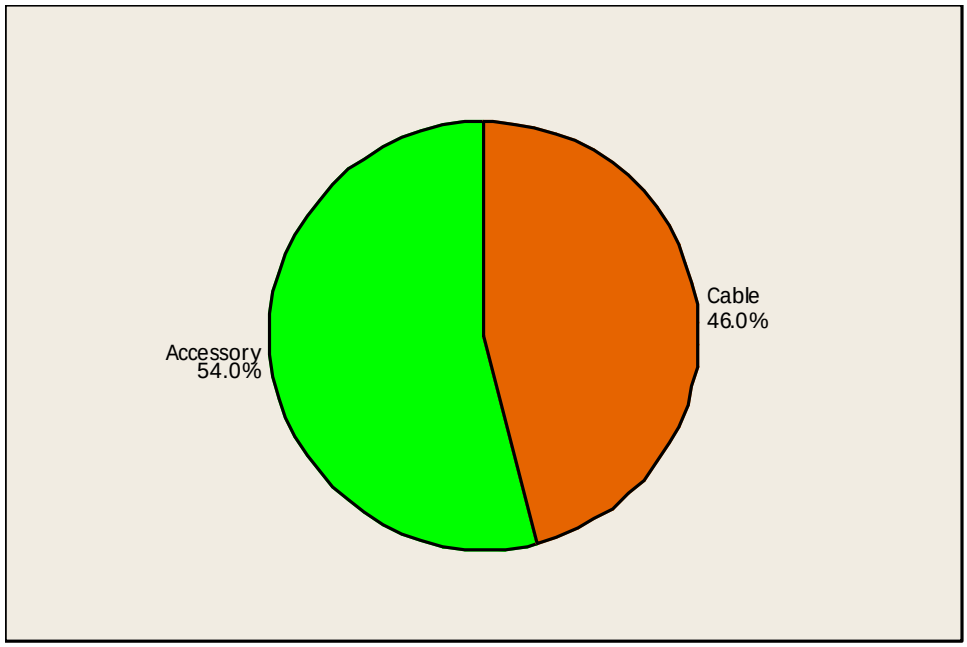

Figure 53: Split between PD Sources – Online

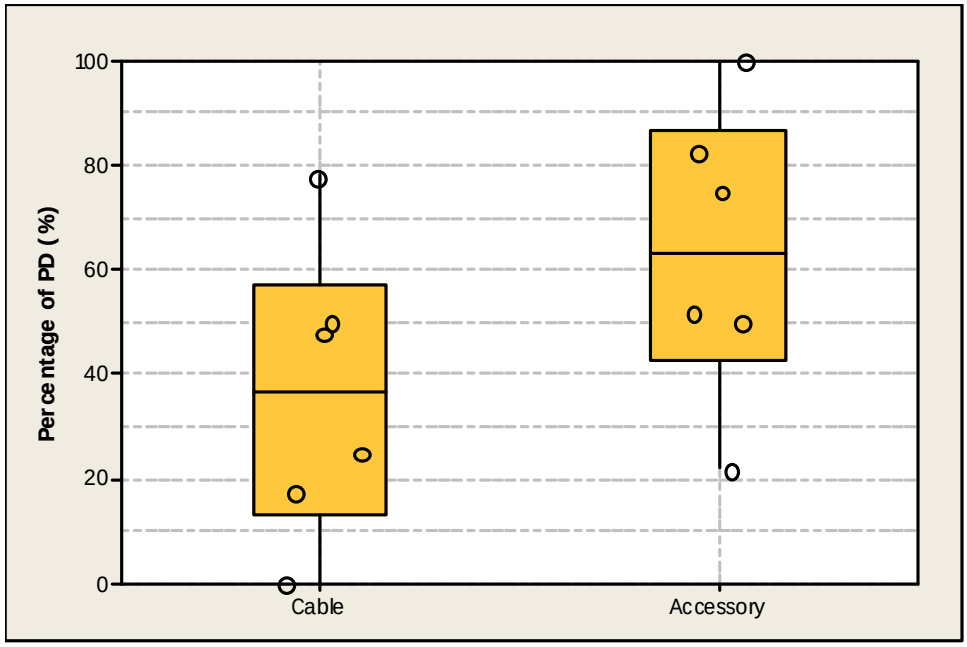

Figure 54: Range of within PD Sources – Online

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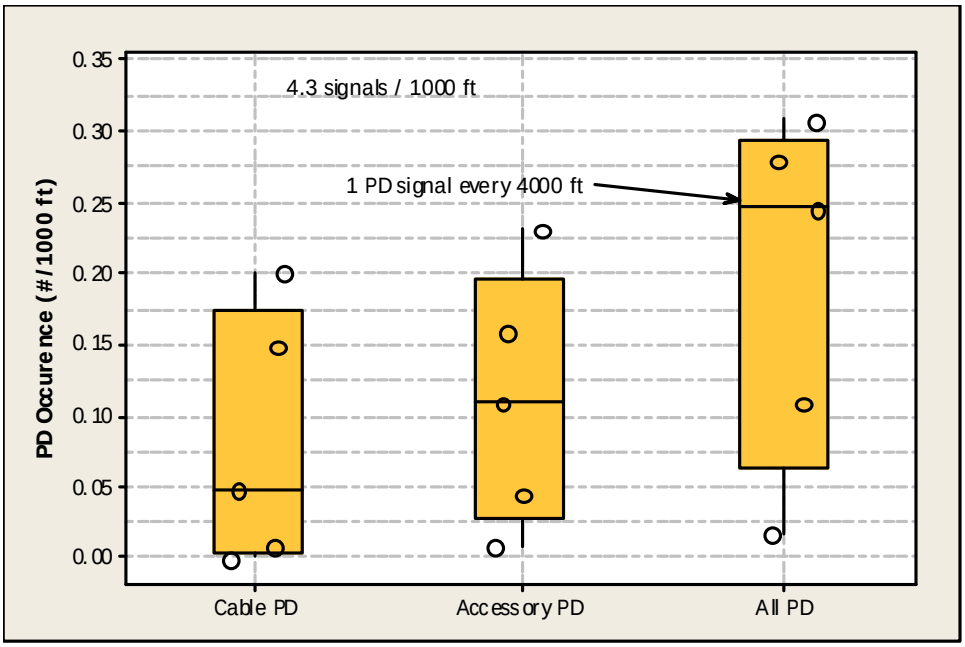

Figure 55: Range of PD Occurrence per 1,000 ft – Online

When pilot studies were undertaken (with the diagnosed cable systems left in service) and the post-test service performance was followed, it was possible to determine Diagnostic Performance Curves. These curves show how failures have accumulated within circuits in the same classification group. Figure 56 shows diagnostic performance curves for one of the Online PD technologies from data supplied by a diagnostic provider. This approach uses the provider's custom classifications for discharges (1 to 5, Levels 4 and 5 refer to "discharge" signals while it is not clear what Levels 1, 2, and 3 represent). The collated service failures recorded after the test enable the probabilities of failure (shown as percent on the y-axis) for Levels 3, 4, and 5 to be estimated since the systems were left untreated. Interpreting these curves entails estimating the probability of service failure for selected times. As an example, systems classified as Level 5 have a failure probability of 40% within one year after the test and greater than 99% within 2.5 years after the test.

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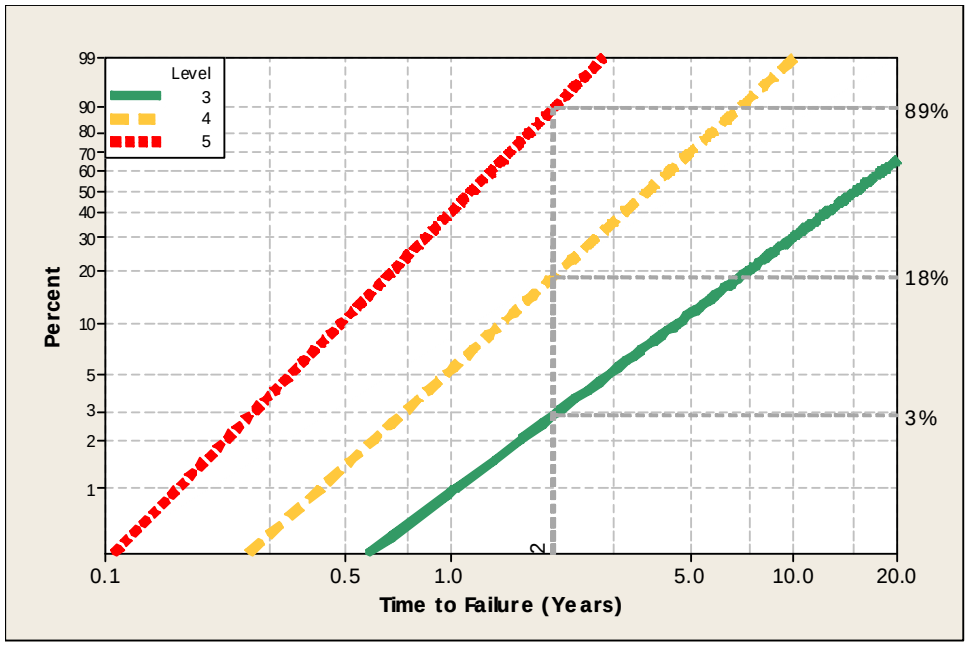

Figure 56: Diagnostic Performance Curves for One Online PD Test Technique

Figure 57 shows the diagnostic performance curves for PD sites detected using one Offline PD technique. The curves originate from failure data supplied by a participating utility. Note that these curves are for individual PD sites located in cables and splices.

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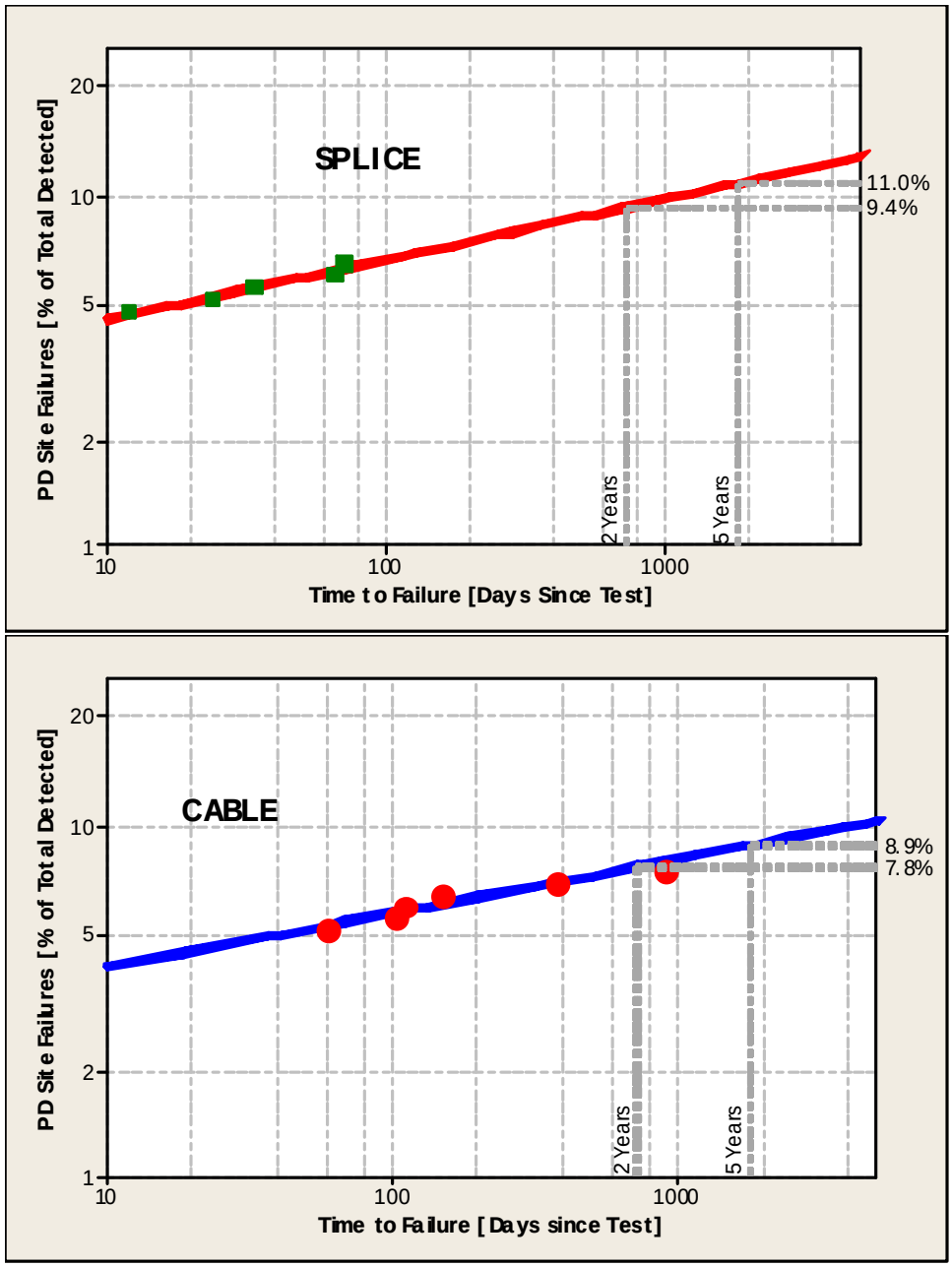

Figure 57: Diagnostic Performance Curves from a Cable System in Service for One Offline PD Test Technique, Separated by Cable (bottom) and Splices (top)

The Diagnostic Performance Curves of the type shown in Figure 56 and Figure 57 are useful as they help utilities interpret diagnostic test results by indicating expected results. A number of these benefits appear below:

As noted previously, one of the aspects of custom indicators is that the level codes are ranks that do not convey the relative differences between levels. Performance curves enable level interpretation or renaming as shown in Table 24. Levels are based on the probability of failure for circuits classified at each level shown in Figure 56 within two years after the test. The alternate codes show

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that the separations between Level 3 and Level 4 are different as compared to the difference between Level 4 and Level 5. The available data in Figure 56 do not include information on Level 1 or Level 2. Thus, these levels only indicate a lower probability of failure than Level 3.

Table 24: Interpretation or Alternate Codes for Custom Level Assessments from Figure 56	
PD Level Code	**Alternate Code**
Level 1	<< 3
Level 2	< 3
Level 3	3
Level 4	18
Level 5	90

The Diagnostic Performance Curves also enable utilities to estimate the potential number of failures over time and, thus, make an informed economic evaluation of potential actions to take based on the test results. Table 25 shows a computation for a 14-mile MV cable system segregated into 100 systems (the dispersion of PD sites is shown in Figure 48 and the occurrence of PD appears in Figure 50). The estimates show that approximately 12% of the defects will have led to failure within 5 years. It is important to recognize that all defects need to be treated, repaired, or replaced to improve reliability because which ones will fail first is unknown.

Table 25: Example Scenario Evaluation for an Offline PD Program			
PD Location	**Sites [#]**	**Predicted Failures**	
		After 2 Years	**After 5 Years**
Cable	31	3	3
Accessories	47	5	6
TOTAL	78	8 [10.2%]	9 [11.5%]

7.6.12 Noise

As PD measurements constitute the detection of an induced high frequency (HF), very high frequency (VHF) and/or ultra-high frequency (UHF) electric signals on cable systems, rejection of similar non-PD related signals is imperative. Such signals are commonly referred to as noise. Noise is always present and different for each test when performing PD measurements in the field. It can come from radio stations, television stations, electronic switching devices operating nearby, stray currents in the earth or on the cable metallic shield and a wide variety of other sources.

Noise can be a critical impediment to successfully detecting PD. Both Sensitivity and Range Checks are affected by external noise. Magnitudes of the PD pulses registered by the measuring equipment are in the order of fractions of millivolts to several tens of millivolts. In addition, when PD pulses reach the detection equipment, they generally have a bandwidth of several tens of megahertz. Unfortunately, this frequency range includes most of the amplitude and frequency modulated communication signals and, in some cases, these signals can have a higher magnitude than the partial discharge signals.

The level of noise depends on several factors that include system parameters such as length, location, design, structure, signal degradation mechanisms, and neutral condition, as well as on the particular nature of the PD present in the cable system. From the perspective of noise, the cable acts as an antenna that picks up the communication signals as well as other noise that may be related to the grounding. In reality, it is impossible to avoid these signals in the field.

Several techniques have been used to reduce background noise levels. Analog and digital filters are typically applied; however, other digital signal processing techniques such as wavelet transforms have recently been used as well. Improvements over the past decade in signal classification have greatly improved the value and interpretation of acquired PD data. One of the more important improvements was the development and application of the time-frequency classification map. This map is based on the fact that PD pulse waveforms depend on the nature of the defect and its location within the cable system. Thus, pulses having similar waveforms should be from the same source.

Manufacturers and providers of PD test equipment have implemented various approaches to this technique. The technique involves classifying individual measured pulses on the basis on their frequency content, duration, and other characteristics associated with the pulse shape. The processing and generation of a classification map relies upon the acquisition of a large number of pulses. This technique is particularly useful for on-line PD measurements where, very often, multiple PD sources are present. Classification of different categories of measured pulses can help separate multiple PD sources from one another and thus produce individual pulse phase analysis plots for each source. Different examples for the application of the classification map from different providers appear in Figure 58.

There is no doubt that noise will continue to be a challenge for PD measurements even though the effectiveness and sophistication of noise mitigation techniques continues to advance.

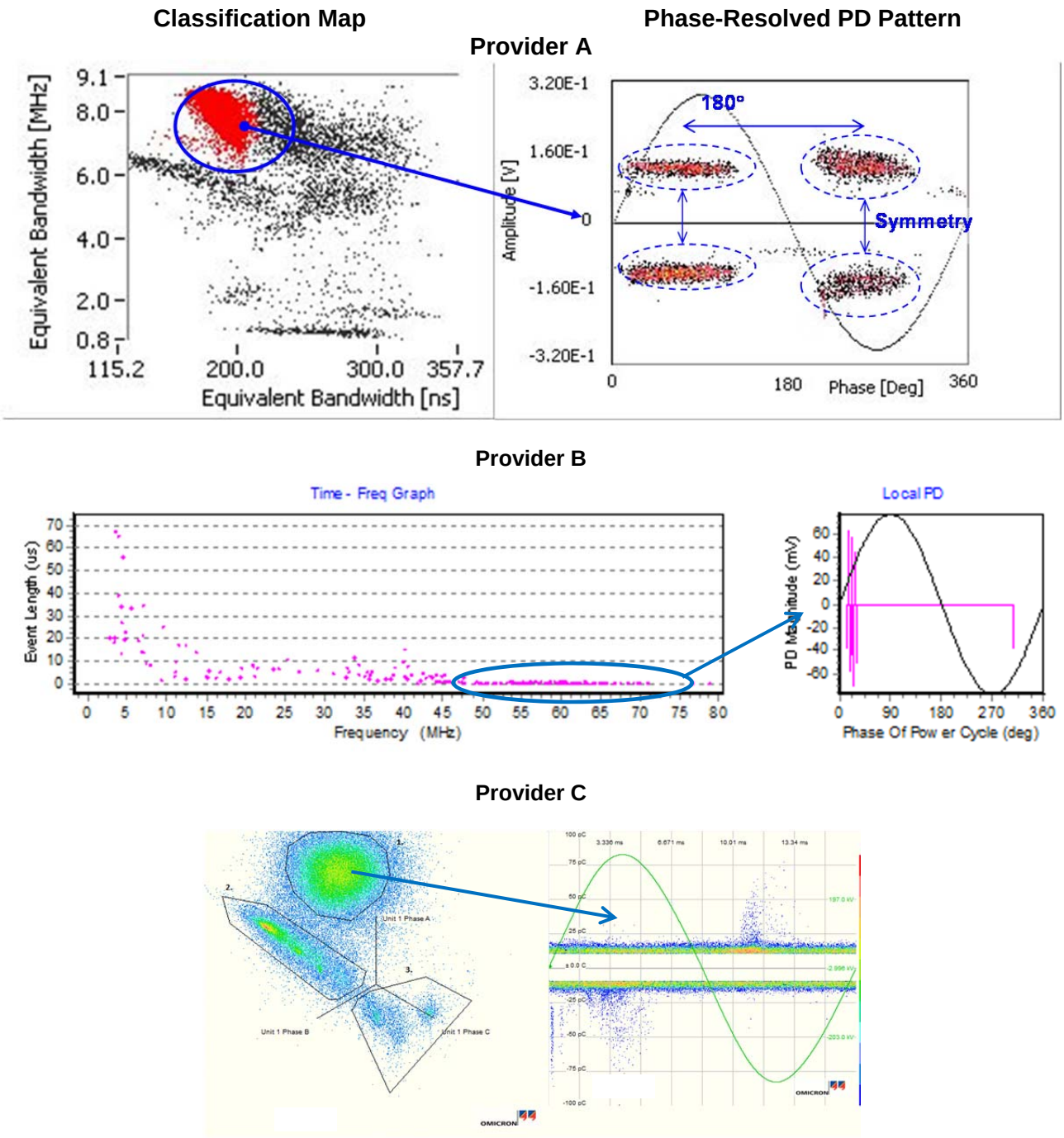

Figure 58: Different Examples for the Application of the Classification Map from Different Providers

7.6.13 Conundrum between PD Scaled Charge and Energy

The idea of signal "size" is crucial to many applications. Examples of such applications might include knowing how much electricity can be used in a defibrillator without causing permanent damage to the patient, or it would be also nice to know if the signal driving a set of headphones is enough to create a sound. While both of these examples deal with electric signals, they are clearly very different dealing with signals of significantly different scale from those seen in PD measurements. For this reason, it is imperative to quantify this idea of "size" of a signal in its specific context. The quantification of the "size" of a signal then leads to the ideas of area under the curve and energy.

Since a signal is generally thought of as a function of varying amplitude through time, it is reasonable to assume that a good measurement of the strength of a signal would be the area under the curve. However, this area may have a negative portion. This negative portion does not have less strength than a positive signal of the same size; however, by taking the area encompassed by the curve the areas below the time axis cancel with the areas above it. A better approach to estimating the signal strength would be to either square the signal or take its absolute value, and then find the area under that curve. In fact, the energy of a signal is defined as the area under the curve of the squared signal. An illustration of the area under the curve and energy for a signal as a function of time ($f_{(t)}$) appears in Figure 59.

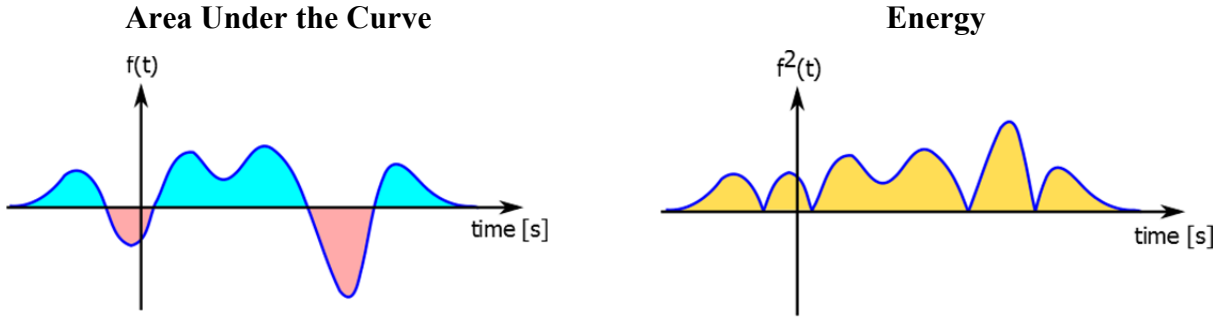

Figure 59: Illustration of the Area Under the Curve and Energy for a Signal as a Function of Time ($f_{(t)}$)

In the case of PD, the relationship between the area under the curve (scaled charge) and energy is important. Traditionally, PD activity was simply quantified by the scaled charge. The use of scaled charge as a metric for PD and low frequency bandwidths, make measurements insensitive to PD pulse shape and other signal aberrations. However, this assumption is only valid if it is assumed that the cable system acts as a low-pass filter and thus the scaled charge (DC component of the PD signal) is completely transferred from the PD site to the location of the PD measuring equipment. Under this scenario, another frequently overlooked issue, even for an ideal (lossless) cable system, is that the peak amplitude of the traveling PD pulse can decrease to the point that it is comparable to the background noise level and thus no triggering/detection is possible.

In reality, both the scaled charge and signal energy change as the PD signal propagates through the cable system. This situation is unavoidable and is a consequence of the very high frequency components of PD signals and the non-linear frequency response of the cable system that results in

interactions between frequencies components. Therefore, to understand the conundrum between PD scaled charge and energy, two studies are presented:

- cable system simulation based on simple filtering; and
- cable system simulation based on a frequency dependent, distributed model.

The two studies are presented in detail in the next subsections.

7.6.13.1 Simple Filtering Model

In this case, the cable system is modeled as a simple low-pass filter, the input PD pulse is run through the filter and output PD pulse is recorded. The origin for this cable system simulation is based on simple filtering as is shown in Figure 60.

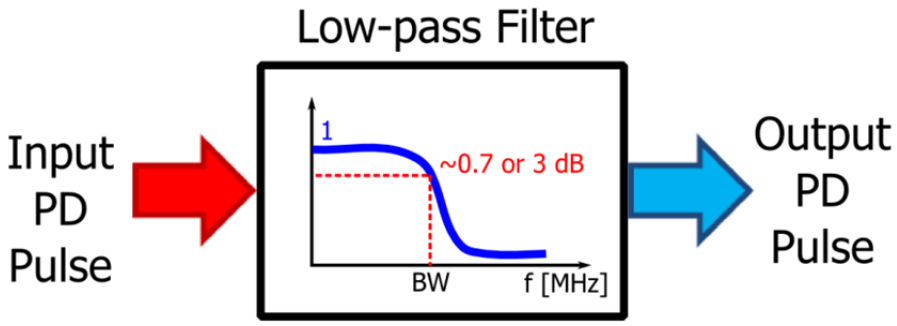

Figure 60: Illustration of Cable System Simulation Based on Simple Filtering

The purpose of this simulation using simple filtering is to demonstrate the effect of filter bandwidth on a PD pulse's scaled charge and energy as a function of the input PD pulse. As the input pulse, a Gaussian pulse of 5 pC and 20 ns (time width) is considered, its time domain waveform and frequency domain spectrum are shown in Figure 61.

Time Domain **Frequency Domain**

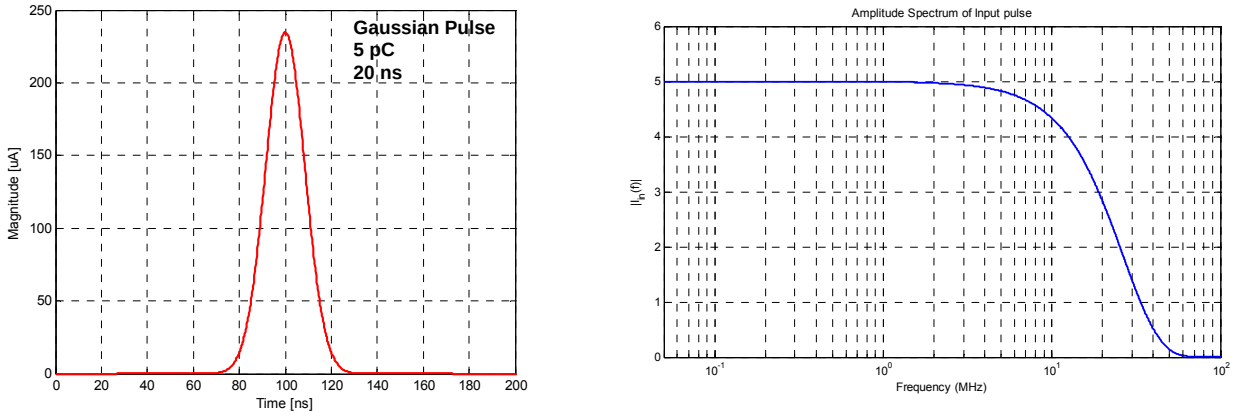

Figure 61: Waveform and Frequency Spectrum of the Input PD Pulse

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The simulation results considering filter bandwidths of 30, 20, 10, 5, and 1 MHz are shown in Table 26.

Table 26: Results for Cable System Simulation Based on Simple Filtering

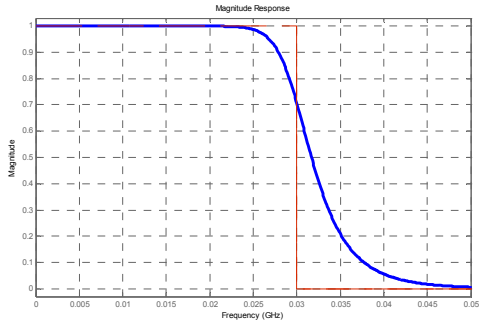
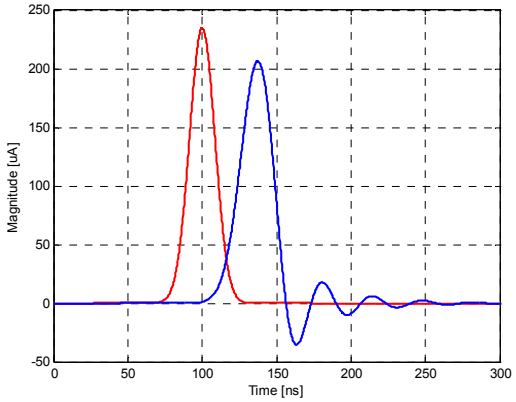
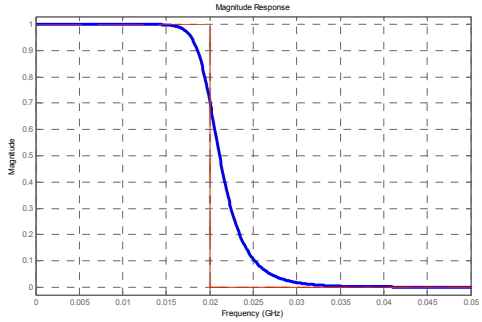
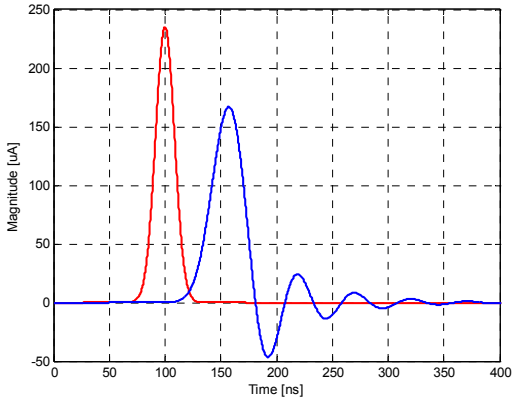
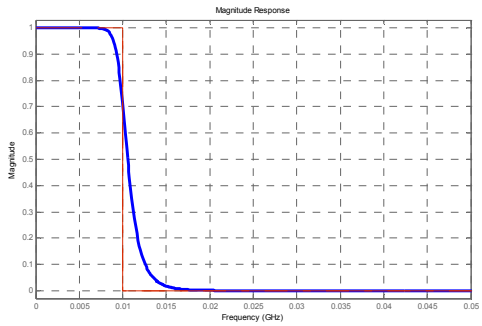
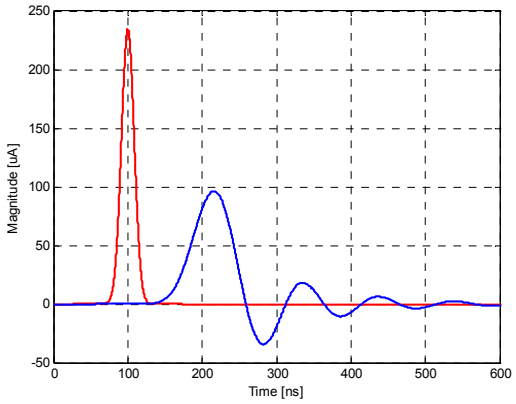
Filter Frequency Response	Input (Red) and Output (Blue) PD Pulses
30 MHz Bandwidth	
	
20 MHz Bandwidth	
	
10 MHz Bandwidth	
	

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Table 26: Results for Cable System Simulation Based on Simple Filtering

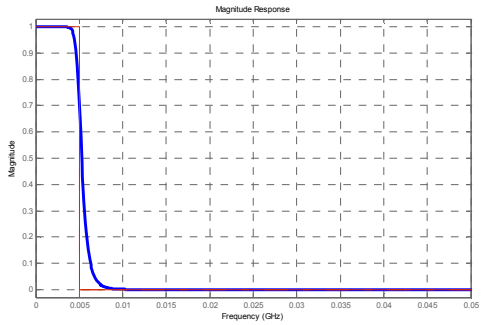
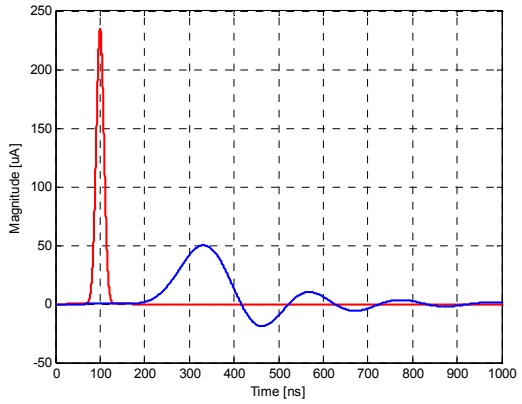
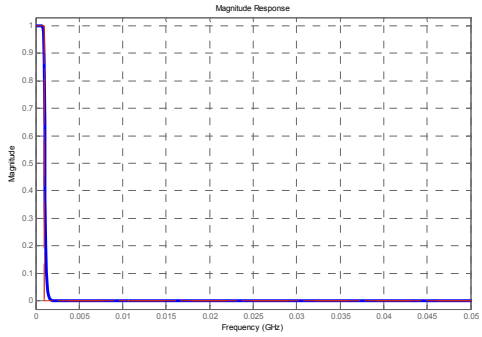
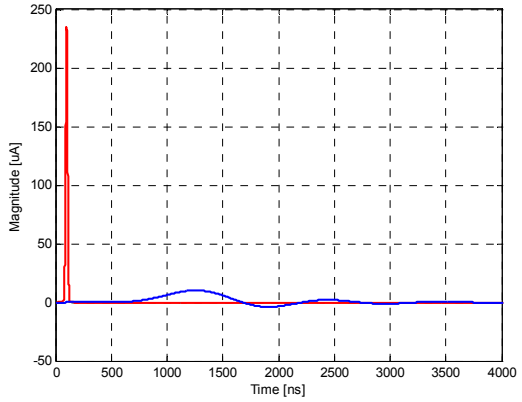
Filter Frequency Response	Input (Red) and Output (Blue) PD Pulses
5 MHz Bandwidth	
	
1 MHz Bandwidth	
	

Table 27 shows the scaled charge results for the cable system simulation based on simple filtering.

Table 27: Scaled Charge Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Scaled Charge [pC]	Output Scaled Charge [pC]	Scaled Charge Ratio [%]
30	5.0	5.0	100
20		5.0	100
10		5.0	100
5		5.0	100
1		5.0	100

As seen in Table 27, the output scaled charge is independent of the bandwidth; in other words, it remains unaltered over changes in bandwidth. The independence of the scaled charge with respect to bandwidth is due to the low-pass characteristics of the filtering, as mentioned earlier, the scaled charge represents the dc (zero frequency) component of the input PD pulse that is always transferred to the output without change. The main contribution of the results shown in Table 27 is

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that they help in understanding why, when PD first appeared, the scaled charge was selected as the most attractive metric for quantifying PD measurements. As the detection equipment and associated understanding have evolved, it is apparent that alternative metrics to quantify PD activity could be used for diagnosis.

Simulation results for the PD output pulse energy appear in Table 28 and are plotted in Figure 62. However, Figure 62 shows the energy loss in percent relative to the energy of the input pulse as a function of bandwidth. The energy loss shown in Figure 62 is obtained by subtracting from 100% the energy ratio in percent column shown in Table 28.

Table 28: PD Energy Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Energy [μA^2*ns]	Output Energy [μA^2*ns]	Energy Ratio [%]
30	4.15	4.04	97.4
20		3.60	86.7
10		2.28	55.0
5		1.23	29.5
1		0.25	6.0

As seen in Table 28 and Figure 62, the output PD pulse energy loss dramatically increases as the filter bandwidth decreases (i.e. more energy is rejected by the filter). For example, the energy losses are 2.6% and 94% for filter bandwidths of 100 MHz and 1 MHz, respectively. Specifically, note that for a bandwidth of 100 MHz, the energy loss can be considered negligible, while for 1 MHz bandwidth the energy loss is high. The relationship between energy loss and filter bandwidth is highly dependent on the energy content the input PD pulse. In this case, the input pulse has a bandwidth of approximately 15 MHz. Therefore, the 30 MHz bandwidth filter allows most of the input PD pulse energy through to the output. On the other hand, the 1 MHz filter only allows a small fraction of the pulse energy though.

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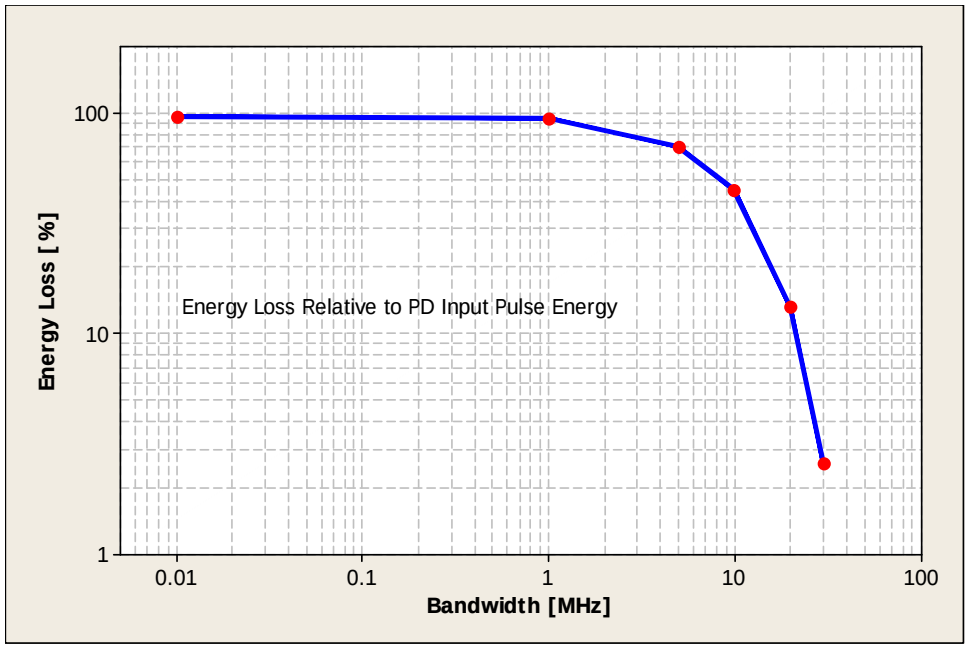

Figure 62: PD Signal Energy Loss versus Filter Bandwidth

As mentioned earlier, another issue to consider is how the peak amplitude of the PD output pulse changes with bandwidth; this is shown in Figure 63.

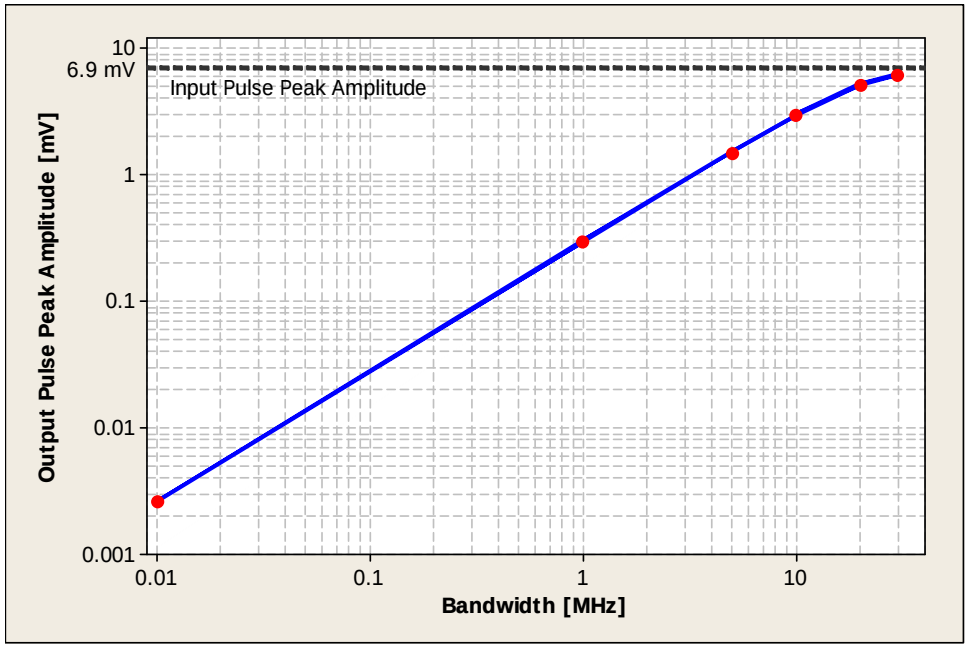

Figure 63: Output PD Pulse Peak Amplitude versus Filter Bandwidth

As observed in Figure 63, the peak amplitude of the output PD pulse increases with increasing filter bandwidth. Since the peak amplitude of the output PD pulse is often used to trigger the detection equipment, care must be taken when selecting the bandwidth of the detection equipment (as well as

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any noise filters) to avoid reducing the amplitude below the background noise level. Equipment that does not utilize a triggering approach would be more immune to this issue.

7.6.13.2 Frequency Dependent and Distributed Model

Another approach is to simulate the cable system simulation using a frequency dependent, distributed model. An illustration of the simulation appears in Figure 64.

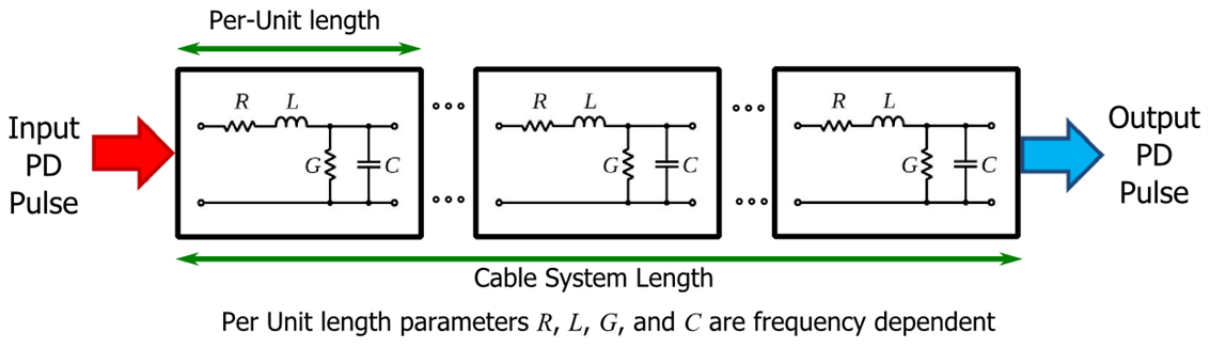

Figure 64: Frequency Dependent Simulation Model

As illustrated in Figure 64, the simulation process is as follows: A Gaussian PD input pulse of specified charge and time width enters the cable system model, which consists of a series of equivalent circuits of per-unit length connected in series. The output of the last equivalent circuit represents the PD output pulse that would be received by the PD sensor. Using this model, changes in the charge can be observed as functions of pulse parameters and distance travelled along the cable system. A set of five input PD pulses with different time widths and the same charge magnitude (50 pC) were used in the simulation. The resulting pulses appear in Figure 65.

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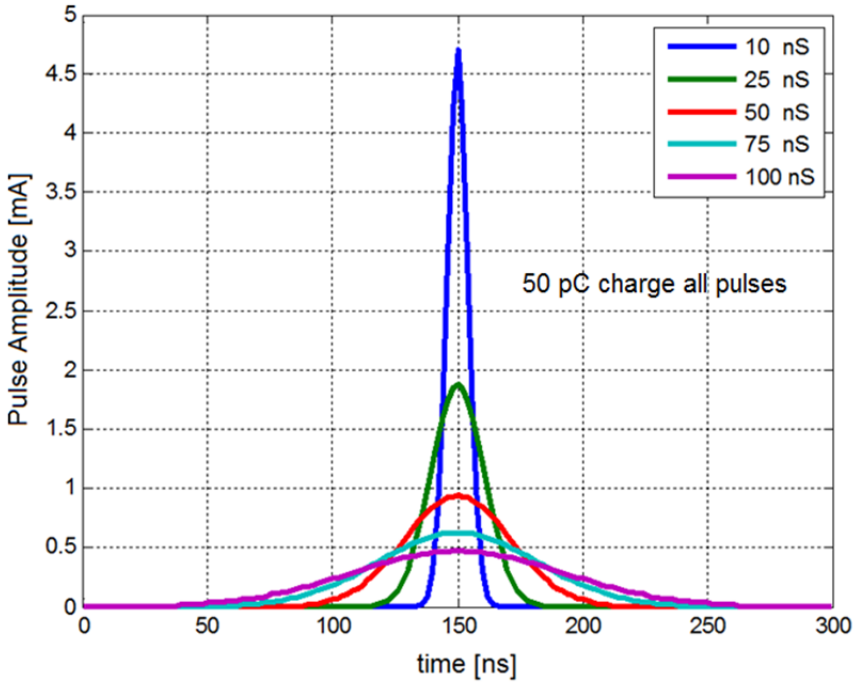

Figure 65: Gaussian PD Pulses for Simulation of Loss of Charge using Frequency Dependent and Distibuted Modeling.

The cable system modeling in these simulations was a 1/0 AWG, XLPE, 15 kV, and 175 mil wall cable system. The simulation results for the PD input pulses of Figure 65 are shown in Figure 66. This figure shows PD pulse charge loss as a function of the distance traveled from the discharge site.

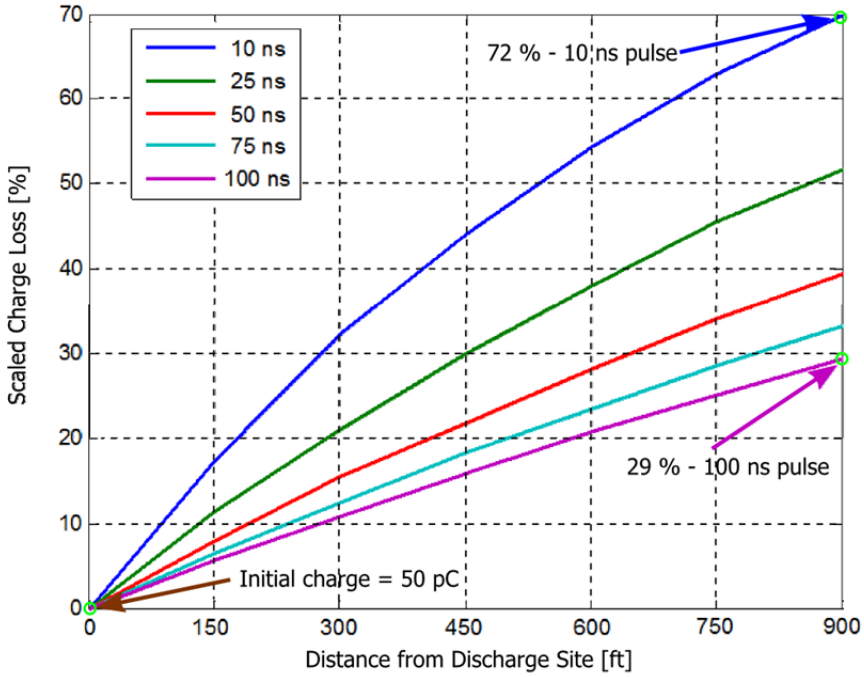

Figure 66: PD Pulse Scaled Charge Loss as a Function of Distance from Discharge Site

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The results presented in Figure 66 should be interpreted as follows: the PD pulse originating at the discharge site has an initial charge magnitude of 50 pC and charge is lost as the pulse travels away from the discharge site. For example, consider the 100 ns and 10 ns pulses after they have propagated 900 ft from the source. According to the results in Figure 66, the 100 ns PD pulse would be expected to exhibit 29% charge loss. Similarly, the 10 ns pulse exhibits a charge loss of 72%. Therefore, the corresponding scaled charge magnitudes at 900 ft would be 36 pC for the 100 ns pulse and 14 pC for the 10 ns pulse.

The results shown in Figure 66 are relevant because they show that the scaled charge loss for a PD pulse is a function of three main factors:

- **PD Pulse Waveform:** Different PD pulse waveforms would have different frequency spectra and thus different charge loss profiles. Since the PD pulse waveform depends upon the nature of the "void-type" defects responsible for the PD then the scaled charge loss profile also depends on the nature of the defect.
- **Distance from PD Source:** The PD pulse scaled charge typically thought to be independent of cable system length, actually is not. In reality, this phenomenon is always present and unawareness of its existence may lead to a confused interpretation.
- **Other Factors:** Other factors affecting scaled charge loss of a PD pulse are cable system design, structure, aging, and degradation conditions.

7.6.14 Limitations Of Repeat Tests

Early approaches for characterization of PD phenomena in cable systems required determining a metric for the PD level or mean PD value usually expressed in the units of picocoulomb. There is no question that these approaches are convenient because of their simplicity in as much as only a single number is reported for a given set of system parameters and operating conditions. The inception and extinction voltages were also used in conjunction with the PD magnitude as metrics for condition assessment. Early efforts also considered attempts to estimate the mean PD magnitude from field-theoretical considerations on different types of voids within the bulk volume of the insulation material [25].

Although there is much that can be learned from a deterministic approach to PD theory and measurement, the fact remains that PD phenomena are fundamentally stochastic processes in which there can be significant statistical variability (e.g. pulse peak amplitude, pulse waveform, and time of occurrence). However, it can be argued that some of the individual interactions or steps that take place in the creation of a PD event can be considered as deterministic. Unfortunately, this oversimplifies the nature of PD so an accurate characterization can never be accomplished using a deterministic approach [25].

Consequently, PD phenomena are characterized by adopting a stochastic description in which their properties are described in terms of time-dependent random variables. The random variables such as pulse amplitude and time of occurrence that describe the PD process can be specified in terms of probability distribution functions. The stochastic behavior of PD phenomena can also be revealed by appropriate measurements and analyses. A complete explanation of the factors that determine the statistical behavior of PD is beyond the scope of this document. One of the main consequences from this stochastic nature is that PD measurements from repeated tests cannot be compared beyond the simple question of "Is PD still present?".

To provide experimental evidence of the stochastic nature of PD phenomena, a laboratory test program was implemented. The program considered sequential and repeat PD tests on a cable sample that was removed from the field after testing showed that it had had PD. The sequential measurements were performed the same day with a two-hour difference between measurements while the repeat tests were performed a few days apart. In this case, two sequential measurements are considered a measurement set. The test program timing is illustrated in Figure 67.

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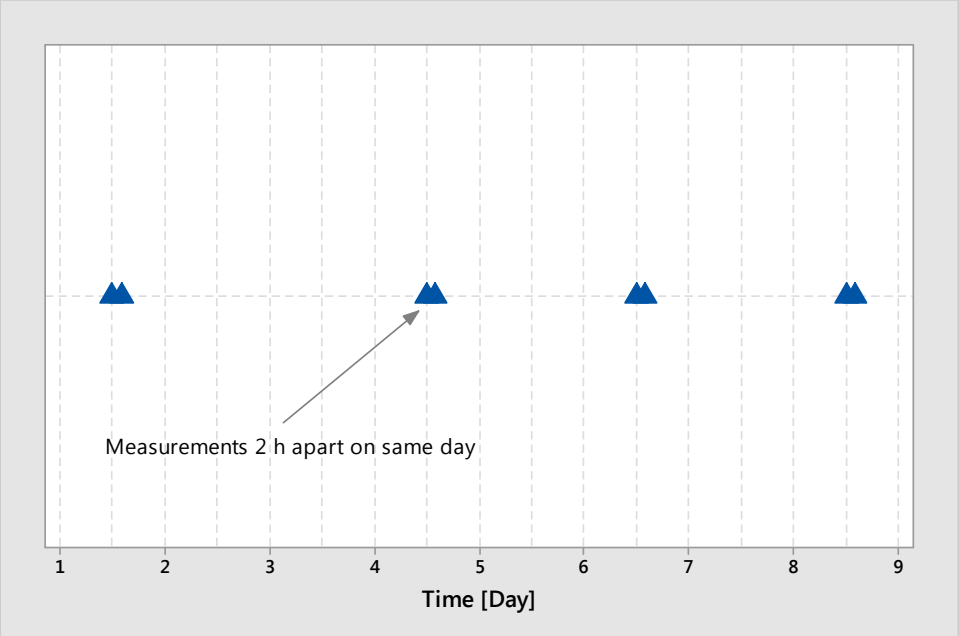

Figure 67: Measurement Timing (Two Measurements per Day)

Table 29 shows the cable sample used during the test program.

Table 29: Sample Description for Experimental Evidence of PD Stochastic Nature

Condition	Length [ft]	Year of Manufacture	Voltage Class	AWG	Insulation Material
Field-aged cable	17	1968 Phelps Dodge	15 kV U_0 = 7.2 kV	1/0 Unjacketed Concentric Neutrals	XLPE

Since this field-aged cable sample was stored in a de-energized state, a preconditioning procedure was conducted before each PD measurement by applying 0.5 U_0 (3.6 kV) for 15 minutes. The inception voltage after preconditioning was then determined and recorded for each measurement. Before recording, each termination was checked for discharge to ensure they were PD free. Details of the test program appear in Table 30.

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Table 30: Laboratory Test Program Measurement Details		
Preconditioning	**PD Measurements [#]**	**Details for each data capture**
15 min At 0.5 U_0 (3.6 kV)	8	Inception voltage after preconditioning Two sequential PD measurements at 1.25 the measured inception voltage after preconditioning Each acquisition lasts 30 sec or until 5000 pulses are acquired, whichever happens first

The test program shown in Figure 67 and Table 30 includes PD measurements at one test voltage level of 1.25, the inception voltage after preconditioning.

The schematic of the test set-up appears in Figure 68. The sample was an unjacketed cable and was submerged in a water tank to guarantee good electrical contact between the cable metallic shield and insulation shield. This avoids any potential external arcing that could result from a poor contact.

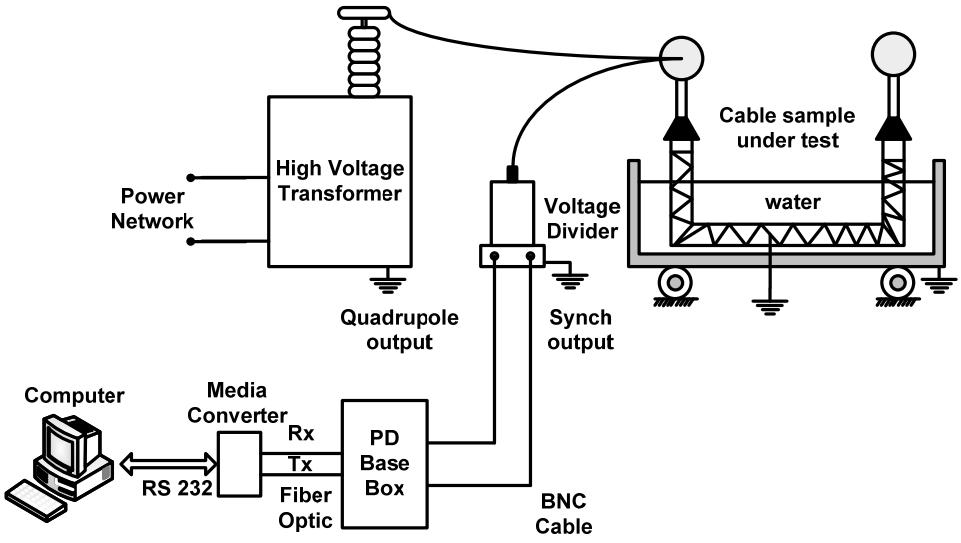

Figure 68: Test Set-up for Laboratory PD Test Program

Figure 69 shows the actual test set-up; the water tank, the voltage divider and the transformer can be observed in the figure.

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Figure 69: Test Set-up with Water Tank, Transformer, and Capacitive Divider

The PD measurement results presented below are based on the phase-resolved PD pattern (PRPD). There is no question that a considerable number of PD diagnostic features can be obtained from each pattern using statistical tools. However, for a simpler analysis, nine PD diagnostic features were used to quantify the results. The features are as follows:

1. **Inception Voltage:** Inception voltage after preconditioning, measured in kV;
2. **Pos. Max Amp:** Maximum PD amplitude for the positive polarity of the test voltage, measured in mV;
3. **Pos. Mean Amp:** Mean PD amplitude for the positive polarity of the test voltage, measured in mV;
4. **Pos. Mean Phase:** Mean phase for the positive polarity of the test voltage, measured in degrees;
5. **Neg. Max Amp:** Maximum PD amplitude for the negative polarity of the test voltage, measured in mV;
6. **Neg. Mean Amp:** Mean PD amplitude for the negative polarity of the test voltage, measured in mV;
7. **Neg. Mean Phase:** Mean phase for the negative polarity of the test voltage, measured in degrees;
8. **Symmetry Factor – D:** Symmetry factor, positive over negative number of pulses;
9. **Mean No. Pulses per Cycle – Nw:** Average number of pulses per period of the test voltage, i.e. number of acquired pulses in 16.7 ms for a 60 Hz test voltage.

Since each PD measurement is characterized by a set of nine diagnostic features, a total of eight sets are considered and their results appear in Table 31.

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Table 31: PD Measurement Results for Experimental Evidence of PD Stochastic Nature								
Feature	**PD Measurement Sequence**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1 - Inception Voltage [kV]	5.7	5.6	5.2	5.6	5.9	5.5	5.7	4.7
2 - Pos. Max Amp [mV]	232	222	191	246	225	210	102	90
3 - Pos. Mean Amp [mV]	97	101	101	122	55	73	10	11
4 - Pos. Mean Phase [Deg]	48	58	41	61	52	52	53	55
5 - Neg. Max Amp [mV]	238	193	229	240	227	216	156	113
6 - Neg. Mean Amp [mV]	77	82	113	140	67	132	19	17
7 - Neg. Mean Phase [Deg]	33	32	63	48	46	37	50	53
8 - Symmetry Factor - D	0.45	0.45	0.52	0.54	0.55	0.63	0.65	0.62
9 - Mean No. Pulses per Cycle - Nw	1.96	1.27	0.83	0.48	5.79	0.56	38.30	41.20

As seen in Table 31, each PD measurement set is different from all the others. Every diagnostic feature has a different, non-repeating value. This illustrates the stochastic nature of PD as these tests were conducted in a highly controlled manner. A comparison between maximum and mean amplitudes segregated by the polarity of the test voltage and as a function of the PD measurement number is presented in Figure 70.

In Figure 70, note that larger changes are observed for the mean amplitudes on both polarities; specifically, for the PD measurements numbers 7 and 8 when they are compared to PD measurements numbers 1 through 6, the observed changes are approximately one order of magnitude.

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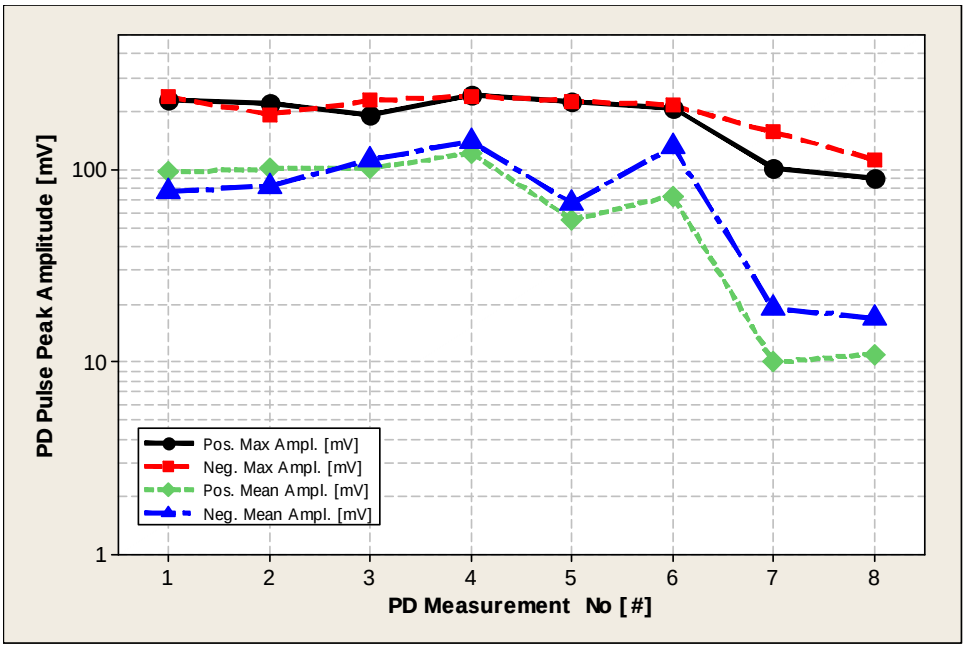

Figure 70: Mean and Maximum PD Amplitudes by Polarity

To further understand PD variability and thus its stochastic nature, Figure 71 shows the inception voltage and the average number of captured PD pulses per cycle of the test voltage as a function of the PD measurement number.

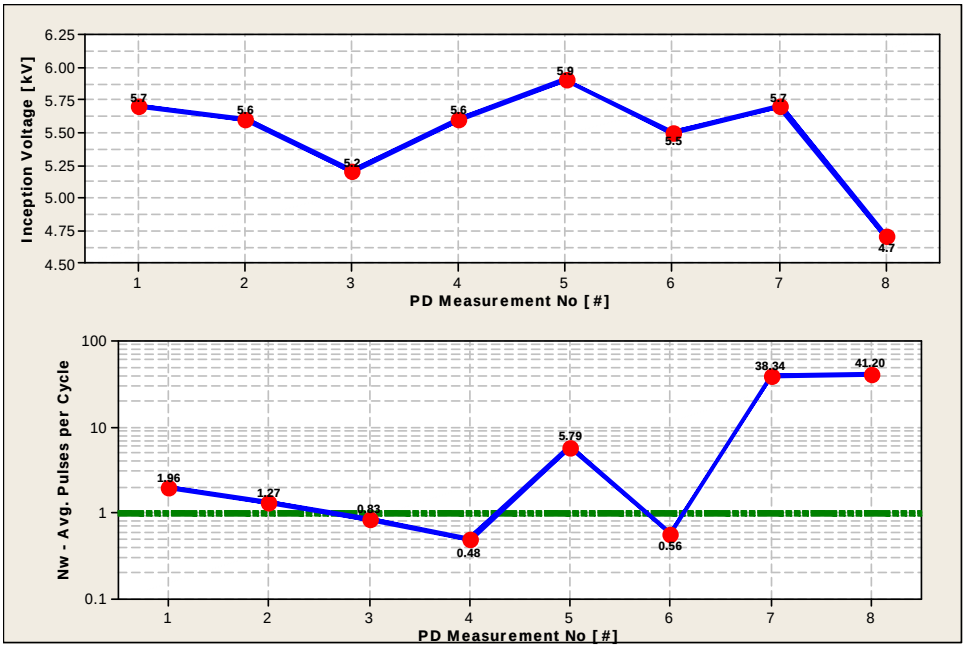

Figure 71: Inception Voltage and PD Repetition Rates for each Measurement

According to Figure 71, the maximum and minimum inception voltages were 5.9 kV and 4.7 kV. The range of inception voltages, therefore, is 1.2 kV or 20% - 26% of the measured inception

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voltages. In the case of PD pulses per cycle (Nw), the variability is the highest with a range of 0.48 PD pulses per cycle to 41.20 PD pulses per cycle. Complete phase-resolved patterns for all eight PD measurements appear in Figure 72 using the same amplitude scale so that differences between them are clearer.

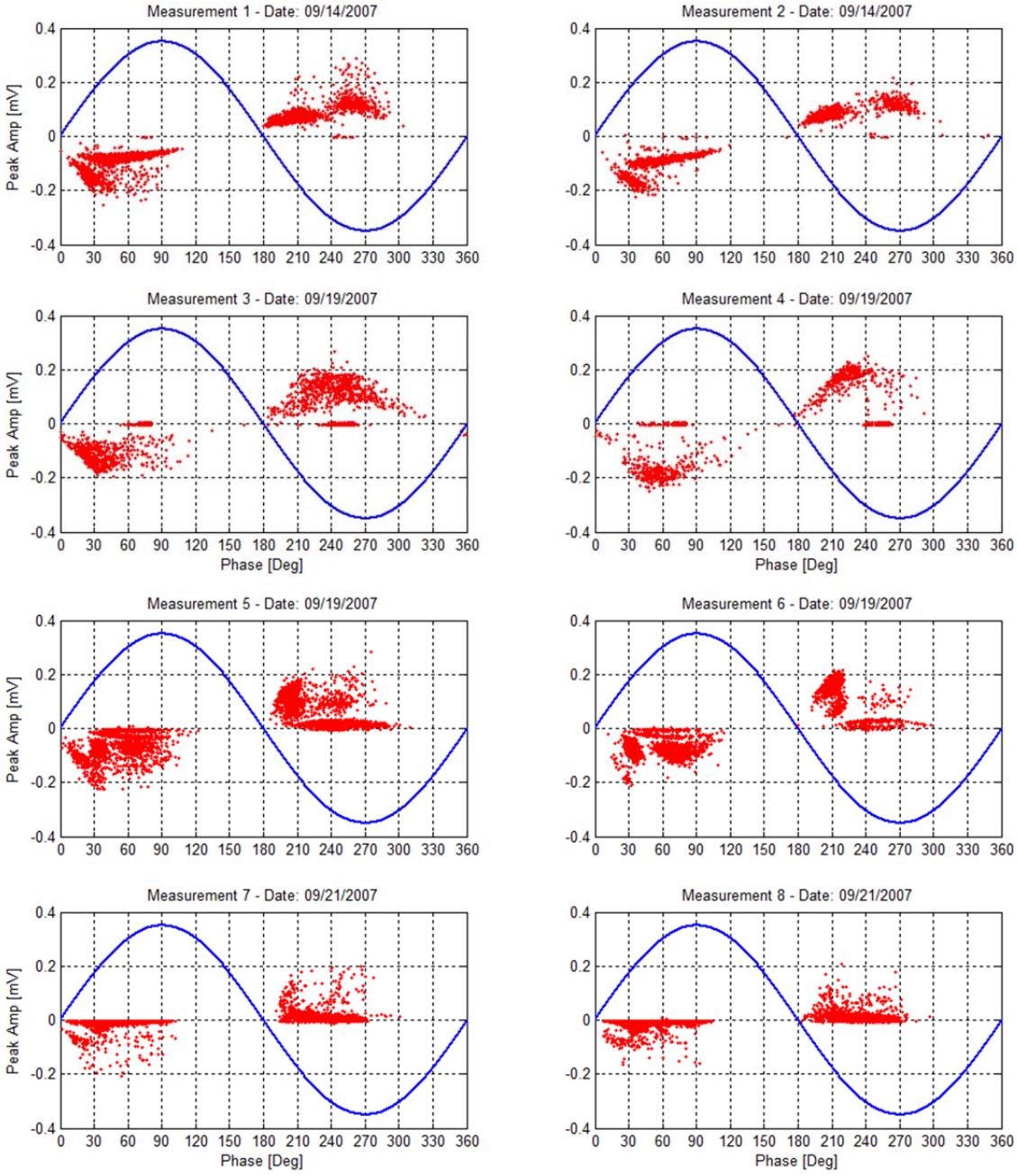

Figure 72: Phase-resolved Patterns for all PD Measurements

Given the dramatic differences in the PD measurements observed over an eight-day period, it is important to recognize that PD is a stochastic process that by definition changes over time. Awareness of this issue helps the user better the understand PD measurements.

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7.7 Outstanding Issues

As seen in Section 7.6, issues that affect PD measurements on MV power cable systems are numerous and diverse. They have been identified and analyzed in the *CDFI* during both phases. The analysis focused on crucial characteristics and limitations of PD measurements. According to this research, the following outstanding issues for PD measurement as a condition assessment diagnostic for MV power cable systems are identified:

1. When used as a field diagnostic, PD is generally measured on aged assets (maintenance testing). See Section 7.6.4.
2. Field measurements cannot be correlated to laboratory/factory test results. See Sections 7.6.1, 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.8, 7.6.12, and 7.6.13.
3. PD magnitude does not provide a direct link to estimates of deterioration or likelihood of failure. See Sections 7.6.1, 7.6.4, 7.6.6, 7.6.9, 7.6.10, and 7.6.13.
4. Tests, analysis, and reporting are used to obtain a diagnosis from a single test. Trending or comparison with an identifiable benchmark are rare and difficult to interpret. See Section 7.6.10.
5. Results from different PD measurement approaches/technologies cannot be compared. See Sections 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.7, 7.6.8, 7.6.10, 7.6.11, and 7.6.13.
6. Complicated test data are commonly processed and reported/recorded as a classification category. Re-analysis/reconsideration by a user is not possible and only coarse trending (across class boundaries but not within a class) is possible by a user. See Section 7.6.10.
7. Measurements and analysis techniques are proprietary so that detailed information about the measurement is unavailable. See Sections 7.6.2, 7.6.3, 7.6.5, and 7.6.11.
8. Measurements are mostly made from one end of the system (terminal measurements). See Section 7.6.3.
9. Noise and PD signal deterioration are unavoidable and can limit effective PD detection. See Section 7.6.1, 7.6.6, and 7.6.12.
10. Variability in measurement results makes it difficult to compare results with specific criteria and to compare results when the tests are repeated. See Section 7.6.14.

Due to the issues listed above, the information in this chapter provides the user an increased awareness of PD measurements on MV cable systems rather than a detailed explanation of how to conduct tests or analyze data.

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7.9 Relevant Industry Standards and Guides

- ICEA S-94-649 – 2004: *Standard for Concentric Neutral Cables Rated 5 Through 46 kV*
- ICEA S-97-682 – 2007: *Standards for Utility Shielded Power Cables Rated 5 Through 46 kV*
- IEC 60270 - 2000: *High-Voltage Test Techniques – Partial Discharge Measurements*
- IEC 60840 – 2011: *Power Cables with Extruded Insulation and their Accessories for Rated Voltages Above 30 kV (Um = 36 kV) up to 150 kV (Um = 170 kV) – Test Methods and Requirements*
- IEC 60885-2 - 1987: *Electrical Test Methods for Electric Cables. Part 2: Partial Discharge Tests*
- IEC 60885-3 - 1988: *Electrical Test Methods for Electric Cables. Part 3: Test Methods for Partial Discharge Measurements on Lengths of Extruded Power Cables*
- IEC 62067 – 2011: *Power Cables with Extruded Insulation and their Accessories for Rated Voltages Above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) – Test Methods and Requirements*
- CIGRE TB B1.28 – 2014 Omnibus: *On-Site PD Measurements*
- IEEE Std. 48 – 2009: *IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV*
- IEEE Std. 386 – 2006: *IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V*
- IEEE Std. 404– 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*
- IEEE Std. 400 – 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.3 – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*

CHAPTER 8

Partial Discharge (PD) HV and EHV Power Cable Systems

Jean Carlos Hernandez-Mejia & Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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8.0 PARTIAL DISCHARGE (PD) – HV AND EHV POWER CABLE SYSTEMS

A large amount of research published over the past decade investigates the characterization of partial discharge sources in cable systems. Much of this work was done for aged MV cable systems. There has been growing interest in the application of PD measurement technologies to HV and EHV cable systems. The objectives and thus requirements for tests on these cable systems are quite different to those considered for MV cable systems. The focus at HV and EHV is on commissioning tests (i.e. tests on newly installed systems) rather than maintenance tests on aged systems. This greatly reduces the interpretation side of PD testing as the presence of discharge on these new systems is in itself considered unacceptable. As a result, the focus of PD measurements is on the detection (is it detectable?) and location so the discharge source can be repaired. The remaining sections in this chapter focus on PD measurements on HV and EHV systems and discuss where appropriate the differences between these systems and measurements on MV cable systems.

8.1 Test Scope

Partial Discharge detects localized "void-type" defects, primarily in the form of voids in cable or accessories. Voids in this context can be:

- Quasi-spherical (most often due to manufacturing process problems).
- Dendritic (often due to aging processes that lead to the development of electrical trees resulting from enhanced voltage stresses).
- Interfacial (due to the delamination of components, or a loose fit between the cable and an accessory).
- Irregular (mechanical damage either before or after installation).

PD is applicable to all cable types, although its usefulness may be limited when performed on discharge resistant cables (as defined in ICEA S-94-649 and S-97-682) or on oil impregnated paper insulated cables (PILC or MIND) that also have a significant resistance to partial discharge. These cables may have considerable PD when new. Mixed systems of discharge-free and discharge-resistant cable designs can be especially challenging.

This method is attractive; as all discharge-free cable and many accessories are PD tested at the factory prior to shipping. As such, they are PD free as defined in the appropriate IEC, ICEA, and IEEE standards. Therefore, any additional PD detected in service must be due to problems caused by installation or defects that develop over time. However, it is important to be aware that there are no industry recognized testing procedures or PD limits for PD tests conducted on complete cable systems installed in the field.

Consequently, although appealing, there are some limitations to PD testing in the field, they are as follows:

- Factory and field tests use different approaches.
- In factory tests, components are tested separately (cable, terminations, and joints), while field tests *de facto* involve the complete cable system.

- Different field test environments impose a number of complications that must be addressed in order to yield acceptable results.
- Different cable system length scales (HV and EHV systems can be many miles long with a large number of joints).
- Interaction and impact on PD signals from cable system components are not completely understood.
- Different measurement approaches generally detect the same PD sources but quantify them differently.

8.2 How it Works

A high voltage is applied to the cable system. If conditions are right at the void location, a partial discharge (i.e. a discharge across the void) occurs. The PD measurement equipment detects transient millivolt or microampere level signals generated at the discharge site that travel through the cable to the detection equipment. The exact shape and bandwidth of these pulses depends on the discharge source, frequency response of the cable system, relative locations of the discharge source and detection equipment, and frequency response of the measurement equipment. Each of these elements alters the shape of the original PD pulse. The PD pulses themselves must then be separated from ambient noise signals. The available PD instruments are classified by bandwidth as they can have bandwidths of hundreds of kilohertz (narrow band and wide band according to IEC Std. 60270 – 2000) to up to 100 MHz (ultra-wide bandwidth (UWB)).

Figure 1 shows the commonly used equivalent circuit to describe PD measurements. The capacitances (C) are identified by the subscripts *a*, *b* and *c*. C_a represents the capacitance of an element of power cable that does not contain a defect. C_b and C_c represent an element of cable that contains a void defect, where C_c is the capacitance of the void and C_b represents the remnant cable element capacitance. S_g is the spark gap that represents the discharging defect/void.

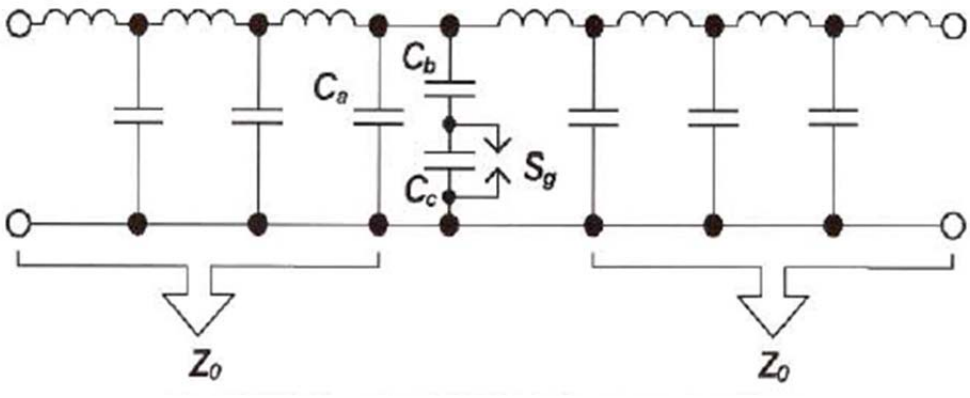

Figure 1: Equivalent Circuit for Power Cable PD [16]

It is important to consider that the capacitances *b* and *c*, and thus the charge generated in the measurement circuit, will depend upon the radial position of the void within the cable. This is because the capacitances depend upon the relative amount of insulation on either side of the defect.

Although outside the scope of this project, a brief discussion on the physics of discharges in voids is included to help users better understand the complexity of this test. PD is a Townsend discharge in a small cavity (a gas ionization process where, initially, a small number of free electrons, accelerated by a sufficiently strong electric field, results in electrical conduction through a gas by avalanche multiplication). The stress at which the discharge initiates (V_{PD}) is described by Paschen's Law, where the critical parameter is the product of the void size [diameter d] and the internal pressure [p]; β and χ are constants related to the gas within the void.

$$V_{PD} = \frac{\beta \cdot p \cdot d}{\chi + \ln(p \cdot d)} \qquad \textbf{Equation 1}$$

The Paschen Equation identifies a number of fundamental issues that the cable system engineer using PD testing must understand:

- Discharges only occur in gaps – PD testing can only find voids, not contaminants unless they subsequently debond from the insulation, thus leaving a void.
- Voids need to satisfy three further conditions to discharge:
  - They must not be completely filled with a liquid.
  - If they are gas filled, then the gas must be at a low enough pressure for the discharge initiation stress to be at or below the test stress. See Figure 2.
  - They must be large enough; small voids require higher initiation stresses (Figure 2).

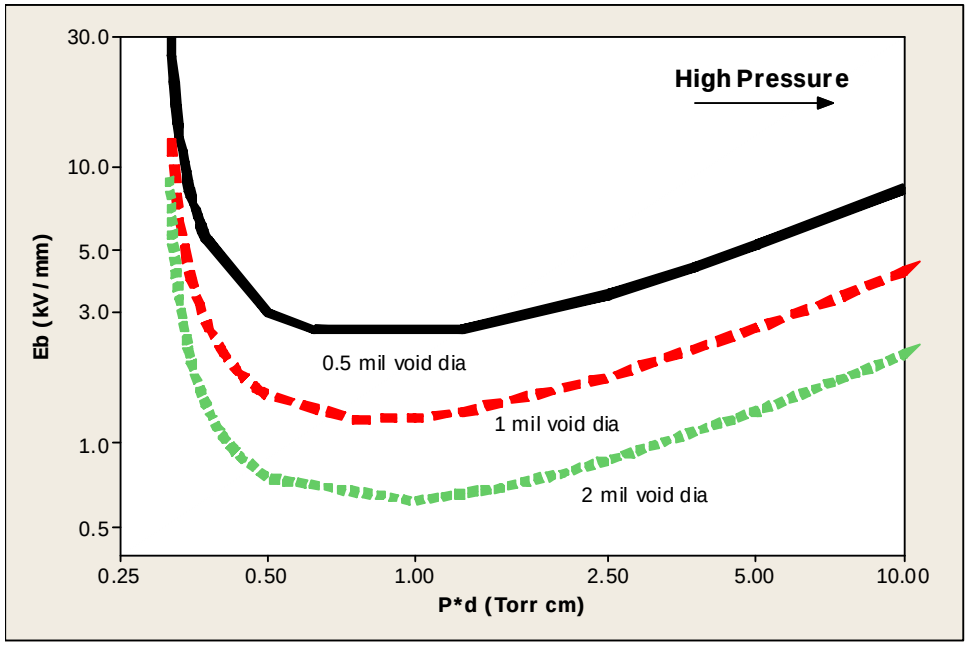

Figure 2: Theoretical Paschen Curves for Air-Filled Voids (Selected Void Sizes)

When measuring PD, three prerequisites must be satisfied during the measurement period:

- The voids must be in a state that allows them to discharge,
- The voltage must be high enough to initiate the discharge (inception voltage), and

- The PD signal must reach the detector in a suitably un-attenuated, undispersed state to be recognizable as PD signals with respect to the background noise.

Addressing the first point, PD is a stochastic (probabilistic) process. It may or may not be present at a void depending on all the parameters and conditions described above. Thus if no PD is detected, it can mean either that no voids are present or that a void is present but that that conditions are not right for it to discharge. This is significant for short measurement times and the risk of "false negative" results should be recognized.

A number of technical articles have described instances where PD pulses (at most a few nanoseconds wide) spread and reduce in magnitude as they propagate away from the PD source as a result of high frequency attenuation in the cable due to dispersion (frequency-dependence of the propagation velocity) [16]. The loss of high frequency energy from the PD pulse reduces its magnitude and distorts its shape. This can make it difficult to acquire the PD pulses and accurately identify the source and type of the PD.

8.3 How it is applied

PD testing can be performed online and offline [2 - 29]. Online techniques typically employ high frequency current transformers (CTs) or capacitively coupled voltage sensors to detect transient signals from discharges.

Offline voltage sources can be:

- 10 – 300 Hz AC: Equipment typically consists of an excitation transformer connected in series or parallel with a variable inductance reactor. The equipment is heavy and requires a truck or van.
- 0.01 – 1 Hz (nominal) ac Offline Very Low Frequency (VLF): Equipment is relatively light and portable compared to ac resonant systems but may act as an additional source of noise. Waveform used is sinusoidal.
- Damped AC (DAC): Equipment is relatively light and portable. The applied voltage is a damped sine wave with a frequency range of 30-500 Hz, though frequency varies with cable length and can, in some cases, be tuned with an external element (capacitor).

Most offline techniques apply $1.3U_0$ to $1.7\ U_0$, where U_0 is the operating phase-to-ground RMS voltage of the circuit.

Field PD results may be reported in terms of:

- Customized indicators (mV or mV·s).
- Scaled charge magnitude (pC) at a given test voltage level.
- Estimated PD source location(s).
- Inception voltage (voltage magnitude at which discharge initiates as the voltage is increased).
- Number of pulses per unit time.

- Frequency content of the PD pulses.
- Phase relationship of the PD pulses to the applied voltage (Phase-Resolved PD Pattern).

PD measurements are influenced by the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type and number of joints, ambient noise, and other factors discussed earlier. Therefore, accurate interpretation of the PD data requires sound knowledge of temporal (time dependency) PD behavior.

The application of high voltages for a long period (cycles or time) may cause some level of further degradation of an aged cable system. Consider this potential degradation when performing any diagnostic test requiring the application of voltage above the operating voltage. The precise degree of degradation will depend on the voltage level, frequency, and time of application. Thus, when undertaking elevated voltage PD measurements (or any other elevated voltage test), a utility should consider that a failure might occur and resources may be needed to make repairs. The section on expected outcomes in the *CDFI* Perspective provides insight on the likelihood of failure on test.

The advantages and disadvantages of different approaches to PD testing appear in Table 1 and Table 2 as a function of voltage source used to perform the test. In general, all techniques require skilled personnel for testing and interpretation. Table 3 shows the overall advantages, disadvantages, and open issues for PD testing.

Table 1: Advantages and Disadvantages of Online PD Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
60 Hz AC Voltage Supplied by Utility System (De-energizing not needed)	• No non-system energization equipment is required. • Testing wave shape and frequency are the same as the service voltage. • The cable circuit is not de-energized as part of the test. • It is relatively easy to monitor over an extended period (10 to 60 minutes or longer) so that PD sites are more likely to discharge and be detectable. • Test may be performed while the cable system is at normal operating temperature (maintenance tests only).	• Cannot detect PD that would occur at voltages above normal operating voltage. • Sensitivity assessment typically not possible. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Detailed assessments are not available for several days to weeks. • Sensors must be applied at every cable accessory (either sequentially or simultaneously) and at each end of the tested cable circuit segment. • In most approaches, PD sites in cable are not specifically located. They are only identified as occurring between two sensors or at a sensor on an accessory. • In some approaches, results are reported as levels - the specific meaning of each level is difficult to interpret. • Cannot be combined with other diagnostic tests.

Table 2: Advantages and Disadvantages of Offline PD Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
Power Frequency AC (10 – 300 Hz)	• Testing wave shape and frequency are close to the operating voltage and factory test voltage. • Sensitivity assessment can establish the lowest detectable partial discharge level. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured. • Withstand test can be performed simultaneously.	• Equipment is large, heavy, and expensive. • Application of elevated voltage (> U_0) may cause further degradation. • Results are reported in levels or voltages - the specific meaning of each level is difficult to interpret or re-interpret later.
0.01 – 1 Hz AC Very Low Frequency (VLF) Sinusoidal External Voltage (Offline)	• Equipment is smaller than ac resonant systems. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured. • Withstand test can be performed simultaneously.	• Application of elevated voltage (> U_0) may cause further degradation. • Does not replicate operating voltage wave shape or frequency. • PD behavior is not well understood at these frequencies. • Difficulty syncing with voltage waveform when phase-resolved data is needed. • Special filtering needed for VLF generators
Damped AC (DAC) (30 Hz to 1 kHz)	• Voltage source and PD acquisition are integrated in a single unit. • Straightforward to use.	• Only the first voltage cycle is controlled. • Does not replicate operating voltage wave shape or frequency. • Comparisons between circuits are difficult because the applied voltage frequency varies as a function of the circuit impedance characteristics. • PD behavior is not well understood when using decaying voltage waveform. • Difficult to define consistent PD test process. • Few cycles during which to detect PD. • Does not included integrated withstand approach.

Table 3: Overall Advantages and Disadvantages of PD Measurement Techniques	
Advantages	• Identifies single or multiple localized void-type defects. • Applicable for all cable and accessory designs. • If PD test interpretation indicates that cable circuit is PD-free then there is a high probability that the circuit will not fail within the next several years. • Offline techniques allow for the detection of PD at voltages above U_0. • Can detect electrical trees, interface tracking, and voids. • Basic results available at end of test. • Test can be stopped if "unacceptable PD" is observed.
Open Issues	• It is unknown whether cycles or time at elevated voltage is the critical parameter in determining the risk of damage to the cable system. • PD results on cable systems are not directly comparable to the factory test results on the individual components. • Different providers perform PD measurements using different measurement methods, sensors, measurement frequencies, bandwidth, metrics, and sensitivity assessment. Results from different PD providers/equipment are difficult to compare. • Locating PD sources can be difficult because of noise, attenuation, dispersion, cable accessories, and cable system complexity. • Voltage exposure (impact of voltage and time on cable system) caused by elevated 60 Hz ac, DAC, and VLF has not been established.
Disadvantages	• Cannot detect all possible cable system defects – only those that discharge and are detected by the measurement equipment.

8.3.1 Partial Discharge Sensors

Two groups of sensors are used for PD measurements, they are as follows:

- **Sensors for PD detection:** transducer that responds to an input PD quantity by generating a functionally related output usually in the form of a mechanical or electrical signal.
- **Sensors for PD synchronization:** transducer that detects the energizing high voltage and provides a low voltage electrical signal.

Partial discharge measurements are most commonly performed using both sensor types.

A variety of PD detection sensors are available:

- **Capacitive:** The PD signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well in the form of a sheath sensor. Some accessories will include internal capacitive sensors than is accessible from the accessory housing.

- **Inductive:** The PD signal is detected through the induction principle most commonly in the form of a high frequency current transformer (HFCT). This type of sensor can also be used for online and offline application. In addition, as no connection is required with the high voltage terminal, the use of inductive sensors is practical and easier to deploy than high voltage capacitive sensors.
- **Piezoelectric:** Partial discharges generate micro explosions that mechanically propagate through the cable system and may be detectable. In this case the sensor is deformed by the wave and the deformation generates an electrical signal.
- **Acoustic:** Similar to the piezoelectric sensor, the acoustic sensor detects the sonic wave that propagates through the surrounding air/soil and converts this to an electrical signal.

Although all four types of PD sensors are applicable, the more commonly used are capacitive and inductive sensors. The reasoning behind this is that detection via electrical measurement (either voltage or current) is the most direct means of quantifying PD. Consequently, electrical measurement is also the only means of providing some estimation of the PD magnitude. The piezoelectric and acoustic sensors can only provide an indication that PD is present and, generally, the sensor must be located near the discharge site to be effective. This in itself causes accessibility issues and would limit applicability to terminations, riser cable sections, and accessories in vaults/manholes. On the other hand, piezoelectric and acoustic sensors may also be combined with capacitive and inductive sensors to improve PD source location.

Table 4 shows illustrative pictures of all the different types of sensors for PD detection.

Table 4: Different Types of Sensors for PD Detection	
Type	**Illustrative Image**
Capacitive – Capacitive Coupler PD and Synch signals	
Capacitive – Direct Coupler PD signal	
Inductive – High Frequency Current Transformer (HFCT) PD signal	
Piezoelectric	
Acoustic	

Two voltage synchronization sensor types are available:

- **Capacitive:** The synchronization signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both PD detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well. Because it connects with the high voltage terminal, the sensor must be able to withstand test voltages.
- **Inductive:** The PD synchronization signal is obtained by the sensor through the induction principle. The most common device here is the Rogowsky Coil. The Rogowsky coil detects the current flowing in the cable system and generates a corresponding voltage signal. It is necessary, therefore, to adjust the signal phase from the Rogowsky Coil to account for the

phase difference between the current and energizing voltage to provide the correct voltage reference. This type of sensor can be used for online and offline applications.

Table 5 shows examples of all the different types of sensors for PD synchronization.

Table 5: Different Types of PD Sensors for Synchronization

Type	Example
Capacitive – Capacitive Coupler PD and Synch signals	
Inductive – Rogowsky Coil Synch signal	

It is important to mention that PD synchronization can also be accomplished by an external signal if available. For example, the energizing voltage source may include a low voltage output that could be used as a synchronization signal. In the case of online measurements, some PD instruments can use an internal synchronization signal generated from its ac source. However, care must be taken when using this approach because the phase difference between the external synchronization signal and the PD test voltage must be properly determined to allow for noise-PD signal separation.

8.3.2 Partial Discharge Source Location

Before conducting PD measurement in the field, the location of the cable system joints should be determined so that PD signals originating from accessories can be distinguished from those coming from the cable. Most HV and EHV cable systems have significantly high attenuation characteristics such that signals from adjoining accessories are not detectable. This causes significant issues in MV cable systems; however, at HV and EHV this is an advantage. In general, a sensor is temporarily installed at each accessory location and so any signals detected at that accessory location are assumed to be only from that accessory or the nearby cable.

In the case of terminal only measurements, the TDR is performed off-line. Once the joint locations are known, the PD source location can be performed. There are two approaches used:

- Location using PD data in time-domain and
- Location using PD data in frequency-domain.

In both approaches, PD instrument bandwidth on the order of several megahertz is necessary to provide a reasonably precise location along the conductor length.

Each of the PD source location approaches is discussed following sections.

8.3.2.1 Source Location in Time-Domain

This approach is based on the same principle as TDR and is illustrated in Figure 3.

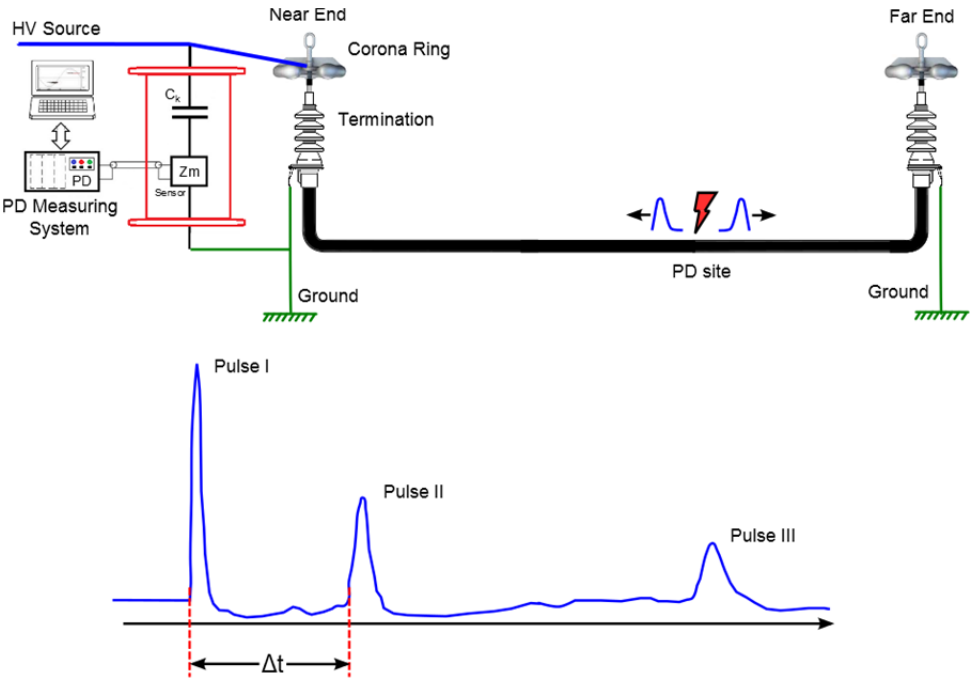

Figure 3: Illustration of PD Location in Time Domain

As shown in Figure 3, the energizing voltage and the PD detection equipment are located at the near end of the cable system. A discharge event occurring at a source located somewhere within the cable system generates a pulse that then splits into two pulses that travel in opposite directions along the circuit. The PD pulse travelling directly to the near end is acquired first as Pulse I. As time passes, the pulse travelling towards the far end is completely reflected at the far end back to the near end where it is acquired as Pulse II. Using the difference between the arrival times of Pulse I and Pulse II (Δt), the total length of the circuit, and the speed of propagation the location of the PD source along the conductor length can be estimated.

Additional reflections may be recorded. Pulse III in Figure 3 represents the round trip (near-far-near ends) Pulse I takes through the cable system after reflecting off the near end.

This method may also be used in cases where multiple synchronized sensors are deployed along the circuit. In this scenario, the PD source location is determined by analyzing the arrival times of the pulses at each sensor. This is particularly useful on branched and extremely long cable systems and it assumes accessibility to the locations of interest where the PD sensors (usually HFCTs) are to be deployed.

8.3.2.2 Source Location in Frequency-Domain

PD source location using frequency domain data can be performed for both offline and online approaches. This method uses the calculated frequency components of the PD pulse and the fact that the energy signature of a PD pulse as a function of its frequency components is highly correlated to the distance from the PD source. The calculated energy is higher at sensors locations near the PD site. By examining the energy signatures measured at each sensor location, an approximate PD source location can be determined.

The accuracy of this technique can be influenced by two factors, they are as follows:

- Distance between two consecutive sensors – shorter distance between sensors improves accuracy because changes in PD pulse energy versus distance can be better estimated.
- PD sensor frequency range – greater bandwidths result in improved accuracies because a wider frequency range is used to estimate the energy and thus its changes with distance can be better observed.

8.3.3 Laboratory and Field Testing

Partial discharge tests are generally classified into two categories: laboratory and field tests. Each category has different objectives and issues. The categories are determined by the location at which tests are performed. Each of the categories covers different test types. The relationship between test types and the test categories is in Table 6.

Table 6: Relationship between Test Types and Test Categories for PD Measurements		
Test Type	**Laboratory**	**Field (On site)**
	• Routine / Production • Qualification • Sample	• Commissioning • Maintenance

To better explain Table 6, each test type is described in detailed as follows:

- In the laboratory category:
    - **Laboratory Testing:** Tests that are carried out on new or aged accessories and cable together as a cable system to study the interactions between them from a research perspective. The research is commonly focused on investigating design issues and/or estimation of the aging and degradation mechanisms that a cable system as a whole experiences during its service life.
    - **Factory Testing:** Tests carried out on new accessories or cable separately to verify that they comply with industry standards. Tests are performed routinely as part of the production line.
    - **Qualification Testing:** Industry standard tests completed to ensure the effectiveness of the manufacturing processes, equipment, and procedures used to produce cable system components for field use.

- In the field (on site) category:
    - **Commissioning:** Tests deployed to check the integrity of the individual components (cable and accessories) and their interfaces and the cable system as a whole including damage that may had been occurred during installation and/or workmanship issues.
    - **Maintenance:** Tests intended to detect deterioration and to verify the serviceability of cable systems that have been operated in service for some period of time.

The deployment conditions for laboratory and field PD test categories are different; the goal of each test type differs from one another and more importantly the factors that influence PD measurements for each of them may vary significantly. A basic understanding by utility engineers of each PD test type is important. Therefore, Table 7 aids on the understanding by comparing laboratory and field PD tests.

Table 7: Overall Comparison of Laboratory and Field PD Tests
Laboratory Tests
• Cable and accessories tested together as a short cable system. • Focused on investigating design issues and aging and degradation mechanisms. • Focused on new systems. • Performed under controlled conditions of noise, grounding, temperature, accessibility, etc. • Short systems allow for lumped equivalent circuit modeling. • Conventional and Non-conventional measurements can be deployed. • Does not replicate operating environment. • New systems – presence of PD indicates cable, accessories, or interface design/installation issues.
Factory Tests
• Only new cables and accessories tested separately. • Focused on identifying cable system components that comply with industry standards for maximum discharge magnitude. • Performed under controlled conditions of noise, grounding, temperature, accessibility, etc. • Long cable runs are modeled by a lumped equivalent circuit. • Only conventional measurements are deployed. • Performed routinely as part of the production line. • Does not replicate operating environment. • PD magnitudes that exceed requirements cause components to be examined more thoroughly.
Qualification Tests
• Only new cables and accessories tested as part of a cable system. • Generally performed before full-scale production begins. • Ensures the effectiveness of the manufacturing process, equipment, and procedures. • Allows independent evaluation against industry standards. • Focused on PD detection and location. • Performed under controlled conditions of noise, grounding, temperature, accessibility, etc. • Short cable length allows for lumped circuit modeling. • Only conventional measurements are deployed. • Does not replicate operating environment. • Presence of PD can indicate design, compatibility, or installation issues.
Commissioning Tests
• Complete cable system that is tested prior to beginning its service life. • Focused on PD detection and PD source location. • Performed under uncontrolled test conditions of noise, grounding, temperature, accessibility, etc. • Long systems require distributed impedance circuit modeling. • Attenuation, dispersion and reflections cause PD signal degradation that affects the measurements. • Conventional and Non-conventional measurements can be deployed. • Presence of PD could indicate design, after-laying, and/or workmanship issues.

Table 7: Overall Comparison of Laboratory and Field PD Tests
• Generally performed at test voltages above normal operating voltage.
Maintenance Tests
• Complete cable system that is tested at some point during its service life. • Focused on detecting and localizing PD sources with some assessment of severity. • Done under uncontrolled test conditions of noise, grounding, temperature, accessibility, etc. • Long systems require distributed impedance equivalent circuit modeling. • Attenuation, dispersion and reflections cause signal degradation affecting measurements. • Conventional and Non-conventional measurements can be deployed. • Presence of PD could indicate design, degradation, or installation issues.

As factory and laboratory testing are familiar to many engineers involved in cable system diagnosis the tendency has been to try and transfer criteria for factory and laboratory tests to field testing. However, these criteria cannot be directly applied to field tests as the underlying assumptions used in factory and laboratory tests are no longer valid.

8.4 Success Criteria

As mentioned above, PD results may be reported in a number of ways. However, many providers of PD testing services prefer not to supply detailed PD data. They suggest that interpretation of the test results requires analysis of charges, voltages, pulse shapes, pulse frequencies, etc. that is best undertaken by the provider. Instead, they process the data to identify any discharge activity and to locate its source within the cable system. In principle, there are two main classes: Pass – no action required and Not Pass – action required. As most of the HV and EHV partial discharge tests are performed as commissioning tests, the presence of discharge activity is in itself sufficient to classify the circuit as Not Pass. The industry as a whole has been able to reach this level of agreement while specific severity levels for discharge activity remains proprietary.

Criteria for PD levels are available in standards for use during qualification and design tests as well as production tests. However, these criteria are intended to be used under specific conditions that are rarely achievable under field conditions. Furthermore, the measurement equipment used in field tests are designed with wider signal bandwidths and advanced signal processing algorithms that are simply beyond the scope of the available standards documents.

8.5 Estimated Accuracy

As discharge activity is generally eliminated after detection as part of the commissioning / recommissioning process, accuracy data cannot be estimated for PD tests on HV and EHV cable systems.

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8.6 *CDFI* Perspective

Partial discharge is useful for cable system commissioning because it is the technique that has the most potential to provide a localized assessment of the cable system. Although PD tests cannot identify the presence of all defects that can impact the life of a cable system, they can detect "void-type" defects that are most likely to put at risk the life of an HV or EHV cable system.

As a consequence, at HV, PD technologies are generally deployed on new or recently installed assets/systems as part of a commissioning test prior to entering service. The PD at commissioning test is generally undertaken as a Monitored Withstand test (i.e. simple withstand and PD combined). The goal is to provide assurance to the installer and the user that the system does not contain defects or installation errors. Hence, PD technologies implemented at HV/EHV strive to identify the presence and likely location of PD. Little effort is made to make a judgment of the severity of any detected signals. The basic assumption is that HV and EHV cable systems should be PD free at the start of their service lives.

One of the main goals of this section is to help users understand field PD measurements techniques on HV and EHV cable systems. The issues are many and diverse, during *CDFI Phase II* we identified the most crucial characteristics and limitations of PD measurements; the most important of which are listed below:

1. Technologies are generally deployed on new assets, i.e. oriented to commissioning testing. See section 8.6.4, 8.6.5, & 8.6.8.
2. Field measurements cannot be correlated to laboratory / factory test results. See sections 8.6.1, 8.6.2, 8.6.3, 8.6.5, & 8.6.6.
3. Measurements are carried out as part of an ac Monitored Withstand protocol (i.e. simple withstand and PD combined). a) ac withstand {$1.7U_0$ for 60 min} combined with b) PD tests {PD checks at 0.5 U_0, U_0, and 1.5 U_0 on ramp up and monitoring throughout the withstand portion} are commonly deployed and effectiveness is supported by international data. See sections 8.6.4 & 8.6.5.
4. The aim is to detect the presence and location of PD – the magnitude is generally not of interest. See section 8.6.4, 8.6.5, & 8.6.8.
5. Systems are long and have complicated architectures (laboratory/factory tests assume short lengths and a simple architecture). See section 8.6.1 & 8.6.2.
6. Calibration commonly found in laboratory/factory tests is not valid for field tests. See section 8.6.1, 8.6.2, 8.6.6, & 8.6.11.
7. PD signal deterioration is significant and unavoidable, this imposes limitations on the range of detection (i.e. how far can be seen into the cable system). Hence, only terminal (tests from one end) are rare while distributed measurements (measurements at each accessory – joint hopping) are most commonly used. See sections 8.6.1, 8.6.7, 8.6.9, and 8.6.10.
8. Tests, analysis and reporting are orientated towards establishing the absence of PD from a single test, though multiple PD technologies may be used (trending or comparison with an identifiable benchmark are rare). See section 8.6.4 & 8.6.5.
9. Results showing the absence of PD obtained from different PD technologies can be collated. See section 8.6.3, 8.6.5, & 8.6.8.
10. Trending/repeat tests are rarely carried out. See section 8.6.4, 8.6.5, & 8.6.8.

Due to the issues and limitations above, the information in this Chapter provides the user with an increased awareness of PD measurements on HV and EHV cable systems rather than a detailed explanation of how to conduct tests or analyze data.

During *CDFI Phase II*, a number of laboratory PD tests on HV and EHV cable systems were conducted in conjunction with analyses of a number of HV/EHV PD (Monitored Withstand) data sets. These tests and analyses have enabled the development of the perspective presented here. The *CDFI* perspective is based on knowledge gained from specific hands-on activities that are listed as follows:

- Gather and analyze experience (NEETRAC & others) with PD testing of HV/EHV cable systems, with respect to test methods, equipment, and results– primarily in the form of commissioning tests.
- Conduct laboratory tests to assess and support field test processes and procedures.
- Recommend practices to enhance field PD measurements (calibration, sensitivity, and range checks).
- Provide general guidelines for PD test procedures on site (voltage levels, measuring time, measuring conditions, and pass criteria).
- Understand the impact of generally acceptable requirements on the value that field PD testing on HV and EHV systems might add to a user.

8.6.1 PD Signal Characteristics and Behavior in Cable Systems

A PD current signal or pulse constitutes a displacement of electrons and positively charged ions parallel to the direction of the local electrical field. For a "void-type" defect inside the bulk dielectric insulation of a cable system, the PD current generates a time varying electro-magnetic field which permeates the bulk dielectric insulation and induces current flows on both the conductor and the metallic shield of the cable system [17].

Partial discharge pulses can be described in terms of their shapes. The typical parameters of a PD pulse are its amplitude and width. The amplitude is defined as the peak amplitude of the PD pulse; in other words, it is the maximum magnitude that the PD pulse reaches independently of its shape. On the other hand, the pulse width is generally defined as the difference in time between those points in the PD pulse that have amplitude of 50% the peak amplitude. The amplitude and width of a PD pulse are illustrated in Figure 4.

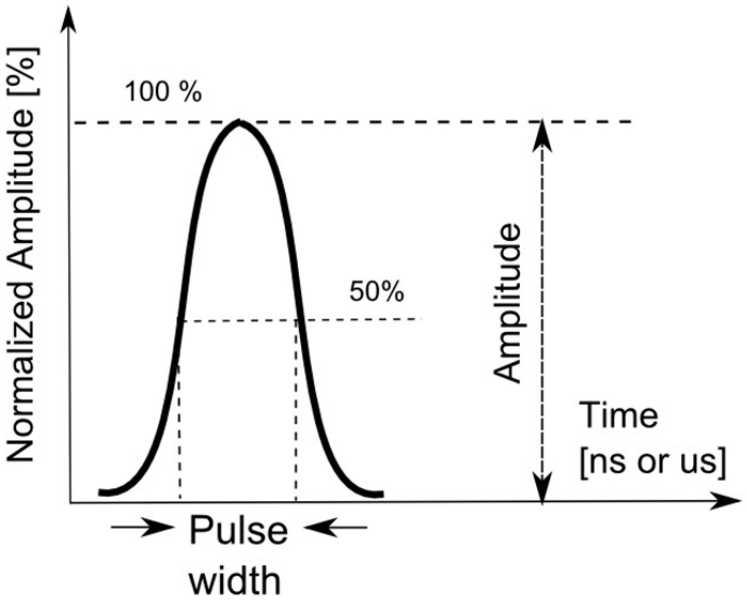

Figure 4: Typical Parameters of PD Pulse

The time-domain waveform of a PD pulse occurring within a cable system depends on the nature of the "void-type" defect and its location. However, the typical pulse width is on the order of fractions to tens of nanoseconds. Therefore, the frequency content of an actual PD pulse (at the discharge site) would be on the order of tens to several hundreds of megahertz [17]. The magnitude of the induced current depends on the strength and direction of the electromagnetic field generated by the discharge itself at the conductor and metallic shield. Thus, the magnitude of the induced PD signal on both conductors also depends upon the location of the "void-type" defect relative to the insulation and conductor screens.

8.6.1.1 Pulse Propagation

Partial discharge pulses are electromagnetic waves that propagate along the cable system. According to Maxwell's Equations, the propagation velocity is a constant and is the product of the frequency (*f*) and wavelength (λ) as shown below:

$$v = f\lambda$$

Where:

v is the speed of light within the cable system as defined by the permittivity and permeability of the insulation:

$$v_{insulation} = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}}$$

$\varepsilon_0 \approx 8.854$ E-12 F/m

$\mu_0 = 4\pi$ E-7 H/m

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PE-Based insulation materials have permittivity and permeability ratios of 2.3 and 1, respectively. Thus, the theoretical propagation velocity inside polyethylene material is 1.98E8 m/s. Consequently, a 1 MHz (1 μs) pulse would have a wavelength of 198 m while a 1 GHz (1 ns) pulse is 0.2 m in length. The wavelength represents the physical space within the material that the pulse occupies. Cable systems include other parameters that further reduce the propagation velocity.

A cable system component can affect a pulse, the component must be similar in size to the pulse wavelength. A joint is unlikely to change the shape of a 1 μs duration pulse since the pulse is much longer than the joint length. As Chapter 5 describes, TDR pulses tend to be less than 100 ns in duration so that they are short enough in wavelength to be affected by a joint.

Unfortunately, cable systems cause a number of changes in the characteristics of propagating pulses. Suffice it to say, as the pulse propagates, its high frequency components degrade faster than those in the lower frequency ranges. For illustration, simulation results of the relationship between the PD pulse bandwidth and propagation distance from the discharge site are shown in Figure 5. These simulation results use a 15 kV 1/0 XLPE cable system with a 175 mil insulation wall.

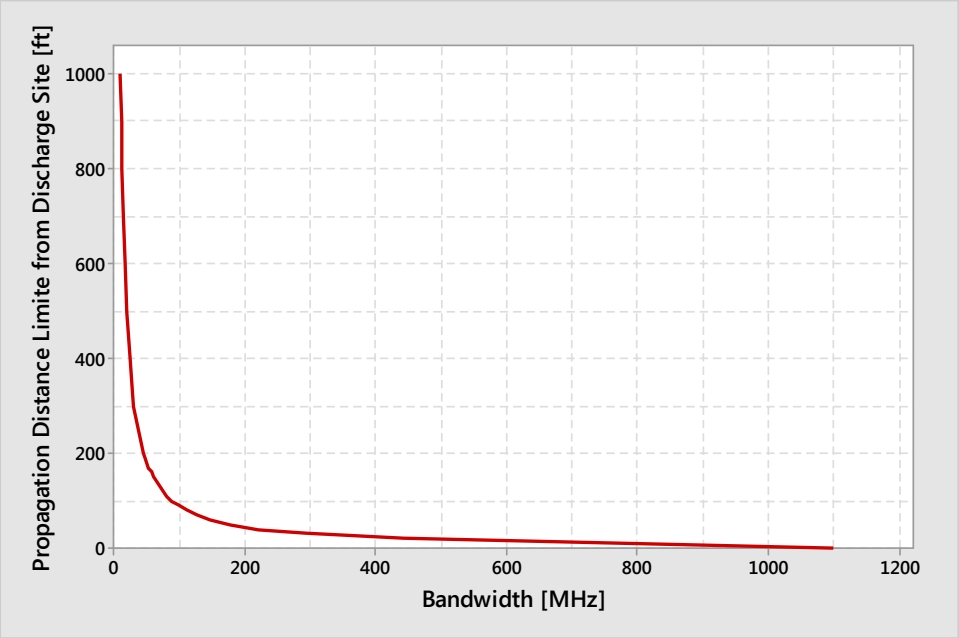

Figure 5: PD Pulse Bandwidth and Propagation Distance from Discharge Site – Linear Scale

As shown in Figure 5, the bandwidth of the propagating pulse decreases rapidly as the pulse moves away from the discharge site; as the propagation distance increases, the bandwidth seems to reach an asymptote. However, to better visualize the bandwidth behavior over all frequencies, the bandwidth axis in Figure 5 may be transformed into a logarithmic scale as shown in Figure 6. The frequency ranges for practical field measurements (yellow rectangle) and IEC 60270 (green rectangle) are included for reference in Figure 6.

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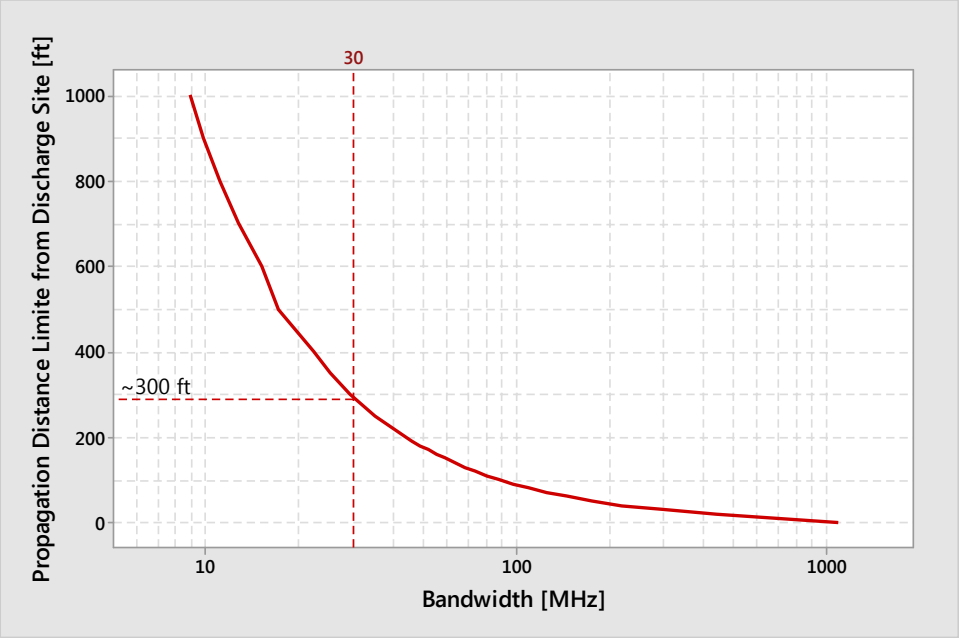

Figure 6: PD Pulse Bandwidth and Propagation Distance from Discharge Site

The most important interpretation of Figure 5 and Figure 6 is that they clearly show that the bandwidth of a PD pulse propagating along the cable system becomes limited as the PD pulse moves farther away from the discharge source.

8.6.1.2 Attenuation and Dispersion

As mentioned above, PD pulses are distorted as they propagate away from their sources. The distortion is caused by several types of cable system losses which are frequency dependent. The longer the cable system is, the greater the distortion [17]. The example in Figure 5 and Figure 6 shows that attenuation can eliminate frequencies present in the original PD pulse once the pulse has traveled short distances from the source location. This fact is used as an advantage in HV and EHV systems as the joints can be spaced far enough apart so as not to allow much signal to pass from one all the way to the next. The physical processes that characterize the changes are well known and defined: skin effect, dielectric loss, reflection and radiation [17]. These physical processes can be represented by two major sources of PD pulse distortion: attenuation and dispersion.

As PD pulses travel along a cable system, the system behaves as a "lossy" transmission line. The various physical sources for these losses can be categorized into two primary mechanisms:

1. Loss of energy (attenuation) and
2. Different propagation velocities for different frequencies (dispersion).

In addition, spurious pulses will appear that are introduced by reflections of PD pulses at the system ends and at joint locations. Attenuation and dispersion are discussed in more detail in the next paragraphs.

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Attenuation: Energy lost as a function of the distance traveled by the pulse and its frequency spectrum. In a cable system, attenuation is due to losses in the bulk insulation and propagation through the resistance of the conductor, neutral, and semi-conductive screens. Normally, attenuation increases with frequency; energy losses may be quite high for frequencies on the order of a few megahertz. As a consequence, fast PD pulses can only travel limited distances (because of their high frequency components) before they are attenuated to a level at which they may be hidden by the induced background noise. Figure 7 shows the relationship between attenuation per unit length and PD pulse width for a 300 ft cable system of 33 kV, 630 mm^2 conductor, XLPE cable. Note in Figure 7 that faster pulses show higher attenuation levels.

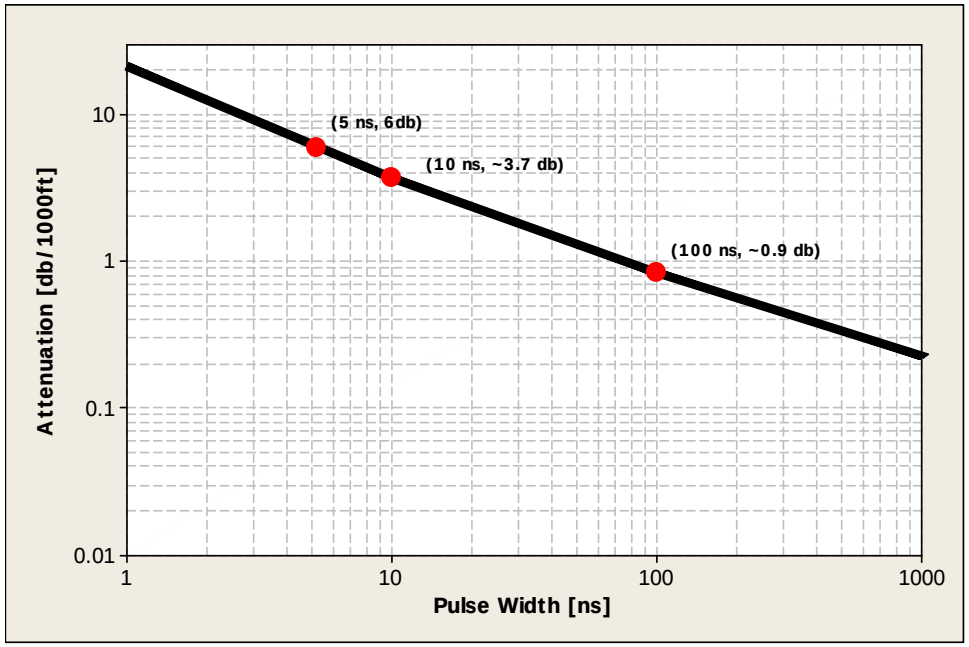


Figure 7: Calculated Attenuation as a Function of PD Pulse Width for 300 ft of 33 kV, 630 mm^2, XLPE Cable

The attenuation per unit length provides useful information regarding how far a PD pulse could theoretically travel through a cable system before being attenuated by a specified amount. For example, by analyzing the attenuation function shown in Figure 7, several observations can be made:

- A 5 ns PD pulse has an attenuation of 6 dB/1,000 ft; consequently, the pulse only travels 1,000 ft before losing 50% of its initial amplitude.
- A 10 ns PD pulse has an attenuation of approximately 3.5 dB/1,000 ft; consequently, the pulse travels 1,700 ft before losing 50% of its initial amplitude.
- A 100 ns PD pulse has an attenuation of approximately 0.9 dB/1,000 ft; consequently, the pulse travels 6,700 ft before losing 50% of its initial amplitude.

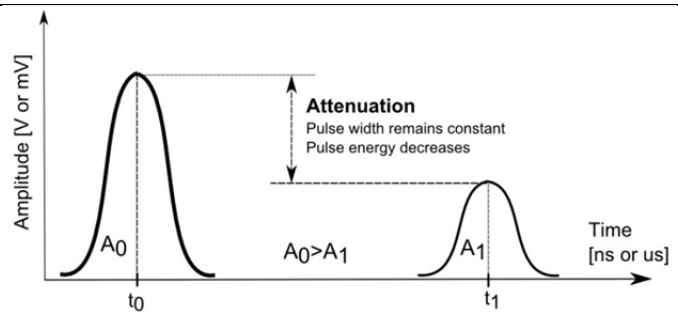
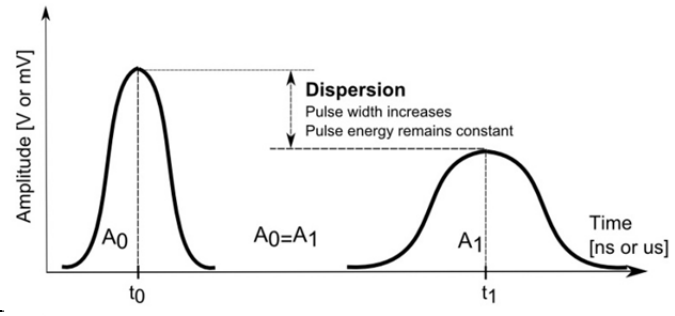
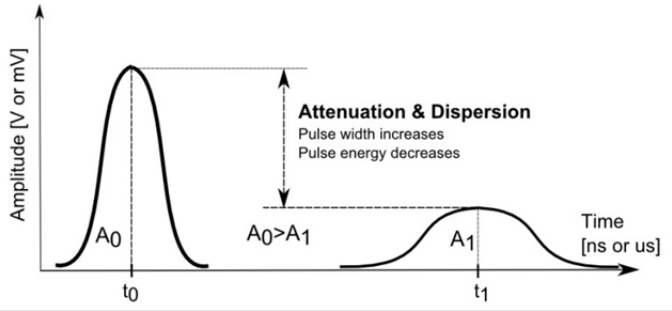
Even though the attenuation information is useful; generally, it cannot be considered alone. PD pulse distortion is always due to both attenuation and dispersion.

Dispersion: The velocity of a pulse through a medium generally depends on the frequency and

wavelength of that pulse. As a result, different pulses will travel at different velocities and different components of a pulse will travel at different velocities as well. Since a PD pulse is composed of different frequency components, these components travel at different velocities along the cable system. This difference causes the distortion known as dispersion. The distortion can be seen as a phase shift of each of the individual frequency components of the PD pulse and generally results in lower amplitude, longer duration pulses as compared to pulse shapes at their sources. Dispersion distorts PD pulses without loss of energy.

As a rule of thumb, it can be understood that attenuation causes the loss of frequency content of the PD pulses while they are distorted and spread out in time due to the dispersion effect. Table 8 presents the cases on how a PD pulse is distorted by attenuation, dispersion, and both.

Table 8: Attenuation and Dispersion of PD Pulses

Observations	Case
Attenuation: • Reduced amplitude • Constant pulse width • Reduced energy	
Dispersion: • Reduced amplitude • Increased pulse width • Constant energy	
Attenuation & Dispersion: • Reduced amplitude • Increased pulse width • Reduced energy	

Both attenuation and dispersion of PD pulses have been observed through laboratory measurements. The observation is possible by injecting a fast voltage pulse into a non-aged 25 kV WTRXLPE cable. The pulse travels approximately 2,300 ft and its initial and final traces at the near and far ends, respectively, are shown in Figure 8 and rescaled for comparison in Figure 9.

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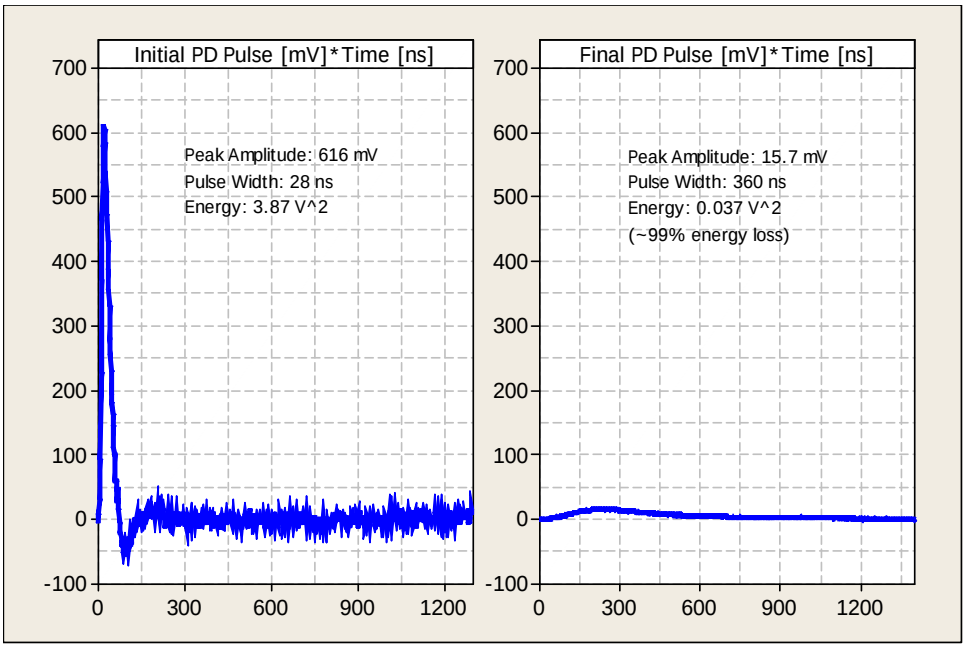

Figure 8: Laboratory Recorded Initial and Final Traces (Equal Axis Scales) of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

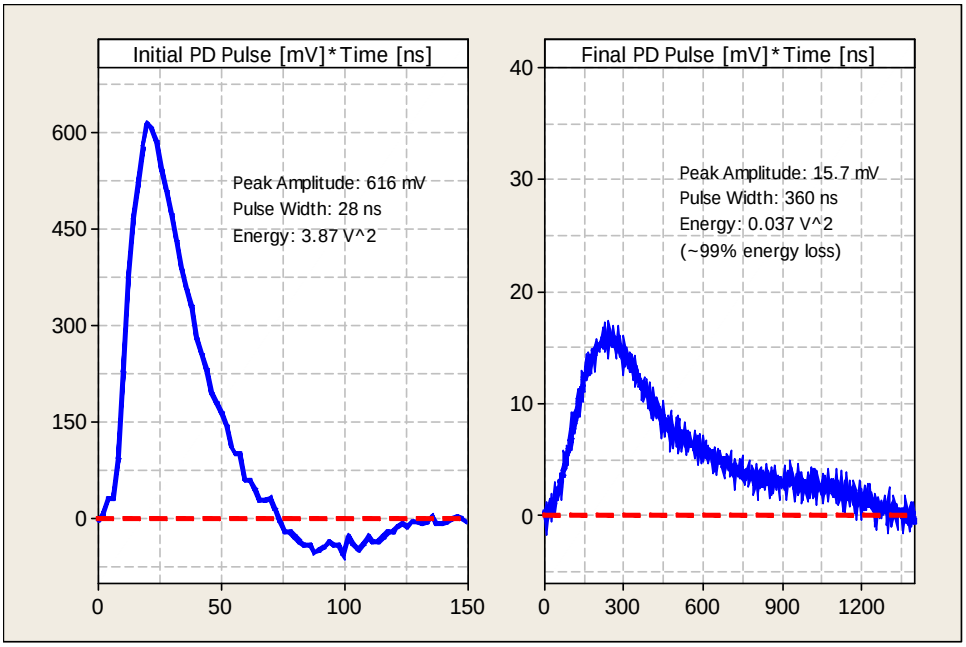

Figure 9: Laboratory Recorded Initial and Final Rescaled Traces of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

As seen in Figure 9, the attenuation and dispersion phenomena greatly affect the pulse shape parameters; specifically, it is observed that the peak amplitude decreases from 616 mV to 15.7 mV, which represents a reduction in amplitude of approximately 30 dB over the 2,300 ft of cable length. Similarly, the pulse width increases from 28 ns to 360 ns. Regarding the change in energy, the initial pulse shows an initial energy of 3.87 V^2 while the final pulse has 0.037 V^2 of energy which represents an energy loss of 99%.

8.6.1.3 Reflections from Cable System Structural Elements

In addition to deterioration from attenuation and dispersion, PD signals are further degraded as a consequence of the cable system structure (i.e. number of cable sections and accessories that compose the system). This is caused by characteristic impedance changes between cable sections and accessories that cause portions of the pulses to be reflected. These impedance mismatches occur at all transitions between cable and joints and between cable and terminations/elbows.

To illustrate the effect of reflections, two different cable system structures are shown in Figure 10 and Figure 11. The system in Figure 10 is the least complex system possible in the field: one cable length and two terminations. The second system, shown in Figure 11, adds a joint to the system shown in Figure 10.

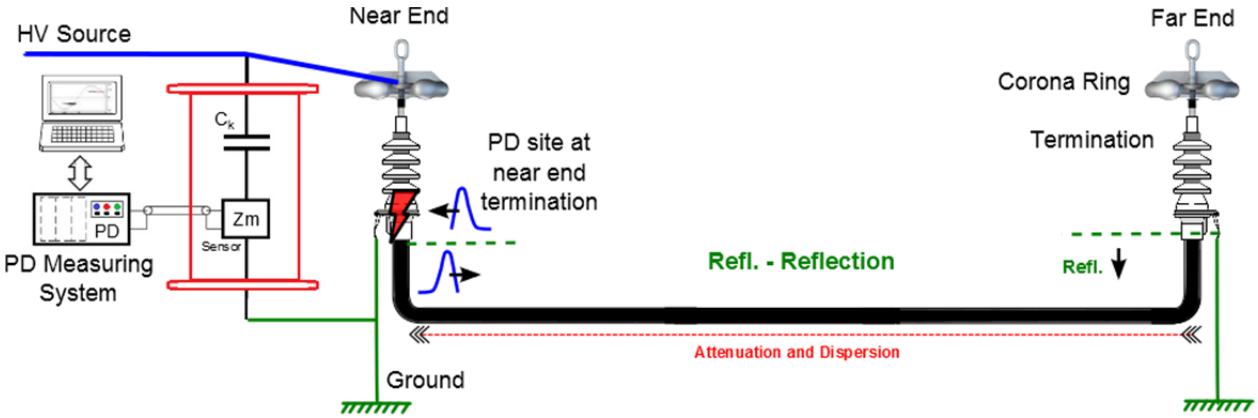

Figure 10: Illustration of PD Signal Degradation by Attenuation and Dispersion

In Figure 10, PD signal degradation results only from attenuation and dispersion (ignoring reflections off the far end termination) of PD pulses traveling from their source site along the cable system length to the detection equipment.

The signal degradation that occurs in Figure 11, on the other hand, includes attenuation, dispersion, and reflection of the PD pulse at the joint. The mismatch in characteristic impedance between the joint and cable does not allow all the PD pulse energy to transfer from one side of the joint to the other as a portion is reflected. Thus, additional signal degradation occurs and more energy is lost.

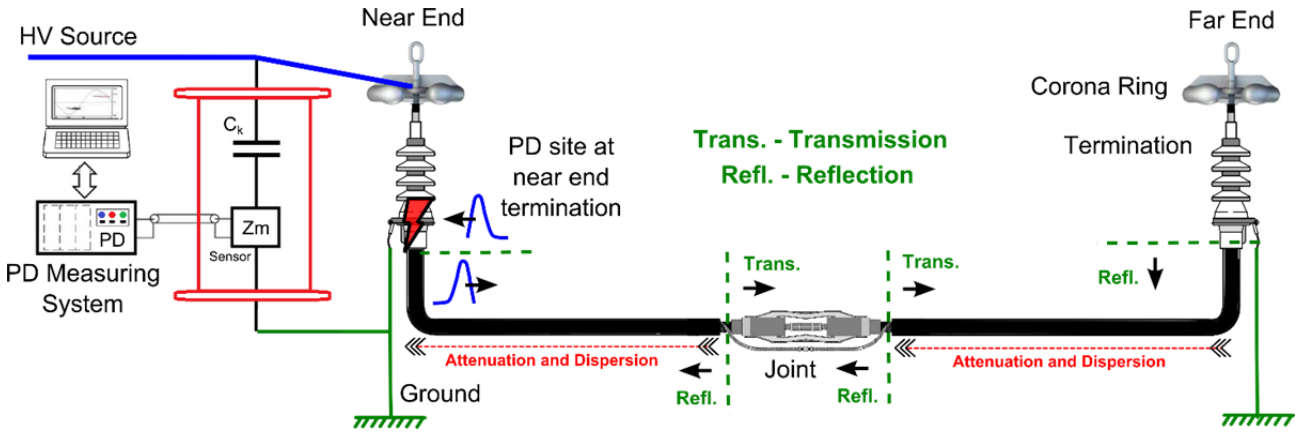

Figure 11: Illustration of PD Signal Degradation by Attenuation, Dispersion, and Cable System Complexity (Structure)

Figure 12 shows the resulting TDR trace for a PD pulse generated at the near end termination for the systems shown in Figure 10 and Figure 11. In both cases, the most important feature to consider is the amplitude of the far end reflection with respect to the initial PD pulse amplitude at the near end termination; the difference between these two amplitudes can be used as a metric to quantify and compare the signal degradation.

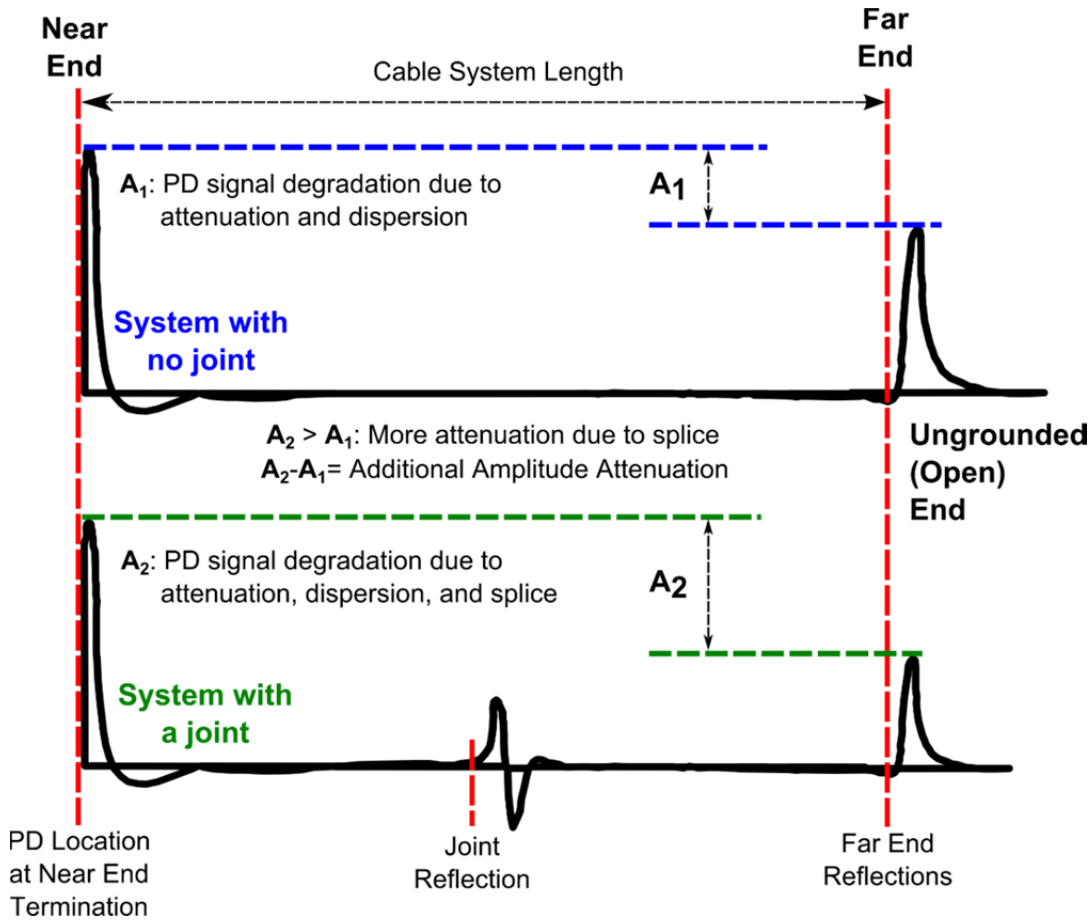

Figure 12: Impact of Cable System Complexity on Additional PD Signals Deterioration

As shown in Figure 12, signal degradation for the cable system with no joints (top Figure 12) and for the cable system with a joint (Figure 12) are quantified by A_1 and A_2, respectively. The signal degradation is worse for the system with the joint as compared to the system with cable and terminations only. Assuming that both systems have the same length, type of cable, and that the joint length is negligible when compared with the total system length, then the signal deterioration as result of attenuation and dispersion can be also assumed to be equal on both systems. Therefore, the difference between A_1 and A_2 is the result of the joint.

Users that are not familiar with this issue may tend to think that a good way around this issue would be to characterize, in some consistent way, the interactions between characteristic impedances of all different cable system components. While this approach may work, its application is only possible if all the information about cable and components is known. This process has a higher chance of success at HV and EHV than at MV. A manufacturer tends to utilize a limited number of joint and termination designs and so undertaking this process would be theoretically possible.

Ultimately, the system composition has a significant effect on the resulting pulse shapes and amplitudes so care must be taken when determining the presence or absence of PD.

8.6.2 Conventional and Non-conventional PD Measurements

At present, PD measurements are categorized as Conventional and Non-Conventional approaches. The categorization is done with respect to the frequency bandwidth of the measurement equipment used to detect and quantify the PD activity. The frequency bandwidth is typically defined by users from recommendations given in IEC 60270; specifically the standard refers to the NB (narrow-band), WB (wide-band), and UWB (ultra-wide-band) bandwidths. Conventional and Non-conventional measurement approaches relate to the bandwidths as follows:

- **Conventional PD Measurement:** Measurement methodology outlined in IEC 60270 and makes use of either NB or WB bandwidths. Results are typically reported in terms of charge magnitude (pC).
- **Non-Conventional PD measurement:** Measurement methodology that utilizes UWB equipment that is outside the scope of IEC 60270. Results can take a variety of formats but are not provided as charge magnitude. UWB is understood to be 1 MHz to 200 MHz and above. The lack of standard recommendations has consequentially led to a diverse group of commercially available equipment from multiple manufacturers and service providers.

A comparison between Conventional and Non-Conventional PD measurements categories, considering a set of important topics, is presented in Table 9.

Table 9: Comparison between Conventional and Non-conventional PD Measurement Approaches		
Topic	**Category**	
	Conventional	**Non-Conventional**
Typical Deployments	Factory Field Laboratory	Field Laboratory
Standards / Guides	• Factory – IEC 60885-3 • Laboratory – IEC 60270	IEEE Std. 400.3
Typical Approach for Measurements	Single-ended terminal measurement	
Sensor	Coupling Capacitor	Coupling Capacitor HFCT LFCT
Typical Cable or Cable System Length	• Factory – Less than 3,000 ft (~1,000 m) • Field – 50 ft to 10,000 ft (16 m to 3,300 m) with average of 300 ft (100 m) • Laboratory – Less than 300 ft (~100 m)	50 ft to 10,000 ft (16 m to 3,300 m) Average of 300 ft (100 m)
Metric for Reporting on PD Magnitude	Scaled charge – apparent charge by quasi-integration (usually in pC)	Multi-featured – amplitude of pulse in mV or area under pulse waveform (mV·s)
Measurement System Bandwidth	• Factory – f_2 [§] < 500 kHz • Laboratory – f_2 [§] < 1 MHz • Narrow band (NB) – Δf [£] =[9 kHz, 30 kHz] with f_2 [§] < 1 MHz • Wide band (WB) – Δf [£] =[100 kHz, 400 kHz] with f_2 [§] < 500 kHz	1 MHz to 200 MHz (manufacturer dependent)
Calibration	• Factory – Injection of known charge at one end or both ends bonded together, injector must comply with IEC 60885-3 • Laboratory – Injection of known charge only at the near end, injector must comply with IEC 60270	Not Applicable
Scale Factor	Not Applicable	Used in some cases
Sensitivity Check	• Factory – Capacitive sensors are assumed to have a negligible effect • Laboratory – Capacitive sensors	Resolve minimum amplitude that can be detected

Table 9: Comparison between Conventional and Non-conventional PD Measurement Approaches		
Topic	**Category**	
	Conventional	**Non-Conventional**
	are assumed to have a negligible effect if test set-up conforms IEC Std. 60270	
Performance Check	Included in the calibration procedure	Included in the sensitivity check
Range Check	Not required as it is assumed that if the requirements of the standards are met, all PD signals can be measured at the ends	Generally ignored
Background Noise	< 5 pC	No established criteria
Loss of Charge	• Factory – Loss is assumed to be insignificant • Laboratory – Conservation of charge is assumed	Not relevant
§: f_2 – upper limit frequency and f_1 – lower limit frequency £: Δf – bandwidth (BW), $\Delta f = f_2 - f_1$		

8.6.2.1 Filtering Approaches Compliant with IEC Std. 60270 – 2000

One important point to mention for conventional PD measurements is the way the required bandwidths are met. The required bandwidths can be accomplished in two different ways through filtering:

- **Analog:** The filtering is deployed as analog hardware before the signals are digitally processed (see Figure 13).
- **Digital:** The filtering is deployed in digital signal processing software (see Figure 14).

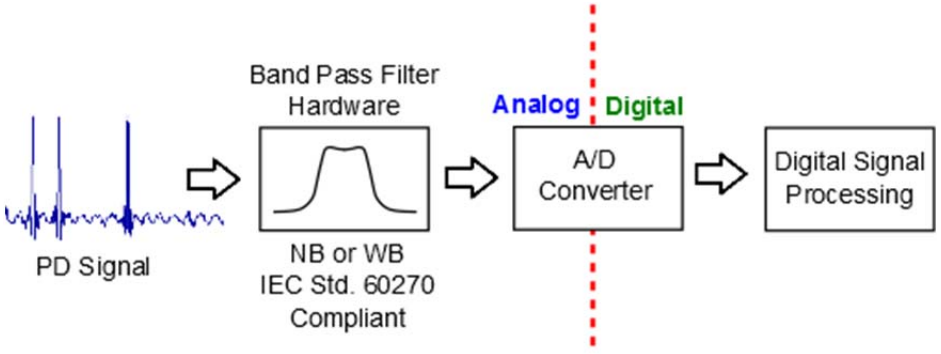

Figure 13: Conventional PD Measurements Using Analog IEC Std. 60270 – 2000 Compliant Bandpass Filter

Both filtering deployments are valid and compliant with IEC Std. 60270 – 2000. However, the digital filtering deployment provides more flexibility because higher frequency components and thus sharper/faster PD pulses are captured and they may be used for an eventual PD location. PD location using NB and WB bandwidths is not possible due to the large width of the captured PD pulses; the large width directly translates to poor location resolution. It must be also recognized that the capturing of sharper/faster PD pulses requires faster A/D converters and related hardware and software, which can impact equipment cost.

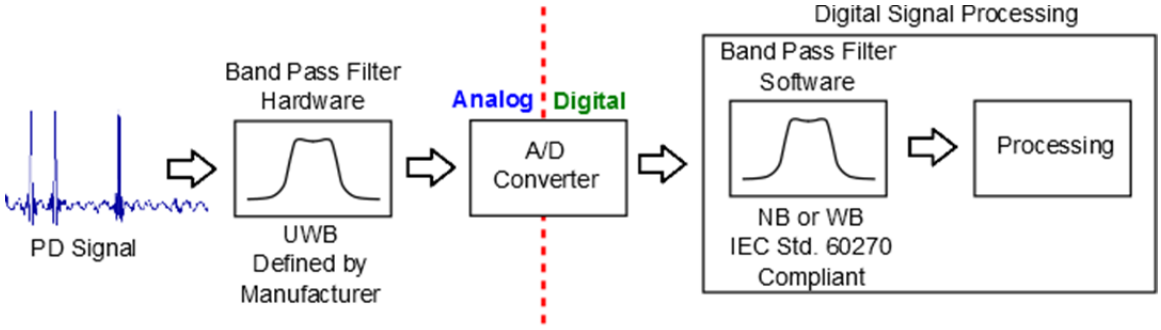

Figure 14: Conventional PD Measurements Using Digital IEC Std. 60270 – 2000 Compliant Bandpass Filter

8.6.2.2 Cable System Modeling

Partial discharge signals at their sources can include frequency components in excess of 1 GHz. In Conventional PD measurements, the calibration and interpretation procedures are based on a simplified lumped capacitive model of the cable system as shown in Figure 15. This is generally a reasonable modeling assumption at MV since the low frequencies considered by the NB and WB bandwidths have wavelengths longer than the typical tested cable system lengths. Longer lengths may be achieved with lower frequencies. Unfortunately, the electrical noise tends to increase at lower frequencies and longer cable system lengths.

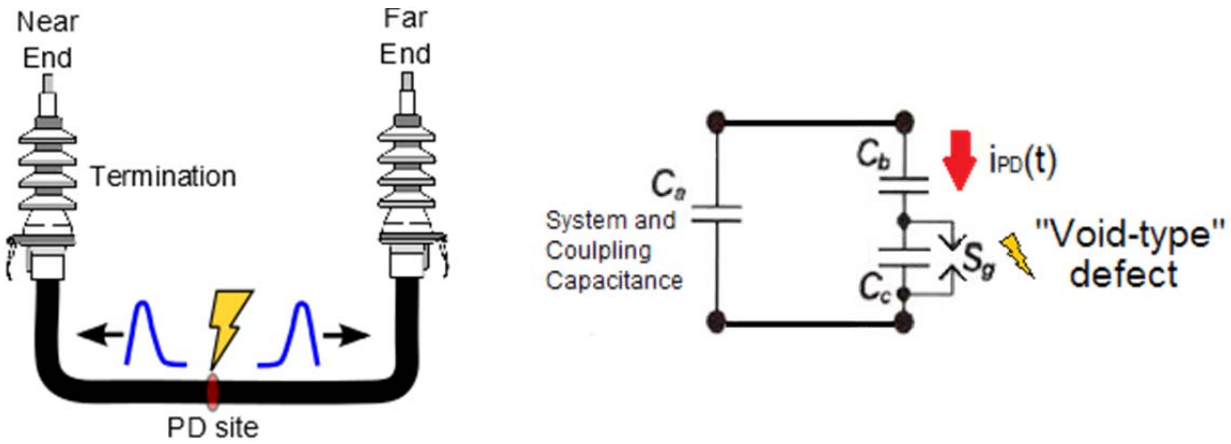

Figure 15: Lumped Capacitive Model

The narrow bandwidths (NB and WB) focus on scaled charge for PD magnitude. IEC 60270 makes compliant detection systems relatively insensitive to variations in the PD pulse wave shape and duration, so long as the PD pulse is fast relative to the detection equipment. Thus, conventional PD measurements are insensitive to high frequency attenuation, dispersion, and other signal deterioration factors caused by the cable system structure and internal configuration as previously discussed. The primary disadvantage of low bandwidths and long cable systems is that multiple pulses can be captured at the same time resulting in an error in the estimated charge magnitude. A further complication is that the location function of a PD system requires a travelling pulse in order to perform the localization. As deployed for HV and EHV, the location function of PD measurement systems is critical for users. As a result, the cable system must be modeled as distributed impedance and not as a lumped capacitance.

In recent years, users have tended to move away from the conventions of IEC 60270 to avail themselves of more advanced electronics, digital signal processing, and lower noise levels to perform the diagnosis using higher frequency measurements; i.e. measurements in the non-conventional category. Such measurements tend to use UWB bandwidths, with upper frequency responses in excess of 200 MHz, depending on equipment manufacturer. These high frequencies by definition have shorter wavelengths (as compared to frequencies in either the IEC NB or WB) and so they become comparable in size to the cable system and even the components within that cable system. Thus, the non-conventional category is based on the more general distributed impedance model that is shown in Figure 16.

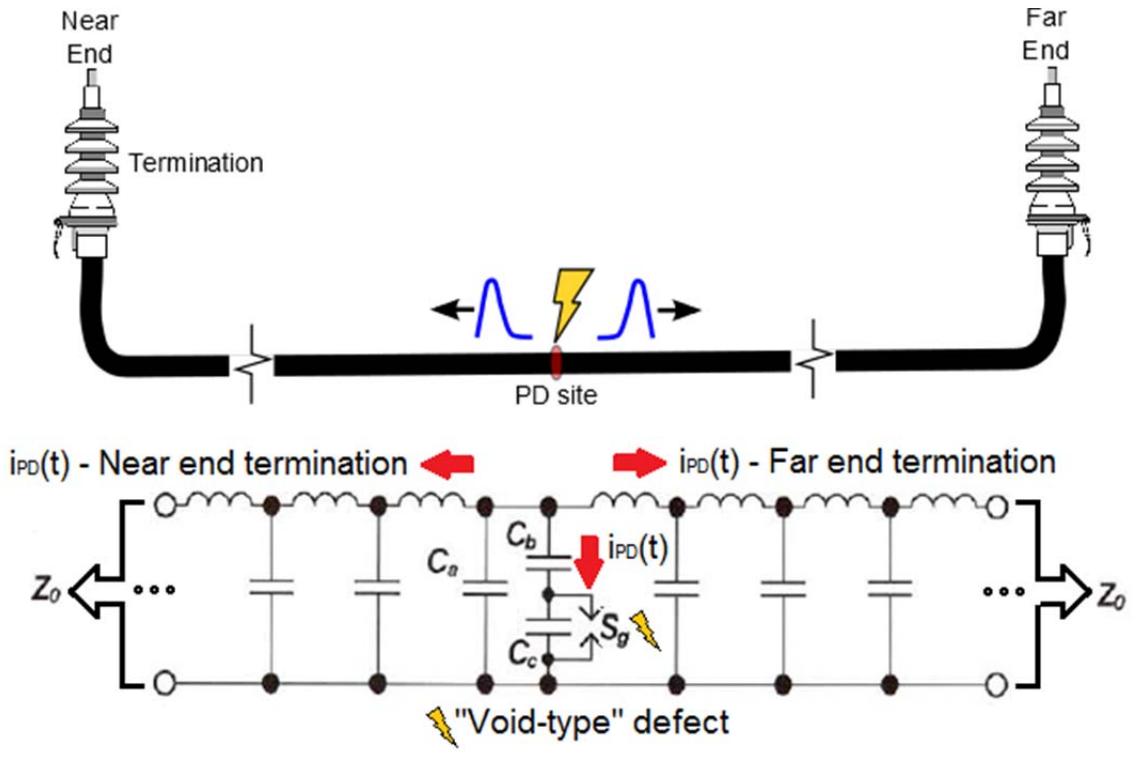

Figure 16: Distributed Impedance Model for Long Cable Systems

There is a complicated relationship between conventional and non-conventional PD measurements, measurement bandwidth, cable system length, and modeling. The following sections attempt to unravel some of this complexity.

8.6.2.3 The "Bandwidth-Length" Relationship

The challenge of which cable system model to use may be addressed by considering frequency wavelengths and comparing them with the cable system length. Well established guidelines from signal theory exist for demarking the boundary between lumped and distributed modeling. This threshold is illustrated in Figure 17.

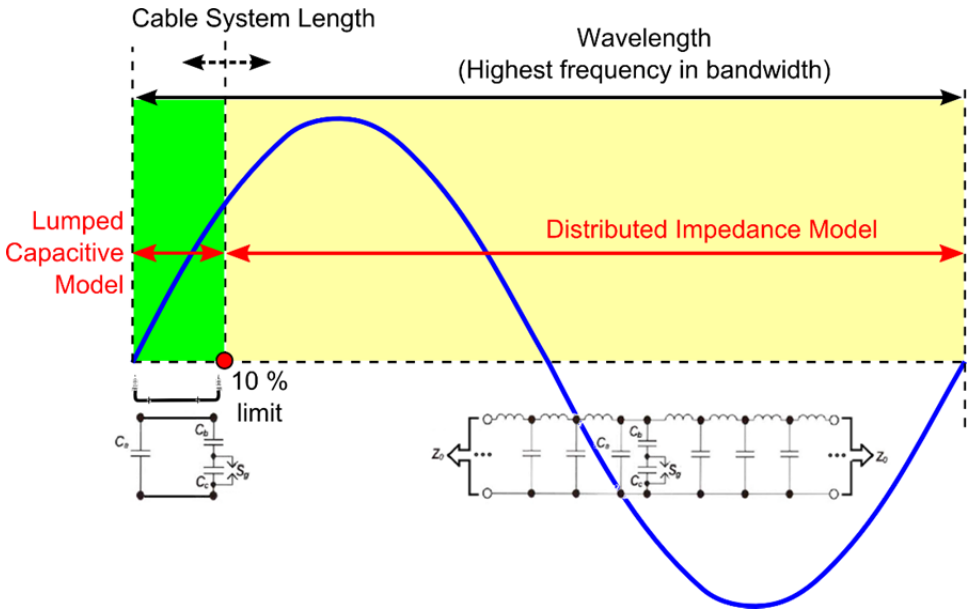

Figure 17: Illustration of Criteria for Lumped or Distributed Modeling

As seen in Figure 17, the accepted criterion indicates that if the cable system length is less than 10% of the wavelength corresponding to the highest frequency under evaluation (i.e. the shortest wavelength) then the cable system model may be simplified to the lumped capacitance approach. On the other hand, cable systems which are longer than this threshold should only be modeled using the distributed impedance approach. It should be noted that the distributed impedance approach is valid for *any* cable system length.

IEC 60270 limits the bandwidth so that cable systems can be tested using the lumped capacitance approach. The recommended frequency bands from IEC 60270 are shown in Table 10 and are illustrated in Figure 18.

Table 10: Recommended Frequency Bandwidths According to IEC 60270		
System Type	**Frequency Requirements [kHz]**	**Observations**
Wide Band – WB	$30 \leq f_1 \leq 100$ $f_2 \leq 500$ $100 \leq \Delta f \leq 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \leq \Delta f \leq 30$ $50 \leq f_m \leq 1{,}000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

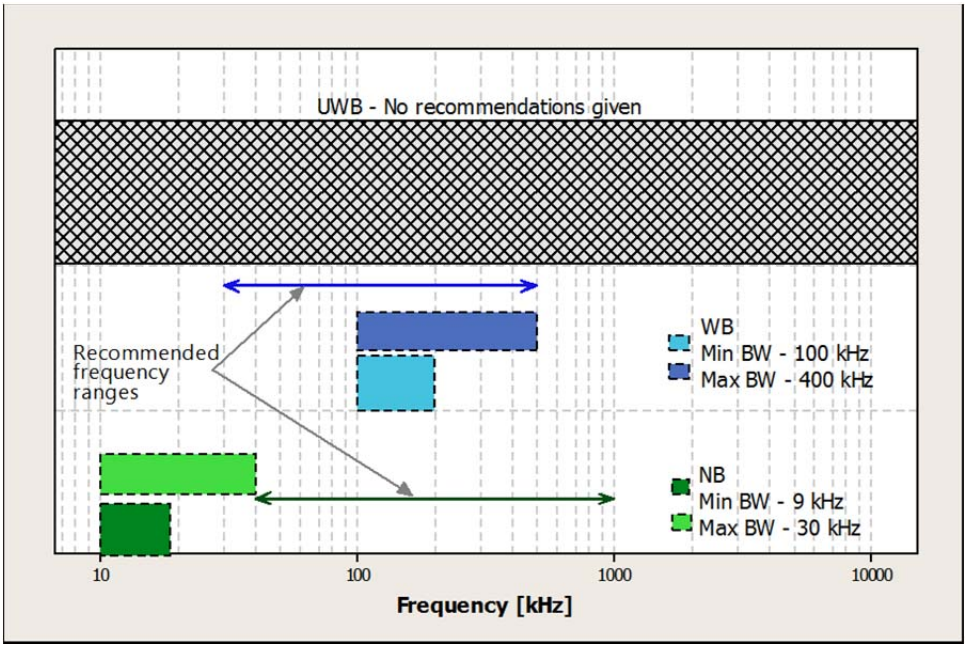

Figure 18: Illustration of Frequency Recommendations According to IEC 60270

The "10%" wavelength guideline can then be applied to the recommendations shown in Figure 17 and Figure 18 and a "map" may be constructed for the appropriate modeling conditions (see Figure 19).

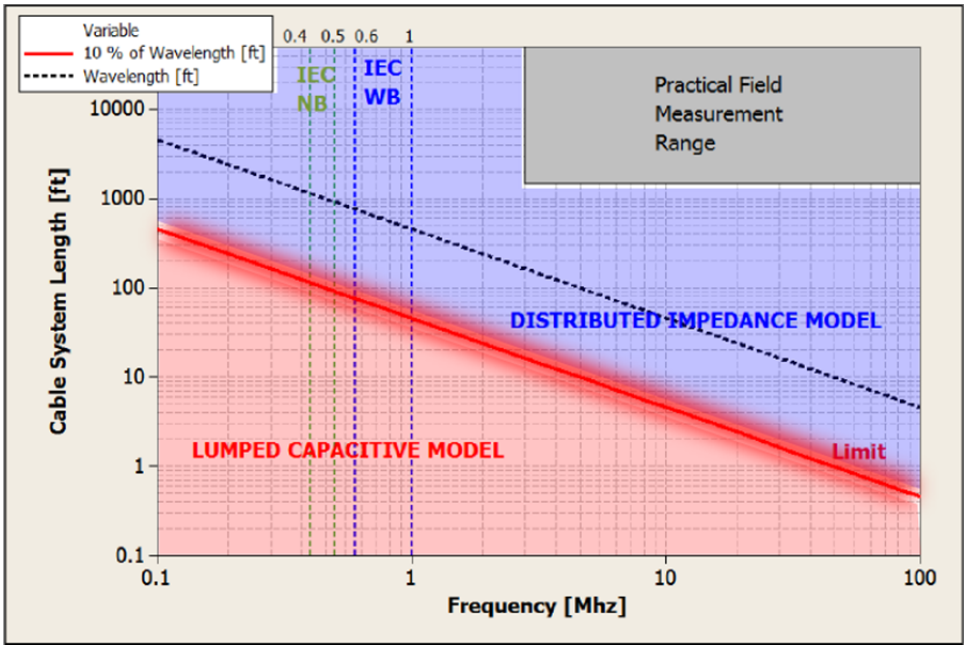

Figure 19: Relationship between PD Measurements Highest Frequency on Bandwidth and Applicability of the Cable system Modeling Categories (Figure 15 and Figure 16).

Figure 19 can be interpreted as follows:

- Within the frequency and bandwidth range specified by IEC Std. 60270 – 2000, the assumption that the cable system predominantly behaves like a lumped capacitance is not valid for lengths encountered in the field. As a consequence, calibration of the measured PD magnitude as per by IEC Std. 60270 – 2000 is not a valid concept.
- All HV and EHV cable systems should be modeled by the distributed impedance model and should be tested as such for all practically deployed PD measurements. In this case, the assumptions that are made in IEC Std. 60270 – 2000 for system modeling and calibration are no longer valid.

In addition, Figure 19 serves to demonstrate the reason why it is not possible to directly compare measured PD magnitude data between factory (conventional) PD tests and field PD tests. Although other PD metrics such as occurrence, PDIV, PDEV, and pulse repetition rate may still be performed on cable systems with lengths and frequencies above the black line in Figure 19, the calibration of measured PD magnitude for these cases as per IEC Std. 60270 – 2000 is no longer valid. The practical field measurement range in terms of frequency and cable system length is represented in Figure 19 by the gray box centered positioned above 1,200 ft, which is the typical minimum expected length of HV and EHV power cable system in the field.

Finally, PD technology users need to be aware that most non-conventional partial discharge measurement equipment offer advantages over the conventional category and they are as follows:

- Allows the use different types of sensors.
- Generates high resolution phase-resolved PD patterns.
- Measures and/or stores acquired PD pulse shapes.

- Classifies measured signals into groups including the ability to separate noise from PD signals using advanced data processing techniques.
- Uses digital filtering improving signal to noise ratios.

8.6.3 Measurement Approaches

The underlying principles of PD measurements are common to all approaches to PD detection. However, there are many ways to de-noise and quantify these discharge signals. This large number of approaches makes comparisons between test results from different PD diagnostic technologies so difficult that utilities are cautioned against making such comparisons.

8.6.3.1 Capturing PD Signals

Data acquisition systems are the interface between the sensors and computers. Through the data acquisition systems, the signal data that comes to the sensors gets converted, from its physical form, into an analog electrical signal that the acquisition system transforms a digital form to be processed and analyzed by computers. The signal is then run through a series of algorithms and results can be sent to other computers to be presented to the user. For PD measurements, there are two main data acquisition philosophies, they are as follows:

- Triggered Instruments
- Continuous Acquisition Instruments

Each of the PD measurement philosophies is discussed below.

Triggered Instruments

The first instrument type is the "triggered" class. The decision by a PD acquisition unit as to whether or not to record a signal is determined by, as its name states, an amplitude trigger. In other words, the instrument records a signal whose instantaneous amplitude exceeds a user selected value. Once the trigger level is reached, the instrument records the signal for a preset length of time. The instrument typically maintains a "pre-trigger" buffer that allows for the portions of signals that occur before the trigger level is reached to be captured as well. To assist in demonstrating the concept, its illustration in time domain is shown in Figure 20.

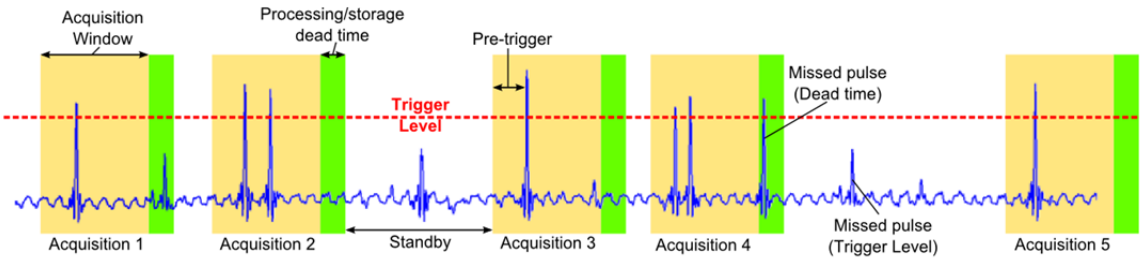

Figure 20: Time Domain Illustration for Trigger Level Based PD Measurement Philosophy

In Figure 20, the set trigger level is represented by the red dashed line and the incoming signal (waveform) by the blue solid line. With these settings, only five pulses reach the trigger level and thus only five acquisition windows are recorded. Note that for each acquisition window, there is a pre-trigger time (time before triggering instant) and a processing/storage dead time (time after the acquisition window has ended). The pre-triggering time is used to capture the waveform before the trigger instant while the processing/storage dead time is time required to run the acquired data through a series of algorithms that characterize and store the acquired signals to memory. After an acquisition window and its corresponding dead time, the acquisition system goes to standby mode waiting on the next pulse to reach the trigger level and thus repeat the process.

Also note in Figure 20 that some pulses can be missed. This occurs for two reasons:

- **Pulses that do not meet the trigger level:** The missed pulses that do not meet the trigger level can be captured by decreasing the trigger level to an adequate value. The *CDFI* perspective considers that the best practice is to have the trigger level just above the average background noise level; in this case, all pulses having a higher peak amplitude than the average background noise level are captured and more importantly the acquisition system would not get continuously triggered ("stuck") on the noise.
- **Pulses that meet the trigger level but come during the processing/storage dead time:** There is no clear solution around the issue of missed pulses that meet the trigger level but come during the processing/storage dead time. However, continuing improvements in computer processing and communication times have resulted in small dead times such there is not much concern.

As mentioned earlier, once the data are acquired, it must be stored to memory and analyzed. The typical analysis and storage process scenario (i.e. data processing) for a trigger level based PD instrument is illustrated in Figure 21. The synchronization signal in Figure 21 provides information about the phase of the test voltage.

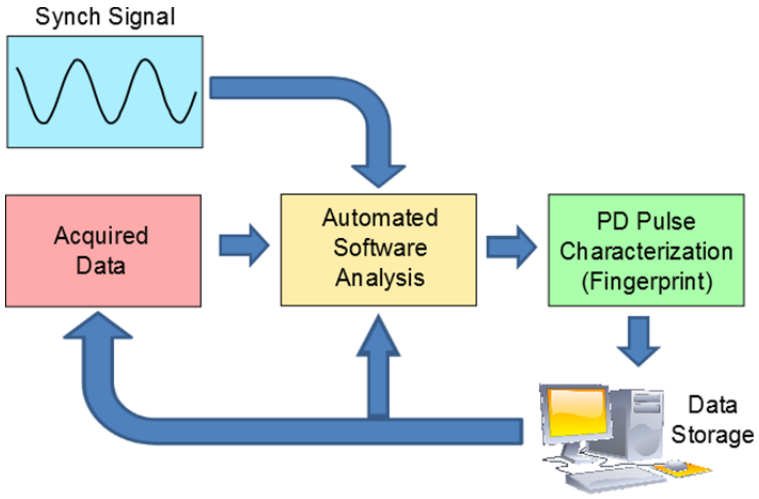

Figure 21: Typical Data Processing Scenario for Trigger Level Based PD Measurement Philosophy

As seen in Figure 21, the acquired PD and synchronization signals are automatically analyzed by software providing a basic characterization or fingerprint of the acquired pulse. After the automated analysis, all the information can then be communicated and stored to memory in a remote computer. The remote computer is generally used as the operator interface. Based on the information, the operator may take control actions on the acquired data or automated software analysis process, adapting the acquisition system to his/her needs.

Continuous Acquisition Based PD Measurement

The second philosophy is the continuous acquisition based PD measurement. In this case, the measurement is based on a single acquisition window in which all signals that come from the sensor are continuously acquired. The start and end times for the acquisition window define the acquisition time and are not trigger driven; they are selected by the operator of the PD measuring equipment. Typical predefined acquisition times are one cycle of the test voltage (typically 30 - 300 Hz). It is also possible to have alternative operator specified acquisition times. For ease in understanding the concept of continuous acquisition based PD measurement, its illustration in time domain is shown Figure 22. The incoming signal in Figure 22 is represented by the blue solid line.

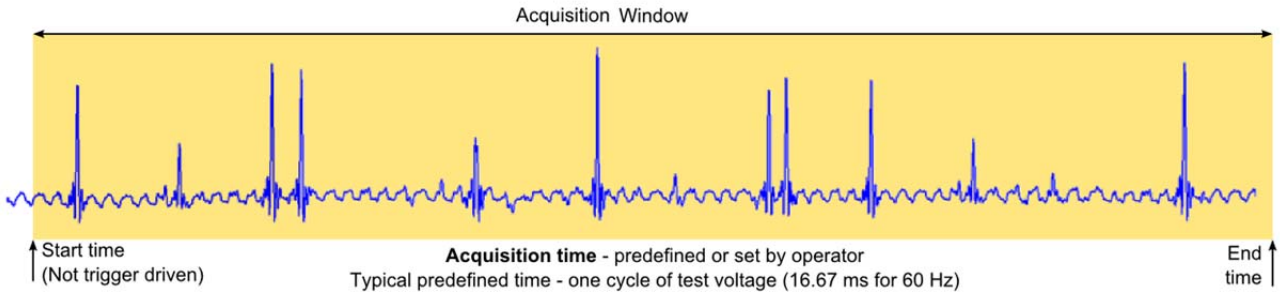

Figure 22: Time Domain Illustration for Continuous Acquisition Based PD Measurement Philosophy

Because of its nature, no pre-triggering or dead time issues exist for the continuous acquisition based PD measurement philosophy. The extraction, analysis, and characterization (i.e. data processing) of the PD signals are generally done offline, i.e. after all the data have been acquired over a range of test conditions. A typical data processing scenario for this approach is shown in Figure 23. As before, the synchronization signal in Figure 23 provides information about the phase of the test voltage.

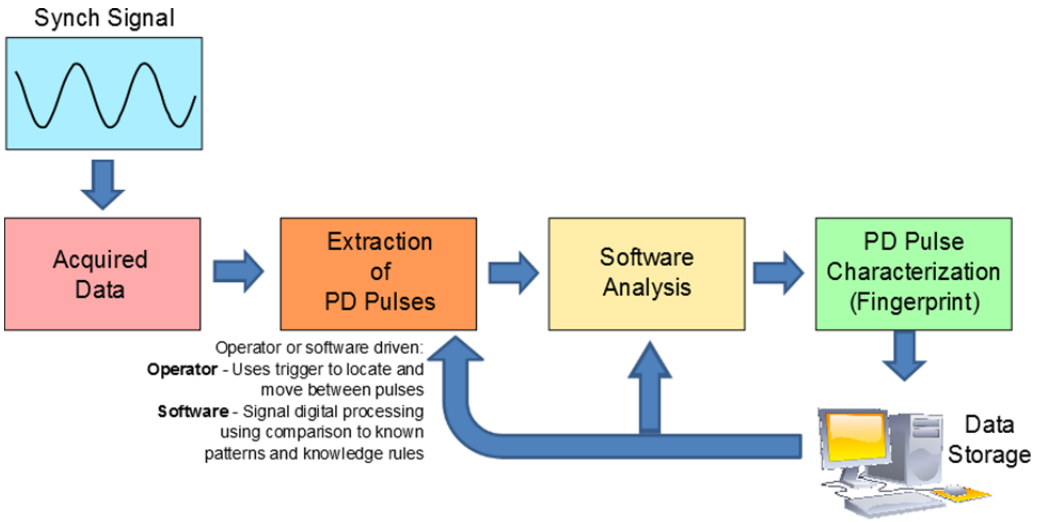

Figure 23: Typical Data Processing Scenario for Continuous Acquisition Based PD Measurement Philosophy

In Figure 23, the extraction of PD pulses can be operator or software driven. When the operator extracts the PD pulses, he/she uses experience and knowledge rules to recognize PD pulses. Various software tools may be used by the operator to extract PD pulses of interest.

Once the PD pulses have been extracted from the raw data, the analysis, characterization, and storage of data is done in a similar manner as the trigger level based instruments.

8.6.3.2 Locating Sensors and Quantifying PD Signals

The two PD instrument types described above can be used for acquiring PD signals at a number of cable system locations including one or both terminations as well as any accessible joint location. This yields three primary deployment types:

- **Single-ended Terminal Measurement:** PD measurements are performed with a PD sensor located at one of the cable ends (typically designated as the "near" end) – see Figure 24.
- **Dual-ended Terminal Measurement:** PD Measurements are performed simultaneously at both cable ends (near and far ends) – see Figure 25.
- **Distributed Measurement:** PD measurements are performed with sensors located at terminations and joints, the measurements can be done sequentially or simultaneously. When a PD sensor is moved from joint to joint and PD measurements are made sequentially, the deployment is often termed "joint hopping" – see Figure 26 and Figure 27.

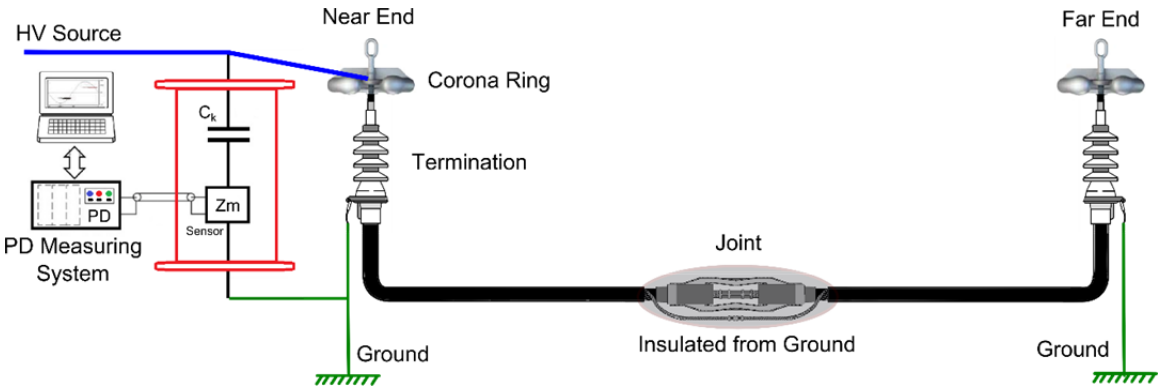

Figure 24: Single-ended Terminal Measurement

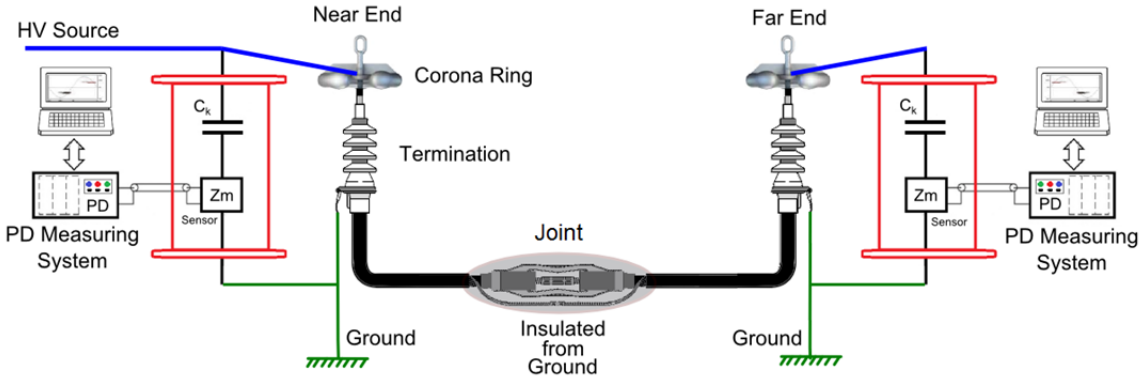

Figure 25: Dual-ended Sequential Terminal Measurement

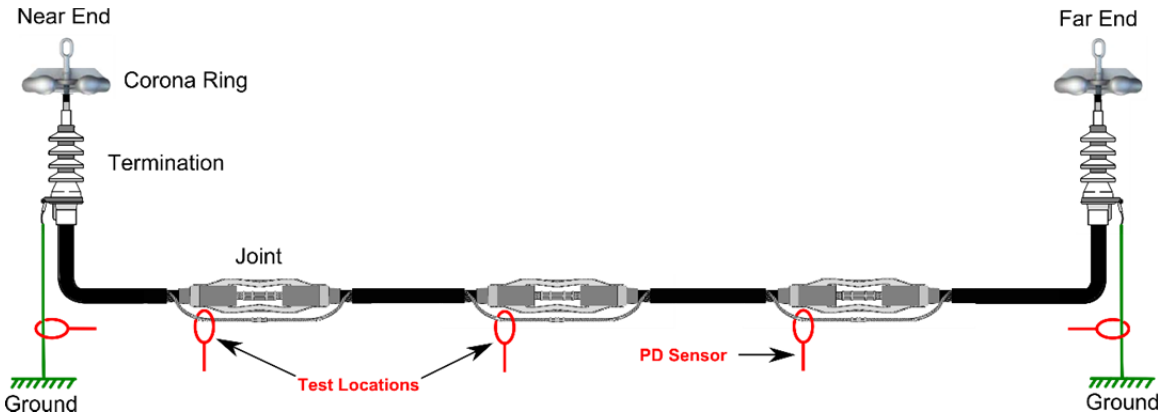

Figure 26: Illustration of PD Distributed Measurement on HV Power Cable Systems

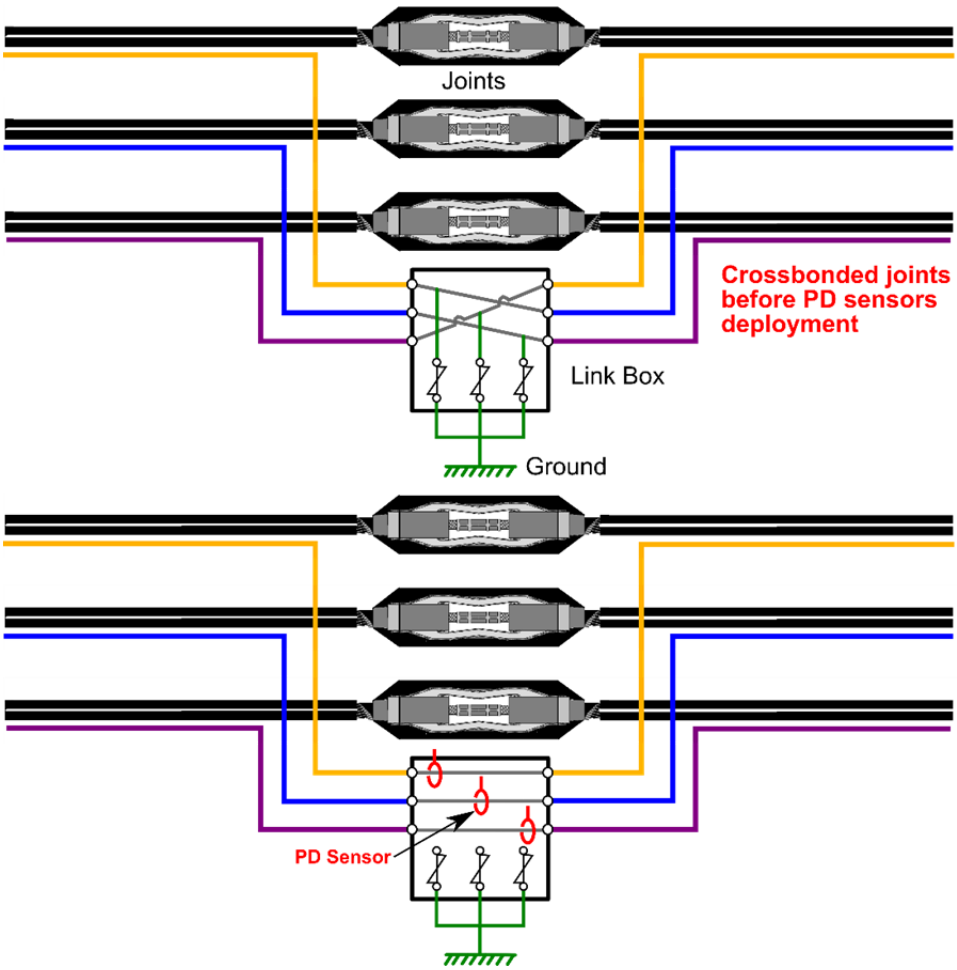

Figure 27: Illustration of PD Measurement on HV Power Cable Systems at Cross-bonded Joints

The measurements approaches shown above can use different methods to estimate the size of the discharge; however, the size of the charge is not typically used in the decision-making. Most users are interested only in the presence or absence of detectable discharge and so its severity is not as important as in MV PD tests. In cases where discharge size is of interest, the following two methods may be used:

- **Scaled Charge (pC):** The apparent charge, expressed in pC, can be estimated using a pre-derived scale factor or integration of PD current waveforms (as captured by the sensor-acquisition equipment). This method is related to the wide-band and narrow-band test setups presented on the IEC 60270 – 2000 and IEC 60885 – 1988. In addition to the PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.
- **Multi Featured (mV):** PD magnitude is estimated from measurement results using any relevant/convenient metric – typically PD magnitudes are referenced to the peak magnitude of PD waveforms (as captured by the sensor-acquisition equipment) in millivolts. Other metrics such as the area under the pulse curve in mV-µs could also be used. This method is related to the ultra-wide-band test described on the IEC Std. 60270 – 2000. In addition to the

PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.

Table 11 shows the relationship between the voltage source type and the measurement approaches for on-site PD testing of HV and EHV cable systems.

Table 11: Usage of source type for On-site PD Testing of MV Power Cable Systems

Source Type	Approach to Measurement	Scaled Charge	Multi-Featured
Power Frequency AC (30-300 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	Yes
Very Low Frequency AC (≤ 0.1 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	No
Damped AC Voltage (20 Hz to 1 kHz)	Terminal (Single and Dual-ended)	Yes	No
	Distributed	No	No

Regardless of the voltage source type, there are several issues that need to be considered:

- Time and test voltage magnitude above U_0.
- PD diagnostic features (e.g. PD magnitude, PDIV, PDEV, or PD Patterns) cannot be compared between voltage source types.

As seen in Table 11, PD tests performed in HV and EHV power cable systems typically fall into one of two configurations:

1. Terminal single and double-ended PD measurements for all source types.
2. Distributed sensors in scaled charge or multi featured PD measurements.

Terminal PD measurements somewhat mimic a conventional PD test like those performed in the laboratory. However, due to the attenuation and dispersion effects, terminal PD measurements are often constrained to short lengths of cable – typically a section containing only a length of cable and two terminations.

Since accessories are often the source of PD in HV and EHV cable systems and these systems have significant attenuation and dispersion effects PD measurements are often performed in a distributed sensor approach. The test can be performed sequentially or simultaneously at each accessory during the test. The latter method requires a PD sensor for each accessory with a communications link between testing locations. The advantage of this approach is that accessories are locally monitored during the test and therefore periodically or cyclically occurring PD sources may be detected. When

measurements cannot be performed simultaneously, the joint hopping approach mentioned above is used. PD sensors are moved from accessory to accessory with short acquisition times at each location.

Table 12 outlines the three different field approaches and relevant features here off for PD tests at HV and EHV.

Table 12: Overview of Field PD Approaches to Measurement [30]				
Test Category	**Terminal Scaled Charge**	**Terminal Multi Feature**	**Distributed Scaled Charge**	**Distributed Multi Feature**
Location of Measurement	Single or Dual-ended		Distributed PD Measurement with sensors at accessories (joints and / or terminations)	
Sensor	Any internal or external sensor (capacitive or inductive)			
Typical Power Cable System Length	• 6,000 ft from each terminal sensor used. • No joints or few straight metal clad joints. • Limited by cable system propagation characteristics maximum lengths often lower due to attenuation and dispersion effects – see Range Check.		Any length	
Upper Cut-off Frequency	< 1MHz Typically	< 30MHz Typically	< 1MHz Typically	< 750MHz Typically
	Or any other specified bandwidth within allowed range			
Calibration	• Any well documented form of either classic calibration or double sensors. • Calibration voltage pulse with a rise time typically 10 times faster than circuit response – see Calibration.		Not applicable.	
Scale Factor	Not applicable		• Any well documented form of either double sensor methods and/or sensitivity by construction. • Includes evaluation of wave propagation in the cable adjacent to sensors.	
Sensitivity Check	• Required across the frequency range of the bandwidth of the measurement. • Includes evaluation of wave propagation in the cable adjacent to sensors – see Sensitivity Check.			
Performance Check	Required to check PD System Operability – see Range Check			
Range Check	Required to establish the length that a PD pulse can travel down a cable at selected levels of amplitude and dispersion – see Range Check			
Noise	Noise mitigation is essential		Noise mitigation may not be essential due to sensor location at accessories and propagation (filter) characteristics of cable	
Loss of charge	Loss assumed to be small enough not to perturb measurement	Recognizes loss of charge / current, especially at bonding of cable systems	Recognizes loss of charge / current, especially at bonding of cable systems	
Reporting on PD magnitude	Apparent charge by suitable (typically digital) integration technique. Any suitable metric (pC, mV, i_{PD})		Induced apparent charge by suitable (typically digital) integration technique.	Any suitable metric (pC, mV, i_{PD})
Location	Location by time of flight from terminals		Location by sensor position and time of flight	

8.6.4 Commissioning versus Maintenance Tests

CDFI Phase II has had the unique opportunity to collaborate with the CIGRE B1.28 Working Group to generate a publication regarding on-site PD assessment of HV and EHV able systems. The CIGRE HV and EHV voltage classifications are based on those in IEC 60840 – 2004 and IEC 62067 – 2011, respectively. One consequence of such designations is that 35 kV and above cable systems are classified as HV while some users, especially in North America, would consider these voltages as MV voltage classes. However, the voltage designations considered here follow the following convention:

- MV – 15 through 35 kV
- HV – 46 through 161 kV
- EHV – greater than 161 kV

One of the more important efforts than the CIGRE B1.28 Working Group has already accomplished is a survey that has been carried out among CIGRE membership countries. In total, 60 survey responses were obtained from 13 different countries. The participation by country is shown in Figure 28.

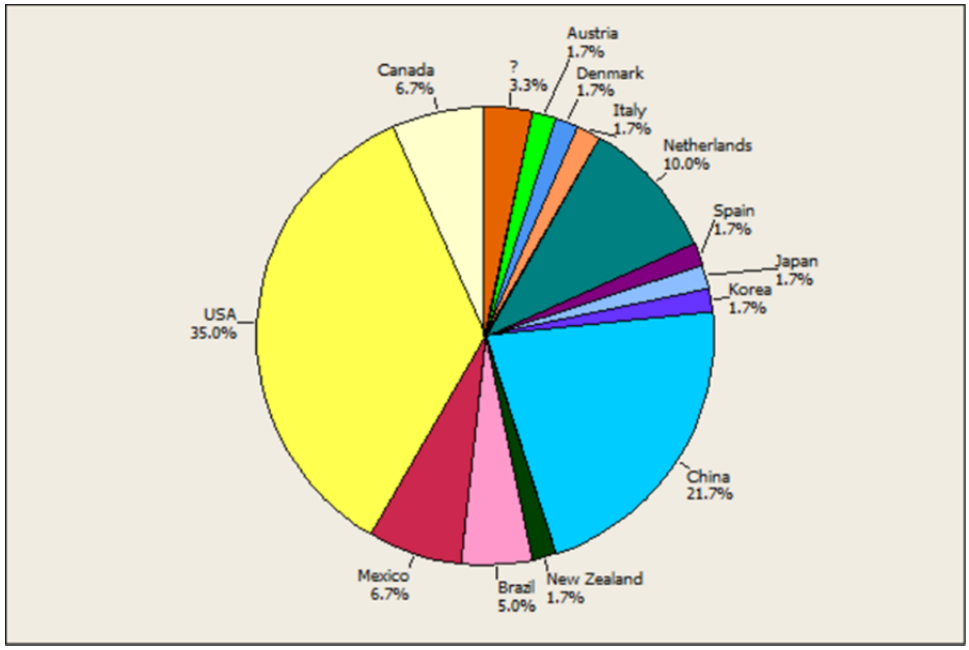

Figure 28: Global Participation of the Survey Conducted by CIGRE B1.28 Working Group

Utilities, manufacturers, and diagnostic service providers had participation levels of 58%, 22%, and 20%, respectively. Survey respondents were requested to describe their normal practice regarding the use of PD measurements as part of testing for HV and EHV cable systems. Results indicated that 27% of respondents do not perform any PD tests on these systems. The remaining 63% of respondents indicate that they do perform PD measurements primarily on new cable systems in the form of commissioning tests.

The survey also explored how the respondents viewed the following common reasons for undertaking PD measurements:

- **Test the quality of the installation:** To verify the installation was done properly.
- **Test the quality of the accessories:** To reduce the likelihood of an accessory failure during the system service life.
- **Test the quality of the cable:** To reduce the likelihood of a cable failure during the system service life.
- **Increase assurance:** To increase confidence in the installation especially where the utility's public perception and quality assessment (QA) program are important.

Within the survey, the respondents were asked to rank the above reasons according to their relative importance (see Figure 29). According to the responses, the most important reason was to test the quality of the installation while the least important was to increase assurance.

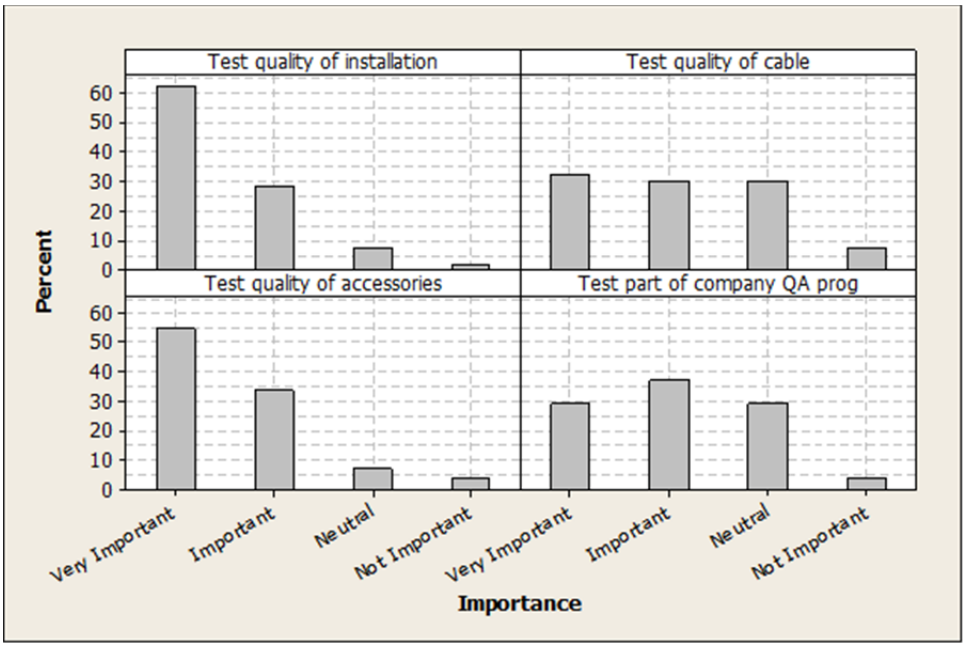

Figure 29: Relative Importance of PD Measurements – Common Reasons

A complimentary study was conducted from survey results to look at the type of PD measurements that have been used and on what voltages and lengths of systems they were employed. A summary of the complimentary study is presented in Table 13. In Table 13 table, PD measurements fall into two groups in terms of deployment (i.e. terminal or distributed) and two groups in terms of data reporting (i.e. scaled charge or multi-feature). In this context a distributed deployment is when sensors are located close to the accessories (terminations or joints) under PD evaluation to avoid as much as possible background noise, signal deterioration, and/or any other issue that may negatively influence successful PD detection. When the sensors are deployed simultaneously or sequentially on the accessories, the deployment is typically known as "Joint Hopping".

The data provided by respondents was also used to estimate typical system lengths upon which the PD measurements were deployed. To provide information about length variability, the typical

system lengths are expressed in terms of interquartile ranges; i.e. the low range (25th percentile of the data), median (50th percentile of the data), and high range (75th percentile of the data) as shown in Table 13. Thus, for HV systems approximately 5% of tests were conducted using a distributed sensor/scaled charge approach for lengths between 10 mile (16 km) and 34 mile (55 km) with a median of 22 mile (35 km), whereas for EHV systems between 65% and 80% of tests were conducted using a distributed sensor/multi-featured approach for lengths between 0.6 mile (1 km) and 8.7 mile (14 km) with a median of 3.6 mile (6 km).

Table 13: Common Practices for Field PD Measurements of HV and EHV Cable Systems

Standards	Field PD measurements are not required to conform to IEC Std. 60270 - 2000 and IEC Std. 60885-3 - 1988		
Deployment	Single or Double Terminal Measurement	Distributed PD Measurement with Sensors at Accessories (i.e. joints and/or terminations)	
Reporting (See Table 12 for further explanation)	Scaled charge with a reference to laboratory calibration procedures according to IEC Std. 60270 - 2000	Scaled charge usually from integration of current vs. time traces of captured pulses	Convenient multiple metrics or features
Sensor	Any internal or external sensor		
HV Cables Systems			
Global Experience (to 2010)	< 50% of tests	<5% of tests	50 to 80% of tests
Length [mile] (Low Range Median High Range)	0.1 0.6 1.2	10 22 34	0.6 3 12.4
EHV Cables Systems			
Global Experience (to 2010)	< 35% of tests	<5% of tests	65 to 80% of tests
Length [mile] (Low Range Median High Range)	0.1 1.8 3.6	8.7 8.7 19.8	0.6 3.7 8.7

As seen in Table 13, the most common practice for field PD measurements on HV and EHV cable systems is distributed measurements with sensors deployed at accessories and using multiple features. This style of field measurement accounts for 50% - 80% of tests for HV systems and 65% - 80% for EHV systems. The data represent tests conducted through 2010.

Therefore, based on survey results, two observations are apparent:

- PD measurements on HV and EHV cable systems are mainly deployed as commissioning tests.
- With the focus on commissioning tests, the interpretation of PD is not as important as for MV systems and so PD diagnostic criteria should not be based on PD severity but rather on its presence/location in the system.

It should be recognized that some cases, e.g. maintenance tests, would require some kind condition assessment. However, the fact that these systems should be PD free leads to the conclusion that any new PD detected during the system service life must be due either to installation problems not detected during commissioning or defects in the system that developed since installation. The latter case is more concerning as these systems have historically performed with very high reliability.

Unfortunately, it is important to be aware that no industry diagnostic criteria for PD condition assessment exist for maintenance tests conducted on HV or EHV cable systems. Criteria do exist for laboratory qualification tests; however, as discussed earlier these cannot be applied to systems installed in the field.

8.6.5 Energizing Cable Systems

To perform a PD test, the cable system must be energized from either the transmission grid or an external voltage source. This section discusses the energization options available for HV and EHV cable system PD tests.

8.6.5.1 Online Testing – Maintenance Tests

On-line monitoring maintenance testing is conducted with the cable system as is normalized energized and connected to the power system. An on-line PD monitoring an assessment can be deployed periodically with PD data acquisitions predetermined intervals or it can be continuous for an extended period which can range from days to years.

While on-line PD measurements are not performed at elevated test voltage levels, several case studies have documented their applicability; in particular, solid dielectric field aged cable systems [11]. In the case of terminations, PD activity can be present for a significant amount of time prior to failure and, thus, on-line PD measurements could potentially be used to identify a defect in a termination with enough warning to allow some action to be taken.

The B1.28 Working Group has developed recommended test procedures for on-line monitoring as shown in Table 14. Similar to elevated voltage tests, these procedures are the result of extensive discussions within the B1.28 Working Group. Since the *CDFI* has participated in these discussions, the test procedures and success criteria in Table 14 also reflect the views within *CDFI*.

Table 14: Recommended Maintenance Test Procedures and Success Criteria for PD On-line Monitoring Maintenance Testing				
Voltage Class [kV]	**Test Level [U_0]**	**Frequency [Hz]**	**Monitoring Duration [min]**	**PD Pass/Fail Criterion**
66-72	1.0	60	10	Guiding criterion is no detectable PD §
110/115				
132/138				
220/230				
345/400				
§: However, experience shows that in some cases utility specific criteria exists depending on the particular application				

8.6.5.2 ac Resonant Testing – Commissioning and Maintenance Tests

The primary purposes of a commissioning test are:

- To verify that the cable system is free of life limiting defects caused by damage during transportation and/or installation.
- To provide a clear contractual hand over to the asset owner. A secondary benefit is that a commissioning test provides a base line measurement for any future PD measurements.

As mentioned earlier, the most common practice for commissioning tests for extruded HV and EHV cable systems is a combination of AC Withstand Testing (performed according to IEC 60840 – 2004 or IEC 62067 – 2011) with PD measurement (this combination can also be seen as a monitored withstand).

Feedback from cable owners of HV and EHV cable systems within the *CDFI* and discussions with the B1.28 Working Group indicate that commissioning tests performed at voltage test levels less than 1.7 U_0 do not adequately identify life-limiting defects via PD measurements. In addition, evidence from test experiences indicate a higher rate of in-service failures is observed on cable systems that have been commissioning tested at voltages lower than $1.7U_0$.

Figure 30 and Figure 31 show recent data provided by the B1.28 Working Group to the *CDFI* in which PD activity was continuously monitored during a 60 min withstand tests. Specifically, Figure 30 shows the cumulative distribution function of PD inception time and Figure 31 shows the cumulative distribution function for the PD inception voltage for commissioning test performed at $1.7U_0$.

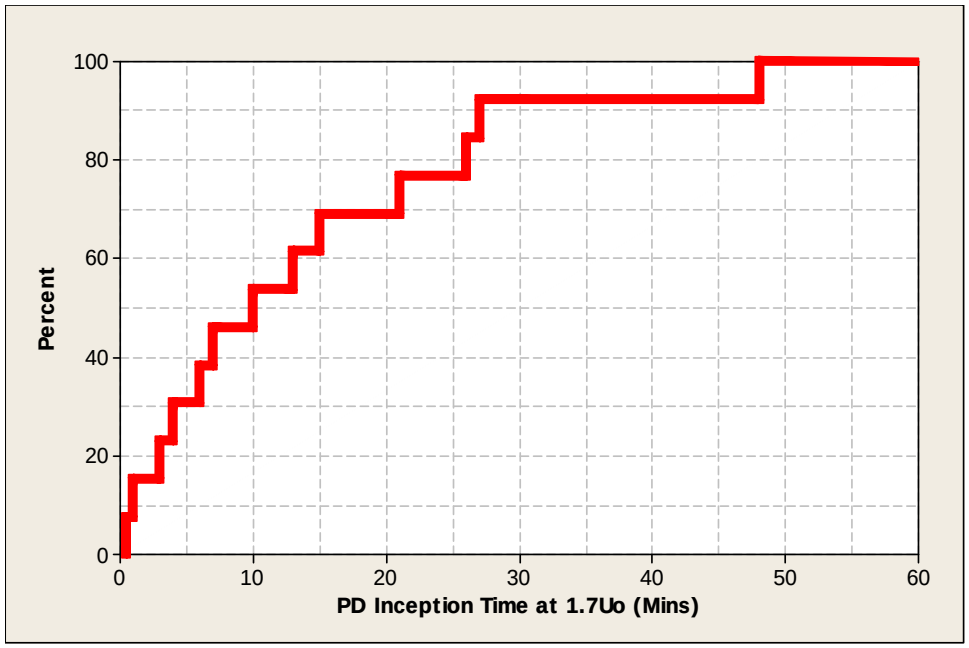

Figure 30: Cumulative Distribution Function of PD Inception Time for Commissioning Tests Performed for 60 min at $1.7U_0$ on HV and EHV Cable Systems

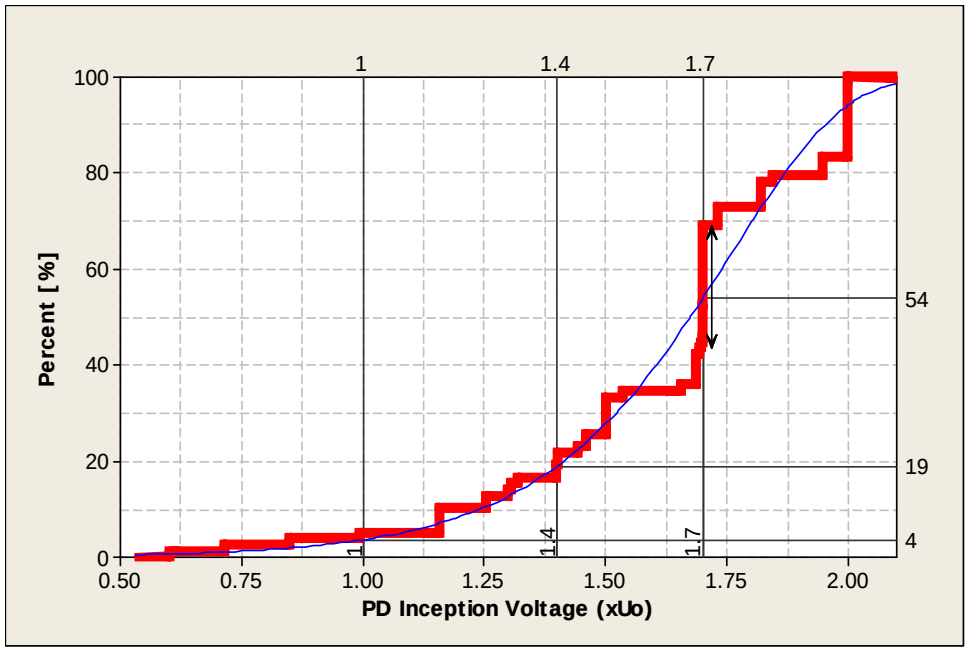

Figure 31: Cumulative Distribution Function of PDIV for Commissioning Tests Performed for 60 min at $1.7U_0$ on HV and EHV Cable Systems

As can be seen from Figure 30 some PD sources require some time to become active after the withstand test has started. More importantly, however, Figure 31 shows that the majority of PD sources require at least $1.5U_0$ to incept. This implies that test voltages below $1.5U_0$ will likely allow a significant number of defects to go undetected.

Consequently, the B1.28 Working Group has recommended the test procedure and success criteria shown in Table 15.

Table 15: Recommended Commissioning Test Procedures and Success Criteria

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Duration [min]	PD Pass/Fail Criterion
66-72	1.7	10-300	60	No Detectable PD
110/115				
132/138				
150/160				
220/230				
275/285				
345/400				
500				

The test voltage is a trade-off between (a) using a high enough voltage to initiate PD from defects (during a one hour test) that would result in an in-service failure during the normal service life of the system and (b) using voltage that is too high and might cause PD around defects in the system which would otherwise not have resulted in an in-service failure. The test voltage recommended in IEC 60840 – 2004 and IEC 62067 – 2011 are 1.9 U_0 and 1.7 U_0, respectively. IEC 62067 – 2011 allows testing lower than 1.7 U_0 if 1.7 U_0 is not technically feasible as a result of long cable lengths.

AC resonant test sets typically have a working frequency range of 20 Hz to 300 Hz. It may be necessary to extend the lower limit to 10 Hz to allow the testing of very long cable systems. Research has shown that when subjected to electrical stresses in the frequency range of 20 Hz to 300 Hz PD inception and electrical tree growth do not vary significantly and, therefore, from a PD point of view, the cable system dielectric behaves similarly as it does at 60 Hz.

A typical test voltage profile for commissioning and re-commissioning tests for HV and EHV power cable systems is shown in Figure 32. The re-commissioning tests are defined here as tests performed within the first 5 years of service life (including before initial energization) or at the end of the warranty period; whichever is longer. The profile shown in Figure 32 holds for single-ended, double-ended, simultaneously distributed, or sequentially distributed PD measurements. In the case of sequentially distributed PD measurements, it is assumed that all joints can be visited and PD tested for a reasonable period of time of 5 min with continuous PD assessment.

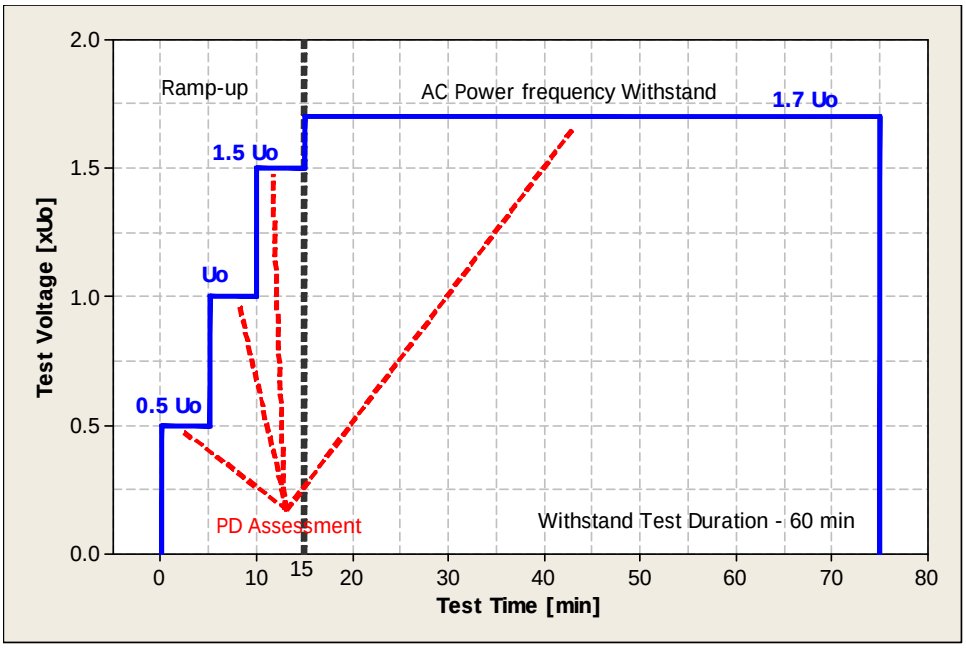

Figure 32: Typical Test Voltage Profile for Commissioning and Re-commissioning (less than 5 years) Tests for HV and EHV Power Cable Systems

For the cases in which all joints cannot be visited during the AC withstand test 60 min period, a "Joint Hopping" or "Daisy Chain" measurement approach must be followed. In this case, the test voltage is maintained for short periods of time and then taken down so that the PD equipment can be relocated to the next joint location. In very long cable systems, the total time at the withstand voltage level may exceed the 60 min minimum. Such a profile is shown in Figure 33 and includes the periods where voltage is reduced to at least operating voltage during the position change.

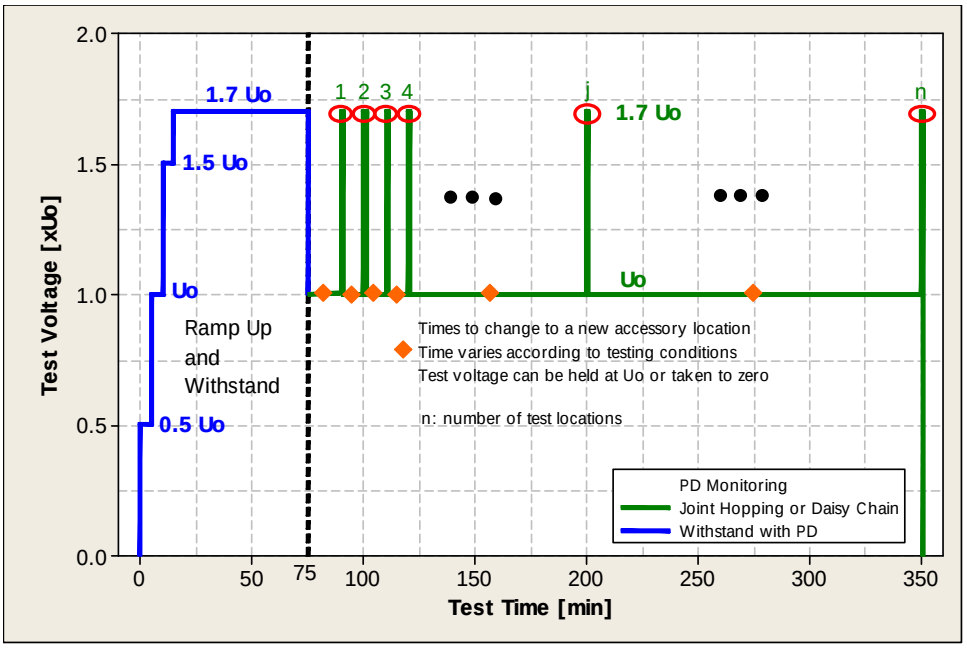

Figure 33: Typical Test Voltage Profile for Commissioning and Re-commissioning Tests for HV and EHV Power Cable Systems using "Joint Hopping" or "Daisy Chain" PD Measurement Approach

Maintenance Tests

The primary purpose of a maintenance test is to check that the cable system is free of life limiting defects caused by aging mechanisms acting on the main insulation system. As mentioned above, the Cigre survey showed that few cable owners in general perform maintenance tests on HV & EHV cable systems. There are, however, some maintenance tests conducted after a system is repaired as the result of a service failure or when reworking an existing cable system (re-routing the cable or adding extra sections). In a few cases, maintenance tests are also performed when a PD source was detected in an accessory but the utility chose to accept the accessory anyway. Each of these cases is handled slightly differently and depend on the cable system age.

In maintenance tests after a repair on systems less than 5 years old the cable system is subjected to a full AC withstand and PD assessment test with withstand voltage levels and durations as indicated in Table 15 (1.7 U_0 for 60 min).

For systems older than 5 years or after the warranty period (whichever is longer), ac withstand and PD testing is performed at a reduced test voltage level and/or duration (Table 16). There are very few data on such tests. Thus, the B1.28 Working Group was guided by the levels used for commissioning with the application of appropriate reduction factor (i.e. in general the test voltages lay mid-way between the commissioning test voltages (Table 15) and the maximum voltage for the cable system (U_m)). It is possible that these levels may be too low and that future experience will reveal more appropriate levels. It has also been suggested that an additional reduction factor should be considered when the cable system is older than 15 years.

In light of the above discussion, Table 16 shows the compiled recommendations from Cigre B1.28. These test voltages and durations also represent the suggested practice within *CDFI*.

Table 16: Recommended Maintenance Test Procedures and Success Criteria for Off-line PD Measurements at Overvoltage

Voltage Class [kV]	Frequency Range [Hz]	Duration [min]	Service Life			
			5 Years§ to 15 Years		More Than 15 Years	
			Test Level [xU_0]	PD Pass/Fail Criterion	Test Level [xU_0]	PD Pass/Fail Criterion
66-72	10-300	60	1.5	No Detectable PD	1.1	No Detectable PD
110/115						
132/138			1.4			
150/160						
220/230						
275/285						
345/400						
500						
§: Or end of warranty period whichever is the longer						

It is also important to mention that field experience has shown that if the PD tests are performed at voltages less than 1.7 U_0 then the cable system is often preconditioned at 1.7 U_0 for 10 – 15 s after which the test voltage level is lowered to the level at which the PD assessment is to be performed. Unfortunately, the risk and impact of this preconditioning have yet to be evaluated. From the *CDFI* perspective, the decision to raise the test voltage to 1.7 U_0 must be made by the cable system owner.

8.6.5.3 Very Low Frequency (VLF) Testing – Commissioning Tests

The Cigre B1.28 survey shows that AC voltage testing (20-300 Hz) is more commonly deployed in the field than other voltage sources. However, there have been some tests where the voltage source was sinusoidal VLF. The limited reported experience with VLF is insufficient to make recommendations on test parameters (voltage levels or durations). Using experience at MV, it is possible to provide some suggestions for how one might proceed to utilize VLF for HV and EHV systems. These suggestions are shown in Table 17.

<table>
<tr><th colspan="5">Table 17: Recommended Commissioning Test Procedures and Success Criteria for VLF Test Voltages</th></tr>
<tr><th>Voltage Class [kV]</th><th>Test Level [U_0]</th><th>Frequency Range [Hz]</th><th>Duration [min]</th><th>PD Pass/Fail Criterion</th></tr>
<tr><td>66-72</td><td rowspan="2">1.9</td><td rowspan="4">0.05 – 0.1</td><td rowspan="4">60§ min for 0.1 Hz</td><td rowspan="7">No Detectable PD</td></tr>
<tr><td>110/115</td></tr>
<tr><td>132/138</td><td rowspan="2">1.7</td></tr>
<tr><td>150/160</td></tr>
<tr><td>220/230</td><td colspan="3">Some reported experiences but insufficient to provide test guidance</td></tr>
<tr><td>275/285</td><td colspan="3"></td></tr>
<tr><td>345/400</td><td colspan="3" rowspan="2">No reported experiences to provide test guidance</td></tr>
<tr><td>500</td></tr>
<tr><td colspan="5">§: Minimum time requirement is currently unknown; however, but for experimental purposes a time of greater or equal to 60 min is suggested, it might be appropriate to use an increased time if the frequency is significantly reduced so that to have the same number of test voltage cycles as 0.1 Hz for 60 min</td></tr>
</table>

There remain a number of issues/unknowns with the use of VLF voltage sources on HV and EHV cable systems, which include:

- The electrical tree initiation and growth dynamics are largely unknown for VLF frequencies and the electrical stresses for HV and EHV cable systems.
- The appropriate initial test voltage levels to initiate PD at life limiting defects in typical HV and EHV cable systems are largely unknown.
- The duration of VLF required to initiate PD at life limiting defects otherwise requiring local losses (some time with constant voltage AC) to be detectable.
- The duration of VLF required to cause insulation failure for life limiting defects which do not give rise to PD during constant voltage resonant tests but do cause insulation failure.

8.6.5.4 Damped AC Testing – Commissioning Tests

Similar to VLF voltage sources, there is some reported usage of Damped AC (DAC) voltage sources for PD measurements on HV and EHV cable systems. The amount and scope of this usage is insufficient to make recommendations on test parameters. However, there may be users who wish to undertake experimentation and gather information on PD under DAC voltage. To this end, Table 18 contains test guidelines for using DAC voltage sources.

<table>
<tr><th colspan="5">Table 18: Recommended Commissioning Test Procedures and Success Criteria for Damped AC Test Voltages</th></tr>
<tr><th>Voltage Class [kV]</th><th>Test Level [U_0]</th><th>Frequency Range [Hz]</th><th>Number of Shots [#]</th><th>PD Pass/Fail Criterion</th></tr>
<tr><td>66-72</td><td rowspan="2">1.9</td><td rowspan="4">10-500</td><td rowspan="4">> 50§</td><td rowspan="8">No Detectable PD</td></tr>
<tr><td>110/115</td></tr>
<tr><td>132/138</td><td rowspan="2">1.7</td></tr>
<tr><td>150/160</td></tr>
<tr><td>220/230</td><td colspan="3">Some reported experiences but insufficient to provide test guidance</td></tr>
<tr><td>275/285</td></tr>
<tr><td>345/400</td><td colspan="3" rowspan="2">No reported experiences to provide test guidance</td></tr>
<tr><td>500</td></tr>
<tr><td colspan="5">§: The number of shots required is currently unknown but for experimental purposes a number greater than 50 is suggested</td></tr>
</table>

There remain a number of issues/unknowns associated with the use of DAC voltage sources, including:

- The damped nature of the voltage waveform thereby making specification of test duration challenging.
- The non-constant nature of the applied test voltage.
- The electrical tree initiation and growth dynamics are largely unknown for repetitive applications of DAC waveforms.
- The appropriate initial voltage test levels to initiate PD at life limiting defects in typical HV and EHV cable systems are largely unknown.
- The appropriate number of shots of Damped AC required to initiate PD at life limiting defects otherwise requiring local losses (some time with constant voltage AC) to be detectable.
- The number of shots required to cause insulation failure for life limiting defects which do not give rise to PD during constant voltage resonant tests but rather cause insulation failure.
- The voltage exposure resulting from long dc charging times relative to the DAC waveform period (minutes versus milliseconds).

8.6.6 Calibration Principles

In the context of cable system PD measurements, the term “calibration” is strictly defined as the process presented in IEC 60270 for relating measurement data to charge magnitudes. Originally, the calibration process was developed for laboratory use; the goal was to develop a practical framework that enabled results between laboratories to be compared. However, there are a number of explicit conditions that must be fulfilled in the field for calibration to be meaningful. The following sections discuss these conditions and the resulting limitations.

8.6.6.1 IEC 60270 Calibration Method

The calibration of PD measuring systems is intended to verify that the measuring system is able to measure a predetermined PD magnitude in pico-coulomb correctly. Calibration is done for the complete test configuration including:

- Cable system under test,
- Coupling capacitor, and
- Measurement hardware.

Calibration must be made for each cable system to be tested unless tests are made on a group of similar cable systems. In this case, "similar" means the same cable type, length, and accessories.

Calibrating a PD measuring system is done by repetitively injecting a short duration current pulse of known charge magnitude (known current and integration time) into one termination of the cable system under test (with all required measuring and source equipment connected). The resulting configuration puts the pulse injector in parallel with the coupling capacitor and high voltage source as shown in Figure 34.

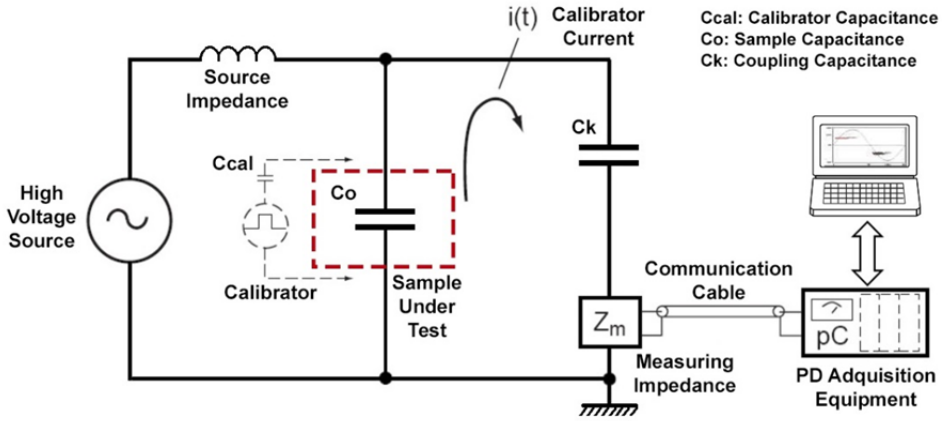

Figure 34: Calibration Test Set-up for PD Measurements

The pulse injection is done using a calibrator (pulse injector) that is designed and is itself calibrated to provide a consistent known charge magnitude. IEC 62070 specifies a number of requirements for the calibrator device. Unfortunately, no specific requirements for the pulse wave shape (i.e. amplitude and pulse width) are specified.

The standard PD measuring test method presented in IEC 60270 is the coupling capacitor method (i.e. independent of the type of electrical sensor used (capacitive or inductive) the presence of the coupling capacitor is always required). Figure 34 illustrates the reasoning behind this. As PD pulses contain high frequency components, these frequency components do not flow through the high voltage source as it is largely inductive and represents high impedance. The coupling capacitor provides a low impedance path for these frequencies allowing PD current pulses to be measured by the sensor (Z_m – measuring impedance).

In this method, the charges of PD pulses are usually determined from the peak magnitudes of the pulses in the detector. These peaks as seen by the PD detector depend on the capacitances of the sample under test and the measuring circuit (coupling capacitance). When the detected PD pulses are compared with the calibration pulses, the apparent charge magnitudes of the PD pulses can be estimated.

The PD calibrator needs to comply with standard requirements and so its characteristics are checked periodically. IEC 60270 regulates the specification to estimate the calibrator performance, and this specification and others related to the calibration procedure are shown in Table 19. This standard specification regulates the type test, routine test, performance test, and performance check of the PD calibrator. Charge, rise time, and pulse repetition rate must be measured and calibrated in these tests, except for the performance check.

Table 19: IEC 60270 Requirements for PD Calibrators

Attribute	Requirement	Comments
Calibrator Charge (q_0)	Tolerance ±5% of set charge and ≤ 1 pC	Clause 7.2.3 whichever is greater
Pulse Rise Time (tr)	Tolerance ±10% of set time and ≤ 60 ns	Clause 7.2.3 tr – 10% to 90% of peak value
Pulse Repetition Rate (**N**)	Tolerance ±1% of set rate	Clause 7.2.3
Linearity of Calibrator	Tolerance ±5% or ±1 pC	Clause 6.3 whichever is greater
PD Measured Metric (Scaled Charge)	50% to 200% of Calibration	Clause 5.2
Calibrator Capacitance (C_{cal})	≤ 0.1 Sample Capacitance (C_0)	Clause 5.2
Coupling Capacitor (C_k)	Always to be present	Regardless sensor type (capacitive or inductive)
Recalibration Sample Capacitance (C_0)	In the range of ± 10% of C_0 allowed	No recalibration required for similar cable systems Clause 5.2

8.6.6.2 Pulse Injectors

Pulse injectors (otherwise known as calibrators) are used in the calibration procedure described above. As Table 19 shows, the waveform the pulse injector generates is not defined and so the bandwidth of the pulse is equally ill-defined. It is, therefore, difficult to reconcile the "calibration" aspect of these devices with the recommended bandwidths for PD instruments when the pulses used in calibration are not specified.

The issue is important since the signal deterioration of high frequency components of PD pulses travelling through a cable system is significant. Pulse injectors themselves are believed to produce pulses that resemble actual PD pulses and so should have quite wide bandwidths. The relationship between the injected pulses and the bandwidth can be analyzed by comparing the power spectrum

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density functions of the pulses with the recommended bandwidths. A study was conducted with three different pulse injectors to determine what differences exist between devices and their effect on the results a PD instrument would report had these injectors been used for calibration.

The pulse injectors used in this experiment are shown in Figure 35.

Figure 35: Commercially Available Pulse Injectors

Figure 36 shows a comparison between pulse waveforms of the different injectors for a setting of 100 pC and into an impedance of 50 Ω. The value of 50 Ω is selected because cable characteristic impedances are usually near this value.

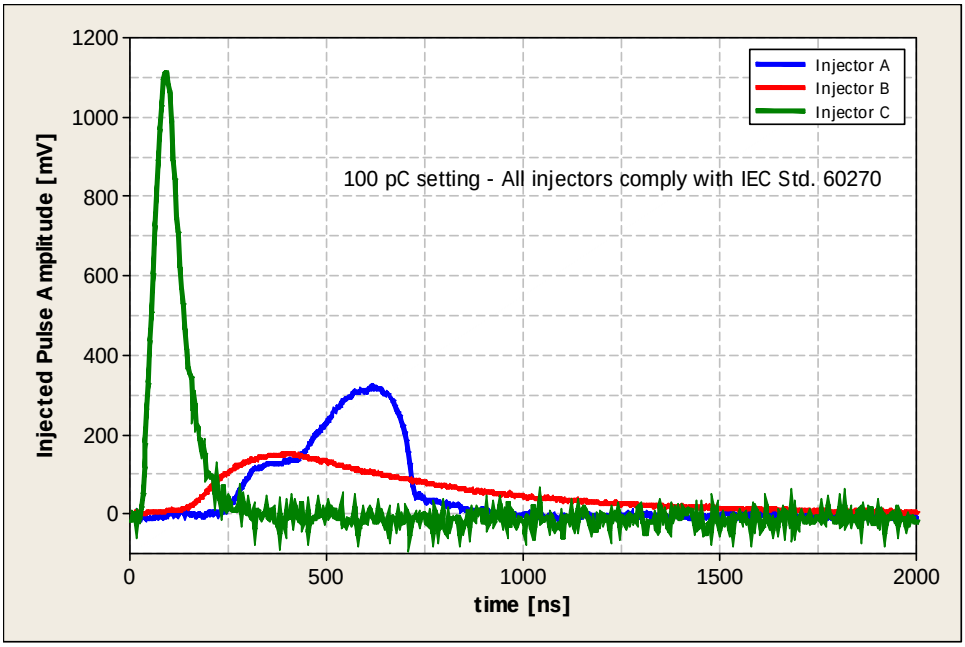

Figure 36: Comparison between Pulse Injectors – 100 pC Setting into a 50 Ω Impedance

As seen in Figure 36, the waveforms between pulse injectors are different; however, they should be compared in terms of their charge settings, which can be estimated by the area under the pulse. This comparison is shown in Figure 37.

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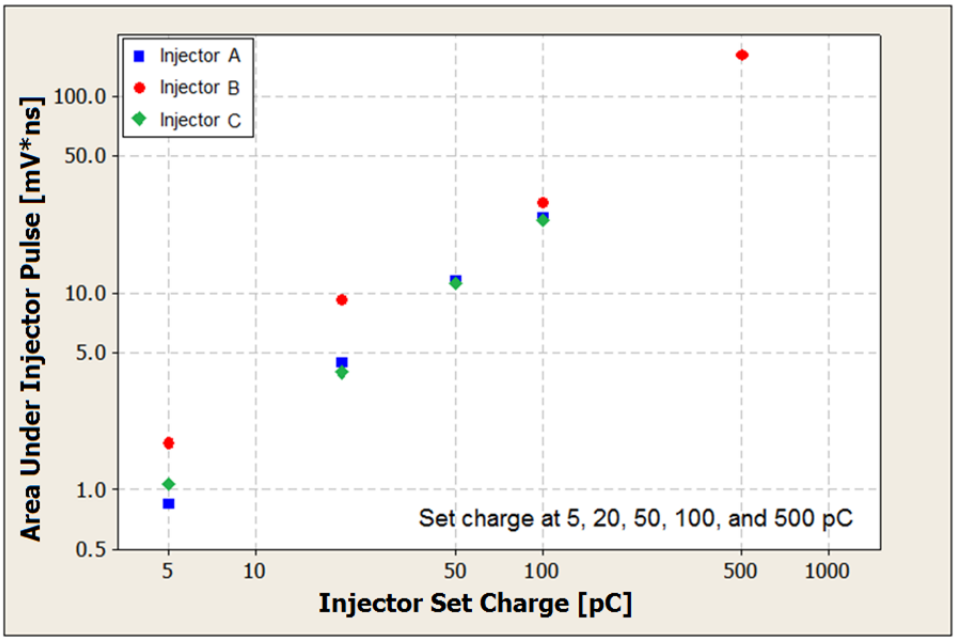

Figure 37: Comparison of Calculated and Actual Charge Settings for Different Injectors

As seen in Figure 37, there is a linear correlation between the charge setting and the area under the pulse for all three injectors. However, the difference between pulse waveform shapes is significant even though they produce similar charge magnitudes. Considerable differences may be observed between the injected pulse waveforms in Figure 36. These differences do not impose limitations on the applicability of pulse injectors because all of them comply with the required scale charge magnitude and other IEC 60270 requirements. However, differences in pulse waveforms directly translate to different frequency spectra. The comparison of these spectra is shown in Figure 38.

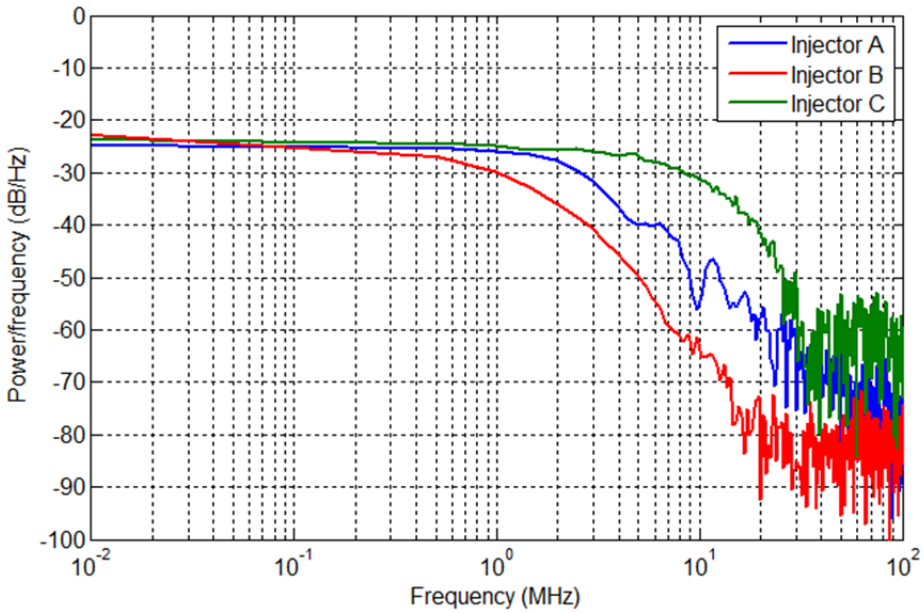

Figure 38: Power Spectral Density of Different Injector Pulses

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As shown in Figure 38, at low frequencies (< 300 kHz) all three pulses have virtually the same spectrum. This is expected since the zero frequency component of the spectrum is directly related to the area under the pulse in time domain and thus the charge setting. However, significant differences are observed between spectra at high frequencies (>1 MHz). For example, the fastest pulse (Injector C) has higher frequency content as compared with the slowest pulse (Injector B) which has the lowest frequency content. It can be also seen in Figure 38 that at high frequencies the pulse from Injector A lies between Injector B and Injector C. This leads to two observations:

- At low frequencies and for the same charge setting, all injector pulses and, thus, devices can be assumed to be the same as long as they comply with IEC requirements.
- At high frequencies and for the same charge setting, all injector pulses and, thus, devices behave differently. Therefore, injected pulse waveform is imperative and should be considered if measurements are to be deployed in this frequency range.

While the above two observations are clearly shown in Figure 38, it is still difficult to define the boundary that should be used for distinguishing the low and the high frequency ranges. This can be overcome by considering the approach adopted in filter design. When designing different filters (low, high, and band pass) the 3 dB-point criterion by which the frequency threshold value is often defined relative to the maximum value of the power spectrum density function. The 3 dB-point corresponds to the frequency where the power spectrum density function is half its maximum value. The 3 dB-point criterion has been applied to the power spectrum density functions of Figure 38 and the results are shown in Figure 39.

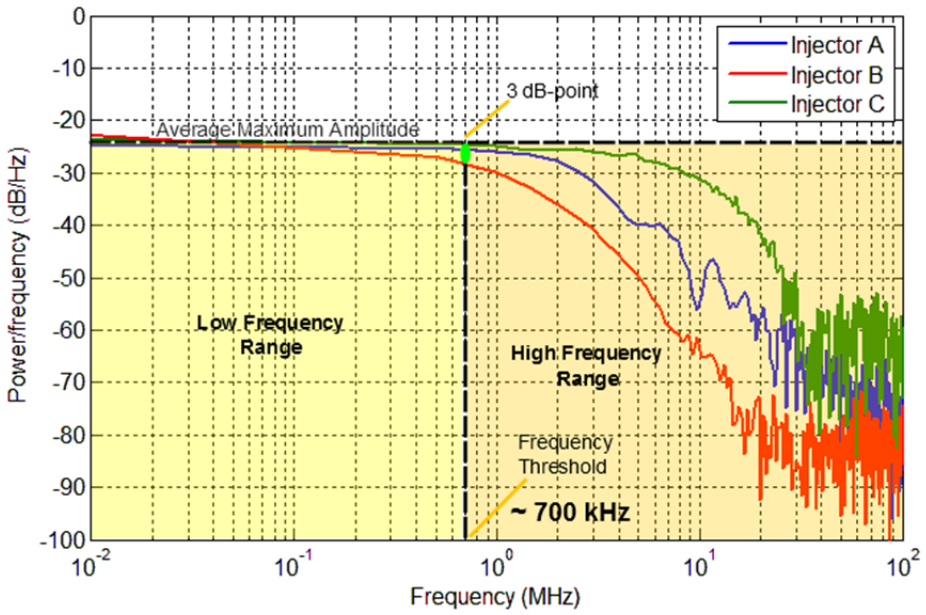

Figure 39: 3 dB-point Criterion to Determine Frequency Threshold

Figure 39 shows the threshold for differentiating the low and the high frequency ranges is approximately 700 kHz using the criterion discussed above.

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Once the threshold frequency between the low and the high frequency ranges is established, a comparison between IEC Std. 60270 – 2000 bandwidth requirements and the power spectrum density functions, of the different injector pulses corresponding to Figure 36, is shown in Figure 40.

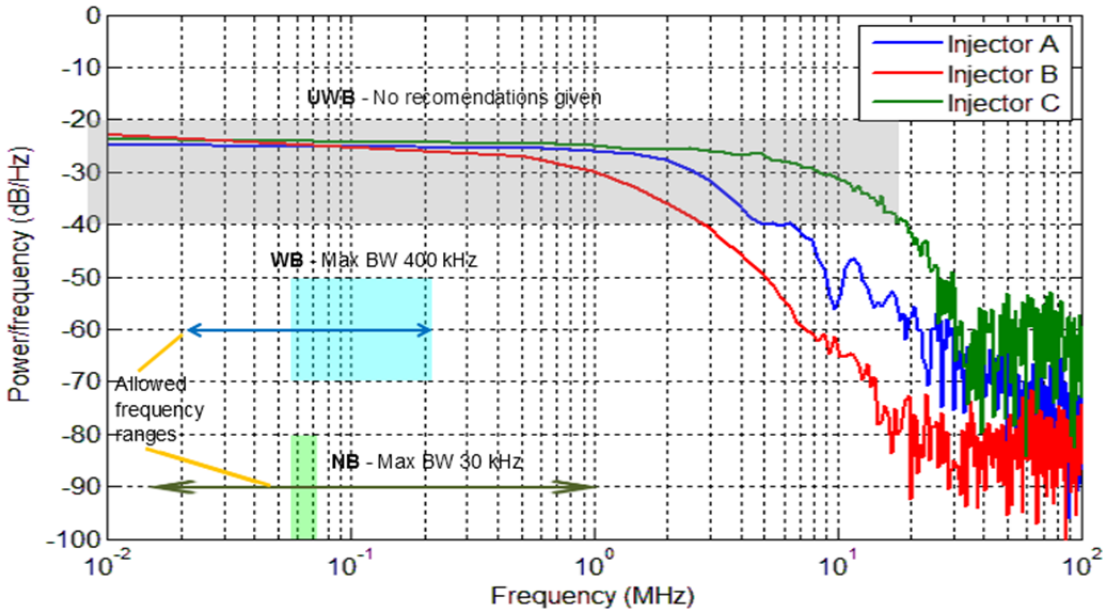


Figure 40: Comparison between IEC Std. 60270 – 2000 Bandwidth Requirements and the Power Spectral Density Function of Different Injector Pulses Corresponding to Figure 36

Considering the frequency threshold level of 700 kHz, then the narrow-band (NB) and wide-band (WB) allowed bandwidths fall in the low frequency range of the spectral density function of the injector pulses; therefore, it can be concluded that if NB or WB frequency ranges as specified by IEC Std. 60270 – 2000 are used for PD measurements, then there are no issues or limitations regarding the waveform of the injector pulses. Under this scenario, different injectors may be used and results can be compared in terms of scale charge through the calibration procedure as specified by the standard.

In contrast, the ultra-wide-band (UWB) as seen in Figure 40 considers frequencies that are below and above the threshold level of 700 kHz. Therefore, the injector pulse waveshape is relevant and results using different injectors cannot be compared. It is also important to note that under these conditions the energy of the injected pulse could be an additional factor to consider since the energy in the Injector C pulse is greater than that from Injector B. The higher energy of Injector C comes from the fact that its power spectrum density function has higher frequency components.

All issues and limitations described here that emerge when using UWB could be diminished by defining the characteristics of pulse injectors such that they produce the same standardized waveform.

8.6.7 Performance Assessment

The current thinking for field PD measurements is that there should be performance checks made before the actual PD test to provide a measure of the "goodness" of the test. This would include quantifying background noise levels, sensitivity, etc. In declaring cable systems to be PD free it is important to understand the detection limitations for the particular circuit, equipment, and noise environment at the time of the test. HV and EHV cable systems are exceedingly good at attenuating PD signals either through the cable or accessories. It is, therefore, difficult to define performance metrics given the nature of these systems and the wide variety of designs in service. At a minimum, the PD provider should provide an indication of the background noise level and confidence level when declaring a cable system to be "PD free". Discussions within the industry continue on this topic.

8.6.8 Expected Outcomes

The effort expended by the Cigre B1.28 Working Group in conjunction with the *CDFI* led to the collation of the world's most extensive HV and EHV testing outcome database. This database was used to extract the expected outcomes for tests on these types of cable systems. As explained above, the focus on commissioning style tests is also evident in the testing database and so the outcomes reported below are for commissioning tests only. When considering these results it is important to be aware of the effect of "confirmation bias" where respondents are more likely to report tests in which PD presence is confirmed rather than its absence. As a consequence, the analysis reported here should be regarded as representing the upper limits for the expected outcomes.

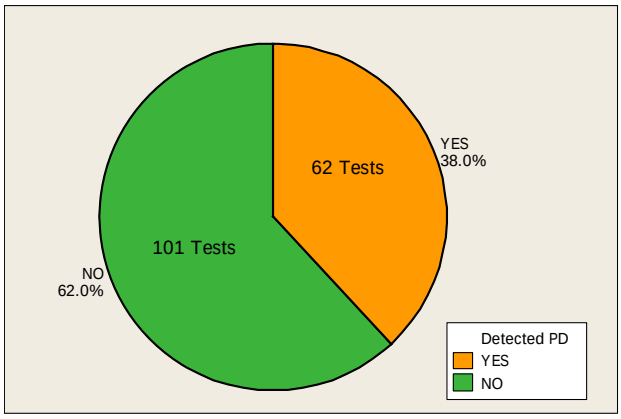
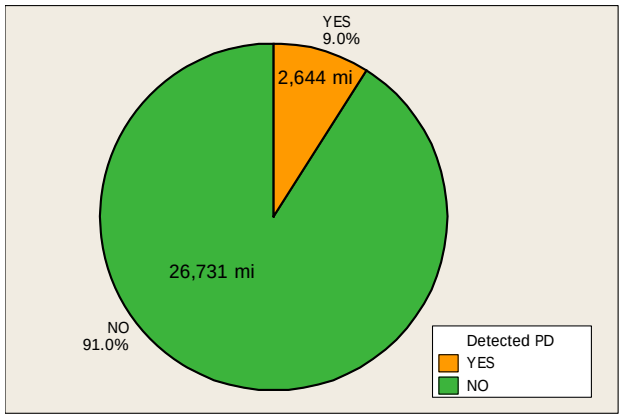
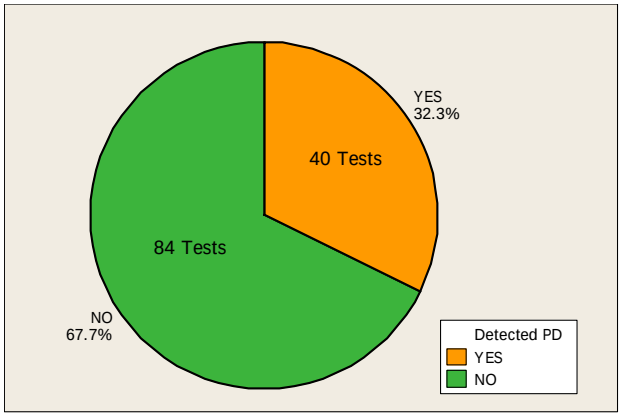
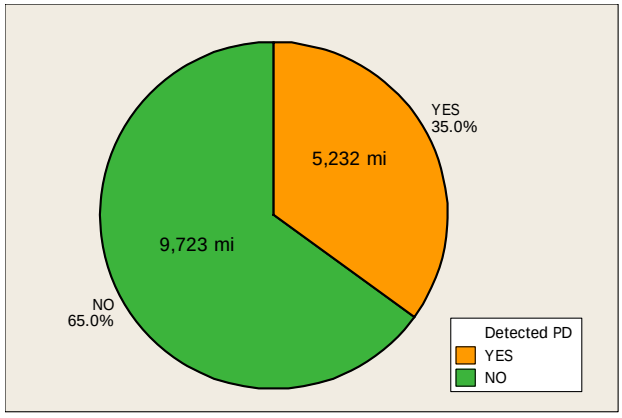
The occurrence of PD within commissioning tests was segregated for HV and EHV cable systems and the percentages are calculated considering the following approaches:

- In terms of total number of PD tests conducted and irrespective of cable system length and
- In terms of total PD tested length.

Considering these alternative approaches, the expected outcomes for PD measurements deployed on HV and EHV cable systems from survey results are shown in Table 20.

The results for HV cable systems are based on a total of 163 tests with a total tested length of 29,375 mi (~ 47,378 km) over 19 years (1990 through 2008). Meanwhile, the results for EHV cable systems are based on 124 tests with a total tested length of 14,955 mi (~ 23,934 km) over the same time period as HV.

Table 20: Expected Outcomes for PD Measurements Deployed in HV and EHV Cable Systems

In terms of Total Number of PD Tests	In terms of Total of PD Length Tested
HV Cable Systems	
	
EHV Cable Systems	
	

One of the benefits of PD testing as part of commissioning is that the detection of PD provides the opportunity for the test to be ended early before an actual failure occurs. This can potentially reduce the costs and time associated with a repair. A number of respondents provided information on whether dielectric failures occurred when PD was detected. In these cases, failure occurred in only 3 – 4% of the tests where PD was detected. Data to determine the failure rate for a non-PD monitored withstand commissioning test (Simple Withstand) to IEC Std. 60840 – 2004 and IEC Std. 62067 – 2011 were not available.

8.6.8.1 Cable System Information

As mentioned earlier, the voltage ranges for the Cigre B1.28 study were determined according to the ranges specified in IEC 60840 and IEC 62067. The distribution of test entries (regardless of whether or not PD assessment was performed) was determined. These data are shown in histogram format in Figure 41. The figures represent the cable system length tested.

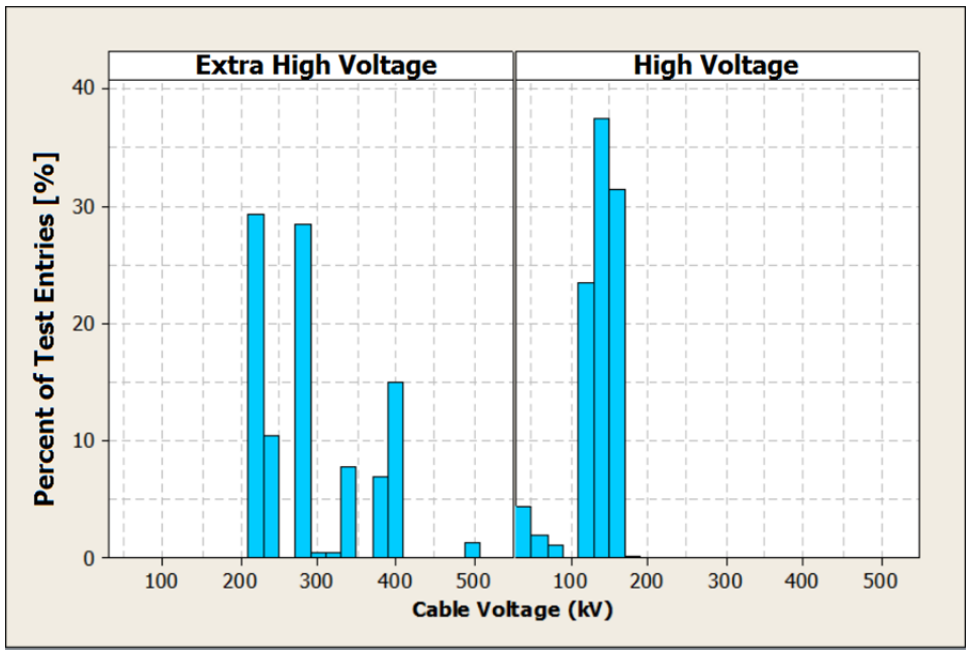


Figure 41: Distribution of Tests within the HV and EHV Voltage Classes (the lengths refer to the cumulative length of the cable systems)

Survey respondents, in general, also provided an indication of the year in which tests were carried out. Thus, it is instructive to examine the evolution of testing in terms of both number of tests and their inclusion of a PD measurement. These data are shown in Figure 42.

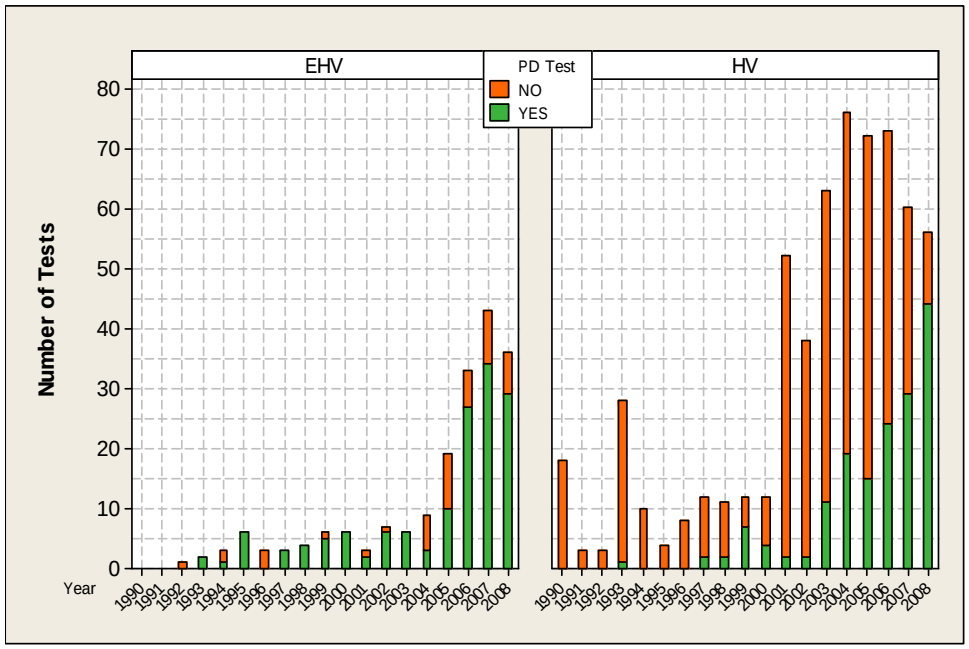


Figure 42: Evolution of Reported Commissioning Tests – Voltage Withstand Tests both with (YES) and without (NO) PD Assessment

As Figure 42 shows, the number of commissioning tests has increased considerably for both HV and EHV systems. It is also evident that the fraction of tests that make use of PD measurements has

also increased. By the end of the 2008, the inclusion of PD measurement during commissioning has become essentially standard practice. However, the results presented in Figure 42 must be viewed as upper limits resulting from the potential "confirmation bias" mentioned earlier.

8.6.9 Influence of Noise

As PD measurement constitutes the detection of induced high frequency, very high frequency and/or ultra-high frequency signals on cable systems, rejection of similar non-PD related signals is imperative. These signals are generally termed as noise. Unfortunately, noise is always present when performing PD measurements.

The noise can be a critical impediment to successfully detecting discharge. Magnitudes of the PD pulses as seen by the measuring equipment are in the order of fractions of a millivolt to several tens of millivolts. In addition, when PD pulses reach the detection equipment, they generally have a bandwidth of several tens of megahertz. Unfortunately, this frequency range includes most of the amplitude and frequency modulated communication signals and, in some cases, these signals can have a higher magnitude than the partial discharge signals that are of interest.

The level of noise depends on several factors that include system parameters such as length, location, design, structure, and signal degradation mechanisms, as well as the particular nature of the discharge itself. From the perspective of noise, the cable acts as an antenna that picks up the communication signals, additional noise may be present due to noisy grounding. Therefore, it is unavoidable for these communication signals or ground noise to be present in the cable system and thus get detected together with the PD signals. Several techniques have been used to reduce the background noise level. Analog and digital filters are typically applied. Most recently the application of powerful digital signal processing techniques such as wavelet transforms have been used to address this issue.

One of the more important improvements for signal classification has been the development and application of the classification map. The basis of the classification map is the fact that PD pulse waveform characteristics depend on the nature of the defect, as well as the signal deterioration they experience while travelling from their source to the measurement equipment. Thus, the main assumption / premise is that pulses having similar waveforms should come from the same source. The classification map is realized by computing features that provide a compact and meaningful representation of the acquired pulses. Several features are possible. Within *CDFI*, the instruments available for HV and EHV PD tests have typically used temporal and frequency content information.

Various approaches to this technique have been implemented by manufactures and providers of PD test equipment. The processing and generation of a classification map relies upon the acquisition of a large number of pulses and can only be applied to acquired data. Unfortunately, in many cases such classification mapping does not significantly improve the true signal-to-noise ratio of a field PD measurement in the presence of high levels of noise. In other cases, there is a noticeable improvement in less intense noise environments as the classification map was shown to provide an improvement in the qualitative signal-to-noise ratio of the test.

The most powerful capability of classification maps are their ability to separate pulses from multiple sources be they discharge or noise. This allows the operator to focus on the pulse classes that are most likely to affect the performance of the cable system. Figure 43 shows some examples of classification maps from different PD providers.

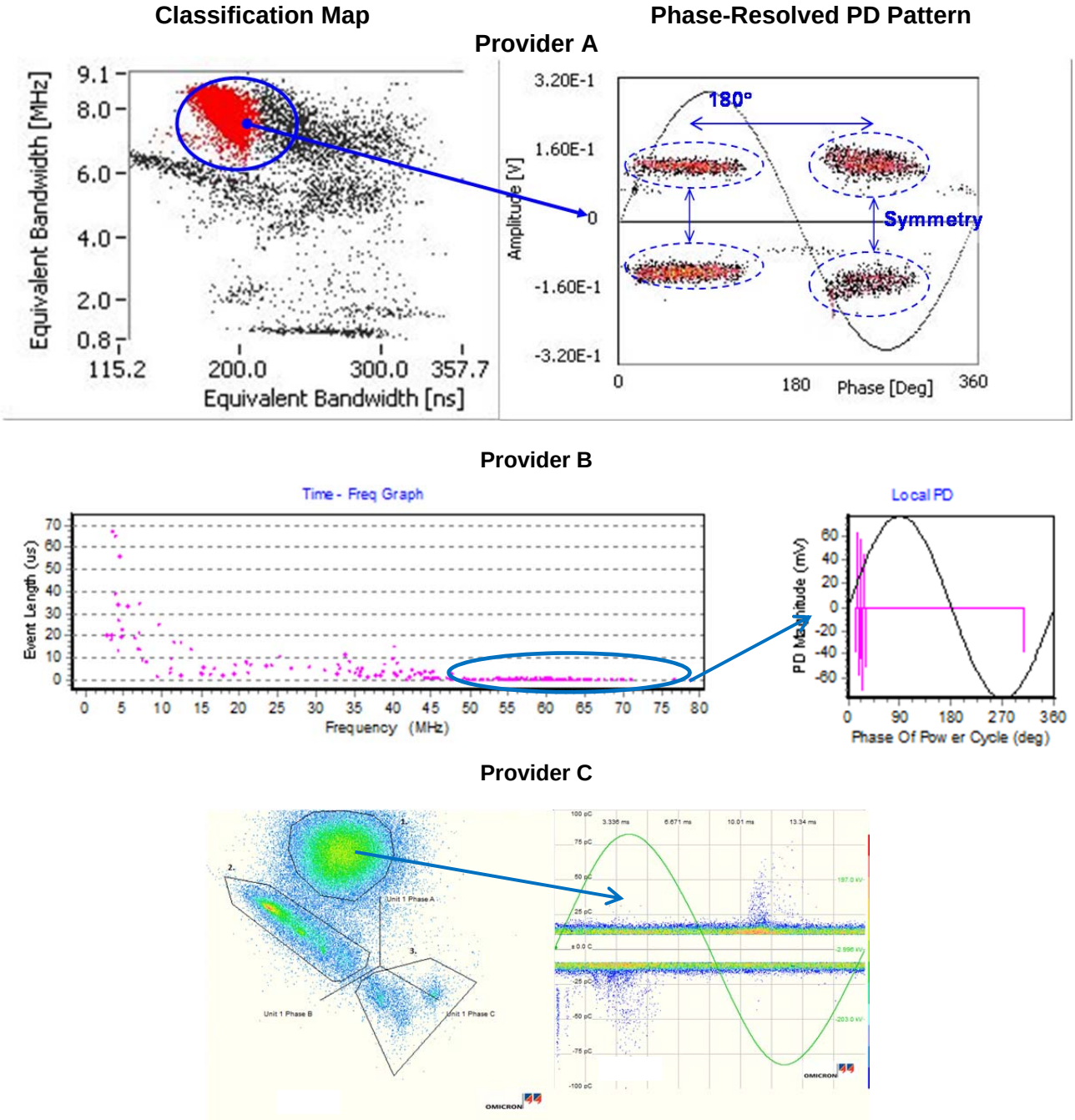


Figure 43: Example Classification Maps from Different PD Providers

8.6.10 Conundrum between PD Apparent Charge and Energy

The idea of signal "size" is crucial to many applications. For example, it would be nice to know how much electricity can be used in a defibrillator without causing permanent damage to the patient, or if the signal driving a set of headphones is enough to create a sound. While both of these examples deal with electrical signals, they are clearly very different cases. For this reason, it is imperative to quantify this idea of "size" of a signal in its specific context. The quantification of the “size” of a signal then leads to the ideas of area under the curve and energy.

Since a signal is generally thought of as a function of varying amplitude through time, it seems to reason that a good measurement of the strength of a signal would be the area under the time curve. However, this area may have the opposite polarity of another portion and could thus cancel each other out. The negative polarity part does not have less strength than the equivalent positive signal. A better approach to estimate the signal strength would then be either squaring the signal magnitude or taking its absolute value, and then finding the area under that curve. As a matter of fact, it turns out that the energy of a signal is defined as the area under the curve of the squared signal. An illustration of the area under the curve and energy for a signal as a function of time ($f_{(t)}$) is shown in Figure 44.

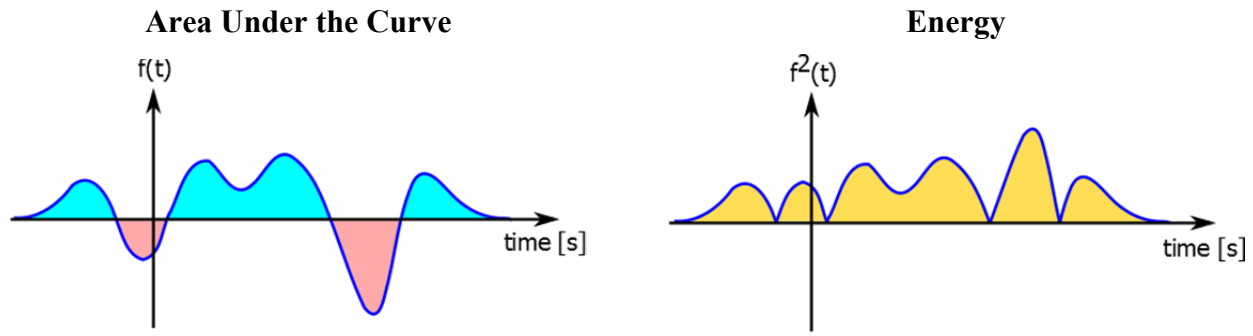


Figure 44: Illustration of the Area Under the Curve and Energy for a Signal as a Function of Time ($f_{(t)}$)

In the case of PD, the relationship between the area under the curve (scaled charge) and energy is rather important to understand. Traditionally, PD activity has been quantified by the scaled charge. The use of scaled charge as a metric for PD and low frequency bandwidths make measurements insensitive to PD pulse shape and other signal aberrations. However, this assumption only holds valid by assuming that the cable system acts as a low-pass filter and thus the scaled charge (dc component of the PD signal) is completely transferred from the PD site to the location of the PD measuring equipment. Under this scenario, another issue that is generally overlooked even for an ideal (lossless) cable system is the fact that the peak amplitude of the traveling PD pulse could decrease to a point at which it is comparable to the background noise level and thus no triggering/detection are possible.

In real cases, both the scaled charge and signal energy change as the PD signal propagates through the cable system. This situation is unavoidable and is a consequence of the very high frequency components of PD signals and the non-linear frequency response of the cable system that results in

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interactions between frequencies components. In order to understand the conundrum between PD scaled charge and energy, two studies are presented:

- Cable system simulation based on simple filtering and
- Cable system simulation based on frequency dependent and distributed model.

The two studies are presented in detailed in the next sections.

8.6.10.1 Simple Filtering Model

In the simple filtering case, the cable system is modeled as low-pass filter, the input PD pulse is run through the filter and the output PD pulse is recorded. The basis for cable system simulation based on simple filtering is shown in Figure 45.

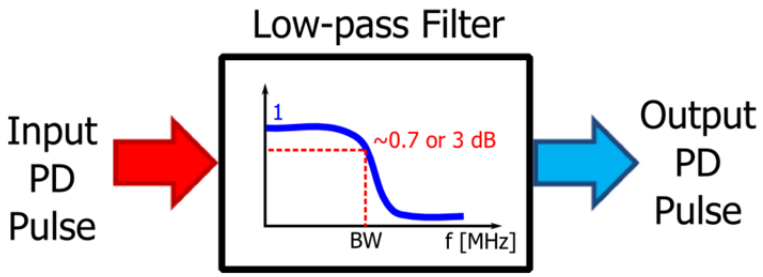

Figure 45: Illustration of Cable System Simulation Based on Simple Filtering

The idea of this example is to consider changes in the filter bandwidth and then study its impact on the PD pulse scaled charge and energy of the output PD pulse referenced to the scaled charge and energy of the input PD pulse. For this example, the input pulse will be a Gaussian pulse of 5 pC and 20 ns (time width). Its time domain waveform and frequency domain spectrum are shown in Figure 46.

Time Domain **Frequency Domain**

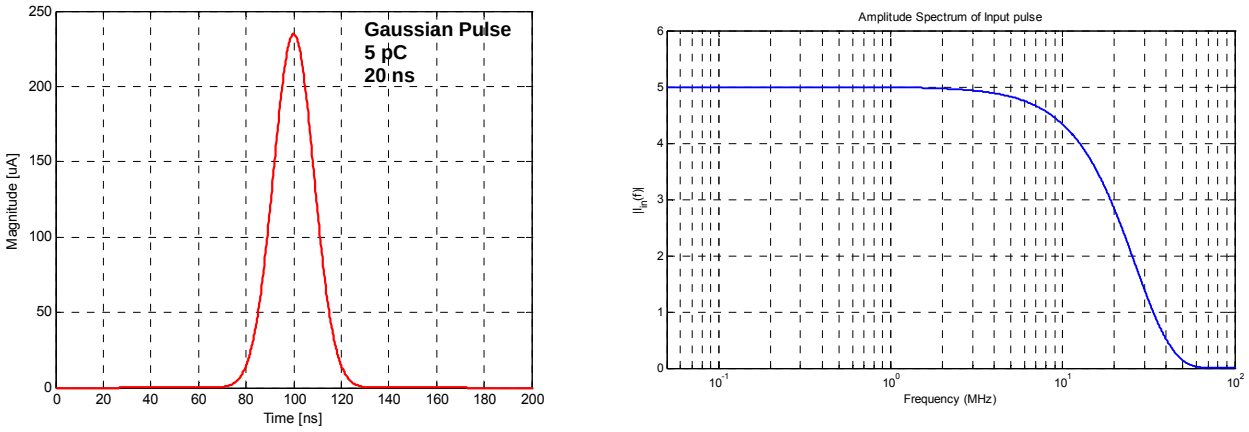

Figure 46: Waveform and Frequency Spectrum of the Input PD Pulse

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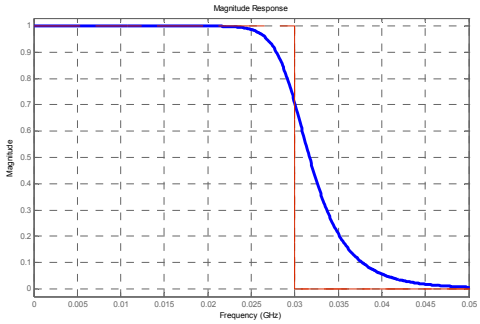
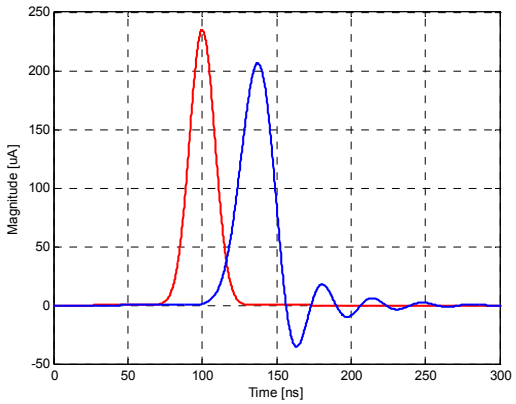
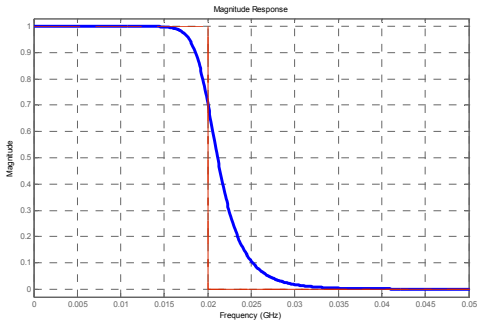
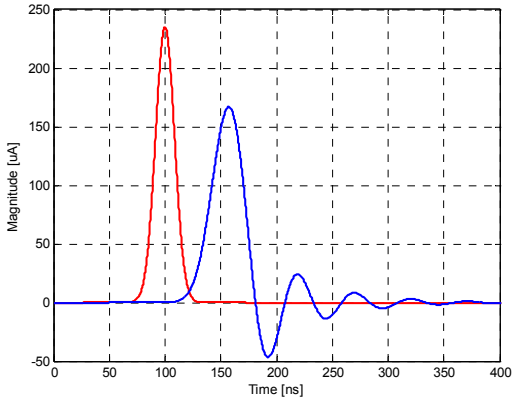
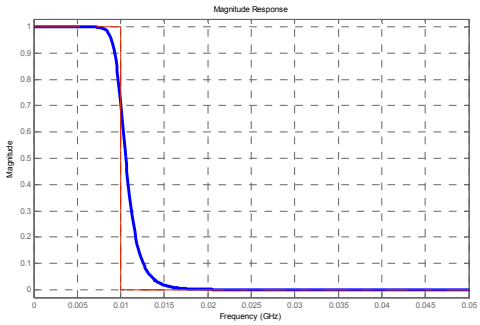
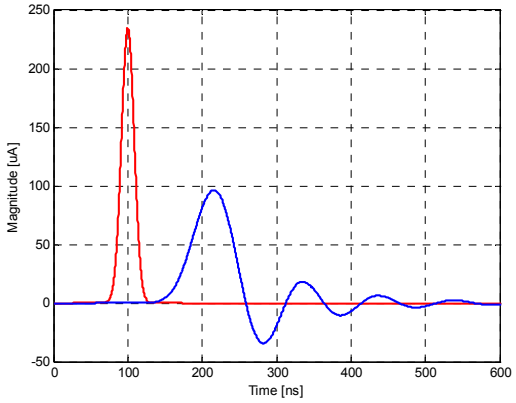
The simulation results considering filter bandwidths of 30, 20, 10, 5, and 1 MHz are shown in Table 21. The resulting effects on the output pulse are shown in blue while the input pulses are shown in red. Note the changes in the pulse heights and shape.

Table 21: Results for Cable System Simulation Based on Simple Filtering

Filter Frequency Response	Input (Red) and Output (Blue) PD Pulses
30 MHz Bandwidth	
	
20 MHz Bandwidth	
	
10 MHz Bandwidth	
	

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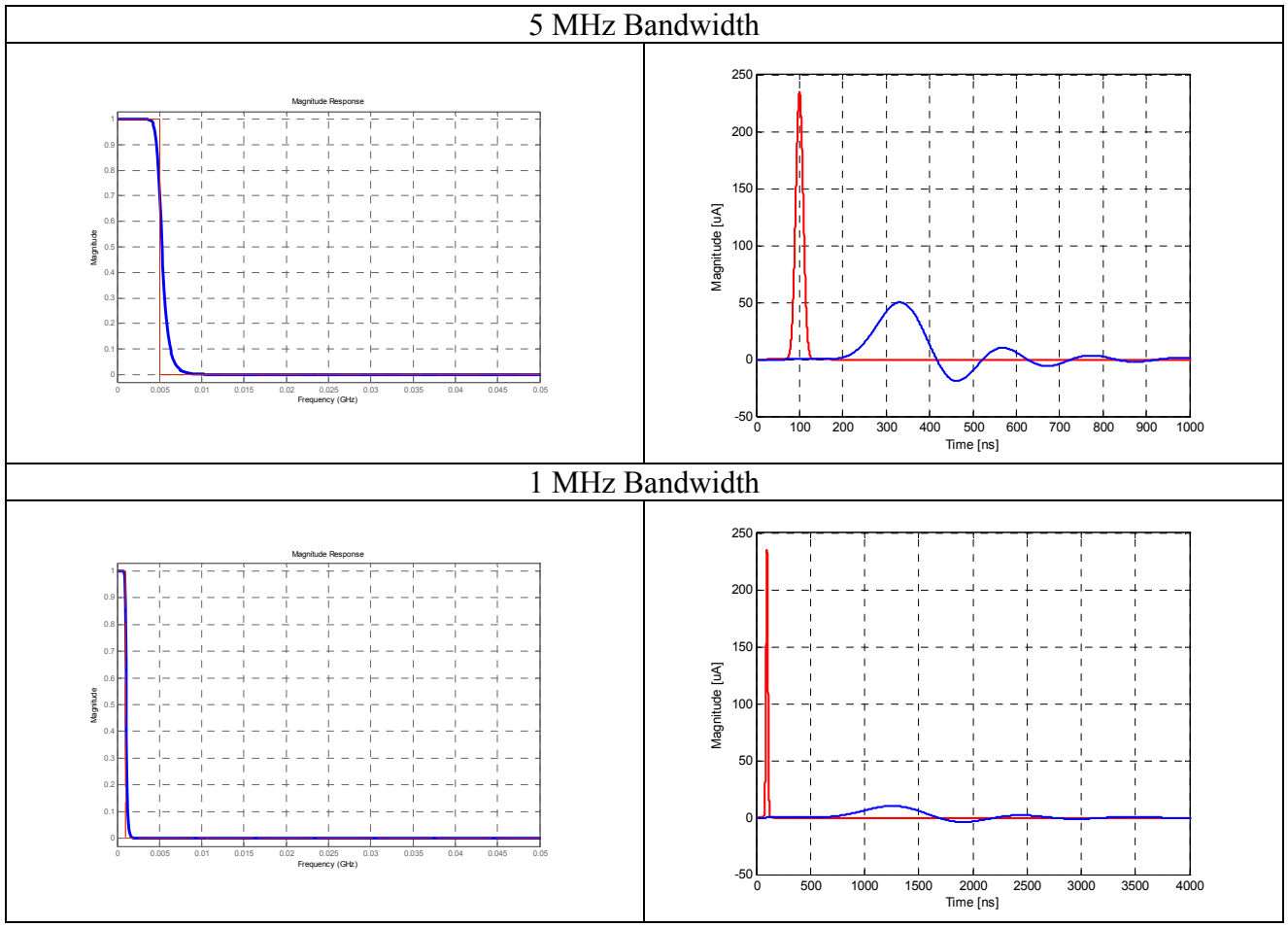

Table 22 shows the scaled charge results for the cable system simulation based on simple filtering.

Table 22: Scaled Charge Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Scaled Charge [pC]	Output Scaled Charge [pC]	Scaled Charge Ratio [%]
30	5.0	5.0	100
20		5.0	100
10		5.0	100
5		5.0	100
1		5.0	100

As seen in Table 22, the output scaled charge is independent of the bandwidth; in other words, it remains unaltered over changes in bandwidth. The independence of the scaled charge with respect to bandwidth is due to the low-pass characteristics of the filtering, as mentioned earlier, the scaled charge represents the dc (zero frequency) component of the input PD pulse that is always transferred to the output without change. This helps explain why when PD was first used that the scaled charge was selected as the most attractive metric for quantifying PD magnitudes. Unfortunately, the use in PD on long cable systems in the field has made the above assumptions inaccurate.

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Simulation results for the PD output pulse energy are shown in Table 23 and are also plotted in Figure 47. However, Figure 47 shows the energy loss in percent relative to the energy of the input pulse as a function of bandwidth. The energy loss shown in Figure 47 is obtained by subtracting from 100% the energy ratio in percent column shown in Table 23.

Table 23: PD Energy Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Energy [μA^2*ns]	Output Energy [μA^2*ns]	Energy Ratio [%]
30	4.15	4.04	97.4
20		3.60	86.7
10		2.28	55.0
5		1.23	29.5
1		0.25	6.0

As seen in Table 23 and Figure 47, the output PD pulse energy loss increases as the filter bandwidth decreases (i.e. more energy is rejected by the filter). For example, the energy losses are 2.6% and 94% for filter bandwidths of 100 MHz and 1 MHz, respectively. Thus, for a bandwidth of 100 MHz, the energy loss is negligible, while the 1 MHz bandwidth energy loss is high. The relationship between energy loss and filter bandwidth is highly dependent on the energy content of the input PD pulse. In this case, the input pulse has a bandwidth of approximately 15 MHz. Therefore, the 30 MHz bandwidth filter allows most of the input PD pulse energy through to the output. On the other hand, the 1 MHz filter only allows a small fraction of the pulse energy though.

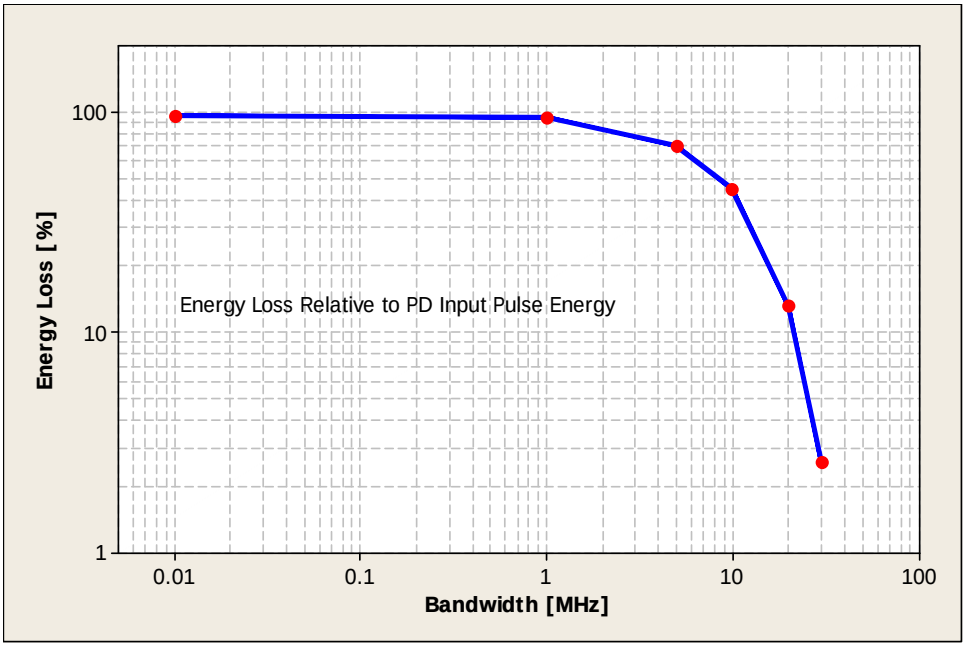

Figure 47: PD Signal Energy Loss versus Filter Bandwidth

As mentioned earlier, another issue to consider is how the peak amplitude of the PD output pulse changes with bandwidth and this is shown in Figure 48.

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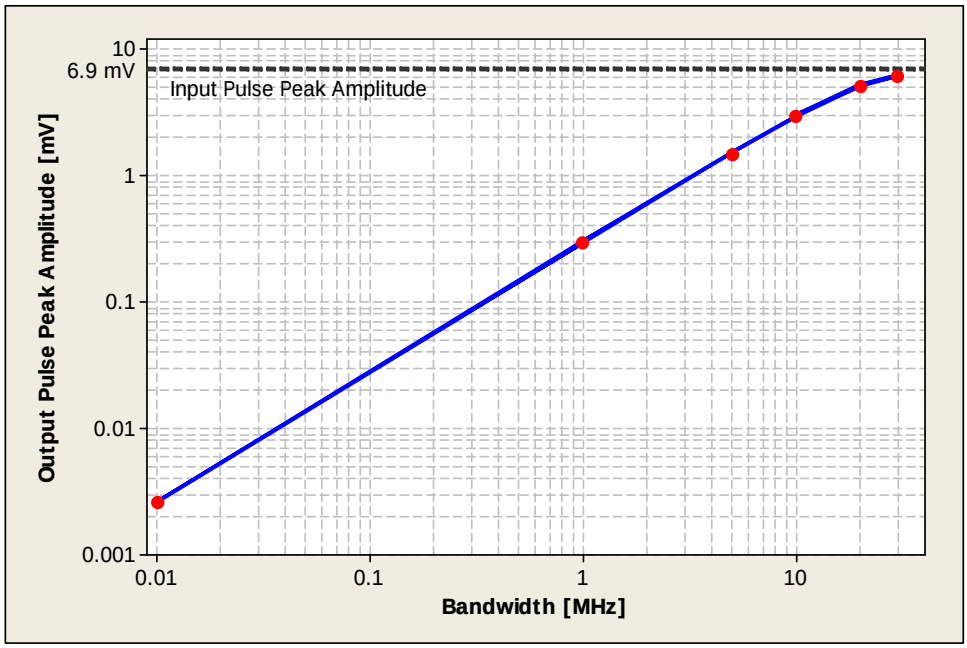

Figure 48: Output PD Pulse Peak Amplitude versus Filter Bandwidth

As observed in Figure 48, the peak amplitude of the output PD pulse increases with increasing filter bandwidth. Since the peak amplitude of the output PD pulse is often used to trigger the detection equipment, care must be taken when selecting the bandwidth of the detection equipment (as well as any noise filters) to avoid reducing the amplitude below the background noise level. Equipment that does not utilize a triggering approach would be more immune to this issue.

8.6.10.2 Frequency Dependent and Distributed Model

The second study is the cable system simulation based on a frequency dependent and distributed model. An illustration of the simulation block diagram is shown in Figure 49.

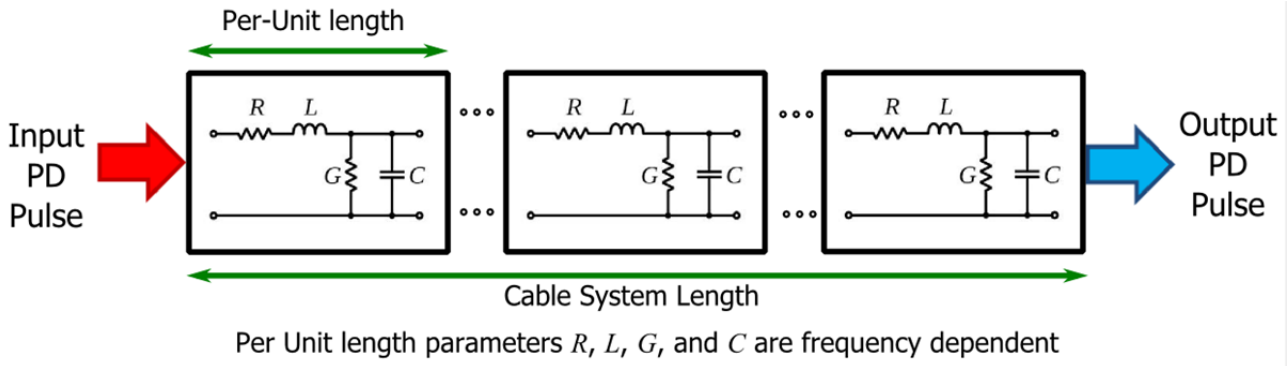

Figure 49: Frequency Dependent Simulation Model

According to Figure 49, the simulation process is as follows: a Gaussian PD input pulse of specified charge and time width enters the cable system model, which consists of a series of equivalent circuits of per-unit length connected in series. The output of the last equivalent circuit represents the

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PD output pulse that would be received by the PD sensor. Using this model, changes in the charge can be observed as functions of pulse parameters and distance travelled along the cable system. A set of five input PD pulses with different time widths and the same charge magnitude (50 pC) were used in the simulation. The resulting pulses are shown in Figure 50.

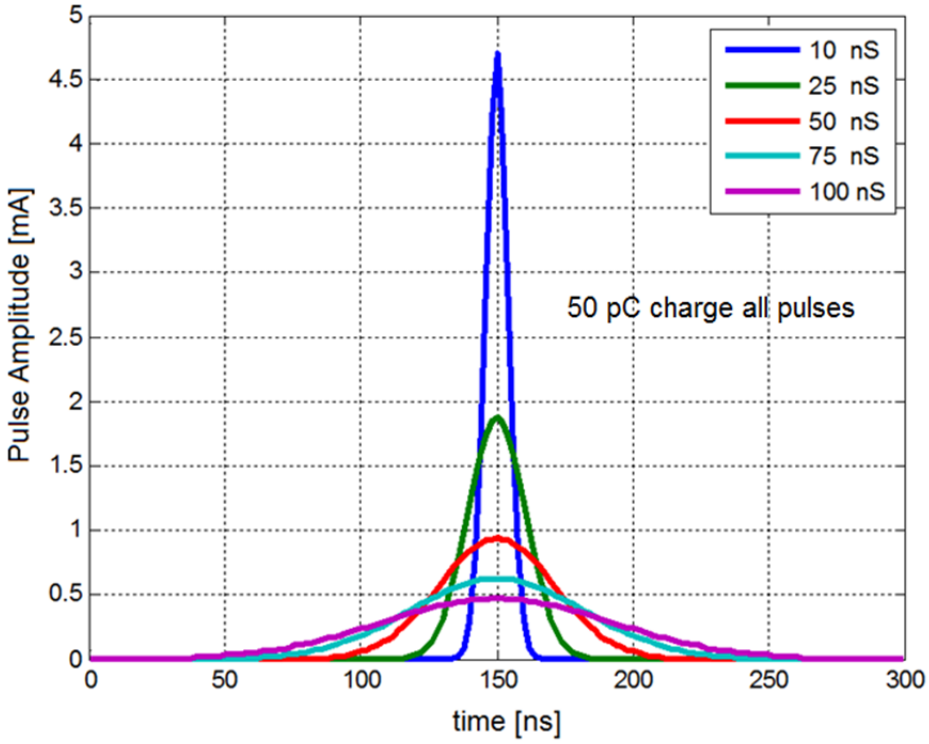

Figure 50: Gaussian PD Pulses for Simulation of Loss of Charge using Frequency Dependent and Distibuted Modeling.

The cable system modeled in these simulations was a 1/0 AWG, XLPE, 15 kV, and 175 mil wall cable system. The simulation results for the PD input pulses of Figure 50 are shown in Figure 51. This figure shows PD pulse charge loss as a function of the distance traveled from the discharge site.

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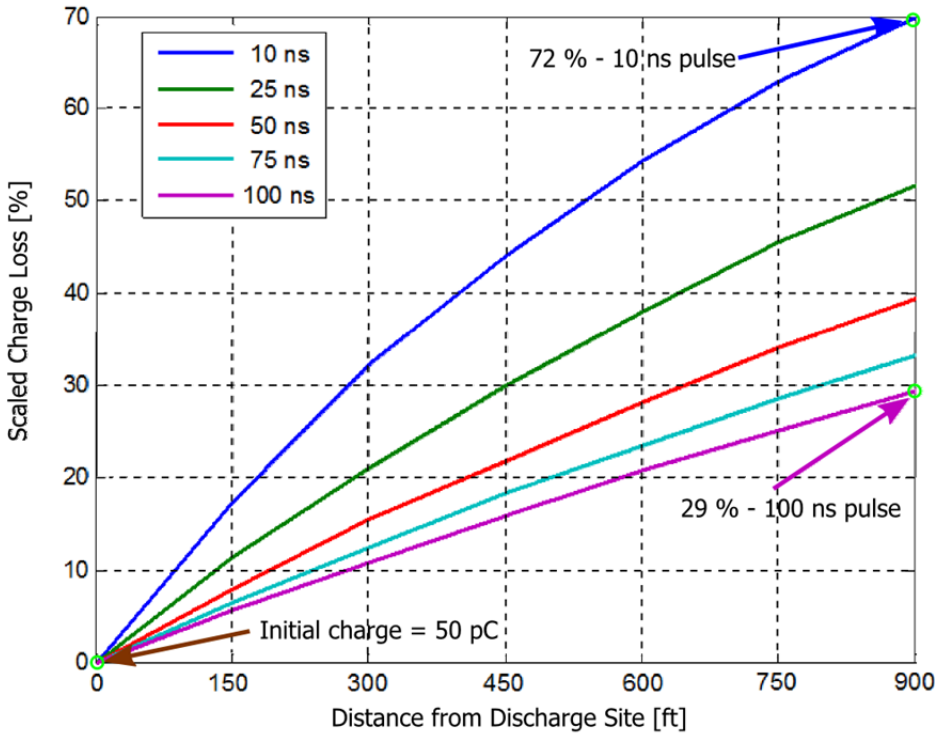


Figure 51: PD Pulse Scaled Charge Loss as a Function of Distance from Discharge Site

The results presented in Figure 51 should be interpreted as follows: the PD pulse originating at the discharge site has an initial charge magnitude of 50 pC and charge is lost as the pulse travels away from the discharge site. For example, consider the 100 ns and 10 ns pulses after they have propagated 900 ft from the source. According to the results in Figure 51, the 100 ns PD pulse would be expected to exhibit 29% charge loss. Similarly, the 10 ns pulse exhibits a charge loss of 72%. Therefore, the corresponding scaled charge magnitudes at 900 ft are would be 36 pC for the 100 ns pulse and 14 pC for the 10 ns pulse.

The results shown in Figure 51 are relevant because they show that the scaled charge loss for a PD pulse is a function of three main factors:

- **PD Pulse Waveform:** Different PD pulse waveforms would have different frequency spectra and thus different charge loss profiles. Since the PD pulse waveform depends upon the nature of the "void-type" defects responsible for the PD then the scaled charge loss profile also depends on the nature of the defect.
- **Distance from PD Source:** The PD pulse scaled charge that is typically thought to be independent of cable system length actually is not. In reality, this phenomenon is always present and the lack of awareness of its existence may cause additional confusion in the interpretation.
- **Other Factors:** Other factors affecting scaled charge loss of a PD pulse are cable system design, structure, aging, and degradation conditions.

8.6.11 Grounding Practices

The main goal of grounding is to provide a low impedance path for fault current to return so that protective equipment can detect the fault and act accordingly. This protects users from equipment that could become energized if the fault were not interrupted. Within the context of PD measurements, the cable system grounding has a large effect on how PD signals propagate within the system. Systems with a single grounding point allow PD detection equipment to capture more signals as there is but one path to ground. Multiple grounds allow signals to exit the cable system where there may not be detection equipment set up. Cross bonding causes signals to travel on different phases while Surge Voltage Limiters (SVLs) prevent PD pulses from reaching ground in the first place. These issues all arise with HV and EHV systems installed in the field.

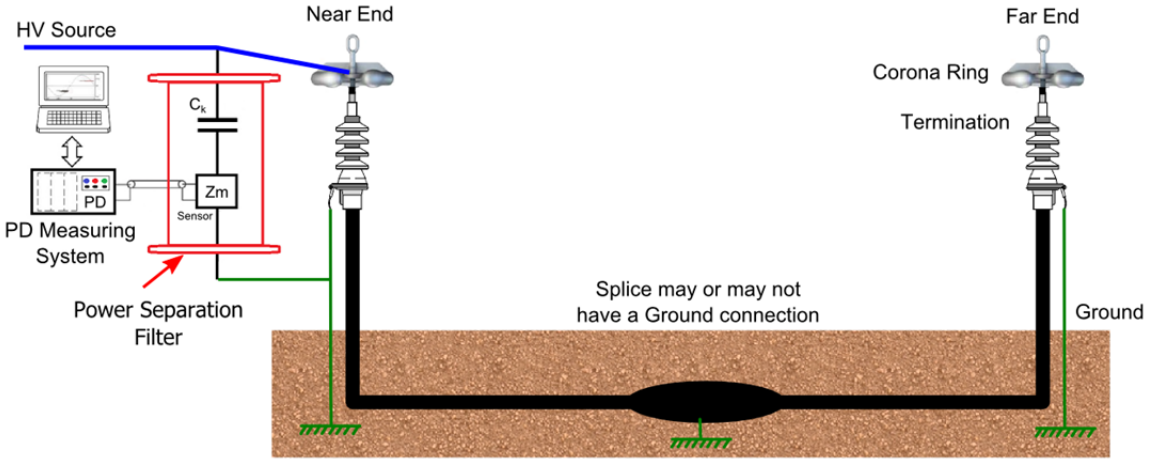
Grounding impacts the signals that are able to flow through the sensors and so sensor placement is a key component to the effect grounding has on PD measurements. Three primary sensor configurations are considered:

- **Capacitive Divider with Built-In Sensor:** This configuration considers the coupling capacitor and the sensor together in the same unit. The PD signal may be detected using either a capacitive or inductive (HFCT) sensor.
- **Coupling Capacitor and Sensor:** This configuration considers the coupling capacitor and sensor as separate units; typically the sensor is an HFCT that can be coupled to the grounding connection of the coupling capacitor or the grounding connection of the cable system under test.
- **Standalone Sensor:** This configuration only considers the presence of the sensor because there are situations in which the use of a coupling capacitor is not possible. Typically the sensor is a HFCT that is coupled to the grounding connection of cable system under test at the near end. Another option is a capacitively coupled sheath sensors.

The various sensor connections and their field and laboratory deployments are shown in Table 24 through Table 26.

Table 24: Capacitive Divider with Built-In Sensor Connections

Field Deployment



Laboratory Deployment

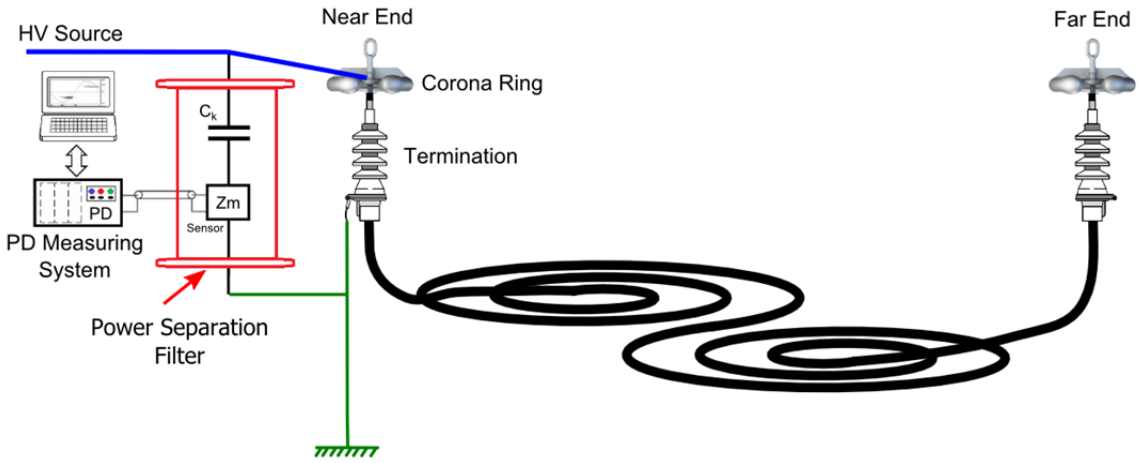
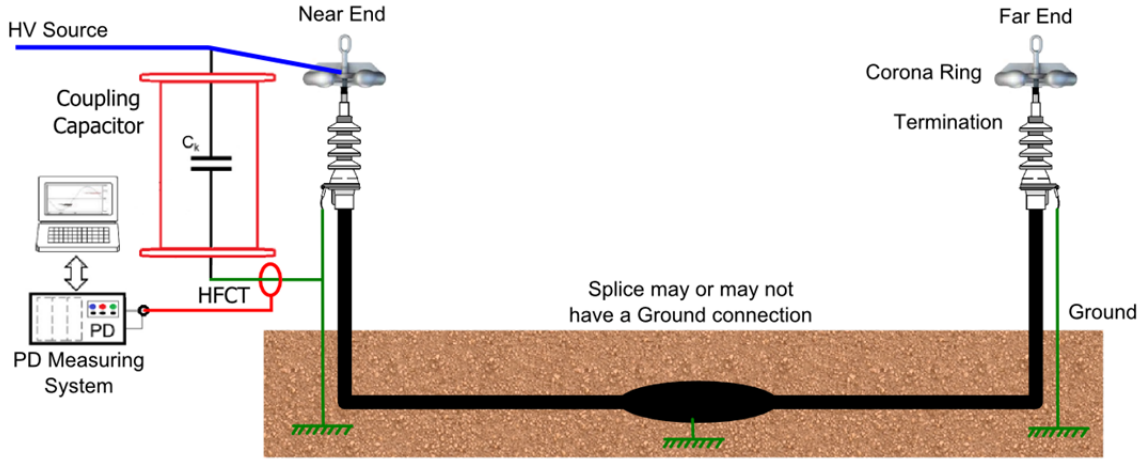


Table 25: Capacitive Divider with Separate Sensor Connections

Field Deployment



Laboratory Deployment

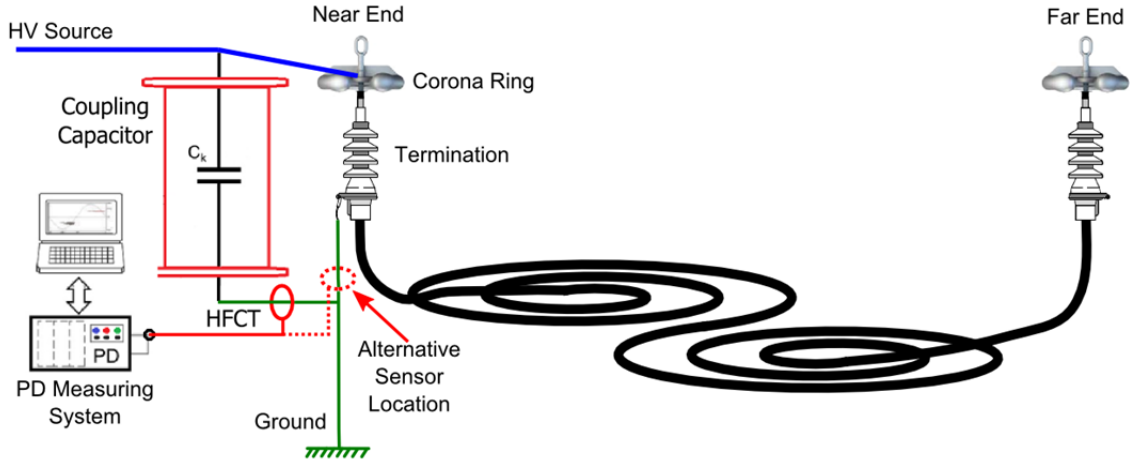
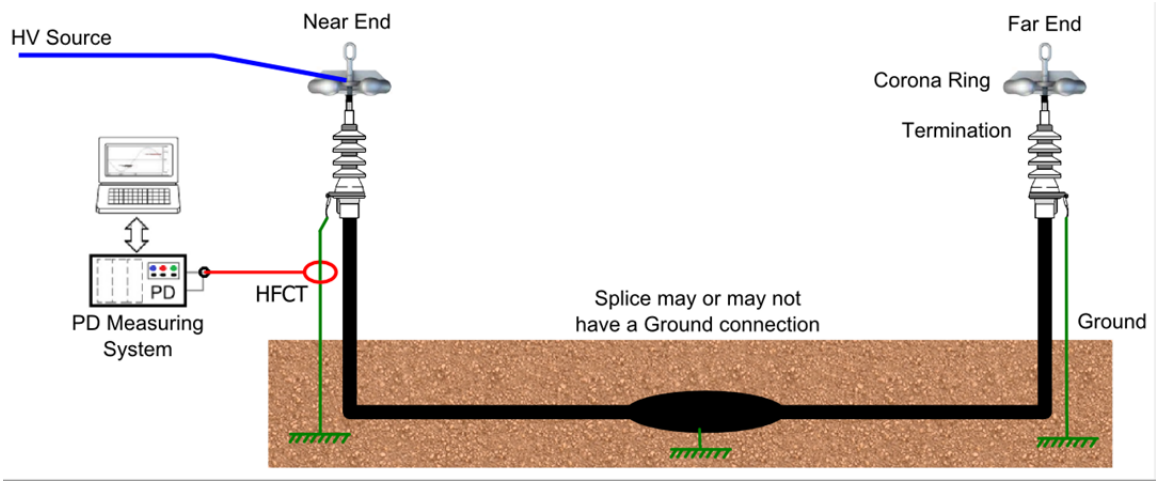
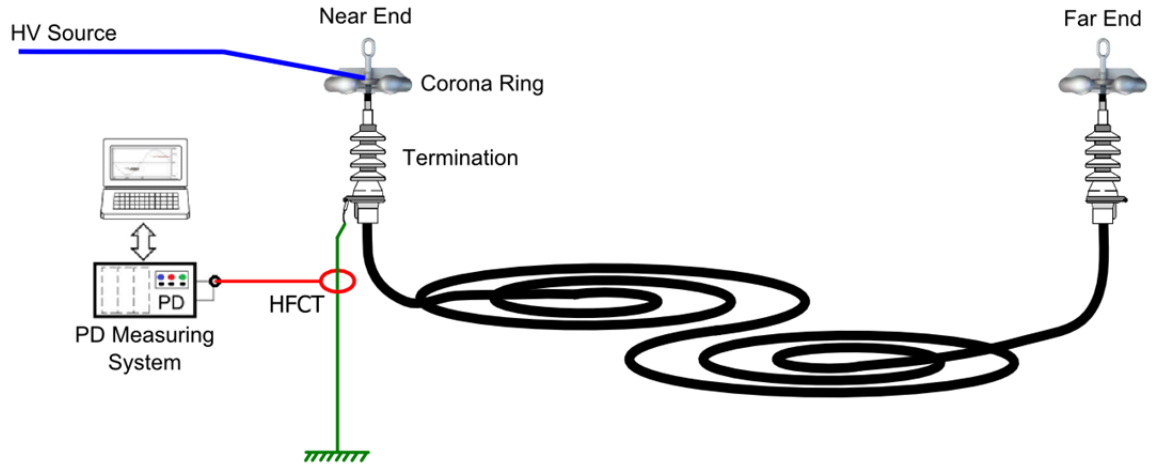


Table 26: Standalone Sensor Connections
Laboratory Deployment

Field Deployment


It is important to note than each of the field connection examples utilize a more complicated grounding arrangement than those employed under laboratory conditions. Care must be taken when trying to employ laboratory techniques and guidance in field situations.

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8.7 Outstanding Issues

As seen in Section 8.6, issues that affect PD measurements on HV and EHV power cable systems are many and diverse; they have been identified and analyzed by the *CDFI*. The identification and analysis have been based focused on crucial characteristics and limitations of PD measurements. Therefore, the outstanding issues, regarding the use of PD measurements as a mean for condition assessment of HV and EHV power cable systems, are as follows:

1. Technologies are generally deployed on new assets, i.e. oriented to commissioning testing. See section 8.6.4, 8.6.5, & 8.6.8.
2. Field measurements cannot be correlated to laboratory / factory test results. See sections 8.6.1, 8.6.2, 8.6.3, 8.6.5, & 8.6.6.
3. Measurements are carried out as part of an ac Monitored Withstand protocol (i.e. simple withstand and PD combined). a) ac withstand {$1.7U_0$ for 60 min} combined with b) PD tests {PD checks at 0.5 U_0, U_0, and 1.5 U_0 on ramp up and monitoring throughout the withstand portion} are commonly deployed and effectiveness is supported by international data. See sections 8.6.4 & 8.6.5.
4. The aim is to detect the presence and location of PD – the magnitude is generally not of interest. See section 8.6.4, 8.6.5, & 8.6.8.
5. Systems are long and have complicated architectures (laboratory/factory tests assume short lengths and a simple architecture). See section 8.6.1 & 8.6.2.
6. Calibration commonly found in laboratory/factory tests is not valid for field tests. See section 8.6.1, 8.6.2, 8.6.6, & 8.6.11.
7. PD signal deterioration is significant and unavoidable, this imposes limitations on the range of detection (i.e. how far can be seen into the cable system). Hence, only terminal (tests from one end) are rare while distributed measurements (measurements at each accessory – joint hopping) are most commonly used. See sections 8.6.1, 8.6.7, 8.6.9, and 8.6.10.
8. Tests, analysis and reporting are orientated towards establishing the absence of PD from a single test, though multiple PD technologies may be used (trending or comparison with an identifiable benchmark are rare). See section 8.6.4 & 8.6.5.
9. Results showing the absence of PD obtained from different PD technologies can be collated. See section 8.6.3, 8.6.5, & 8.6.8.
10. Trending/repeat tests are rarely carried out. See section 8.6.4, 8.6.5, & 8.6.8.

Due to the issues and limitations listed above, the information in this Chapter provides the user with an increased awareness of PD measurements on HV and EHV cable systems with a somewhat detailed explanation of how to conduct tests and analyze their results.

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8.9 Relevant Standards

- IEC Std. 60183 – 1984: *Guide to the Selection of High Voltage Cables*
- IEC Std. 60270 – 2000: *High-Voltage Test Techniques – Partial Discharge Measurements*
- IEC Std. 6084 – 2004 : *Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV (Um = 36 kV) up to 150 kV (Um = 170 kV) – Test Methods and Requirements*
- IEC Std. 60885-2 - 1987: *Electrical Test Methods for Electric Cables. Part 2: Partial Discharge Tests*
- IEC Std. 60885-3 - 1988: *Electrical Test Methods for Electric Cables. Part 3: Test Methods for Partial Discharge Measurements on Lengths of Extruded Power Cables*
- IEC Std. 62067 – 2011: *Power Cables Above 150 kV and their Accessories for Rated Voltages Above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) – Test methods and requirements*
- CIGRE TB B1.28 – 2014 Omnibus: *On-Site PD Assessment (Working Group B1.28)*
- CIGRE TB 21.09 – 1997: *After Laying Tests on High Voltage Extruded Insulation Cable Systems (Working Group 21.09, Std. also typically known as Electra 173, pp. 33- 41)*
- CIGRE TB 182 – 2001: *Partial Discharge Detection in Installed HV Extruded Cable Systems*
- IEEE Std. 48 – 2009: *IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV*
- IEEE Std. 404– 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*
- IEEE Std. 400– 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.3 – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*

CHAPTER 9

Simple Dielectric Withstand

Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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9.0 SIMPLE DIELECTRIC WITHSTAND TECHNIQUES

9.1 Test Scope

Simple dielectric withstand tests require the application of continuous voltage at levels above the normal operating voltage for a prescribed time period. The result of these tests is either Pass (no failure during the test) or Not Pass (failure during the test). This approach is valid for all cable and accessory types and is used for MV, HV, and EHV cable systems, albeit at different applied voltage levels. An alternative use of the Simple Withstand test, called Monitored Withstand, is covered in Chapter 10.

The *CDFI* considers Simple Withstand as a diagnostic because the results can and do help engineers make cable circuit repair and replacement decisions. In addition, the details of the test result (voltage at failure if it occurs during the ramp up or the time of failure within the test period) may be used to categorize the performance. As an example, a failure 2 min into a 2 U_0 Simple Withstand test would be viewed as having poorer performance than a failure 20 min into the same test. Thus many practitioners and utilities use it to determine the "health" of their cable systems.

9.2 How it Works

The applied voltage is raised to a prescribed level, usually between 1.5 and 3.0 times the nominal circuit operating voltage. The purpose is to cause weak points in the circuit to fail during an elevated voltage application, rather than failing while in service. Testing takes place when the impact of having a failure is low and repairs can be made quickly and cost effectively [7 - 16].

HV and EHV cable systems may utilize Simple Withstand tests as part of a commissioning test although this practice is becoming less commonly employed. These tests are more often now performed in conjunction with partial discharge measurements as discussed in Chapter 8.

9.3 How it is applied

This test technique is conducted with the cable system removed from service (offline). The applied voltage can be dc, VLF, or resonant ac. Test voltages range from 1.5 U_0 to 3.0 U_0. If a failure occurs during the test, it is good practice to make a repair and retest the circuit **for the full prescribed test time**.

A withstand test is carefully designed to overstress a cable system to an acceptable risk level and thus to be effective it must include the following three elements:

1. **A Defined Voltage Exposure:** The exposure is characterized by a voltage time waveform (waveshape) that includes a controlled magnitude (voltage metric such as peak or RMS voltage) and degree of application (in terms of specified time, number of cycles, shots, or any other convenient time metric).
2. **A Repeatable Voltage Exposure:** The waveshape is maintained during the voltage application and systems with similar characteristics (insulation type, lengths, etc.) experience the same voltage waveshape**.**
3. **A Well-defined Failure Rate:** The failure rate during the withstand test must be higher than the failure rate at normal service voltage.

Considering these three elements, dc, VLF, and Resonant ac voltage application techniques have these three elements.

DAC voltage sources, on the other hand, only comply with the first two. See Section 9.6.2. A detailed review of all of the literature references provided as technical justification in the recent version of IEEE 400.4 has failed to identify any case where any component of a MV or HV cable system, tested in the field or the laboratory, has suffered a dielectric failure. Such data are readily available for Resonant ac, VLF, and dc. As a result, DAC voltage sources will not be considered further in this chapter.

The key to a successful withstand test is to apply the voltage long enough to cause electrical trees or other significant insulation system defects that could potentially cause failure in service to grow to failure during the test. The voltage should be high enough to grow significant defects but no so high as to cause benign defects to fail. With these objectives in mind, utilities should have a repair crew on standby to make repairs as needed should test failures occur.

Simple Withstand tests are conducted on MV, HV, and EHV systems. For MV systems they are typically used as a maintenance test. For HV or EHV systems they are typically used as a commissioning test. Sections 9.3.1 and 9.3.2 discuss these different approaches in more detail.

9.3.1 MV Cable Withstand Tests

The most commonly deployed voltage source for Simple Withstand tests on MV cable systems is 0.1 Hz VLF (either sinusoidal or cosine-rectangular). Resonant ac sources and dc sources are less often employed on MV systems. DC is not recommended for aged, extruded systems due to the effects of space charge injection, which increase the potential for service failures after a dc test is performed. (Note: This has been shown for HMWPE and XLPE insulated systems, but the impact on TRXLPE and EPR insulated systems is uncertain.) Resonant ac voltage systems are generally not deployed for Simple Withstands tests on MV systems but are more commonly used for HV and EHV systems.

Historically, dc was used exclusively for MV systems but the issue with aged extruded systems mentioned above has led many utilities to switch to VLF sources. Much of the early focus within *CDFI* was on the comparison of the effectiveness of dc versus VLF withstand (hi-pot) tests.

Providers of VLF test equipment advocate [15] the use of VLF withstand voltage magnitudes shown in Figure 1 and Table 1 for a recommended period of 30 min. These are also the test voltages indicated in IEEE Std. 400.2 and are based on electrical tree growth rate data obtained from laboratory tests conducted on molded plaques imbedded with sharp needles. How this laboratory data relates to electrical tree growth rates in actual cables is unknown. However, VLF providers caution that VLF withstand tests must be performed carefully (at the correct voltage level and duration) to avoid leaving weak spots that remain in the cable system after it is tested.

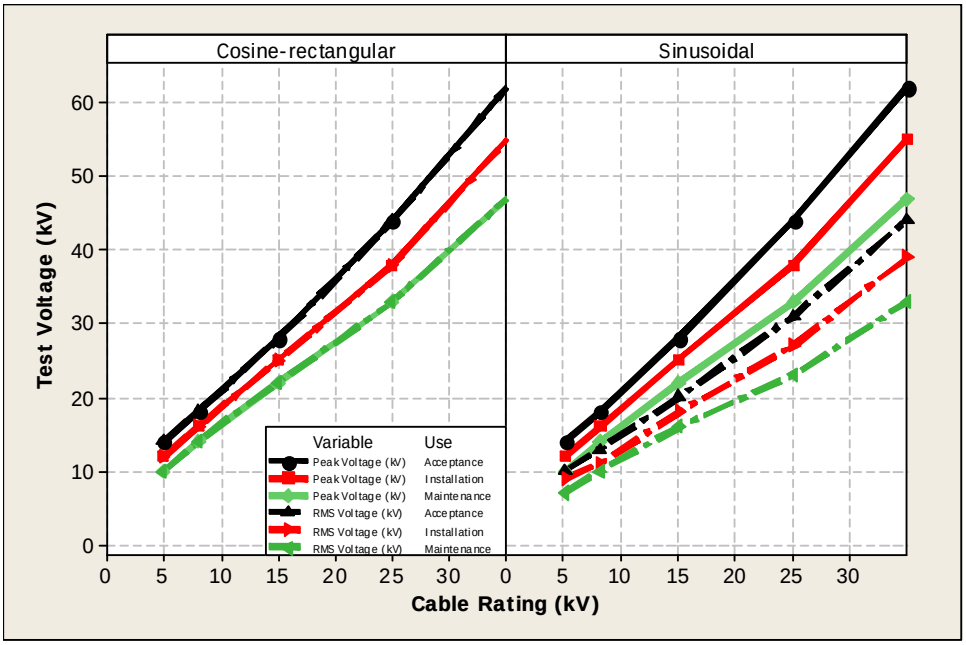

Figure 1: Cosine-Rectangular and Sinusoidal Waveforms (Table 1) VLF Withstand Voltages (IEEE Std. 400.2 Clause 5.1)

Table 1: VLF Maintenance[1] Test Voltages for Cosine-Rectangular and Sinusoidal Waveforms (IEEE Std. 400.2- 2013, Clause 5.1)

Cable Rating phase to phase rms voltage (kV)	Sinusoidal				Cosine Rectangular			
	rms		peak		rms		peak	
	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)
5	7	2.4	10	3.5	10	3.5	10	3.5
8	10	2.2	14	3.0	14	3.0	14	3.0
15	16	1.8	22	2.5	22	2.5	22	2.5
25	23	1.6	33	2.3	33	2.3	33	2.3
35	33	1.6	47	2.3	47	2.3	47	2.3

[1]- field tests made during the operating life of the cable

Waveforms for the most commonly employed VLF test devices are shown in Figure 2**.**

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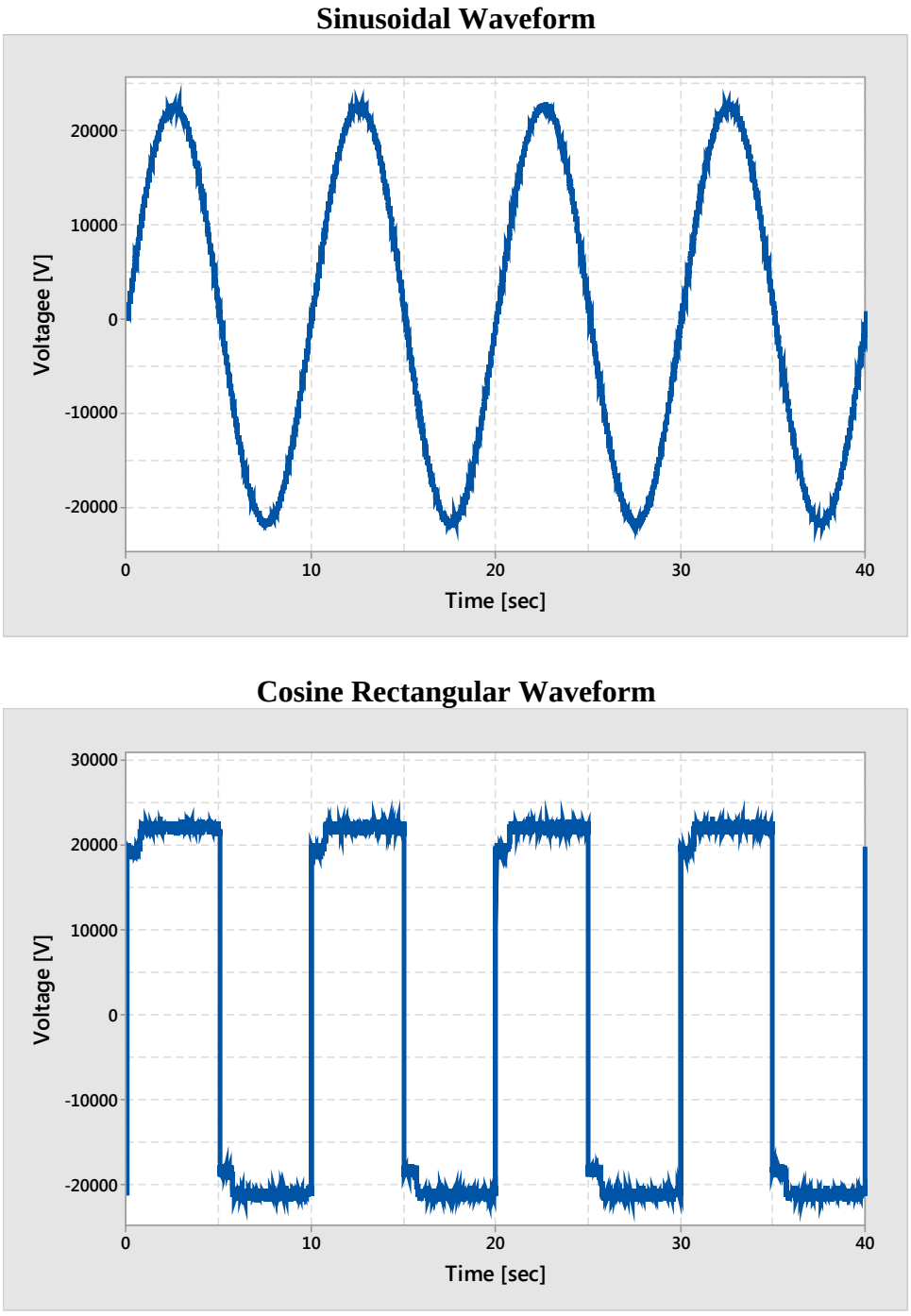

Figure 2: Withstand Voltages Waveforms (Top – Sinusoidal, Bottom – Cosine-Rectangular)

The advantages and disadvantages of Simple Withstand testing are summarized in Table 2 and Table 3.

Table 2: Advantages and Disadvantages of Simple Withstand Tests for Different Voltage Sources used on MV Cable Systems		
Source Type	**Advantages**	**Disadvantages**
60 Hz System Voltage (Online)	• No extra equipment needed. • Serves as an easy-to-deploy commissioning test or post maintenance test at U_0. • Able to test long lengths.	• Not able to test at elevated voltages. • Will find only the most blatant defects. • Failure on test exposes circuit to full system fault current.
10 - 300 Hz Resonant ac Offline	• Test voltage frequency is close to the system voltage frequency. • Allows for the application of test voltages above the operating voltage.	• Testing equipment is large, heavy, expensive, and rare. • Large equipment size limits accessibility.
Very Low Frequency (VLF 0.1 Hz) ac Offline Cosine Rectangular	• Equipment is small and easy to handle. • Can test longer lengths at 0.1 Hz than sinusoidal VLF for the same size test equipment.	• Periods of elevated DC voltage reversing each cycle raises concerns over space charge injection. • Does not replicate normal operating or factory test voltage waveform or frequency.
Very Low Frequency (VLF 0.01 – 1 Hz) ac Offline Sinusoidal	• Equipment is small and easy to handle. • The test voltage waveform is the same as the operating voltage waveform.	• Does not replicate normal operating or factory test voltage frequency. • Longer circuit lengths require reducing either the frequency or voltage.
Direct Current (dc)	• Equipment is small and easy to handle. • Able to test long lengths using small equipment.	• Injects space charges, which are known to accelerate failures in cables with aged HMWPE and XLPE insulations. • Does not replicate electric stress conditions that are present under normal operating voltage. • No evidence that it provides significant benefits for extruded cable circuits. • Cascading failures can occur, which can be time consuming to address.

Table 3: Overall Advantages and Disadvantages of Simple Withstand Techniques on MV Cable Systems	
Advantages	• Easy to employ. • Clear recommendations for test voltages and times in IEEE Std. 400.2 - 2013. • Results for the simple withstand test are unambiguous – Pass / Not Pass. • The required action is clear (repair or replace circuit). • Can be used to test any circuit type: extruded, paper insulated, or hybrid.
Open Issues	• Some voltage-time conditions may weaken the dielectric but not cause failure, resulting in failures soon after the circuit is returned to service. • Frequency-time relationship is unclear for frequencies higher than 0.1 Hz. • Retest procedure after failure and repair are well specified in standards but inconsistently applied by utilities. • Impact of resonant ac and VLF on cable system has not been determined.
Disadvantages	• Significantly elevated dc voltages may create space charge accumulation that can cause HMWPE, XLPE and, possibly other extruded cables to fail prematurely after returning to service. • Cable must be taken out of service for testing. • An inexperienced test operator can cause damage by applying a voltage that is either too high or for too long. • Cannot detect all cable system defects.

9.3.2 HV and EHV Cable Systems

Simple Withstand tests on HV and EHV cable systems are typically performed as commissioning tests on new systems using Resonant ac. These tests are often augmented with partial discharge measurements. Significant work was undertaken in recent years by the CIGRE B1.28 study committee [26] on on-site tests for HV and EHV cable systems using partial discharge. Table 4 shows the recommended test voltage for commissioning tests.

Table 4: CIGRE / IEC Recommended Test Voltages for Commissioning Tests (Generally undertaken in concert with PD measurements)

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Duration [min]
40/47	2.0	10-300	60
60/69	1.9		
110/115			
132/138	1.7		
150/160			
220/230			
275/285			
345/400			
500			

CIGRE B1.28 also generated recommended test voltages for aged systems that are 5-15 years old and greater than 15 years. Table 5 shows the recommendations. Note that the CIGRE working group intended these withstand tests to be conducted in conjunction with partial discharge measurements. However, such tests also carry a withstand element and thus are included here for reference.

Table 5: CIGRE Recommended Test Voltages for Maintenance Tests (Generally undertaken in concert with PD measurements)

Voltage Class [kV]	Frequency Range [Hz]	Duration [min]	Test Voltage	
			5 Years* to 15 Years [U_0]	> 15 Years [U_0]
60-69	10-300	60	1.5	1.1
110/115			1.5	1.1
132/138			1.4	1.1
150/160			1.4	1.1
220/230			1.4	1.1
275/285			1.4	1.1
345/400			1.4	1.1
500			1.4	1.1

9.4 Success Criteria

Simple Withstand test results fall into two basic classes: Pass – no action required; Not Pass – action required. Table 6 shows the requirements for Pass and Not Pass indications for Simple Withstand.

Table 6: Pass and Not Pass Indications for Simple Withstand
(See Section 3.1 for discussion on raw versus weighted accuracies)

Test Type	Cable System	Pass	Not Pass
0.1 Hz & resonant ac	HMWPE	No Failure. No signs of distress[1].	System will not withstand the applied voltage (circuit fails). Any signs of distress[1].
	XLPE		
	WTRXLPE		
	EPR		
	PILC		
dc	PILC		

[1]Distress is defined as excessive power required to energize the tested segment, audible arcing or discharge, or any other unusual observations during the test.

9.5 Estimated Accuracy

For the pass and not pass test result scenarios, the desired outcome is for there to be no failures for an undefined time in service after the test. For purposes of the CDFI, the overall diagnostic accuracy is considered for a two-year horizon. Simple Withstand accuracy must be treated a bit differently than other diagnostics since the required action is integrated with the test for those circuits that fail as they cannot be operated again until repaired. The result of such a test is a failure, not a condition assessment and there is no way to determine how close to failure a circuit was prior to the test. As a result, the condition-specific accuracies cannot be computed for Simple Withstand diagnostics. The only information that can be reported relates to failures in service after a test was performed.

Table 7 summarizes the "accuracies" for the simple withstand technique. As an example, for the seven data sets investigated, 93% of the tested circuits did not fail within two years after the test. On a weighted basis, 87% of the cable tested did not fail. These data correspond to the median overall accuracy obtained from the distribution of all seven available accuracies. The median represents the middle data point if all data are ordered from smallest to largest. In other words, 50% of the data points have values greater than the median and 50% of the data points have values that are less than the median.

Table 7: Summary of Simple Withstand Accuracies

Accuracy Type		Simple Withstand	
		Raw	Weighted
Overall Accuracy (%)	Upper Quartile	100	87
	Median	93.0	87
	Lower Quartile	87.0	87
	Number of Data Sets	7	7
	Length (miles)	7875	7875
Time Span (years)		2001 - 2008	
Cable Systems		XLPE, PAPER, EPR	

9.6 CDFI Perspective

A comprehensive analysis of Simple Withstand testing was performed with respect to circuit performance, both on test and in service after testing. This detailed analysis is possible because:

- Utilities provided the CDFI with a large number of sizeable datasets;
- Several of the datasets represent multi-year diagnostic programs;
- Results of withstand tests are easy to interpret – Pass/Not Pass; and
- Some datasets include additional information (circuit ID, length, age, component that failed, etc.) that enables collation, comparison, and re-analysis / re-interpretation.

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The large amount of detailed analysis performed should not be taken as an approval or endorsement of the simple withstand technique but is merely a consequence of the amount of information contained in this large volume of data.

9.6.1 DC Withstand Usage

The use of dc voltage to assess the condition of extruded cables has been the source of much discussion and significant work. According to this work [10], [21], [22], it is clear that the application of dc withstand voltage generally does not provide very useful information about the condition of a cable circuit. This appears to be true for all cable MV cable types. In fact, for the most part, it is no longer used as a factory production test.

As discussed earlier, the application of dc voltage can cause premature failures in aged, XLPE insulated cables. However, the effect of dc voltage on WTRXLPE and EPR insulations is unclear. Discussions on this topic continue in industry technical committees as experiments show that dc can inject space charges into these insulation materials, just as it does in XLPE insulation. ICEA S-94-649-2004, Section 5.3 limits the voltages and times used for dc testing of new cables. Furthermore, it does not recommend dc testing on **any cables** more than 5 years old.

Therefore, since:

(a) the type of cable is often not known at the time of testing; and
(b) diagnostic tests are carried out on cables much older than 5 years.

The prudent approach is not to use dc voltage for withstand testing of any aged MV extruded cables.

9.6.2 Damped AC Withstand Usage

Damped ac has been discussed in the industry as being useful as a Simple Withstand test. However, it does not fit the definition of Simple Withstand as defined in this document. As indicated in Section 9.3, DAC does not meet the "proven stress enhancement" requirement as no failures on test have been reported. Indeed, an examination of a typical DAC waveform output appears to produce a voltage stress that marginally exceeds the normal operating voltage. Figure 3 shows both sinusoidal VLF (2.2 U_0 for a 7.2 kV phase to ground operating voltage) and DAC (1.7 U_0) including both the DAC portion (last few milliseconds) and the charging period (approx. 4 s for this load).

Utilizing the periodicity of the repeat DAC applications (shots of 15 s each) and sinusoidal VLF (10 s) waveforms, it is straightforward to calculate the corresponding RMS voltages. While not a perfect indicator of the effect of each waveform on the cable system, it is still a useful comparison. The RMS voltage of the sinusoidal VLF waveform is 16 kV while the DAC RMS voltage is 8.9 kV. In the case of a system operating voltage of 7.2 kV, these test voltages translate to 2.2 U_0 and 1.2 U_0.

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A thorough review of the literature for DAC testing was conducted to find data the supports the use of DAC as a withstand test. From the documents referenced in the current draft of IEEE 400.4 (Damped ac testing), all indications suggest that DAC breakdown voltages are far higher than those required for 60 Hz ac, 0.1 Hz VLF, or even dc [see technical references in IEEE 400.4]. This implies that the suggested 1.7 U_0 and 50 shot protocol is likely not sufficient to produce stress enhancement that can cause significant insulation system defects to grow and fail during the test.

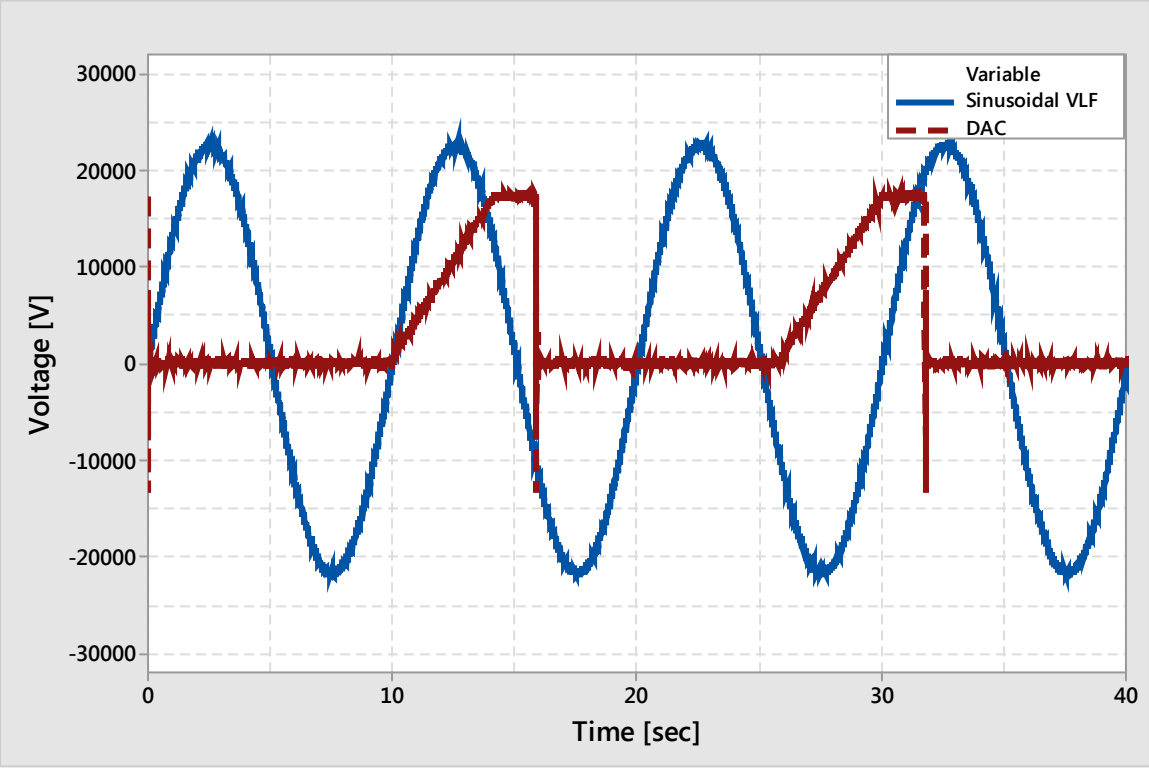

Figure 3: Sinusoidal VLF (0.1 Hz) and DAC Waveforms for 15 kV Cable Systems

The preceding discussion emphasizes the lack of information to support the use of DAC for Simple Withstand purposes. An additional factor to consider is the fact that no DAC unit currently available is designed to be used in a pure withstand mode. None of the systems used within the *CDFI* could be easily configured as Simple Withstand units as the partial discharge portion of the device is always active. Given this information, DAC is not considered in the *CDFI* to be a Simple Withstand test option.

9.6.3 Different Approaches

The underlying principles of withstand tests are common to all Simple Withstand test approaches. However, there are many ways that the required voltage stress may be applied to the system. The variety of approaches (resonant ac, dc, VLF ac – sinusoidal, and VLF ac – cosine rectangular) and cable system makeup makes direct comparison of withstand data difficult. In fact, utilities are cautioned not to attempt such comparisons. Fortunately, there are techniques available that can be used to overcome the difficulties such that an industry-wide perspective on withstand testing can be constructed.

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It is also useful to understand the current usage of these voltage sources for withstand tests on MV and HV/EHV cable systems. Figure 4 shows the current estimated usage of resonant ac, dc, DAC, and VLF for MV cable systems. (DAC is included because at the time the usage survey was conducted, it was thought that it could be used as a Simple Withstand test). As the figure shows, VLF is the most widely deployed source type for Simple Withstand for medium voltage cable systems.

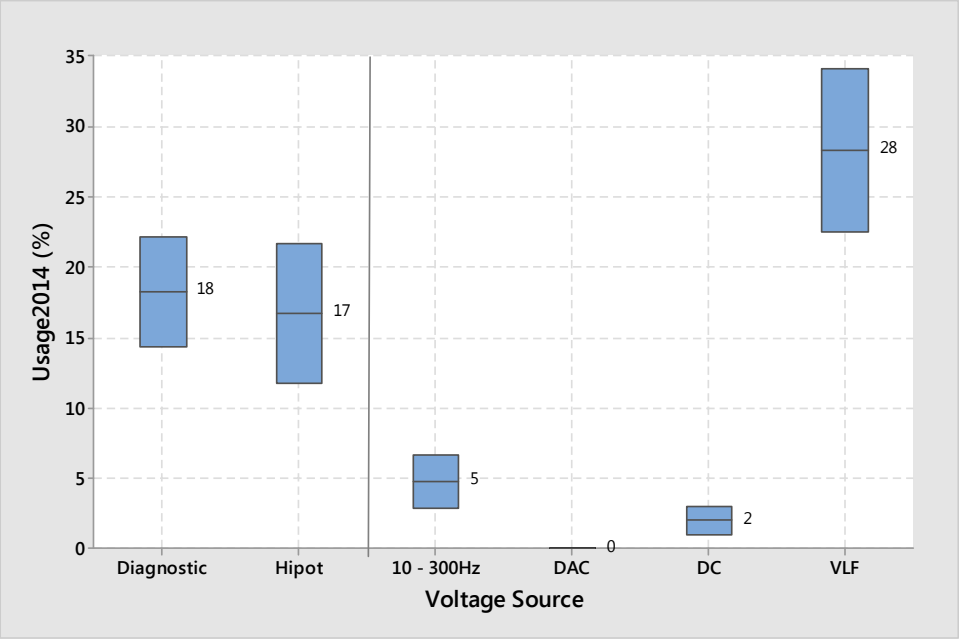

Figure 4: Voltage Source Usage for Utilities Deploying Diagnostics

Resonant ac has been increasingly used as the voltage source for HV and EHV cable systems as evidenced by tests performed since 2000 in Figure 5. At these voltage levels, the test is often conducted as a Monitored Withstand test with Partial Discharge as the monitored property (see Chapter 10).

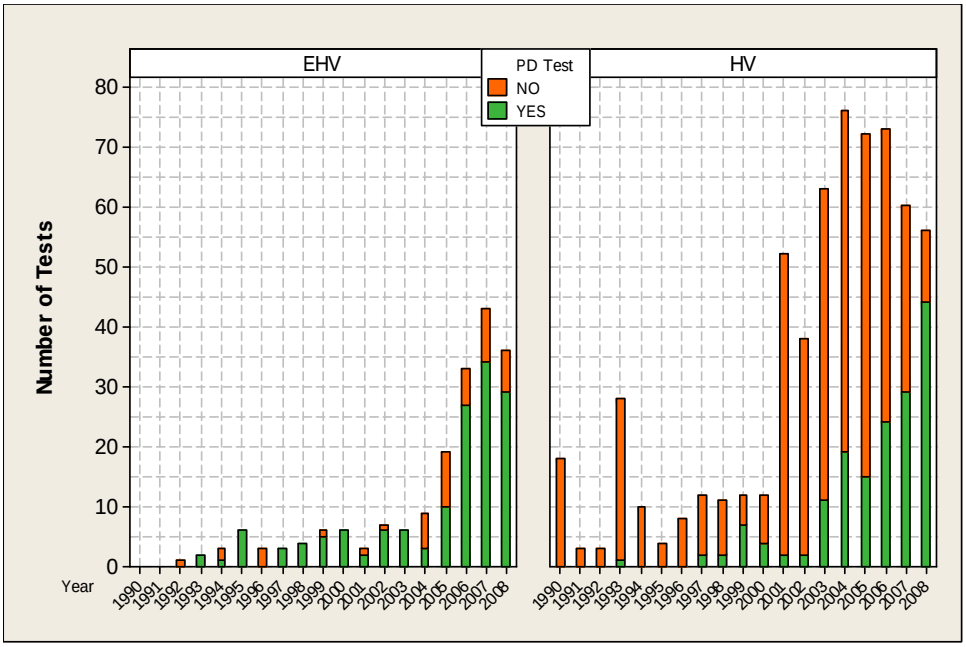

Figure 5: Resonant ac Tests on HV and EHV Cable Systems – Both Simple and Monitored Withstand Approaches Increasing in Usage [26]

As the use of Simple Withstand on HV and EHV systems is declining, the focus for the remainder of this chapter is Simple Withstand testing on MV cable systems.

9.6.4 Reporting and Interpretation

Although all variations of withstand tests report the outcome of the test as either Pass or Not Pass, many other data are often recorded about the tested circuit. Table 8 is an extract from a typical Simple Withstand test data sheet received from a utility.

Table 8: Sample Test Log (VLF ac – Sinusoidal)										
Date	**Feeder**	**Cable Type**	**Ckt Voltage [kV]**	**Phases Tested [#]**	**Conductor Length [ft]**	**Test Voltage & Duration**	**Failure During Test [Yes / No]**	**What failed?**	**Time to Fail**	**Comments**
5/2/2005	Y71465	PL	12	3	12,481	30min @ 16kV rms	Yes		1:00 & 8:00	AØ fail @ 10kV BØ fail @ 8kV
5/3/2005	H706	EX	12	1	300		No			
5/3/2005	Y1932	PL	12	3			Yes		11:00 & 6:00	AØ fail @ 18.1kV CØ fail @ 20.2kV
5/3/2005	Y71465	PL	12	3	12,481		No			Pass retest AØ & BØ
5/5/2005	A619	EX	12	1	450		Yes	CABLE	5:00	AØ fail @ 13.7kV
5/5/2005	E021	EX	12	1	500		Yes	CABLE	0:07	AØ fail@ 2.1kV
5/5/2005	Y1932	PL	12	3	20,000		No			Pass retest after 5/3/05 VLF failure.
5/6/2005	Y1935	PL	12	3			No			
5/9/2005	Y84048	PL	12	3			No			
5/11/2005	Y1960	PL	12	3	32,136		No			
5/16/2005	E2012	EX	12	1	300		Yes	CABLE	3:00	AØ fail @ =22.5kV
5/17/2005	L1675	EX	12	3	1,750		Yes		16:00	BØ fail @ =22.4kV
5/17/2005	W6011	EX	12	1	1,000		No			
5/18/2005	C1314	EX	12	3	800		No			
5/18/2005	L1675	EX	12	3	1,750		Yes		17:00	BØ fail 2nd VLF test @ =22.5kV
5/20/2005	A872	EX	12	1	400		No			
5/20/2005	E2012	EX	12	1	400		Yes	CABLE	8:00	AØ fail @ -16kV

The notes and other observations from Table 8 are provided below:

- These are proactive tests that were carried out using the times and voltages (30 min at 16 kV RMS) recommended for maintenance testing in IEEE Std. 400.2.

- Failures occurred during some of the tests. However, not all of these failures were repaired and retested. (Note A – failures on first test and Note B – full retest after failure on test to

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confirm that a successful repair was made). It is conceivable that some circuits were short enough that the utility chose to replace them rather than repair them.

- Although a circuit that fails the first test is repaired and then passes the retest (a common outcome), there are instances (Note C) where more than one failure on test may occur. This is most likely to take place on longer length cable circuits where multiple defects might exist.

- There are a significant number of failures on test (Note C) at times greater than 15 minutes (the lower limit presently allowed in IEEE Std. 400.2).

Regarding the last bullet above, Figure 6 shows the collated results of VLF tests from two utilities for a one-year period.

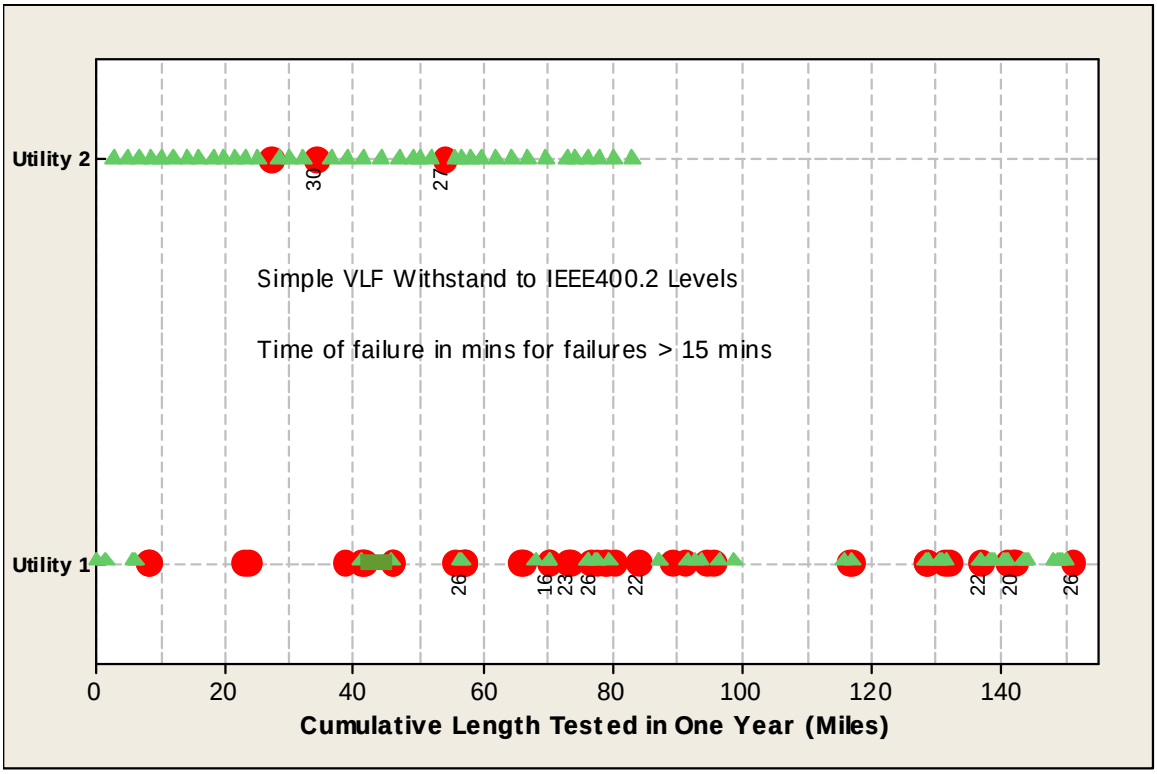

Figure 6: Collated VLF Test Results from Two Utilities over a One-year Period (IEEE Std. 400.2 recommended 30-minute tests)

The test results shown in Figure 6 were completed using the times and voltages recommended in IEEE Std. 400.2 (30 min tests). The X-axis is the cumulative circuit length tested. The red symbols identify tests resulting in Not Pass while the green symbols show the tests that resulted in Pass. The distance between two successive points represents the length of an individual cable system test. The time to failure is shown for only failures that occurred after the 15 minute lower limit allowed in IEEE Std. 400.2 (those failures without times occurred at 15 min or less). The test results in Figure 6 come from data of the type recorded in Table 8.

Although it is not readily apparent from the figure, the majority of circuits tested resulted in a Pass. Additionally, most of the failures are associated with longer test circuit lengths. While IEEE Std. 400.2 recommends a test time of 30 min, the 15 min test time allowed in IEEE Std. 400.2 has found favor with some utilities. Inspection of the failure times shown above for these two utilities indicates ten failures representing more than 230 conductor miles would have gone undetected if the test had been terminated at 15 min.

9.6.5 Collated Performance on Test (MV)

A critical issue for withstand testing is the voltage-time combination used for the test. All withstand tests are performed at voltages higher than normal operating voltage (with the exception of so-called online "soak" tests) with a goal of causing defects to grow to failure at a faster rate than would occur in service. If the voltage is too high, every defect including those that never would have impacted system performance will initiate and grow towards failure. Equally important is the time the defect has to grow during the test. If the time is too short, then degraded cables may be put back into service without failing under test. As a result, the voltage-time combination used for withstand tests must be carefully chosen to balance the need to identify critical defects with the time to grow them to failure during the test.

Traditionally, the outcomes of Simple Withstand tests have been discussed in terms of the number (or proportion) of failures that occur using different test durations and voltage levels (see IEEE Std. 400 and IEEE Std. 400.2). The disadvantage of this approach is that it focuses on the small minority of failures rather than on the overwhelming majority of circuits that typically successfully complete the test. *CDFI* pioneered a way to address this deficiency by performing a survivor analysis. The resulting survivor curves show how the survival rate of a defined area (utility, subdivision, county or country) declines during the Simple Withstand test, though the rate of decline drops off significantly after 15 min. Such an analysis can be conducted empirically without any assumptions or using a distribution approach such as Weibull Analysis. Figure 7 shows the empirical data for cable circuits tested for as long as 60 min for two utilities. It is based on data from two non-US utility studies [9, 12, 15].

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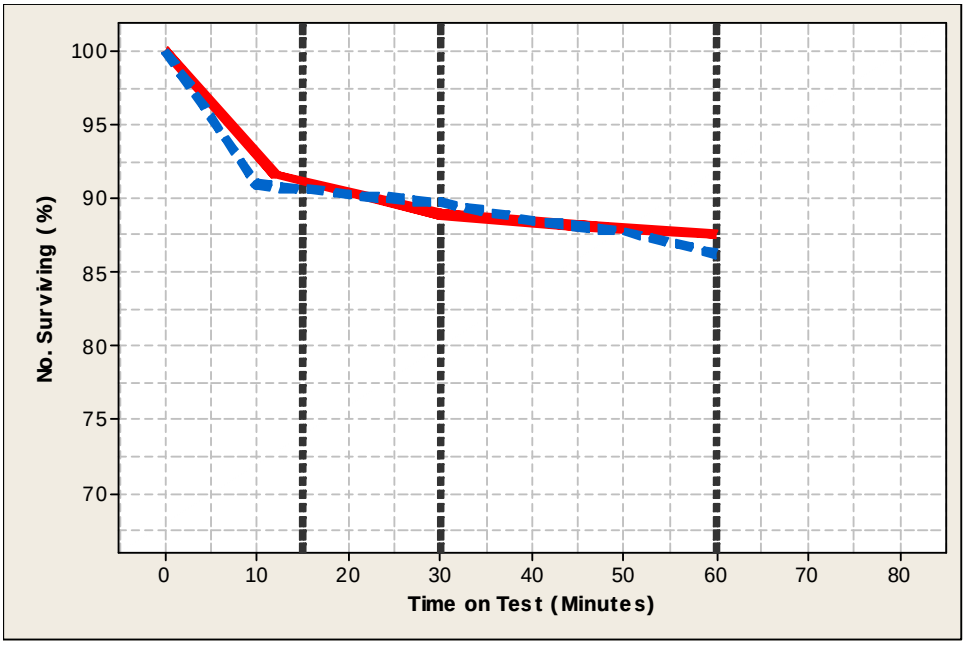

Figure 7: Percentage of Cable Survival for Selected ac VLF Voltage Application Times

Figure 7 shows that the survival curves are similar for these two datasets. However, they are not asymptotic (i.e. flat with respect to test time) at 15, 30, or even 60 minutes. This implies:

- The test time of 15 min may lead to a decision to place back in service circuit segments that would have failed during a longer test.
- A test time of 60 min will likely capture a larger number of failures and there is still a small but finite chance of failure on test at times longer than 60 min.
- The absence of data for test times longer than 60 min makes it impossible to quantify the degree of risk (missed failures) in using test times of 60 min or less.

Several US utilities initiated Simple Withstand diagnostic programs after the publication of initial test protocol recommendations in IEEE Std. 400.2. These datasets are collated within the CDFI. Analyses for both dc and VLF withstand tests were performed, though it is only the more extensive VLF data that are presented in Figure 8. It is important to note that the data contained in this figure are for segments of widely varying lengths (300 – 20,000 ft). The process of length adjusting these data is discussed in Section 9.6.6.

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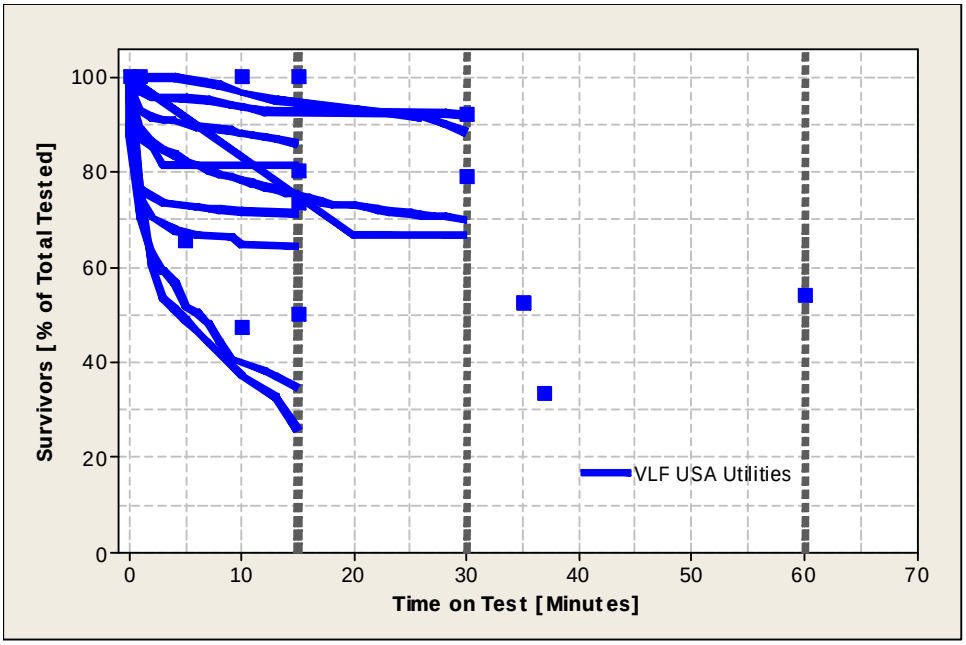

Figure 8: Survivor Curves for Collated US Experience with VLF Withstand Tests [14]

Figure 8 came from data of the type recorded in Table 8 in which the time to failure was recorded for each circuit that resulted in a "Not Pass". The curves all follow the same general trend with 100% survival at the start of the test and differing rates of decline down to some final level.

Prior to this work under the CDFI, no central repository of US data existed. Engineers were required to rely on studies from Germany and Malaysia to interpret test results (data shown in Figure 6). A number of particularly noteworthy observations include:

- The median survival rate at the end of a 15 min test is 77% of the circuits tested. However, there was no allowance for the high variability of circuit lengths included in each dataset.
- Ideally, at the end of a Simple Withstand test, the survivor curve should have decayed to a stable value with a slope of zero. This would indicate there were no additional failures to find. However, it is clear that in 50% of the cases shown in Figure 8, at both 15 and 30 min test times, this is not the case.

9.6.6 Length Adjustments to Performance Data

Inspection of utility test data shows that Simple Withstand techniques are the most widely used diagnostic technique and encompass an extremely broad range of cable system lengths as shown in Figure 9 [14]. The extreme range of lengths presents a number of challenges when attempting a quantitative analysis of a withstand diagnostic as the likelihood of a long length containing a weak spot is higher than a shorter length. In other words, it is unreasonable to treat a 1,000 ft segment the same as a 50,000 ft segment. Figure 8, which shows results for survivor analysis, does not consider whether some groups of tests were conducted on different length circuits. All circuits are treated the same in this approach.

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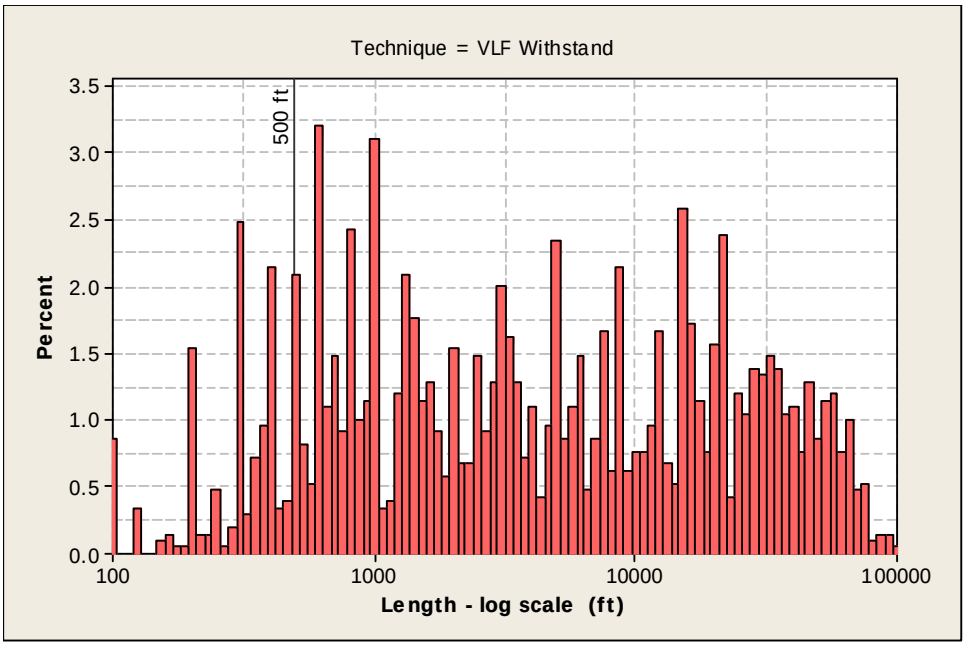

Figure 9: Distribution of Test Lengths for the VLF Withstand Technique [14]

In cases where the segments lengths are known, an adjustment to a common length base can be made. Dividing long lengths into consistent smaller sets is an obvious approach. However, this step is insufficient for meaningful quantitative analysis. Instead, five steps are necessary:

1. Selection of a meaningful and appropriate reference length – A 10,000 ft test length could be subdivided into 100 ft, 5,000 ft, or 1,000 ft lengths, but how meaningful (Figure 9) are 100 ft and 5,000 ft lengths in the context of a utility feeder. In the CDFI, we have used 500 ft and 1,000 ft lengths, but most utilities commonly report data in 1,000 ft lengths.
2. Censoring of non-failed segments where we recognize that there are two subsets of censoring:
    a. The large number of those which survive to the end of the test – five 10,000 ft lengths surviving a 30 min test would provide 50 censors (5×10) at 30 min.
    b. Those that are a part of a circuit where a failure occurs and, thus, have survival times lower than the target test time. For example, using a 1,000 ft reference length, a failure of a 10,000 ft long circuit at 20 min into a 30 min test would provide one failure at 20 min and nine censors at 20 min (all we know is that these nine have survived 20 min, we do not know nor can assume that they would have survived 30 min).
3. The precise logic and mathematical approach is outside the scope of this guide but appears in all reputable Weibull analysis texts.
4. These data are not standard continuous variables, but are essentially "inspections" of "binned" data. Consequently, the analysis needs to accommodate these "non-standard" data.
5. The appropriate mode for the Weibull analysis must be selected. This analysis is accomplished one mode at a time. For Simple Withstand, the early and hold modes need to be separated. Most of the CDFI analyses employing length adjustment have focused on the hold mode.

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Figure 10 shows the impact of reference circuit length on probability of failure for the hold phase of a VLF withstand test. Early failures are treated as "left" censors. In other words, the assumption is that their times to failure are less than, in this case, 1 min. In this analysis, two reference lengths were used, 500 and 1,000 ft. As the reference length shortens, the probability of failure diminishes since there are more and more censored data points. Thus, it is apparent that too short a reference length provides unrealistically optimistic estimates.

An analysis of the data shown in Figure 10 also demonstrates that the data can be well fitted by a simple two-parameter Weibull curve. This means that there is only a single mode of failure. If there were more than a single mode, then there would be curvature, cusps, or breaks in the data that would cause a separation between the data and the fit lines. As this figure shows, the data in the hold phase do not exhibit this sort of behavior.

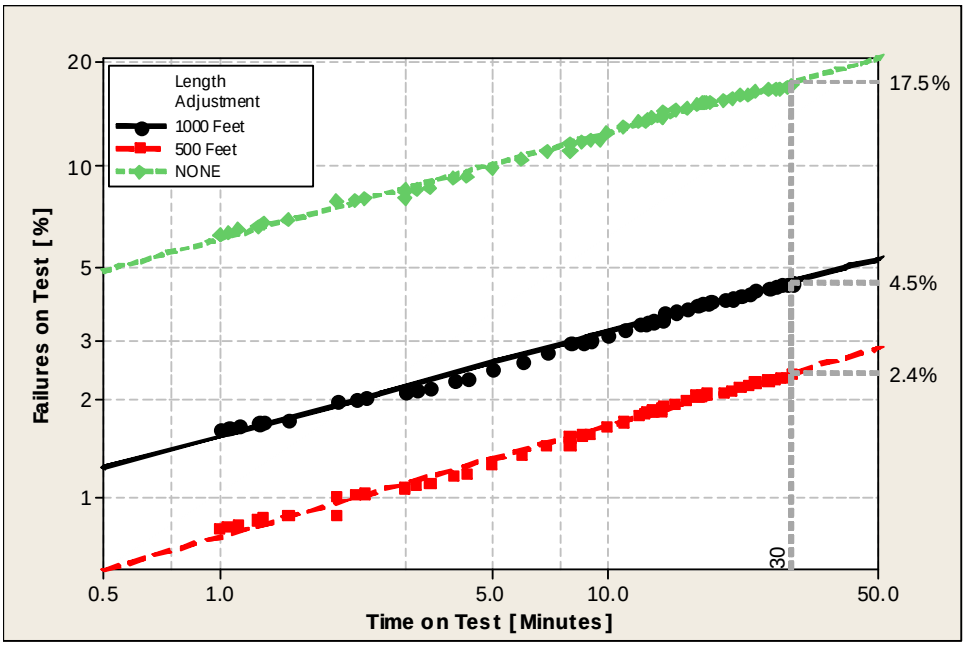

Figure 10: Impact of Reference Circuit Length on Probability of Failure for Hold Phase of VLF Test

Figure 11 shows this same approach applied to cable systems of two different voltage classes (within one utility). The top figure graph shows the data for a 13 kV system; the bottom graph is for a 27 kV system. It is instructive to note that once the length adjustments are made and the early phase failure mode is properly censored, the performance is nearly identical between the systems.

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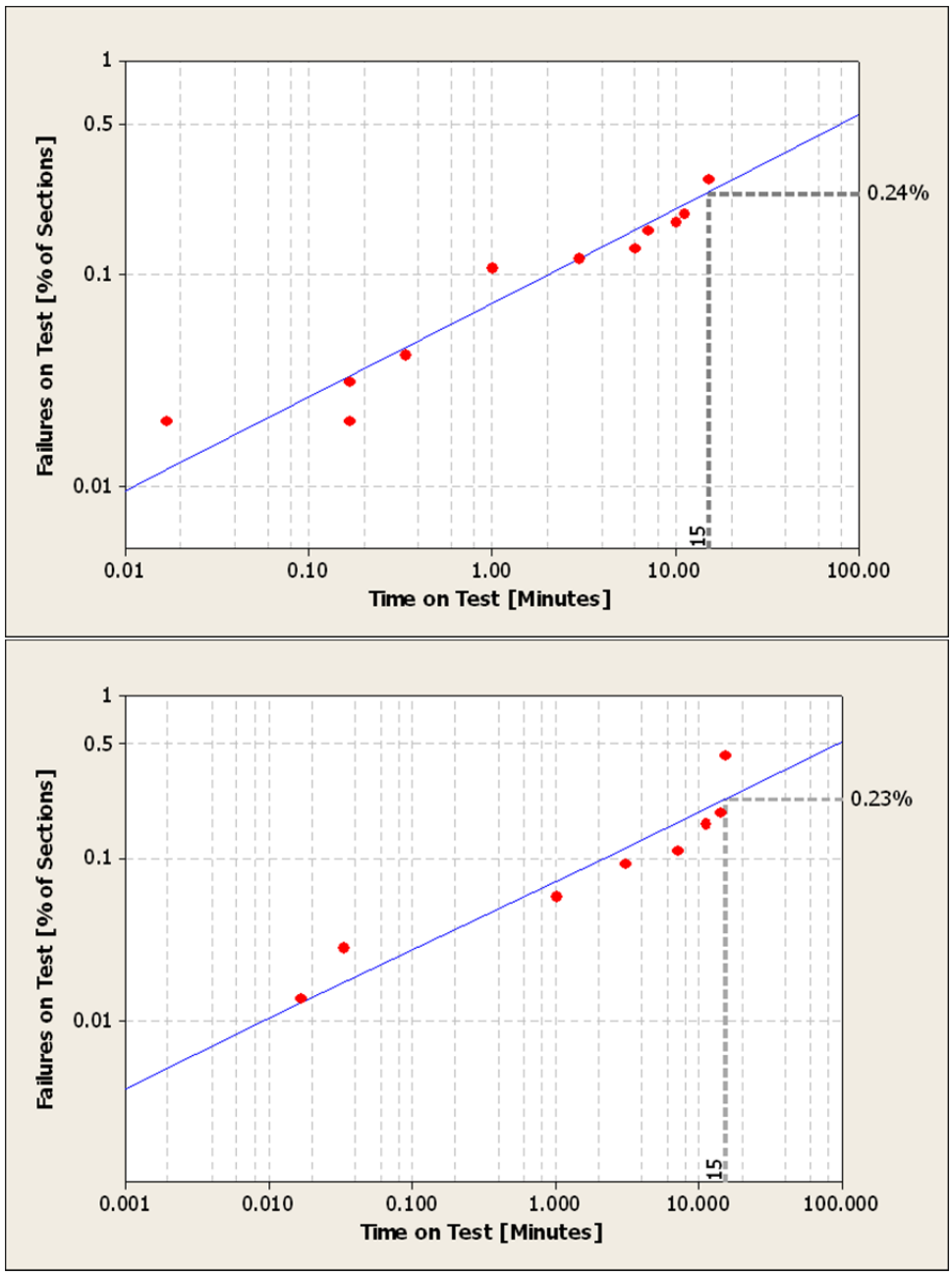

Figure 11: Distributions of Length Adjusted Failures on Test by Time for VLF Tests
Length Adjustment Based on Number of Feeder Sections
13 kV System (Top) and 27 kV System (Bottom)

The results shown in Figure 10 and Figure 11 apply to other utilities as well. Figure 12 shows five of the survivor curves shown originally in Figure 8. These curves appear substantially different from one another in terms of shape and Failure on Test rate.

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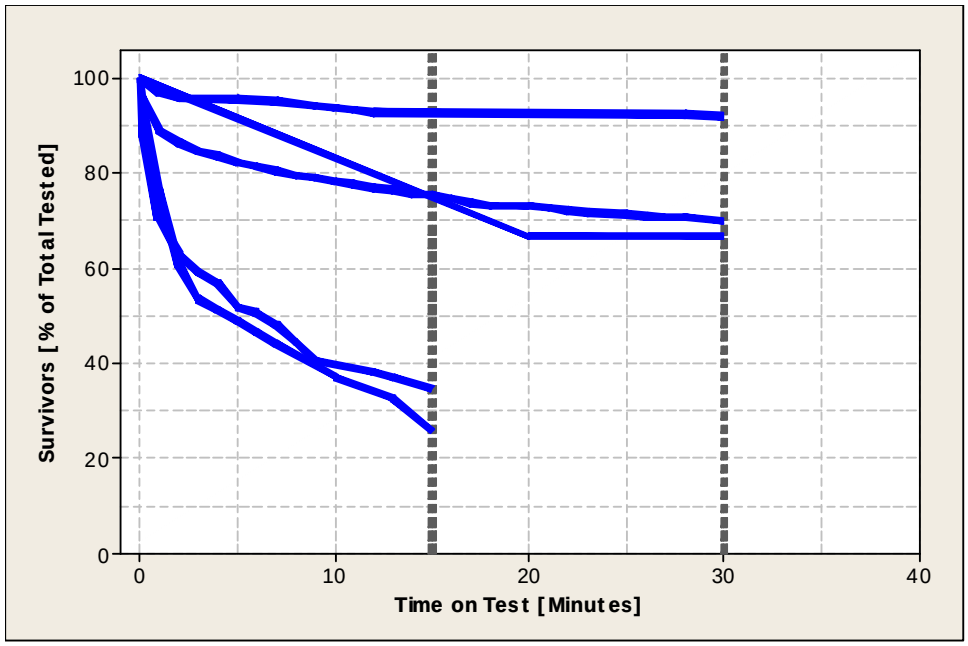

Figure 12: Survivor Curves for Five Datasets

However, by applying the length adjustments (using a base length of 1,000 ft) and censoring the early phase failures, the survivor curves in Figure 12 may be transformed into the Weibull curves shown in Figure 13.

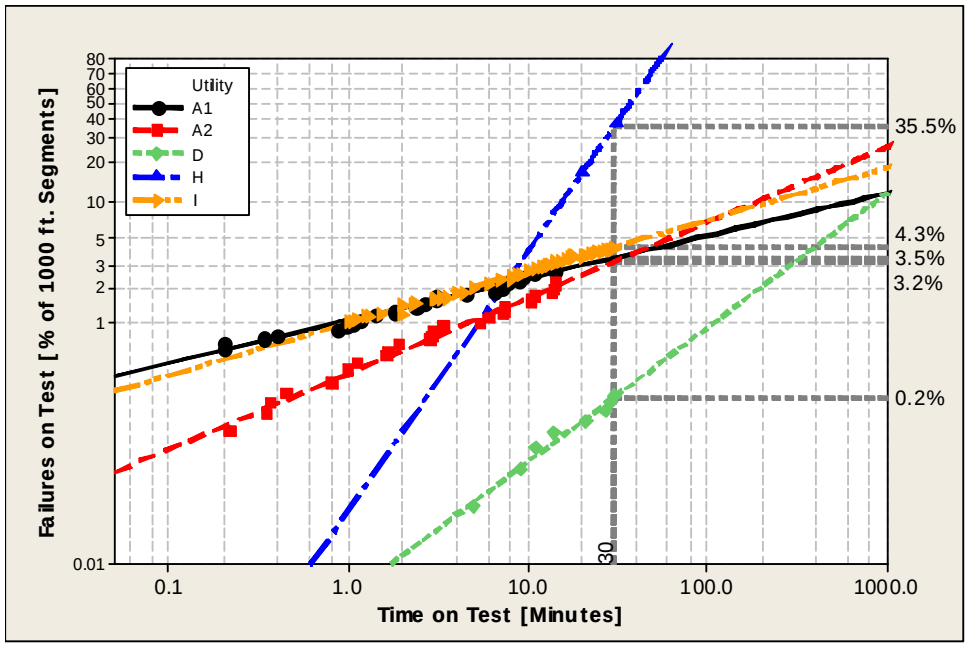

Figure 13: VLF Withstand Test Data Sets Referenced to 1,000 ft Circuit Length [14]

As Figure 13 shows, what appeared to be very different rates of failure on test actually become much more similar once the data are length adjusted. This is more apparent in Figure 14 where the replotted survivor curves use the length-adjusted data. As these figures show, four out of the five datasets have failure-on-test rates of 4.5% or less for 1,000 ft segments.

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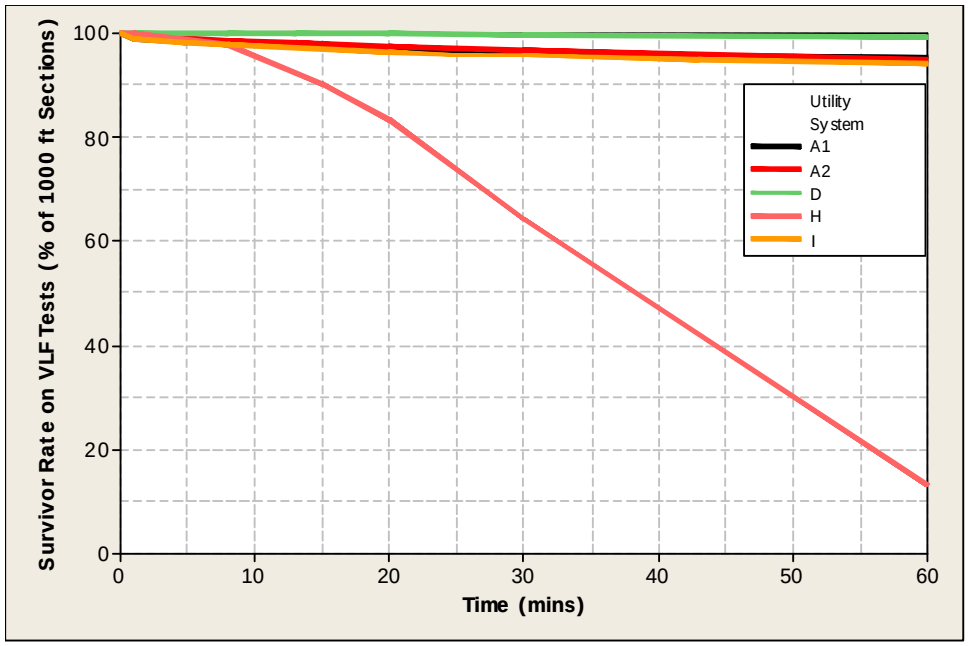

Figure 14: Length Adjusted Survivor Curves

Figure 15 shows a high failure-on-test rate for the one outlier dataset represented as ■ in Figure 14 is a result of the short length tested. The other datasets each represent 250 to 850 miles of tested cable system while the outlier dataset encompasses only one mile of tested cable system.

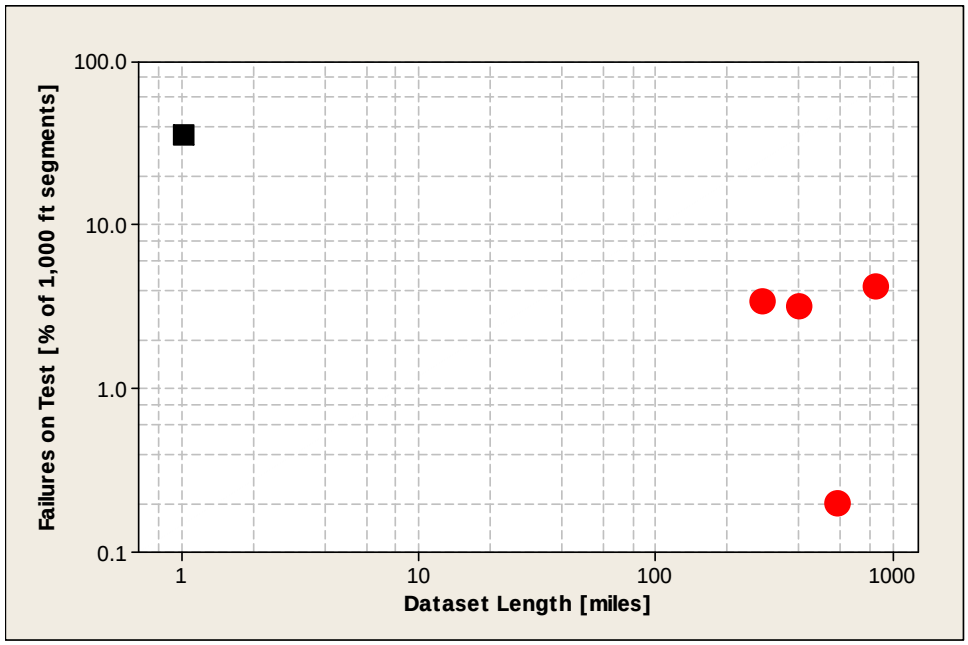

Figure 15: FOT Rates and Total Lengths of Datasets in Figure 12.

A number of observations from this analysis are noteworthy:

- There is a single mode of failure in the hold phase for all of these data sets. This allows for reasonable predictions of the performance on test.

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- The failure modes are remarkably consistent across the data, as evidenced by the similar gradients. This implies that utilities initiating Simple Withstand programs could confidently expect the performance shown above.
- The analysis has provided a robust framework for the analysis of data acquired from both 15 and 30 min tests.
- It is possible to extrapolate the curves to estimate the failures on test at times longer than 30 min. Estimates out to 120 min may be possible. This is useful if a utility wishes to perform non-standard Simple Withstand tests (i.e. longer than 30 min).
- The overall likelihood of failure, as evidenced by the likelihood of failure of 1,000 ft sections tested for 30 min, is approximately 2.7% for populations of significant length.
- These five datasets include both hybrid (paper and extruded) and single insulation cable systems.

As the above observations suggest, there is remarkable consistency in the performance of cable systems tested using VLF Simple Withstand. This consistency holds for different system compositions, locations, lengths, and voltage classes and is based on 2,100 miles of tested cable systems. The above analysis allows predictions as to the expected number of failures a utility should be prepared to address given a certain size test population. For example, for every 100,000 conductor ft tested (100 - 1,000 ft segments), a utility could reasonably expect to see four failures on test. Taking the approach in IEEE Std. 400.2 of combining all datasets, Figure 16 shows that the failure-on-test rate for 30 min test protocols is 2.7% (based on 1,000 ft segments).

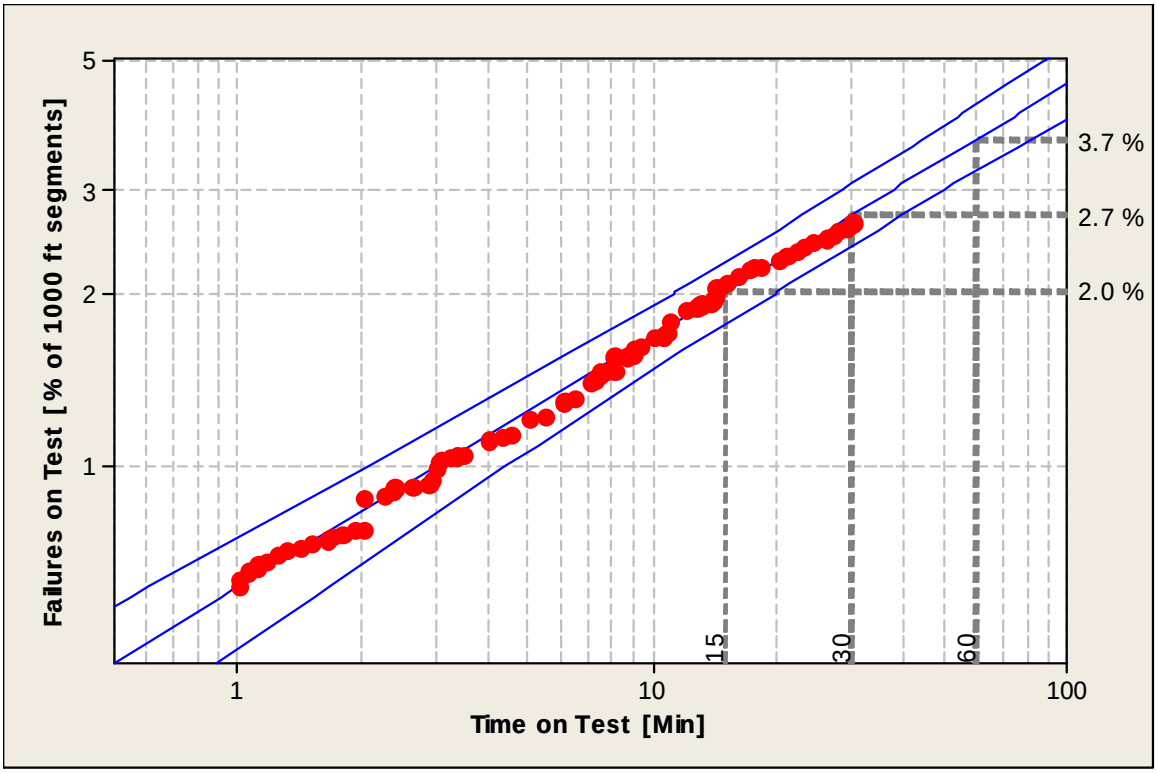

Figure 16: Combined Weibull Curve for all VLF Data in Figure 13

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9.6.7 Separation of Failure Modes – Early and Hold Phases

In the previous section, the early phase failures were censored so that they could be included in the analysis of the hold phase but would not affect the failure gradient calculations. The early phase does make an important contribution to the performance on test for Simple Withstand tests. It is, therefore, worth taking a closer look as these data. A close inspection of the survivor curves in Figure 8 (see previous section) reveals three important observations:

1. The number of survivors decreases rapidly during few first minutes of voltage application for all datasets. This rate decreases as the test time increases.
2. Only a few of the curves show the flattening that would indicate they were approaching an asymptote.
3. None of the survivor curves display a sharp decrease in survivors near the end of the test.

Initially, it was believed that these curves could be modeled by a single failure mode. However, the fact that the survivor curves do not approach asymptotes suggests that there is more than a single failure mode at work during the withstand test.

An analysis of the occurrence of failures-on-test (FOT) for both dc and VLF withstand tests (Figure 17) shows that there are at least two failure modes present in datasets representing a range of cable system voltages, components (accessories and cable), and insulation materials (EPR, PILC, and XLPE). In these tests, the same stresses were applied using both sinusoidal and cosine-rectangular waveforms. An allowance was made for the tests that did not result in a failure using censored data points. In addition, length adjustments were made to allow the cable system populations to be comparable. Most of the difference between the performance of VLF and dc tests comes from the early (ramp) portions of the test (see Figure 17). This finding is only apparent once the failure modes are separated and length adjustments made.

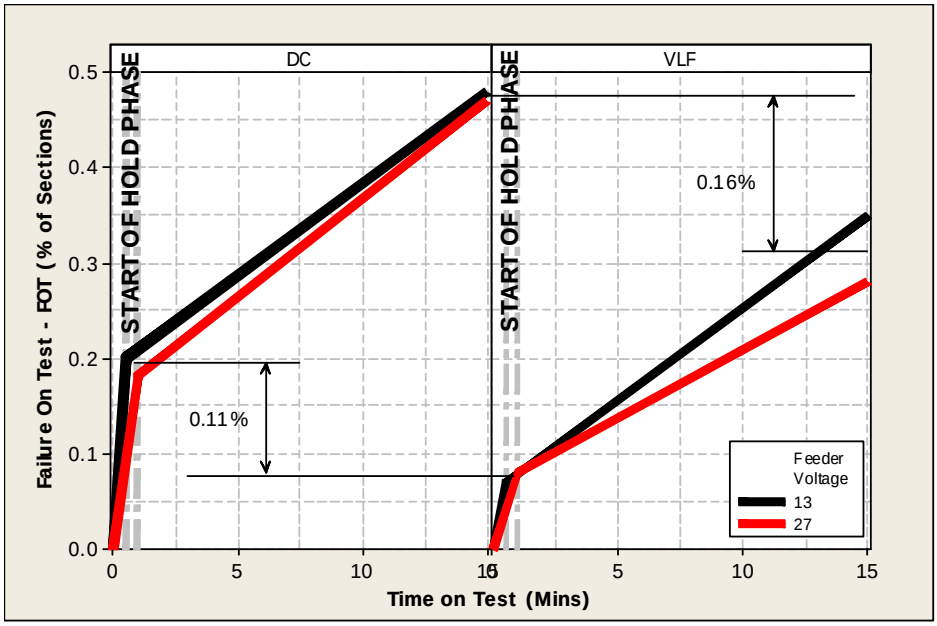

Figure 17: Distribution of Failures on Test as a Function of Test Time for DC and VLF Tests at One Utility [13 = 13 kV & 27 = 27 kV]

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In analyzing the datasets available to the CDFI, it turns out to be common (Figure 18) to see two failure modes present in withstand data. Generally, these data follow the pattern of one or two modes for early failures (Ramp or <1 min into the test) and a different mode for failures during the constant voltage (hold) portion of the test.

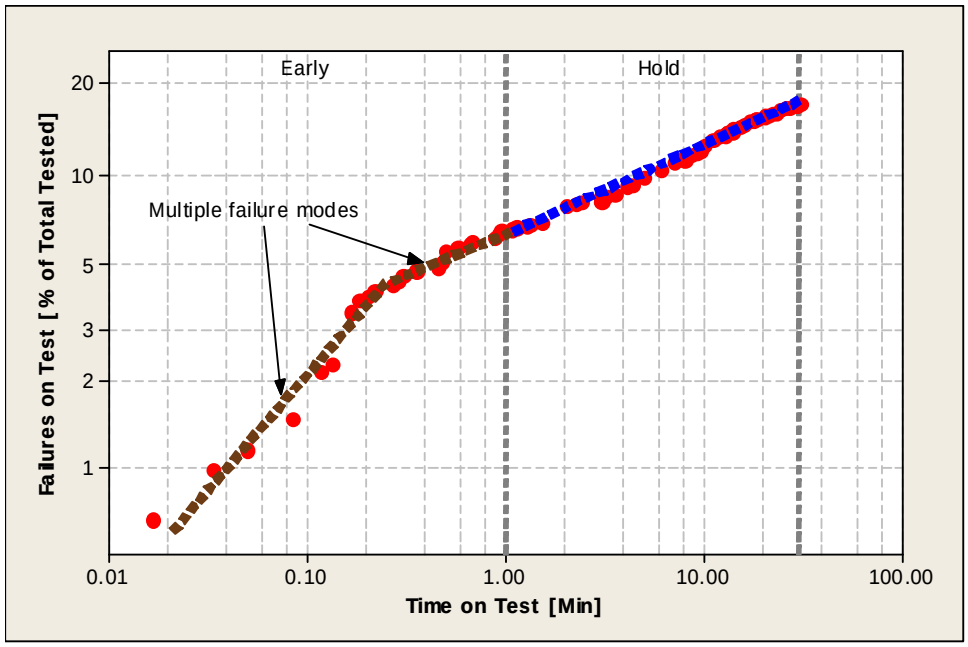

Figure 18: Distribution of Failures on Test as a Function of VLF Test Time (Direct application of test voltage without ramp phase)

Hold failure modes from different datasets appear to be similar while the early failure modes can differ significantly between different utility data sets and voltage sources (Figure 19). The differences in the early failure modes likely arise from the two subclasses that exist for this phase of the test. This behavior results from the two ways voltage can be brought up to the intended test level:

- Ramp / Step Up – the test voltage is raised in steps over 30 sec to 1 min to the final hold voltage, the test time commences once the hold voltage is achieved.

- Hold Entry – the hold voltage is directly applied. The voltage application is instantaneous for dc and VLF ac – cosine-rectangular but requires some time for the VLF ac – sinusoidal approach (one quarter cycle).

Identifying and separating failure modes is important, especially when considering the appropriateness of test times and the expectation for the overall test outcome. Both of these elements are critical when considering the potential economic benefits of withstand test programs.

Figure 19 shows the data on dc and VLF tests where, in both cases, the voltage was raised in steps to the hold (constant voltage) phase. The peak voltage of the failures within the early phase was recorded and plotted using a Weibull format. This representation clearly shows that:

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- There are failures at surprisingly low voltages.
- The risk of failure changes and increases rapidly above a critical stress.

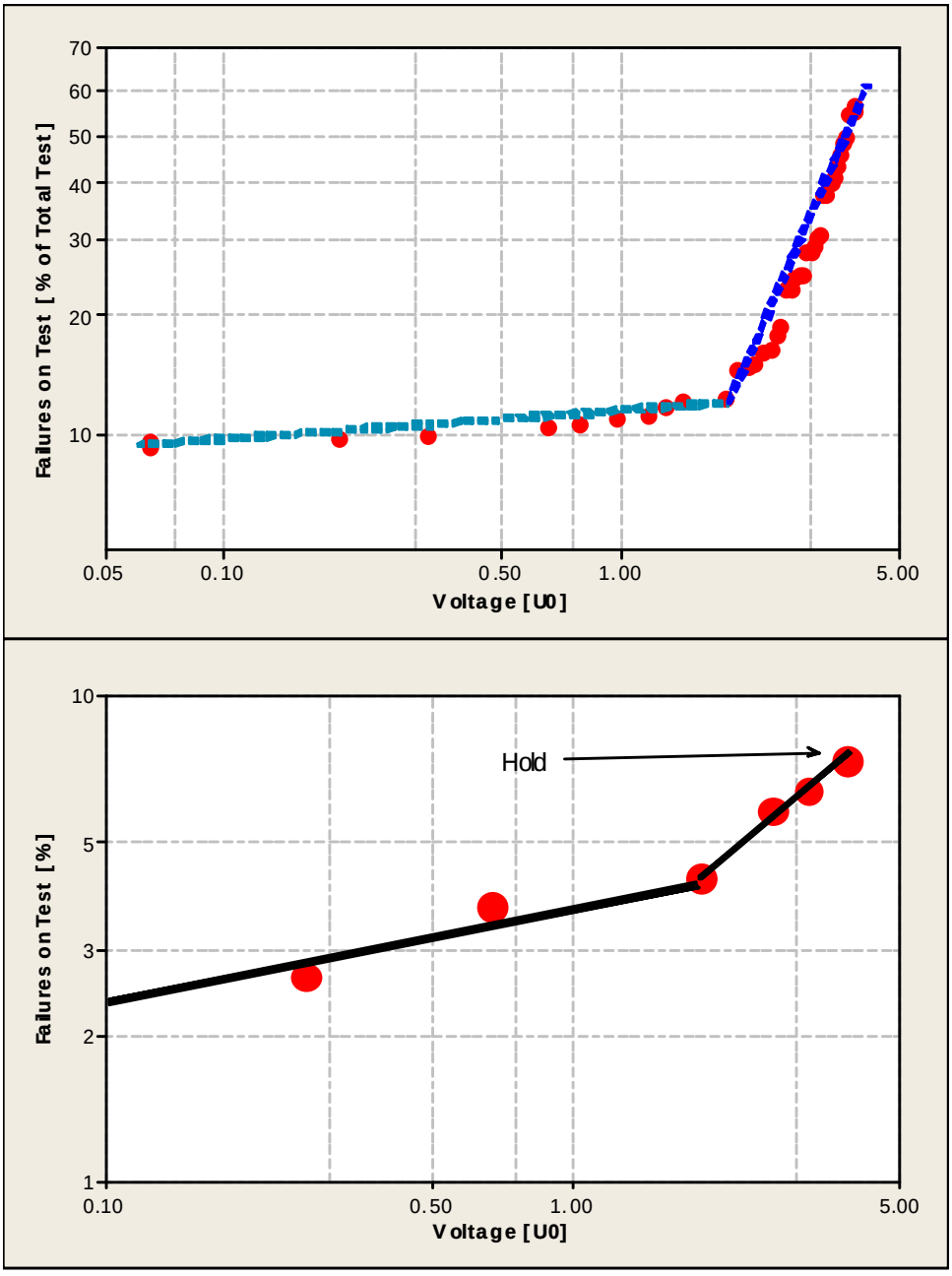

Figure 19: Dispersion of Failures on Test as a Function of Test Voltage during Ramp Phase for DC (Top) and VLF (Bottom)
(Highest VLF Test Voltages Used Exceed IEEE Std. 400.2 Recommendations)

This finding is a consequence of the Simple Withstand procedure itself as essentially identical features are seen when the data are separated by voltage type (dc and VLF), voltage class, insulation (EPR, Paper, XLPE), or component (cable and accessory). In Figure 20, where voltage class is used

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to separate the data, these data show the different modes between the early and hold portions of the test as well as the two voltage related modes within the early portion.

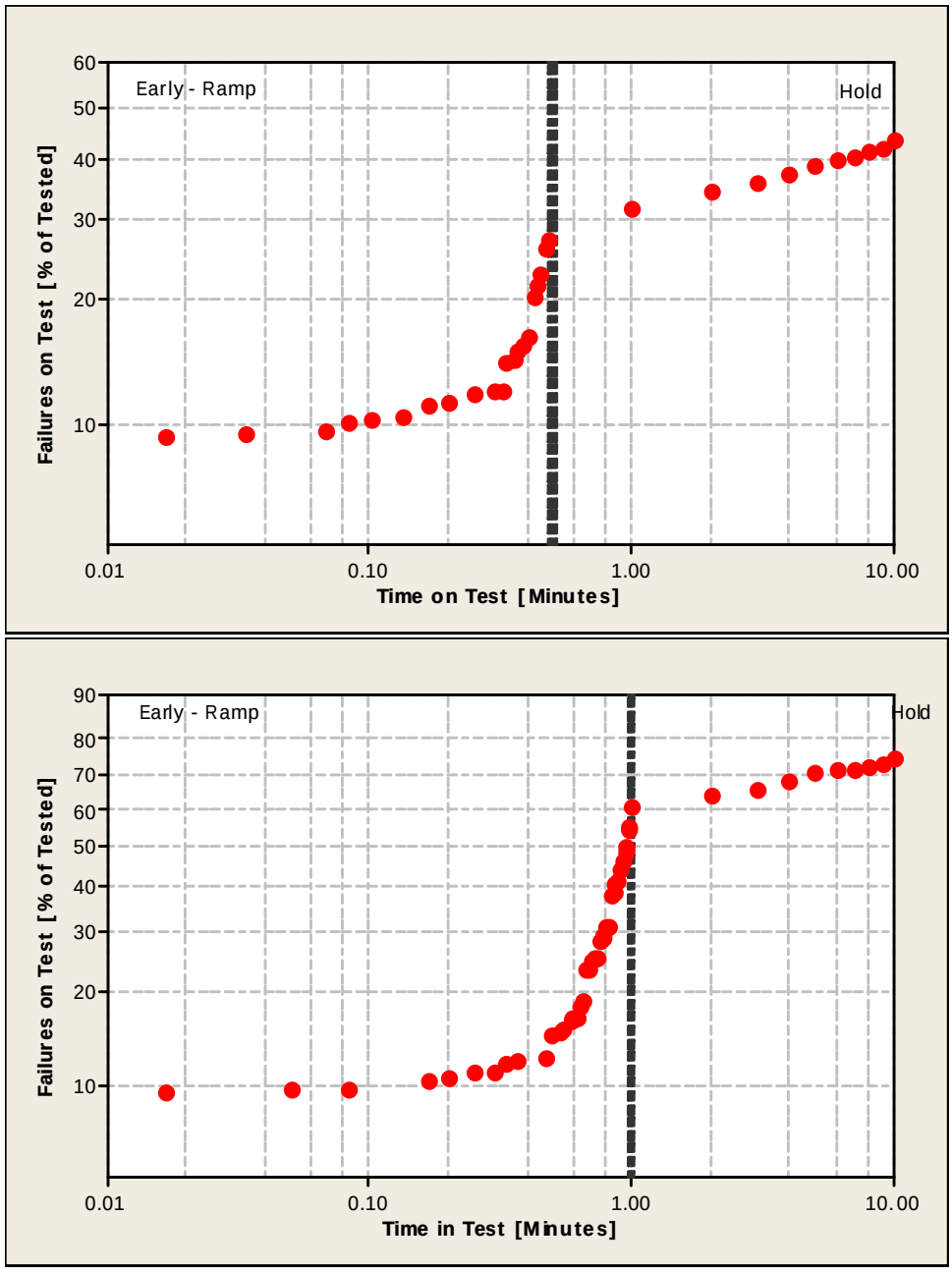

Figure 20: Dispersion of Failures on Test as a Function of DC Test Time 13 kV System (Top) and 27 kV System (Bottom) (After a Linear Increase in Voltage to the Hold Phase)

With these modes identified, it would then be possible to select a test voltage that eliminates a second early mode as this appears to cause an unnecessarily high numbers of failures.

9.6.8 VLF Frequency Studies

The effect of reduced VLF frequency (0.01 Hz versus 0.1 Hz) on the performance on test for Simple Withstand tests was examined as part of *CDFI* in both laboratory and field studies (the latter was carried out using data supplied by *CDFI* participants). The most commonly used VLF frequency is 0.1 Hz; however, it is also often the case that the VLF source must reduce the frequency to as low as 0.01 Hz in order to energize longer cable system lengths. One question left unanswered has been the effect of frequency on the breakdown strength of aged cable systems. IEEE Std. 400.2 specifies the test time and test voltage but not the test frequency. As the test frequency decreases so does the number of cycles that can be completed within the time period specified in IEEE Std. 400.2.

The work in this area is limited, though the most extensive field work is that completed by Shew Chong Moh of TNB in Malaysia. Moh extracted data from VLF cable system tests in the field and a small part of this data was examined in terms of the VLF frequency employed. The reductions in test frequency were the result of increasing length and cable system voltage (both of these increase the power demand on the VLF source and so will cause the frequency to drop). The data suggest that the fraction of failures-on-test (FOT) decrease and the fraction of failures-in-service (FIS) increase as a result of the reduced VLF frequency. On the face of it this would suggest that the lower VLF frequencies are less effective. This implies a potential need to either increase the test voltage or increase the test time to restore the perceived balance between FOT's and FIS's to that seen with the 0.1 Hz tests. The assumption is that an FOT is a future FIS that was forced to occur at a time of the utility's choosing thereby enabling a swifter and lower cost repair and avoiding customer interruptions.

There are other factors are at work in addition to those that may be derived from the VLF frequency. These factors include:

- Longer lengths are likely to experience more failures due to the increased probability of weak links; and
- Higher voltage cables are tested at higher stresses, thereby increasing the number of failures.

Both of the above factors are also correlated with a reduced VFL test frequency as they increase the power required from the voltage source. Hence, the impact on FOT and FIS may be due to a correlation rather than causation with respect to test frequency.

Assessing the impact of length and stress is reasonably straightforward using the Weibull equation. However, the relevant length and stress parameters are not known in these tests; though it may be possible to determine these from other datasets that include more specific data. Another issue to be considered is the relatively small number of test samples in the TNB field tests that were made at test frequencies other than 0.1 Hz tests (5% and 3% of total tests for 0.05 Hz and 0.02 Hz, respectively). Furthermore, the number of FIS are small (64 and 36) compared to the population size thereby increasing any impacts from variations in counting / data collection. It is quite possible, for example, for failures on higher voltage cable systems (33kV in this case) to be more carefully reported than those occurring on more common lower voltage systems (11 kV). These potential differences in reporting could make the lower voltage systems appear disproportionately more

reliable. Although there is no evidence that such reporting issues occurred in the TNB data, much of the results could be explained in this manner.

Furthermore, if the VLF test frequency did impact the effectiveness of the testing then it is expected that there would be differences in the number of FOTs and FITs between 0.1 and 0.05 Hz as well as between 0.05 Hz and 0.02 Hz. Inspection of the results suggests that there is only a difference between 0.1 Hz and 0.02 / 0.05 Hz and no difference between 0.02 Hz and 0.05 Hz. One would expect a similar difference in these two cases if the performance difference was due only to the different frequencies used.

Thus, upon inspection of the data it is not clear whether the VLF frequency has an effect or not given the multitude of issues occurring simultaneously. Clearly, an experimental program would help to:

a) Establish if lower test voltage frequencies are less effective at finding circuit problems or
b) Estimate by how much the test times or voltages might need to be increased to achieve the same effectiveness as the standard 0.1 Hz frequency.

The work by Moh is very useful as it identifies the important elements of an experimental program to address this issue. Such a program needs to address/include the following:

- Test objects that are in a degraded state (i.e. aged in a controlled manner),
- The degradation is achieved using aging mechanisms that are reasonable when compared to true field aging,
- The achieved degradation should be consistent between test samples as multiple test samples are needed,
- The achieved degradation should be quantifiable such that it is possible to compare the degradation on different test samples, and
- The test objects should be sized so that the test frequency may be selected by the test set operator rather than because of a test device limitation (i.e. the voltage source should be capable of energizing the test sample at any frequency between 0.01 – 0.1 Hz without overloading).

The following section describes a laboratory program that was undertaken as a part of the *CDFI* to investigate the effect of frequency on VLF breakdown.

9.6.8.1 Laboratory Study of VLF Frequency Effects

The laboratory program used the Ashcraft Water Tree Growth Method to age plaques of XLPE and EPR insulation compounds. The breakdown strength of these samples was determined for sinusoidal VLF voltage frequencies of 0.1 Hz and 0.05 Hz. The major drawback in field tests is that field aged cables are not homogeneous from segment to segment so establishing the impact of test voltage frequency is difficult. By employing the Ashcraft Method to age cable insulation plaques, a relatively homogeneous population of degraded test samples could be constructed.

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The samples were prepared in accordance with the Ashcraft method (ASTM Test Method D6097-97) as shown in Figure 21.

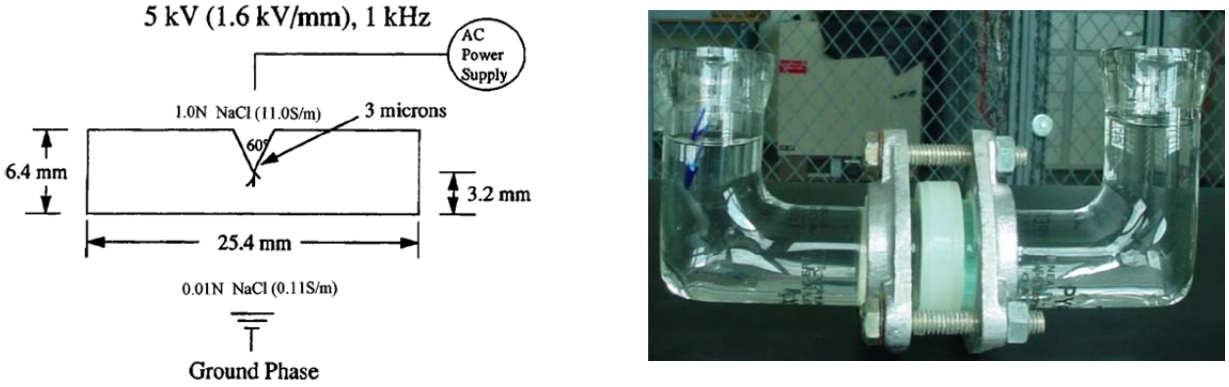

Figure 21: Insulation Plaque Geometry (left) and Aging Cell for Ashcraft Method (right)

These samples were aged at 1.6 kV/mm ac voltage stress for 30 days at ambient temperature prior to performing the ac breakdown tests. A total of 87 samples were tested in groups of three using a sudden death approach (i.e. one sample tested to failure and two samples left intact as censored samples for water tree length and point-to-plane distance measurements).

A ramp protocol was used for the breakdown measurement as shown in Figure 22. Each step voltage was held for 1 min regardless of VLF frequency.

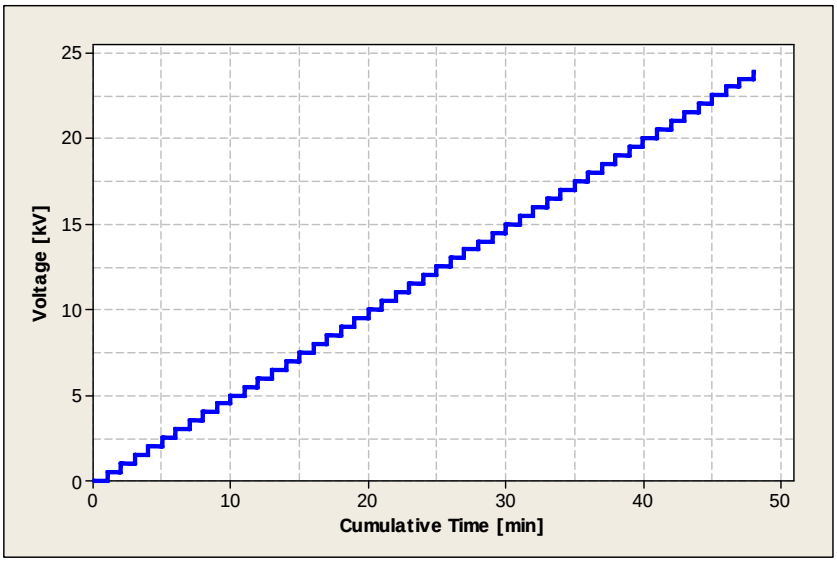

Figure 22: Test Voltage Protocol (Ramp – 1 min hold, 0.5 kV/step)

Test Program Results

The water tree lengths for all materials are shown in Figure 23. Random samples of each insulation type were chosen for 0.05 and 0.1 Hz breakdown tests. As these histograms show, the tree length distributions for each randomly chosen group were quite similar.

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The resulting VLF breakdown stresses for MV insulation materials are shown in Figure 24. The estimated breakdown strengths are based on the results from the group of three samples tested where all three were subjected to the test voltage. When one broke down, the breakdown value was recorded and the other two samples were treated as censored values.

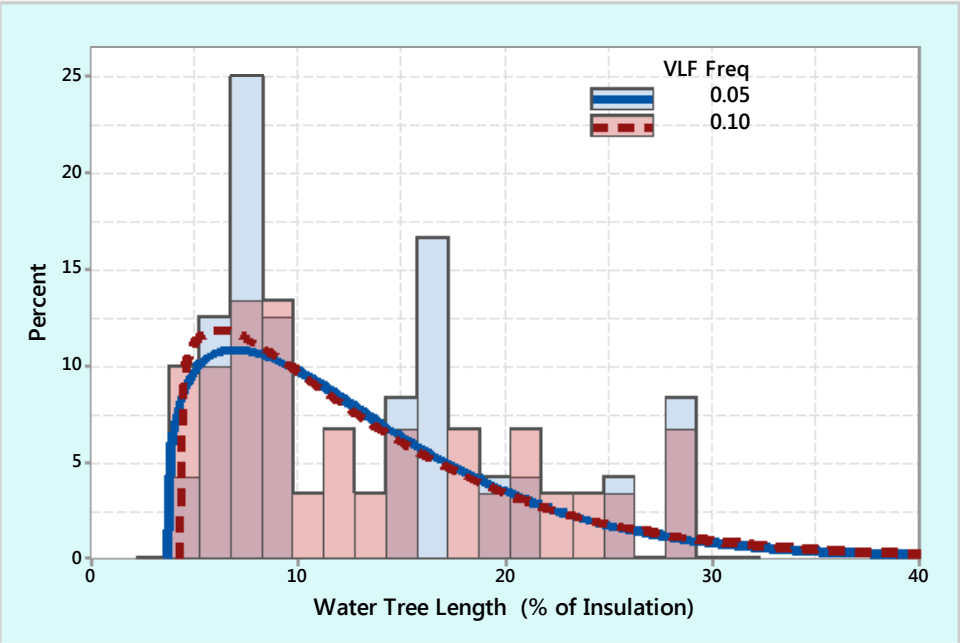

Figure 23: Water Tree Lengths Observed in Ashcraft Tests

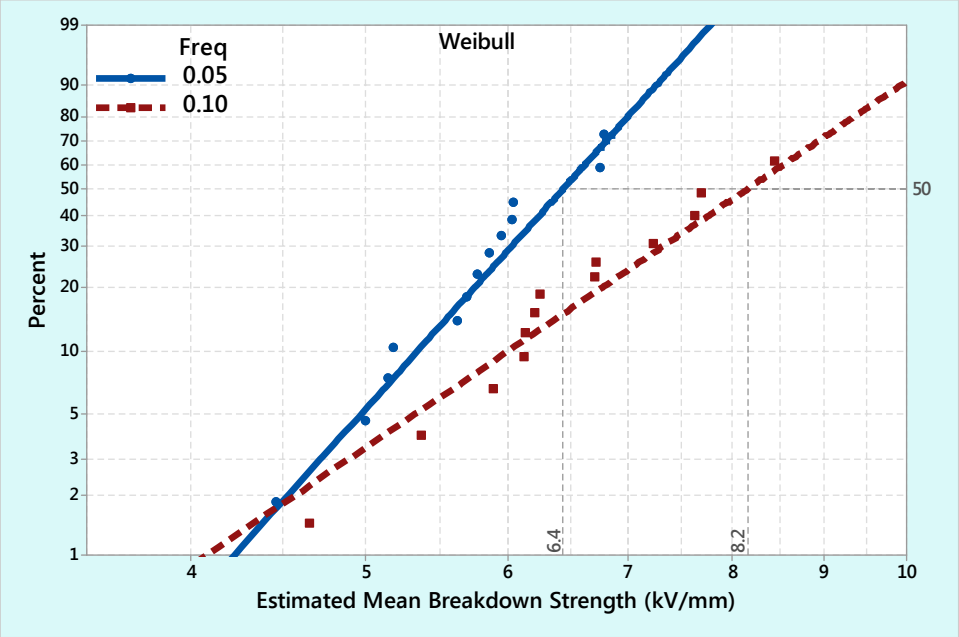

Figure 24: VLF Breakdown Voltages of Aged MV (EPR & PE-Based) Insulations After Accelerated Wet Aging (Separated by VLF Test Frequency)

As Figure 24 shows, the median ac breakdown strength (ACBDS) based on the mean breakdown stress using point to plane distance for this group of insulations was 6.4 kV/mm and 8.2 kV/mm for

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0.05 and 0.1 Hz, respectively. The current IEEE Std. 400.2 test voltages for "maintenance" tests are 3.5 kV/mm and this work suggests that it would require a well treed cable system (i.e. tree growth through > 10% of the insulation) to fail purely as a result of water tree degradation. Figure 25 shows the ranges of breakdown strength as functions of water tree length.

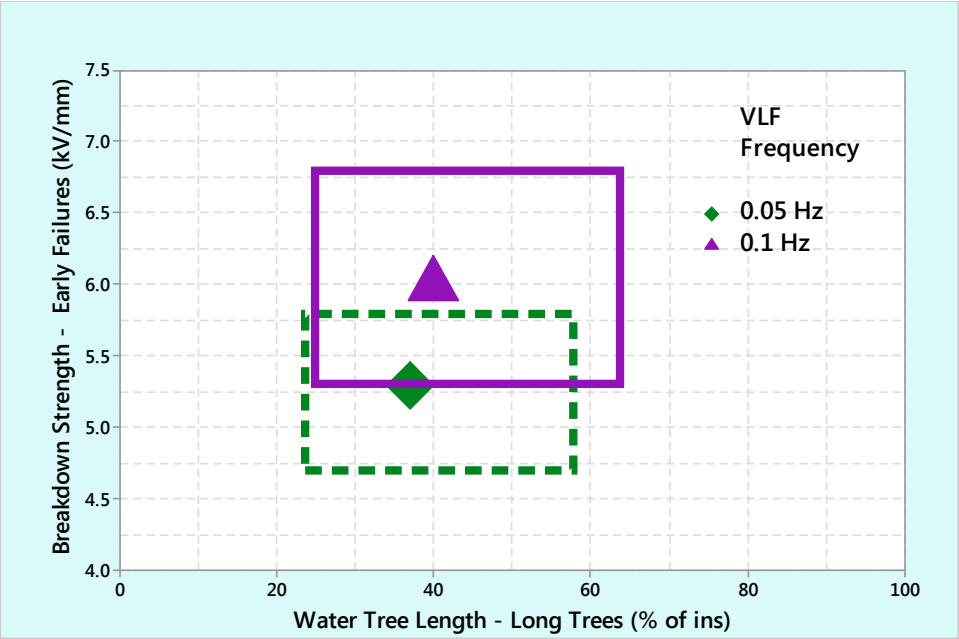

Figure 25: 95% Confidence Intervals of Breakdown Strength and Water Tree

It is also useful to examine the differences in breakdown stress between each of the insulation types: EPR, WTRXLPE, and XLPE. Figure 26 shows Weibull plots of the mean breakdown strengths for each insulation type and VLF frequency. Is it important to note that in all cases, the 0.05 Hz curve is the same or to the left of the 0.1 Hz curve. For reference, the mean stress of 3.53 kV/mm applied during a 15 kV class VLF Maintenance test (as defined in IEEE Std. 400.2) is shown.

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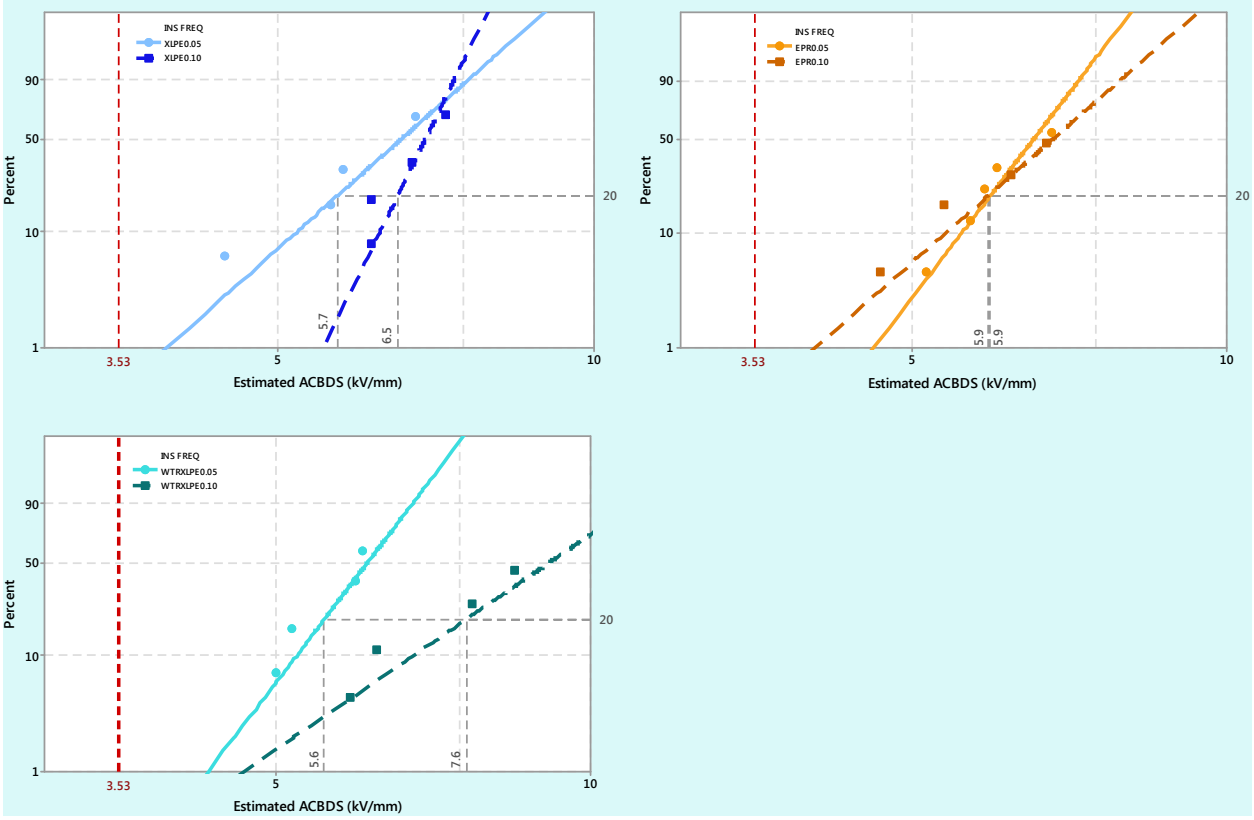

Figure 26: Weibull Mean Breakdown Stresses by Insulation Type

The breakdown data may be further examined using a boxplot as shown in Figure 27. As this figure demonstrates, the distributions for EPR and XLPE at the two frequencies overlap somewhat indicating there is not a significant difference between the different frequencies. On the other hand, there appears to be a much larger difference for the WTRXLPE breakdown data.

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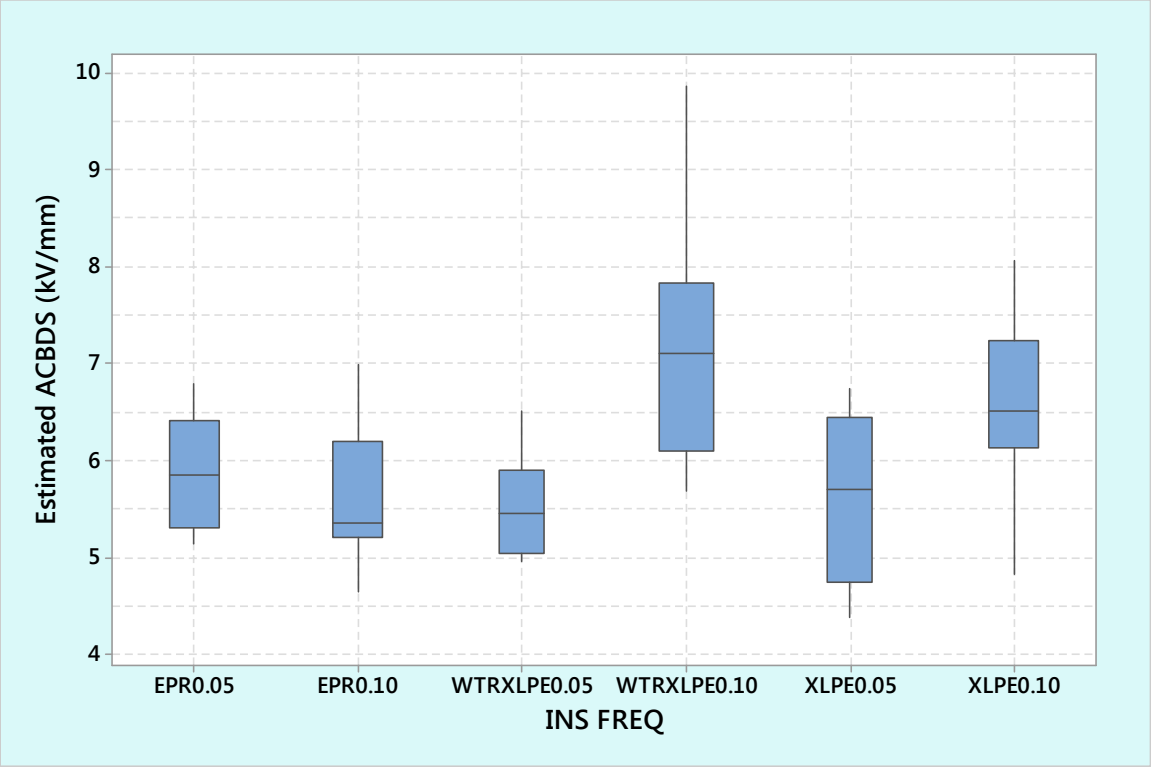

Figure 27: Estimated VLF Breakdown Stress Distributions for Insulation Materials and Frequencies (0.05 & 0.1 Hz)

Figure 24 through Figure 27 imply:

- The 0.05 Hz breakdown strength is likely lower (by 10 – 15%) than the breakdown strength at 0.1 Hz value.
- The notion of higher breakdown strength at lower frequencies (< 0.1 Hz) does not hold and so an increase in the test time is not supported for these lower frequencies.
- Testing at lower frequencies (often required for testing longer lengths) is no less effective and may be marginally more effective than at the more common 0.1Hz frequency.

9.6.8.2 Field Study of VLF Frequency Effects

Analysis was also undertaken on field data derived from tests on aged PILC cables in the field. The data set encompasses Simple VLF Withstand Tests made from 2004 to 2009 using a sinusoidal waveform voltage source. This covers 220 miles of PILC cable systems with a median length of 2 miles per test. Most interesting is that approximately 50% of the tests were undertaken with frequencies below the typical 0.1 Hz. All of the tests were conducted for 30 min at the IEEE Std. 400.2 recommended voltages for the cable systems. The test frequencies and cable system lengths are shown in Figure 28.

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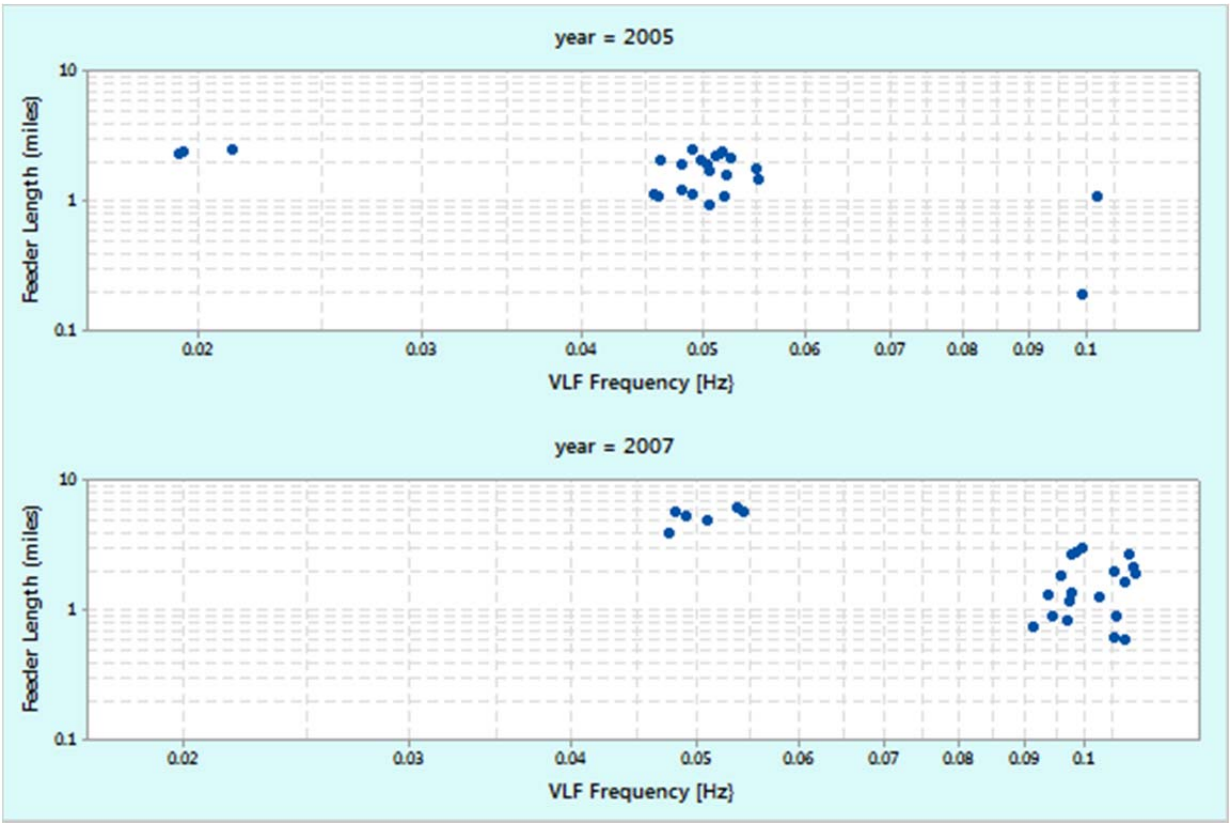

Figure 28: VLF Test Frequencies and Cable System Lengths

The records for these tests are very thorough with the lengths, frequencies, and outcomes all recorded making it possible to conduct a detailed analysis. Inspection of the records enables the ranges of the failure rates to be estimated (Table 9). The failure rates are low overall at 6%. However, the uncertainty in the estimate of the failure rate is large due to the small number of tests and the low number of failures. Although this is not optimal from an analytical point of view, it reflects the reality of trying to derive an understanding of data collected from the field. Nevertheless, using the number of tests as the basis the analysis indicates that there is no difference in failure rate resulting from the application of different test frequencies. The situation is the same if the analysis is extended to include circuit lengths.

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Table 9: VLF Simple Withstand Failure Rates segregated by VLF Frequency based on both Tests Conducted and Lengths Tested			
		VLF Frequency [Hz]	
		0.02 - 0.05	0.1
Length Based	**Length Failing [Miles]**	3	5
	Length Passing [Miles]	87	77
	Failure Rate (95% Confidence Limit)	1% – 9%	2% – 14%
Circuit Based	**Number Failing [Tests]**	3	3
	Number Passing [Tests]	46	45
	Failure Rate (95% Confidence Limit)	1.3% - 18%	1.3% - 18%

Included in the data are the times at which the failures occurred during testing as well as the number circuits that passed. Thus, it was possible to construct a Survival Curve (length adjusted) for the frequency segregated data as shown in Figure 29. This figure shows that, in addition to the ultimate percentages being the same, the survival curves are also the same at 30 min. Furthermore, this analysis again confirms the importance of keeping the Simple VLF Withstand tests as no less than 30 min tests. Reductions to shorter times should only be considered when using a Monitored Withstand test (see Chapter 10).

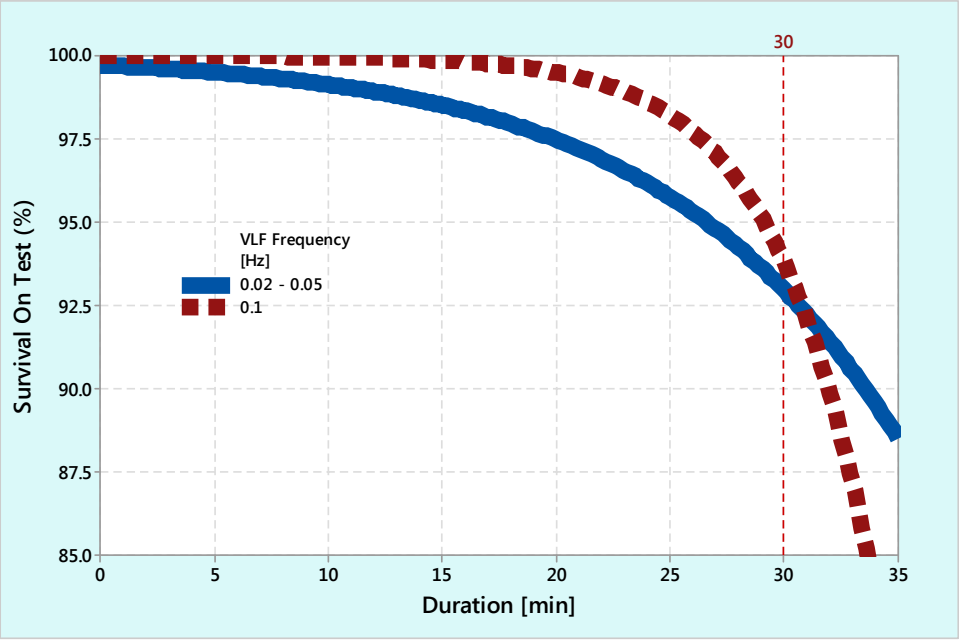

Figure 29: Survival Plot for VLF Tests at 0.1 and 0.02 - 0.05 Hz as Function of Time on Test

This analysis on PILC cable systems shows that data from the field does not display a frequency effect when similar cable systems are tested in the same manner.

The performance of all of these tested cable systems in service after VLF Simple Withstand testing was followed. Up until 2014 there were no dielectric failures recorded for any of the cable systems that were tested at the two voltage frequency groups outlined above. This time period represents considerable service experience: >450 mile-years for 0.02 -0.05 Hz and >200 mile-years for 0.1 Hz. It is likely that any deficiencies in the low frequency tests would have manifested themselves given this experience. Thus, there is no data to suggest that there is any different in the efficacy between the two VLF test frequencies.

9.6.9 VLF Voltage, Time, and Waveform Studies

9.6.9.1 Laboratory Study – Aged Cable

Although simple VLF withstand tests are routinely employed in the field, few if any laboratory studies have studied the effects of the main test variables: test voltage and test duration. To address this issue, the *CDFI* undertook a test program [16] with a number of unique features that included:

- Long cable lengths (140 ft);
- Field aged, triplexed XLPE insulated, unjacketed, concentric neutral cables (circa 1970's) made by one manufacturer and removed from conduit in one service area;
- A wide range of selected test times and voltages; and
- Sequential application of VLF test and 60 Hz aging voltages. Figure 30 shows the general test plan. 60 Hz partial discharge measurements were made at the "field aging voltage" both before and after each elevated withstand test voltage application.

The primary observation (test metric) was the survival of the test cables during the elevated voltage application and the 60 Hz aging periods. Figure 30 schematically illustrates the test program schedule.

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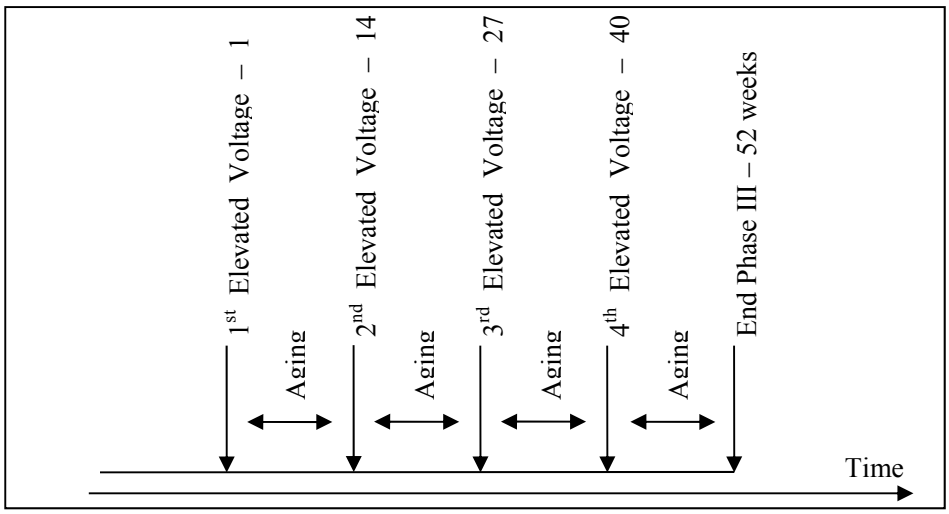

Figure 30: Laboratory Test Schedule for Impact of VLF Withstand Tests

The VLF Simple Withstand test program was originally designed to be conducted in two phases. Phase II of the test program took place six months after Phase I to allow for adjustments in the Phase II test matrix based upon information obtained in Phase I. Phase III was added because most of the test samples survived both earlier phases. Results of these studies appear in Table 10 and Table 11.

Table 10: U_0 Ambient Aging Test Program Results (Phase I and Phase II)
VLF Sinusoidal Withstand Tests

Sample Set	Initial Length [ft]	Elevated Voltage Application (EV)			Test Freq. [Hz]	Test Duration [min, *cycles]*	Failures			
		Multiple of		Actual RMS [kV]			During Aging [#]	Time to Failure During Aging [days]	Total Failures (During Aging and During VLF) [#]	Time on Test [min]
		Rated Voltage	Op Voltage							
1	280	None	None	--	--	--	0	N/A	N/A	N/A
2	280	1.8	2.2	16	0.1	15, 90	0	N/A	0	N/A
3	280	3.0	3.6	26	0.1	120, 720	0	N/A	3	51, 59, 78
4	280	2.1	2.5	18	0.1	60, 360	0	N/A	2	17, 28
5	280	1.8	2.2	16	0.1	120, 720	0	N/A	0	NA
6	280	3.0	3.6	26	60	0.25, 900	0	N/A	2	On Ramp

[1] - Each sample set includes two 140 ft lengths of cable that was divided into 14, 20 ft test samples.

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Table 11: 2 U_0 and 45 °C Aging Test Program Results (Phase III)
VLF Cosine-Rectangular Withstand Tests

Sample Set	Initial Length [ft]	Elevated Voltage Application (EV)			Test Freq. [Hz]	Test Duration [min, *cycles]*	Failures			
		Multiple of		Actual RMS [kV]			During Aging [#]	Time to Failure During Aging [days]	Total Failures (During Aging and During VLF) [#]	Time on Test [min]
		Rated Voltage	Op Voltage							
1	280	None	None	--	--	--	0	N/A	N/A	N/A
2	280	1.8	2.2	16	0.1	15, 90	0	N/A	0	NA
3	220	3.0	3.6	26	0.1	120, 720	0	N/A	10	8, 11, 22, 23, 26, 28, 43, 43, 61, 91
4	240	2.1	2.5	18	0.1	60, 360	0	N/A	2	26, 59
5	280	1.8	2.2	16	0.1	120, 720	0	N/A	0	N/A
6	240	3.0	3.6	26	60	0.25, 900	2	0, 54	0	N/A

A number of useful results are noted from these tables:

- No samples exposed to an elevated VLF withstand test voltage failed during any of the U_0/Ambient or 2 U_0/45 °C "aging" periods (i.e. no failures during aging). All samples exposed to a VLF withstand voltage that failed did so during the VLF withstand voltage application.
- No "failures on test" occurred during elevated voltage applications using a 2.2 U_0 test voltage. This applies to both sinusoidal and cosine-rectangular waveforms. This is the current maximum IEEE Std. 400.2 voltage magnitude recommendation.
- Out of 17 VLF failures on test (all at 2.5 or 3.6 U_0), only two failures occurred within the first 15 min of testing. Three failures occurred after 60 min on test.
- The absence of failures in the aging phase indicates that the VLF test conditions used do not appear to have allowed defects to remain that subsequently degraded "service" performance.
- Some of the test conditions used in the study fell considerably outside the ranges recommended by IEEE Std. 400.2 (i.e. 120 min test time and 3.6 U_0 test voltage). None of these conditions caused incipient defects that led to failure during the "service" aging periods. This was true even when the aging period used twice the normal operating voltage.

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The failures that occurred during the application of the elevated voltage VLF withstand test appear in Figure 31 using a Weibull Analysis for the different VLF test voltages. As a comparison, the time for 10% of tested 20 ft samples to fail appears on each subplot. It is noteworthy that:

- Only two of the 17 failures occurred at times in the range 0 to 15 min.
- Only three of the 17 failures occurred at times in the range 60 to 120 min.
- More failures occurred using the cosine-rectangular waveform and 2 U_0 aging (Table 11) than occurred with the sinusoidal waveform and U_0 aging (Table 10).

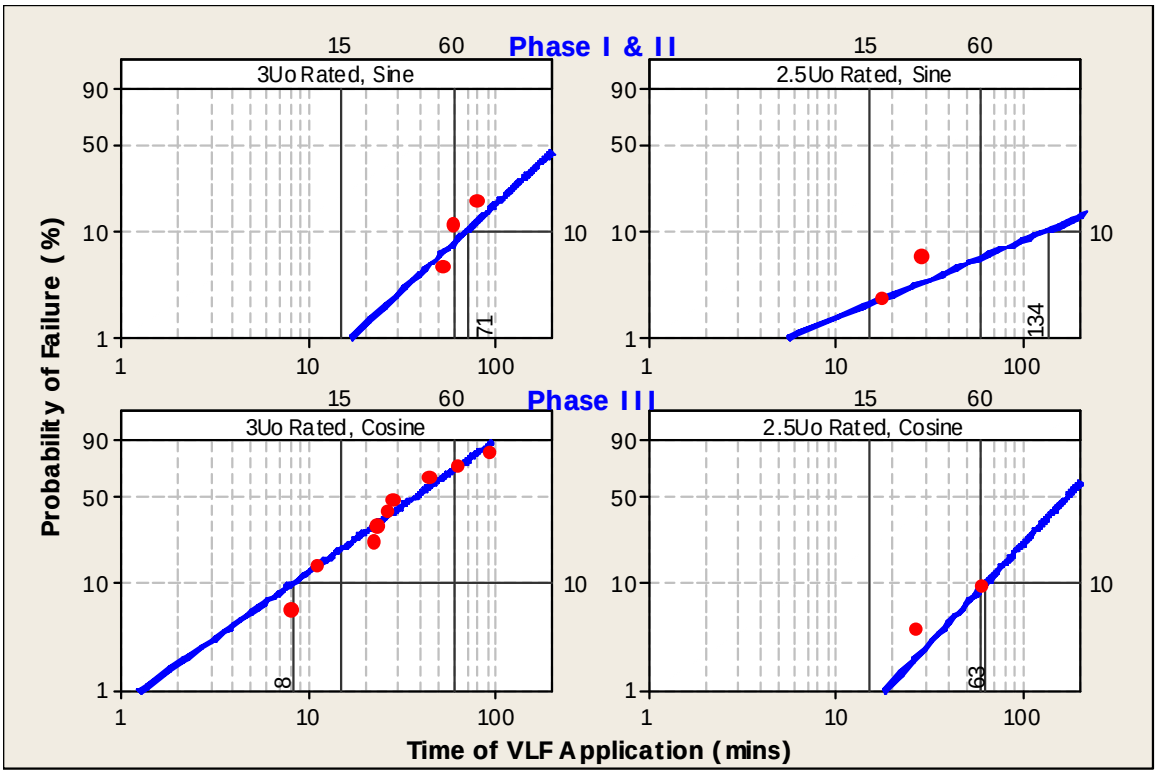

Figure 31: Weibull Analysis of Failures on Test for Phases I, II, and III [16]

Since no failures have occurred on samples tested at 2.2 U_0, the performance of these sample sets are estimated using censoring and assuming a Weibull shape parameter that is less than the cases shown in Figure 31. This corresponds to a standard Bayesian type analysis, commonly used in the aerospace and automobile industries. The resulting lower confidence limit for the Weibull curve appears in Figure 32. This is a limit rather than an estimate. Given the limitations of this analysis technique, all that one can say with any certainty is that the correct result is in the near vicinity to the right side of the line.

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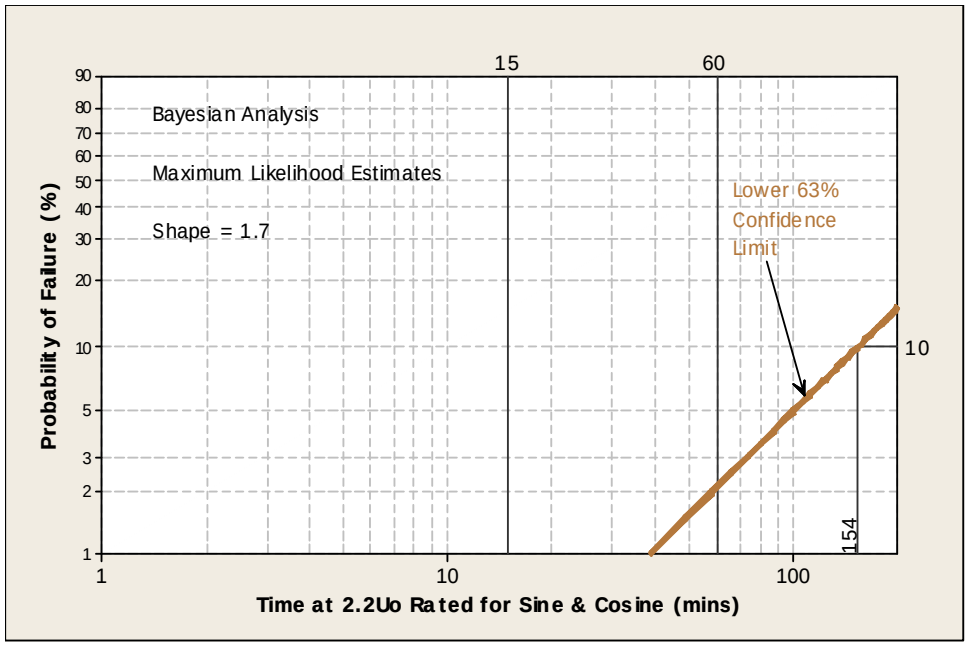

Figure 32: Bayesian Estimate of Weibull Curve for VLF Samples Tested at 2.2 U_0

Using the times on test for the 10% failure rate from Figure 31 and Figure 32, it is possible to plot time on test as a function of the test voltage for all three test phases. Figure 33 shows the results of this analysis. For all test phases, the increasing test voltage clearly translates into a shorter time on test (i.e. higher failure rate). It is important to note that these curves are not comparable numerically to one another since the aging conditions for the tests conducted in Phase III are more aggressive.

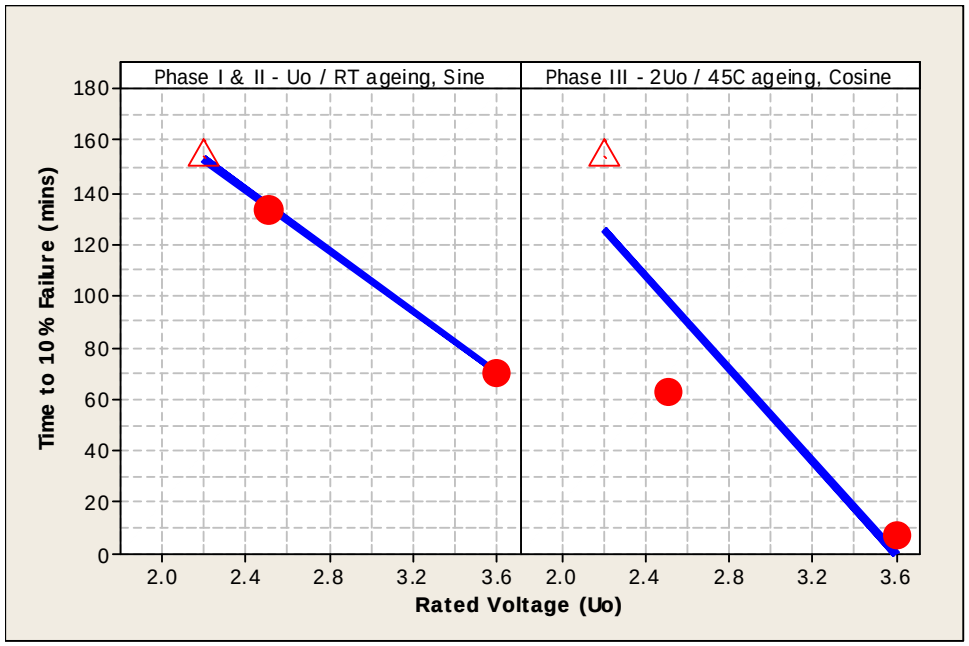

Figure 33: Failures on Test as a Function of Test Voltage [16]
(The Open Upward Arrow Shows that the True Estimate Lies Somewhere Above this Estimate)

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It is apparent from this test program that higher test voltages lead to more failures on test. However, the increased stress does not translate to degraded service performance, at least within the first 13 weeks after testing, which is the duration of the aging periods between elevated voltage applications. Ideally, a utility would like to fail as few segments as possible on test while maintaining a low post-test failure rate in service. This means that the goal is to "grow" to failure only those defects that would ultimately have failed in service. The key is to select the right voltage and test duration to accomplish this goal. Given the available data, these two parameters (time and voltage) are treated as a pair.

9.6.9.2 Field Study – Utility Cable Systems

The study described in the previous section was unique in that for a laboratory study it employed relatively long cable lengths. However, such lengths are still much shorter than those typically seen in the field. Thus, there is a benefit in conducting a parallel analysis on field data. These data also allow for DC withstand and VLF withstand data to be included along with cable system accessory performance data.

Figure 34 shows an analysis of simple DC withstand tests for two types of tests, a regular withstand of 15 min and a "partial" withstand test that employs a shorter time and lower voltage conducted after a repair was completed. Note that this cable system is a hybrid system with PILC, EPR, and XLPE. The data for a number of different feeders within this single utility appear on this graph as different curves (symbol shapes indicate a specific region, open symbols are for proactive 15 min dc hipot tests while the closed symbols are for 5 min return to service dc hipot tests).

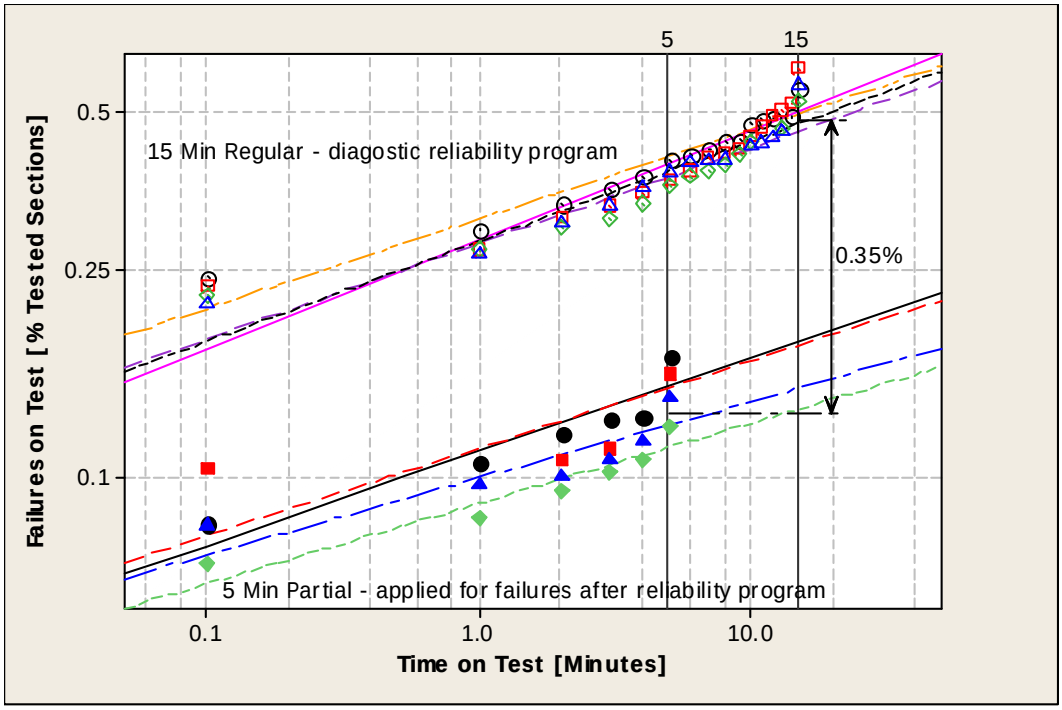

Figure 34: Failures on Test for Proactive (15 min) and Return to Service (5 min) DC Field Tests (Data are Size-Adjusted by the Number of Feeder Sections)

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The analysis shown in Figure 34 provides an estimate of the effectiveness of each diagnostic test program. A number of points emerge in this analysis:

- The average likelihood of failure is much lower (0.12% for 5 min tests vs. 0.47% for the 15 min tests) after the cable section failed in a controlled manner and was then repaired. This implies that a weak location was removed.
- In this case, the analysis does not provide any indication that dc is creating weak spots in the cable system since the curve for the 5 min retest data has the same gradient and lower failure rate than the 15 min test.
- The regular 15 min tests do not cause all of the defects present to fail because the 5 min "partial" test failure rate is not zero.
- Single failure modes are associated with the failures occurring during both tests within the constant voltage "Hold" phase of the test.
- The mechanisms of failure are similar between the before and after repair tests.

Figure 35 shows the results of a service performance audit for one utility system with a hybrid cable system that utilized two different VLF Simple Withstand protocols. Both protocols were performed using sinusoidal VLF but with different voltage-time combinations. The figure shows the distribution of the time to in-service failure after a simple VLF withstand test. The data were segregated for two types of VLF test: 15 min at 2.5 U_0 and 30 min at 1.8 U_0. The analysis uses censoring for the tests that have not resulted in service failures.

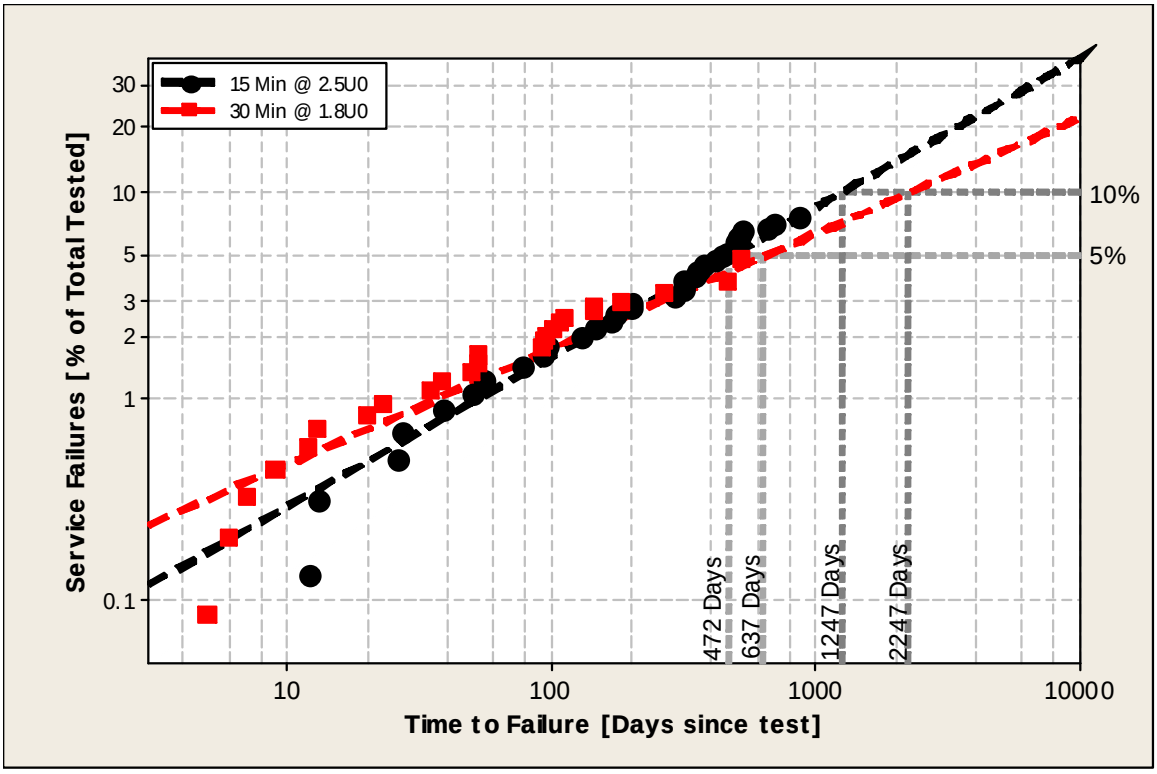

Figure 35: Distribution of Times to In-service Failure after a Simple VLF Withstand Test [14]

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The results in Figure 35 show the percentage of tests that are likely to result in service failures. Inspection shows that for relatively short times, less than 200 days after test, the cable systems tested at the lower voltage (1.8 U_0) longer duration withstand test experienced more early service failures, but the failure rate itself is lower than for those cable systems tested at 2.5 U_0. Furthermore, the failures begin to occur less than 12 days after test in both cases. Therefore, there is no "grace" period in which the tested circuits are failure-free. At 500 days, the 30 min 1.8 U_0 test program results in fewer service failures than the 15 min, 2.5 U_0 test. The magnitude of this difference can conveniently be expressed as the estimated time to reach a specific level of failures as shown in Table 12.

Table 12: Times to Failure for Different VLF Withstand Protocols

Test Conditions	Time to Failure [Days] at Selected Levels of Failure	
	5% of Circuits	10% of Circuits
15 Min @ 2.5 U_0	472	1247
30 Min @ 1.8 U_0	637	2247

The analysis in Figure 35 shows that in the long term the highest reliability results from a test of 1.8 U_0 for 30 min (the current IEEE Std. 400.2 recommended test voltage and duration). However, the approach used for this analysis does not show which test provides the greatest benefits. The benefits are investigated in the analysis shown in Figure 36. The data shown in Figure 35 are segregated for cable sections that completed the VLF tests without failures and sections that failed and were subsequently remediated. Thus, there are four data sets in Figure 36:

a) 15 min test, no failures on test (left);
b) 30 minute test, no failures on test (right);
c) 15 min test, failure on test and repair (left);
d) 30 min test, failure on test and repair (right).

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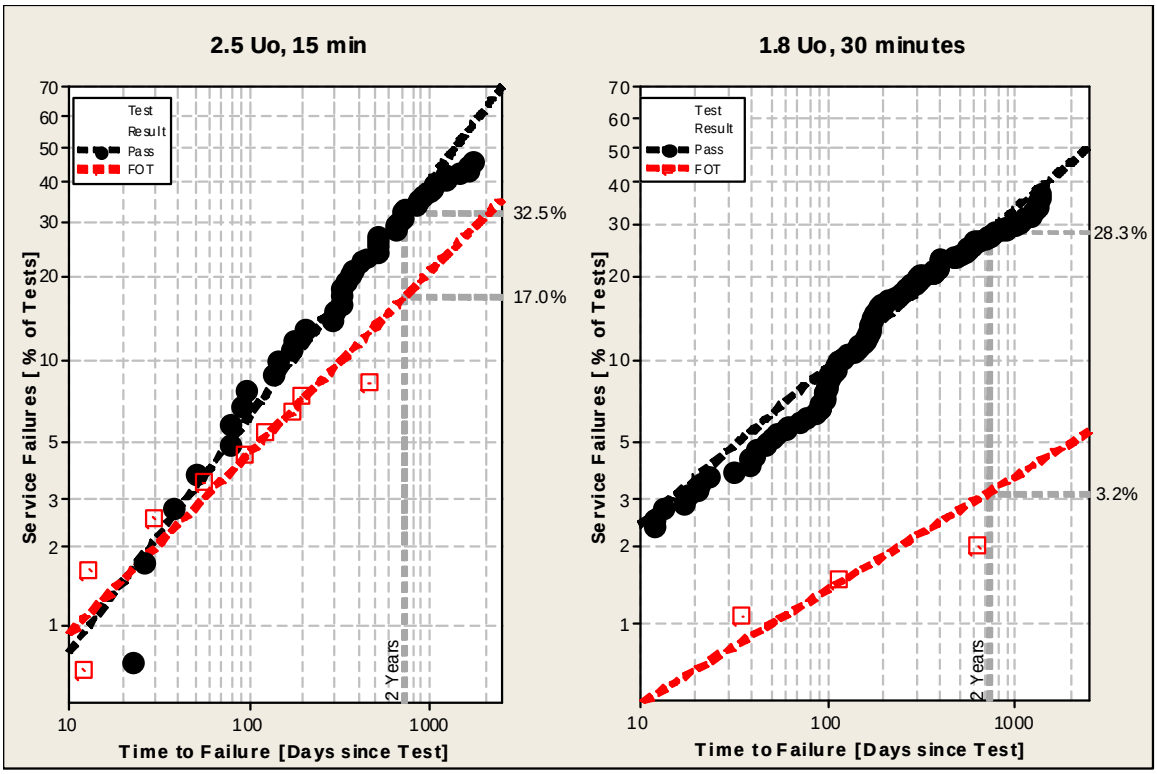

Figure 36: Time to In-Service Failure After Simple VLF Withstand Tests (3-Phase Sections) [14]

The in-service performance of cable segments after 15 and 30 min tests that did not result in failure on test (solid symbols) are quite similar. The research shows that they have similar modes of failure and failure rates. In principle, it suggests that when cable systems are in acceptable health, the applied voltage and test duration have a small influence on the in-service performance (note that this is not the case for performance on test). The data variations are probably due to seasonal influence on utility failure rates. On the other hand, the open symbols in Figure 36 represent the tests that failed and were subsequently remediated. A number of points emerge:

- The likelihood of failure is notably less (3% – 17% vs. 28% – 33% after 2 years) when the cable section fails in a controlled manner and is then repaired.
- The test does not appear to leave weak spots that would later cause failure in service. If this were the case, we would expect the likelihood (percent) of in-service failure to be similar or even higher than where the cable section passes the withstand test.
- The initial tests do not capture all of the defects, as there is a nonzero (albeit lower) failure rate for the cable segments that fail their first withstand test.
- Single and essentially identical failure modes are associated with the subsequent in-service failures occurring for both 15 and 30-minute tests.
- The levels of failure after repair are much lower for the 1.8 U_0, 30 min test than for the 2.5 U_0, 15 min test (3% and 17%, respectively, after 2 years).

Thus, it is possible to conclude that the improved performance of circuits after the 1.8 U_0, 30 min test, as compared to the 2.5 U_0, 15 min, test is the result of improvement of the circuits that failed on test and were then remediated.

Similar analyses were undertaken looking at traditional dc hipot testing and VLF Withstand. The following section discusses a case study in which the performance differences both on test and in service were examined for different testing protocol.

9.6.10 Case Study – Voltage and Time Formulations

Withstand tests using dc voltage were commonly employed on paper insulated cable systems. As extruded insulations became the standard cable system design used by utilities, a great deal of work was invested in explaining the observed negative effects of dc on these newer systems. As things now stand, dc is no longer recommended for general use on aged PE-based cable systems. However, some utility systems have evolved from their originally pure fluid impregnated paper insulated systems to hybrid systems containing both paper and extruded insulations (PE and EPR). As part of the CDFI, an extensive analysis of withstand test data and service performance data was undertaken to quantify the differences in performance between the traditional dc withstand test and VLF (0.1 Hz) withstand tests.

Two different cable systems voltages were analyzed. Each system was tested with two different test protocols (Table 13) as part of a proactive diagnostic program. The VLF protocols were implemented in October 2010. The dc protocols were implemented prior to 2001. It is important to recognize that the voltage-time formulations used in Simple Withstand tests cannot be treated independently. Equally important is the fact that manipulating one parameter has a non-linear effect on the other. As an example, doubling the voltage does not allow the test time to be halved. The time serves one function (growing defects to failure) while the voltage serves another (initiating defects to grow).

Table 13: Withstand Test Protocols

System Voltage [kV]	Source Type	Test Voltage [kV]	Test Duration [min]
13	dc	30	15
	VLF	15	30
27	dc	60	15
	VLF	25	30

As mentioned above, the analysis is split between performance on test and Service Performance resulting from the use of the different withstand protocols. The performance on test is discussed first.

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9.6.10.1 Performance on Test

This section focuses on the Pass/Fail rates of the circuits tested using the withstand protocols in Table 13. Figure 37 provides an overall comparison of the dc protocols (top) with the VLF protocols (bottom) and separates the test results into Pass, Fail (Ramp & Hold) and Unknown. These correspond to the following interpretation:

- Pass – No failure (dielectric puncture) during the withstand test.
- Fail – Failure (dielectric puncture occurs) during the withstand test. Ramp and Hold describe which phase of the test the failure occurred in.
    - Ramp – Beginning of the test when the voltage is raised at a rate of 1 kV/s to the final test voltage. This phase lasts 15 – 60 s depending on the intended test voltage.
    - Hold – Test voltage is held at the target voltage. This phase lasts 15 – 30 min depending on the protocol.
- Unknown – Data do not clearly indicate the result of the test.

As Figure 37 shows, the Pass rates for the two VLF protocols (88% and 82%) are significantly higher than those for the dc protocols (45% and 22%). This figure also demonstrates that many of the failures on test in these cable systems occur during the voltage ramp before the final test voltage is reached.

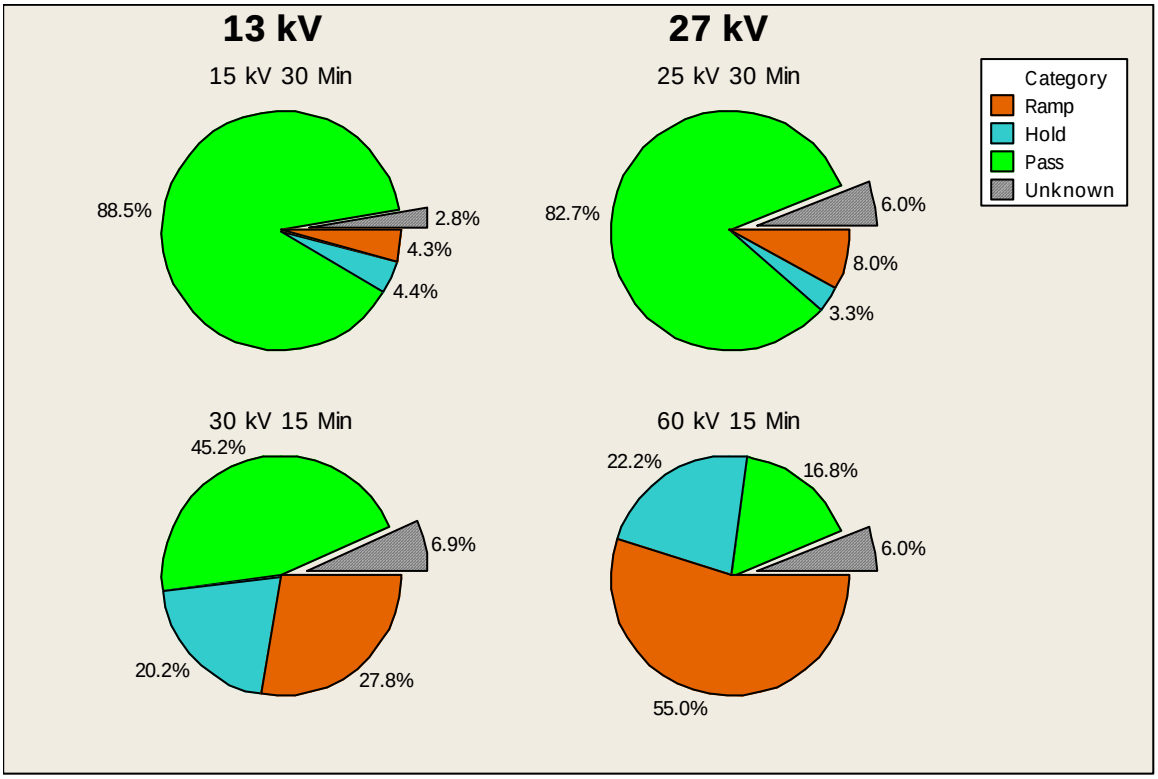

Figure 37: Comparison of VLF (Top) and DC (Bottom) Protocols for 13 kV (left) and 27 kV (Right) Cable Systems

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The above data can be resolved into four different Survivor Curves. Figure 38 shows the historical Survivor Curves with the addition of the dc and VLF curves for the data discussed above.

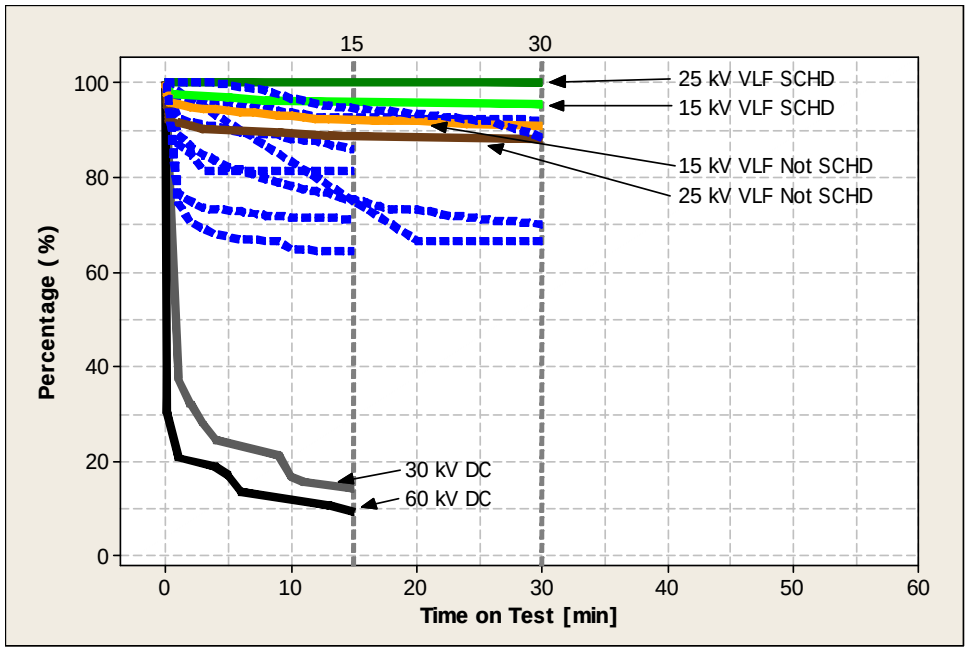

Figure 38: Survivor Curves with New VLF Protocols
(US Utilities are represented by dashed lines)

As Figure 38 illustrates, there are significant differences between the dc protocols at this utility and the VLF protocols currently in use in the North America. The data available for the 13 and 27 kV systems under investigation here allow the VLF tests to be split into "scheduled" (proactive) and "unscheduled" (after work or repair). In both scheduled and unscheduled cases, the survival rates on test are well above 85% while the dc protocols are both less than 20%.

It is worthwhile to examine the cable systems one system at a time as the protocols were implemented at different times.

13 kV System

The Weibull curves for the dc and VLF protocols employed on the 13 kV system are shown in Figure 39. As these curves illustrate, the performance during the Ramp phase is quite different from that of the Hold phase. As the 30 kV 15 min dc curve shows, once the time exceeds 20 sec (20 kV according to the established ramp rate) the slope increases dramatically within the Ramp phase. Once the 30 kV test voltage for these tests is reached (Hold phase), the slope decreases and, in fact, looks remarkably like the slope for the 15 kV 30 min VLF curve. It can be argued that a reduction of test voltage in the dc test would have eliminated the steep portion of the dc Ramp phase curve. This would have the effect of avoiding a large number of failures from the Ramp phase. Unfortunately, this modification could not be verified with field tests.

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Since the Hold phase portions of both curves appear to have similar slopes, it is reasonable to assume that the lower VLF test voltage has not led to a higher failure rate during the Hold phase. Overall, this suggests that the high voltage (> 20 kV) was causing unnecessary failures to occur in the dc protocol.

Overall, the performance on test for the 13 kV system improves significantly from a failure rate of 48% under dc to only 8% with VLF with the voltage modification.

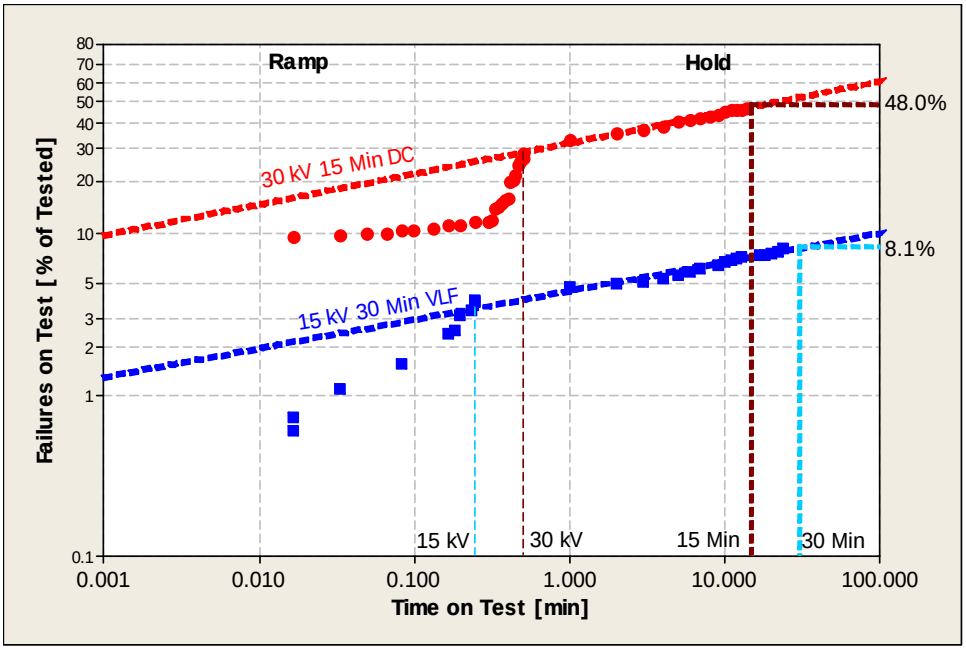

Figure 39: Weibull Analysis of DC (Red) and VLF (Blue) Protocols (not Length-Adjusted)

The performance improvement can be further investigated using Weibull Analysis such that the relative contributions of the different protocol changes can be estimated. Figure 40 shows the performance change caused by each protocol modification. The red text below each bar shows what test parameter was changed from the adjacent bar. The left most bar represents the 30 kV, 15 Min dc protocol while the far right bar represents the final VLF test protocol.

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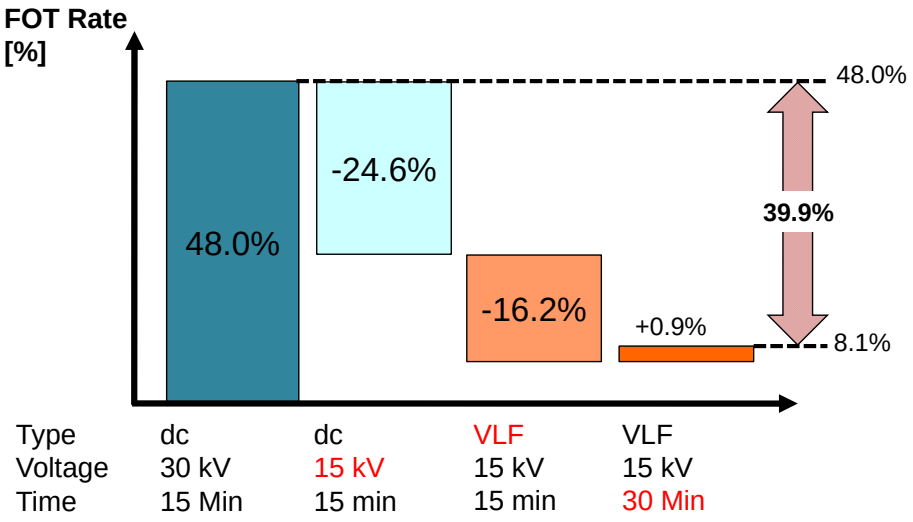

Figure 40: Performance Changes by Protocol Parameter
(Red Indicates the Test Parameter that Changed from Column to Immediate Left)

Figure 40 shows that if the test voltage were reduced from 30 kV to 15 kV, the failures on test would be reduced by over 50% (reduced from 48% to 23.4%). A further reduction of 33% occurs by switching the voltage from dc to VLF (reduces failures on test from 23.4% to 7.2%). The final component, the time increase from 15 to 30 minutes produces a small increase in the failure rate of 0.9% thus yielding the final failure on test rate of 8.1%.

27 kV System

A similar analysis to the one discussed above can be applied to the data from the 27 kV system. The Weibull curves for the dc and VLF protocols are shown in Figure 41. Again, the performance improvement in going from dc to VLF is significant (81.2% for dc and 12.1% for VLF). The key difference appears to be the voltage level.

The primary difference is again in the voltage reduction. Thus, far fewer failures occur during the Ramp phase of the VLF protocol than had occurred with the dc protocol.

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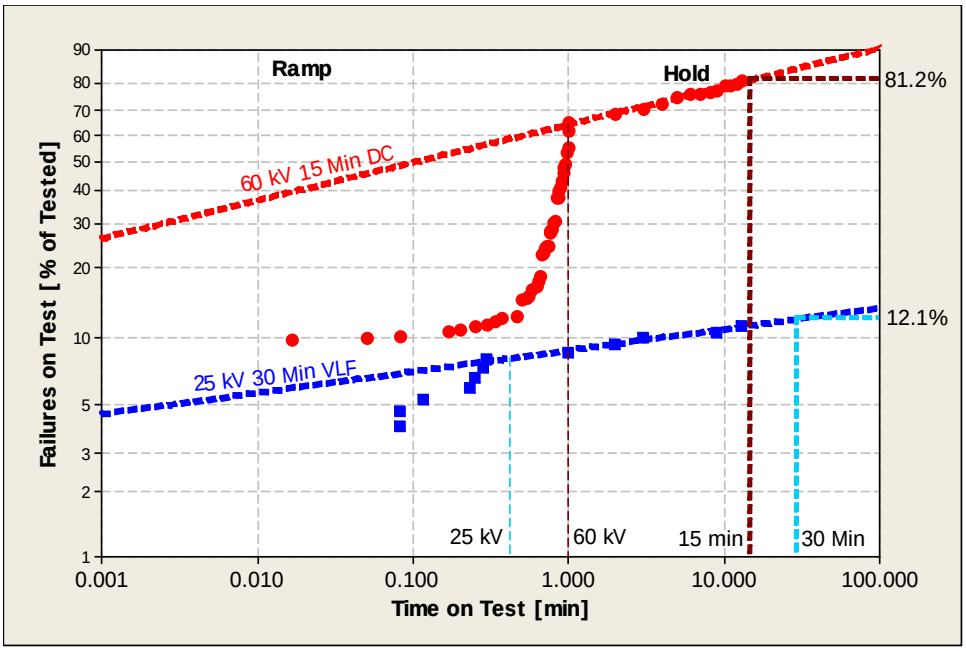

Figure 41: Weibull Analysis of DC (Red) and VLF (Blue) Protocols (not Length-Adjusted)

Estimates of the effects of the different protocol parameters can also be made as shown in Figure 42. The red text below each bar shows what test parameter was changed from the adjacent bar. The left most bar represents the 60 kV, 15 Min dc protocol while the far right bar represents the final VLF test protocol.

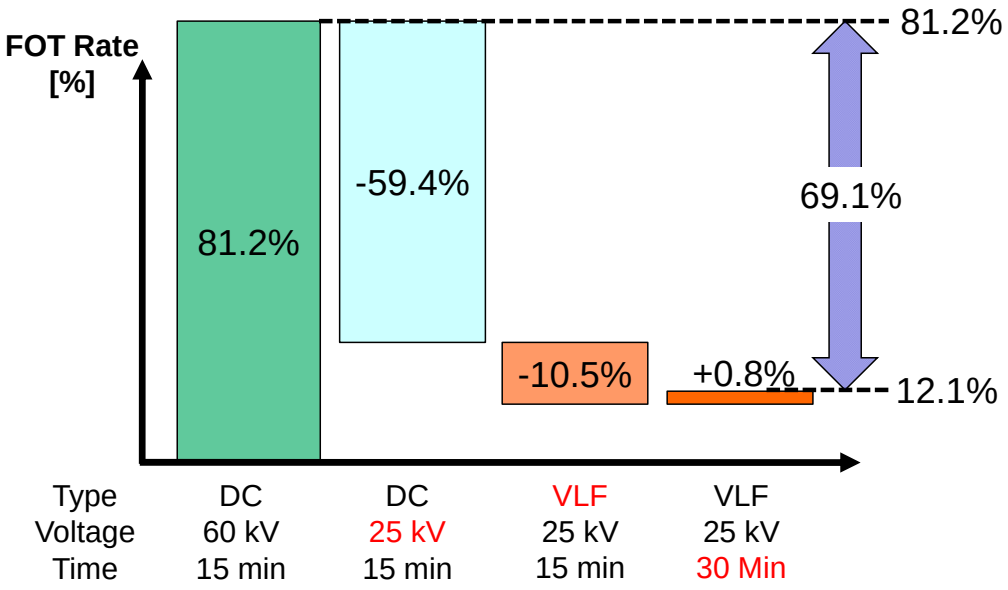

Figure 42: Performance Changes by Protocol Parameter
(Red Indicates the Test Parameter that Changed from Column to Immediate Left)

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Figure 42 shows that the reduced test voltage contributes to a reduction in failures on test of over 72% (failures on test reduced from 81.2% to 21.8%). A further reduction of 13% occurs by switching the voltage from dc to VLF (reduces failures on test from 21.8% to 11.3%). The final component, the time increase from 15 to 30 min again produces a small increase in the failure rate of 0.8% thus yielding the final failure on test rate of 12.1%.

Clearly, both 13 and 27 kV systems experience far fewer failures on test using the VLF protocols than they had using the dc protocols. The question that remains is how this affects the service performance of these systems. The concern being that fewer failures on test could lead to more failures in service. Section 9.6.10.2 examines this question in detail.

9.6.10.2 Service Performance

Service performance data may be analyzed a number of different ways. In this research, the Crow-AMSAA technique was used as this method is very useful for identifying performance changes. In its most basic form, Crow-AMSAA plots cumulative failures versus cumulative time or experience on log-log scales. The idea is to then use linear regression fits to identify regions with similar slopes. The slopes are proportional to the failure rate and so changes in slope correspond to changes in failure rates (i.e. increase in slope = increase in failure rate). Figure 43 illustrates this graphically using artificial data.

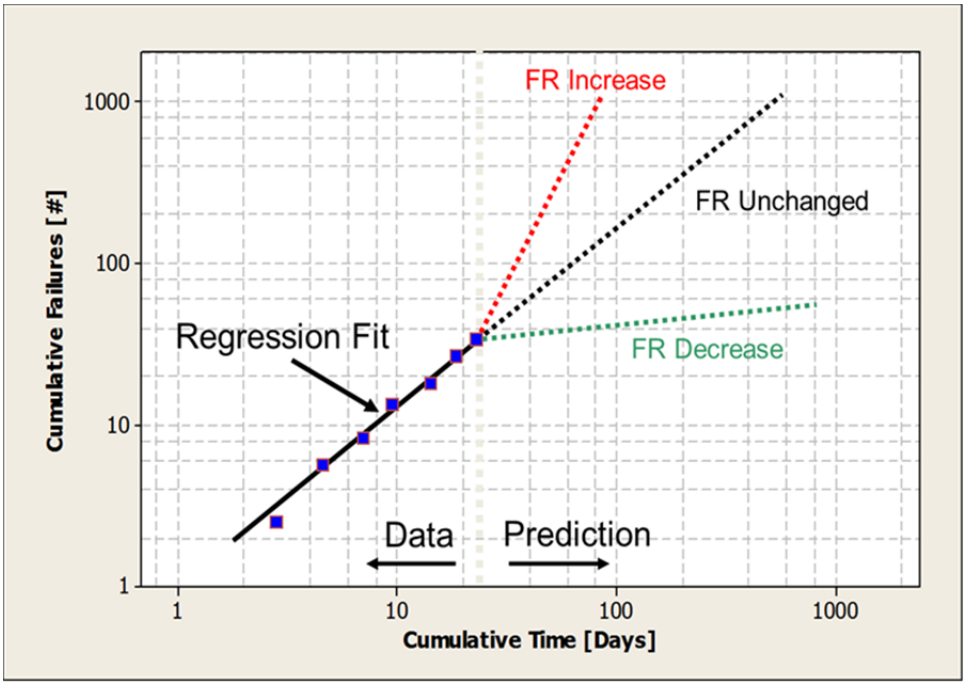

Figure 43: Basic Interpretation of Crow-AMSAA Technique

The linear regression fits may also be used to make predictions about performance in the future assuming the failure rate remains constant.

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The service data for the 13 and 27 kV systems are plotted in Figure 44 in Crow-AMSAA format going back to 2004. Figure 45 shows an expanded view of Figure 44 and focuses on service data after 2007.

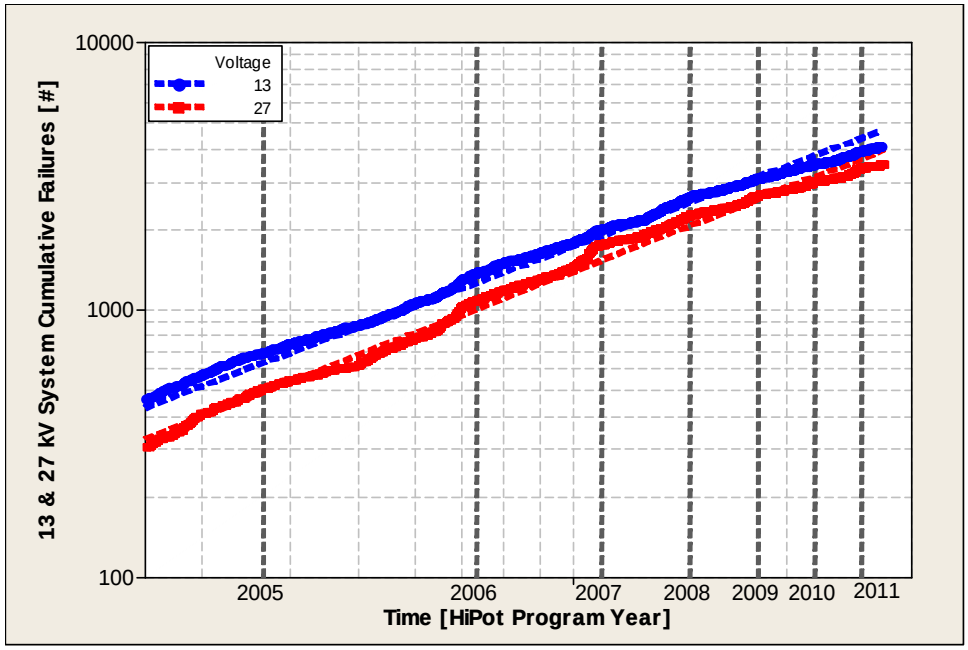

Figure 44: Crow-AMSAA Plot for 13 kV (Blue) and 27 kV (Red) Systems Since 2003

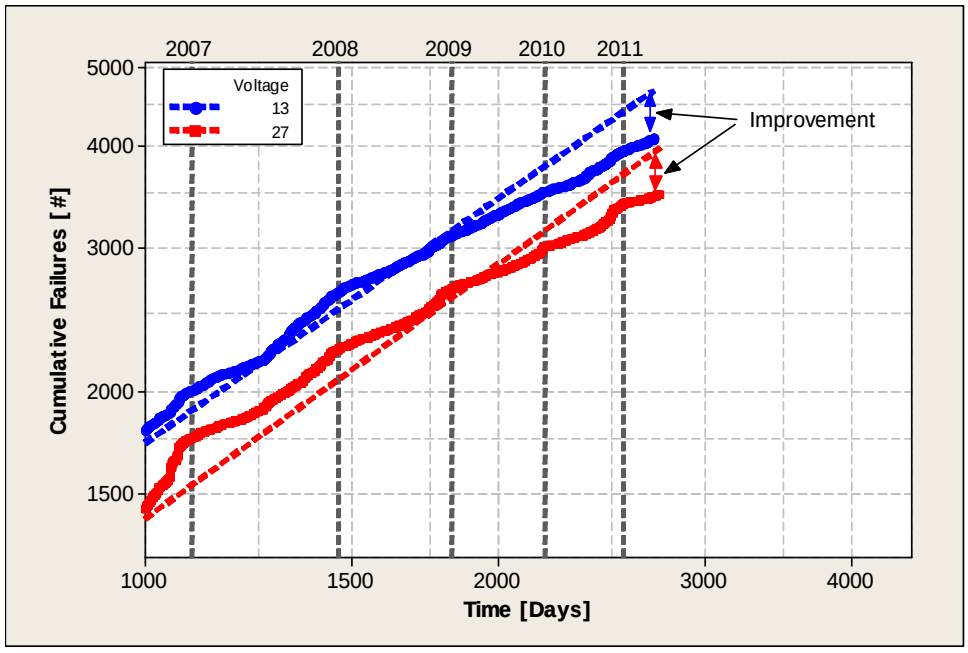

Figure 45: Expanded View of Figure 44 Showing Failure Rate Reductions on Both Systems

Figure 44 shows the failure rate on both systems was relatively constant up to 2008. The ups and downs are indicative of seasonal conditions. This particular utility is a summer utility and so the "ups" correspond to the summer periods. Note that the year designations correspond to September

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of the previous year through August of the named years. In other words, "2006" as shown on these graphs corresponds to September 1, 2005.

Figure 45 shows both the cable system data points as well as the regression fit that uses all the data back to 2004. Clearly, the slope indicated by the data after 2009 is shallower than the slope of the regression line. This indicates the failure rate at present is actually lower than would have been expected based on the past failure data. This reduced failure rate began prior to the implementation of the VLF protocols and was likely due to a number of other system enhancements. The important point to note is that the failure rate has not increased since the switch to VLF. As discussed above, the concern was that the reduction in failures on test would lead to more failures in service. This is clearly not the case. The VLF protocols do not appear to have reduced the reliability of either cable systems.

In order to provide a more quantitative comparison of the system performance, failure estimates for one year were made using the 2009 – 2011 service data. These estimates consider system service performance with the dc protocol (2009 – 2010) and the VLF protocol (2010 – 2011). Figure 46 shows four Crow-AMSAA curves in order to complete the estimates for both types of protocols on each of the cable systems.

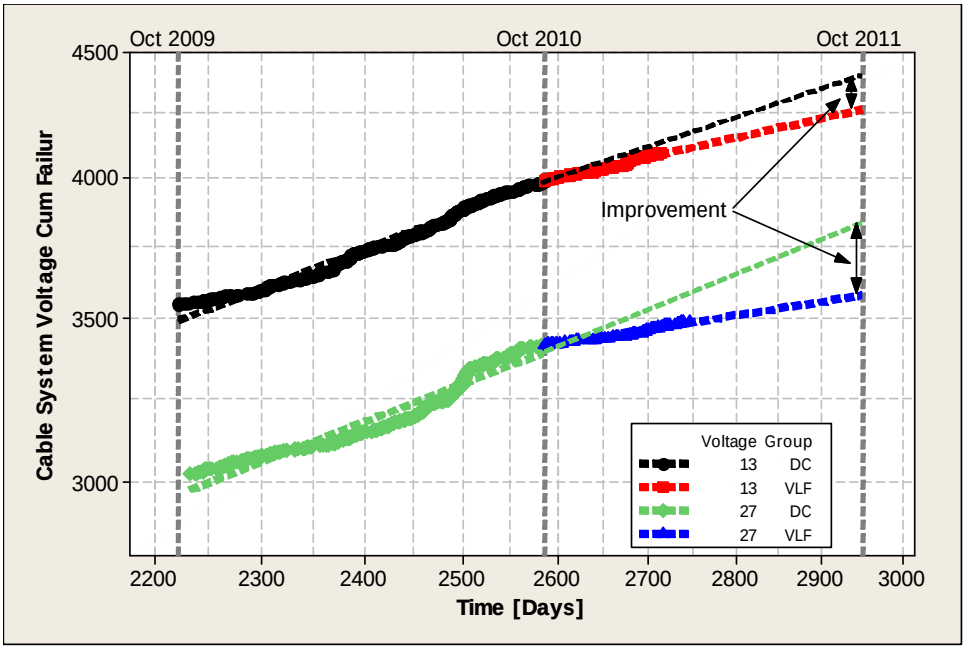

Figure 46: Annual Forward and Reverse Failure Projections (at time of analysis)

A close examination of Figure 46 shows that the slopes after October 2010 are slightly lower than those before 2010. Figure 47 shows the actual performance as monitored by the utility.

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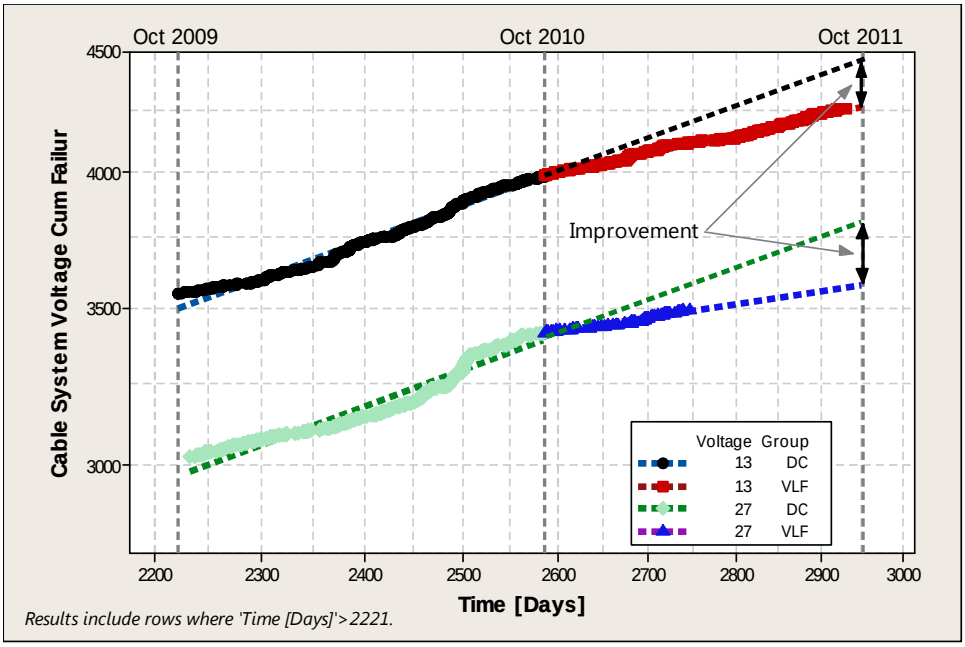

Figure 47: Actual Performance 13 kV System

As Figure 47 shows, the service performance for the 13 kV system continued with the same gradient as shown in Figure 46. Using this information, the differences in the two programs can be estimated. Table 14 shows the resulting estimates and indicates the total failures for 2010-2011 are 40.4% and 60.1% lower than the 2009-2010 levels for the 13 and 27 kV systems, respectively.

Table 14: One Year Failure Performance Estimates

System Voltage [kV]	Type	Total Service Failures (1 Year Prediction) [#]
13	dc	492
	VLF	276
27	dc	427
	VLF	167[1]

[1] – Projections based on available data

This information is useful for comparison purposes; however another way to utilize these data is in a techno-economic capacity. This is discussed in the following section.

9.6.10.3 Techno-Economic Analysis

Avoiding failures both on test and in service carries a certain technical benefit for the utility. On the other hand, it is useful to try and quantifying an economic benefit for the utility. One way of

approaching this is to examine the time the utility was spend implementing and repairing the system. After all, one of the issues that is often raised is the fact that 30 min is twice as long as 15 min.

Within this utility, a repair is reported to require on average 53 h to complete. In addition, a Simple Withstand test is also performed after any repair either on test or in service.

As a result of the differences both on test and in service, the VLF Simple Withstand program yields a net savings of over 55,000 crew hours over the course of the one year program. This includes 140 avoided failures on test and 801 service failures.

Table 15: Summary of Techno-Economic Case for dc and VLF Simple Withstand Programs

Component	DC 30 kV for 15 Min	VLF 15 kV for 30 Min
Set Up Time [1 hour / test]	**600 h**	**600 h**
Test Time	**150 hrs**	**300 h**
Time to Repair FOT [est 53 hours / failure]	**15,264 h** (288 FOT's)	**2,544 h** (48 FOT's)
Modified HiPot (After Repair)	**24 h** (5 Min HiPot)	**24 h** (30 Min HiPot)
Out of Service Time	**16,038 h**	**3,468 h**
Service Failures	**111,459 h** (2,103 OA's)	**69,006 h** (1,302 OA's)
Overall Program Difference	**55,023 h** (140 Avoided FOT's & 801 Avoided OA's)	

9.6.11 Diagnostic Aspects of Simple Withstand Tests

Withstand tests are sometimes described as non-diagnostic as a metric is not provided by the test. However, utilities use them for diagnosis. An important issue is if the Pass / Not Pass result is a valid metric. These results are valid for diagnostics if engineers collate and review them, a requirement common for all techniques. Figure 48 through Figure 50 show an example of withstand data being used diagnostically.

The overall Failure on Test (FOT) rates were approximately 1% and 4.5% for the Early and Hold phases, respectively (Figure 20 and Figure 10). Figure 48 shows the situation for a combination of four regions from within a single utility system (the early failures are not shown in Figure 48 but are accounted for using censoring). The combined Failure on Test rate for these four areas is different

from those mentioned above. Figure 50 shows that higher FOT rates were experienced in three areas, Areas 2, 3, and 4, and that Area 1 had significantly better performance. From such analysis a utility could proactively prioritize test programs by focusing on those areas that experienced poorer performance on test.

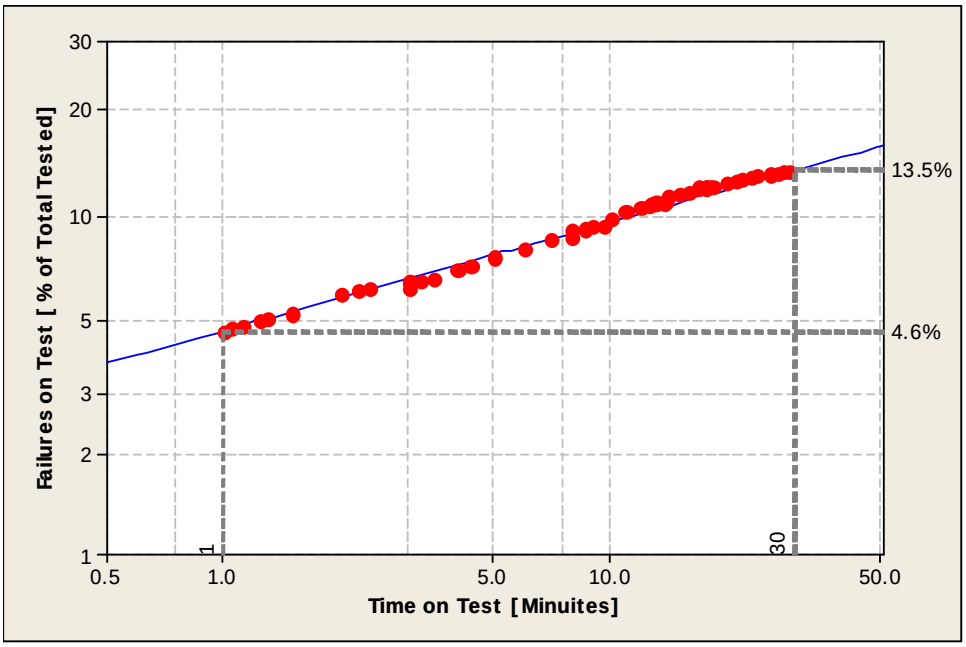

Figure 48: Failures on Test for Four Regions (Combined) within a Utility System (Data Adjusted for a Length of 1,000 feet)

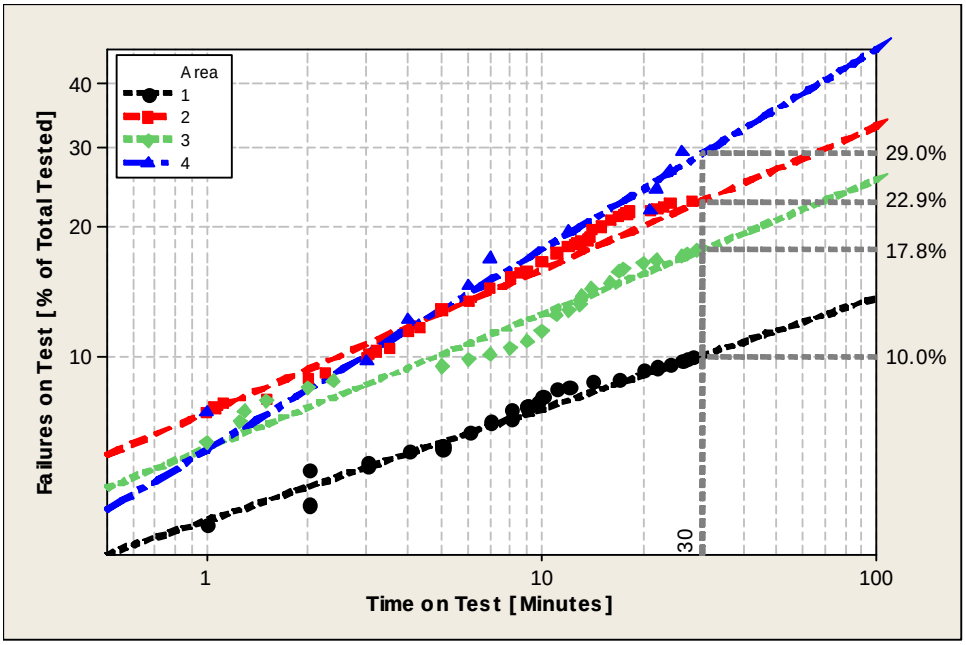

Figure 49: Failures on Test for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet)

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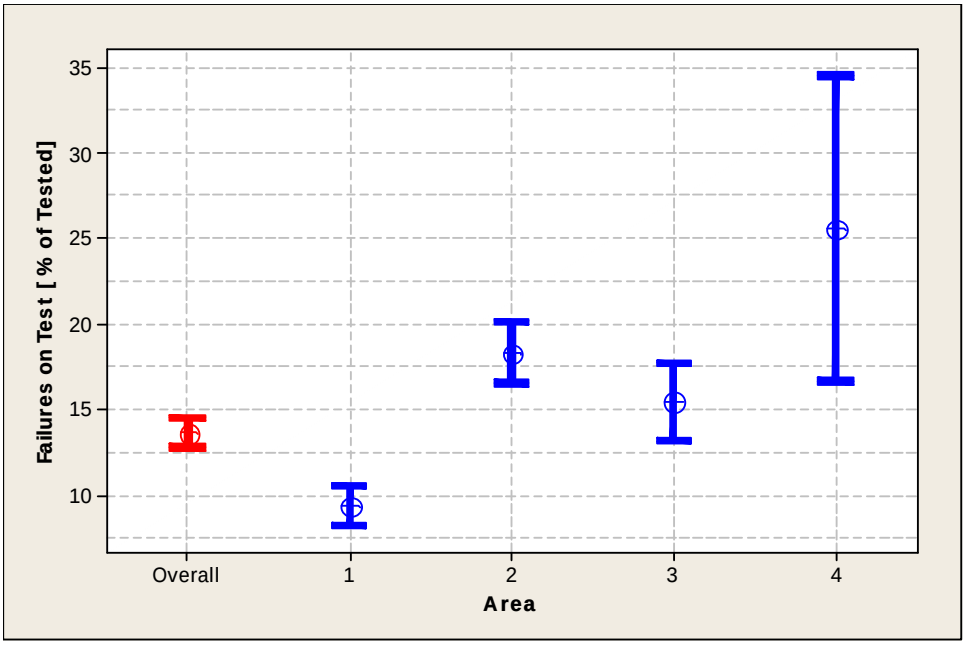

Figure 50: FOT Estimate at 30 minutes for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet, 95% Confidence Limits Shown)

Simple Withstand is a widely deployed diagnostic technique that is applicable to all cable systems. Unlike all other diagnostic techniques, Simple Withstand can be applied to hybrid systems regardless of the combination of insulation materials and accessories.

9.7 Outstanding Issues

There only outstanding issue remaining for Simple Withstand is the comparison of VLF frequencies to performance under 60 Hz ac. A similar experiment to that discussed in Section 9.6.8.1 could be conducted for VLF and 60 Hz.

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9.9 Relevant Standards

- ICEA S-94-649 – 2004: *Standard for Concentric Neutral Cables Rated 5 Through 46 kV*
- ICEA S-97-682 – 2007: *Standards for Utility Shielded Power Cables Rated 5 Through 46 kV*
- IEEE Std. 48 – 2009: *IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV*
- IEEE Std. 386 – 2006: *IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V*
- IEEE Std. 400 – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*
- IEEE Std. 400.1 – 2007: *IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage*
- IEEE Std. 400.2 – 2013: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)*
- IEEE Std. 404 – 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*

CHAPTER 10

Monitored Withstand Techniques

Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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10.0 MONITORED WITHSTAND TECHNIQUES

10.1 Test Scope

Simple Withstand tests are proof tests that apply voltage above the normal operating voltage to stress the insulation of a cable system in a prescribed manner for a set period of time (time-voltage recipe) [1-15]. This is similar to tests applied to new accessories or cables in the factory where a withstand voltage is applied to provide the purchaser with assurance that the component can withstand a defined voltage. An alternative and more sophisticated implementation of the simple withstand approach requires that, in addition to surviving an applied voltage stress, a system property is also measured during the test. The property measured should be selected to correlate with the condition of the system. This implementation of a withstand test, called Monitored Withstand test, is discussed in this chapter and is more sophisticated than a Simple Withstand.

In traditional Simple Withstand tests (VLF, dc, or resonant ac), a significant drawback is the absence of a straightforward way to estimate the "Pass" margin. Once a test (e.g. 30 min at 2 U_0, where U_0 is the nominal system operation voltage) is completed, it is impossible to differentiate among those cable systems that survived the test without failure. As a result, this test cannot distinguish cable system segments that pass the test, but would survive only minutes or days after the test from those that could last months or years after the test.

Thus, it is useful to employ the concept of a Monitored Withstand test whereby a dielectric property or discharge characteristic is monitored to provide additional data. There are four ways these data are useful in making decisions during the test:

1. Provides an estimate of the "Pass" margin for cable systems that have not failed during the hold phase of the Monitored Withstand test.
2. Enables a utility to stop a test after a short time if the monitored property indicates the cable system is near imminent failure on test thereby allowing the required remediation work to take place at a convenient (lowest cost) time.
3. Enables a utility to stop a test early (shorten the duration of the test) if the monitored property provides definitive evidence of good performance, thereby increasing the number of tests that could be completed and improving the overall efficiency of field testing.
4. Enables a utility to extend a test if the monitored property provides indications that the "Pass" margin was questionable, thereby focusing test resources on sections that present the most concern.

In fact, the design of the decision making process can be accomplished by advanced statistical analysis of the data accumulated during *CDFI Phases I* and *II*. This allows for the creation of defined and well-organized monitored withstand testing procedures that can be deployed in real time in the field.

10.2 How it Works

In a Simple Withstand test, the applied voltage is quickly raised to a prescribed level, usually 1.5 to 2.5 U_0 for a set amount of time. The purpose is to cause weak points in the cable system to fail during the elevated voltage application when the system is not supplying customers. This avoids a service failure and the associated reliability penalties as well as potential upstream fault current damage. Testing is usually scheduled by the utility so that it occurs at a time when the impact of a failure (if it occurs) is low and repairs can be made quickly and cost effectively.

In contrast, when performing a Monitored Withstand test, a dielectric or discharge property is monitored during the withstand period or "Hold" phase of the test (see Figure 1). The data and its interpretation should be accessible in real time during the test so that the decisions outlined above can be made.

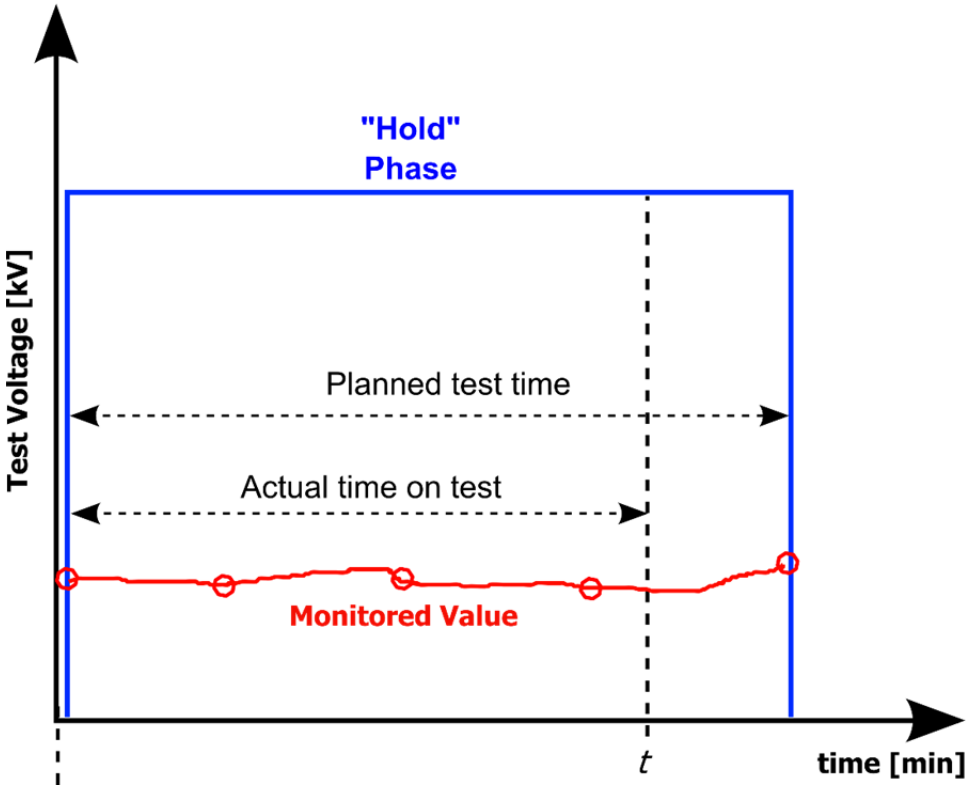

Figure 1: Schematic Representation of a Monitored Withstand Test

The dielectric or discharge monitored property are similar to those described in earlier chapters. However, their implementation and interpretation differs due to the requirement of a fixed voltage and a relatively long period of voltage application for the "Hold" phase of the test. Within these constraints, Leakage Current, Partial Discharge (magnitude and repetition rate) and Tan δ (stability, magnitude, and rate of change over time (speed)) [2] might readily be used as monitors.

10.3 How it is Applied

This technique is conducted offline with the system disconnected from the network. The applied voltage may be dc (not recommended for most applications), VLF (sinusoidal or cosine-rectangular), or 10 - 300 Hz ac using a resonant power supply. Typical testing voltages range from 1.5 - 4.0 U_0 [1-15] though the precise levels depend upon the voltage source, (VLF levels tend to be lower than dc). If a failure occurs during the test according to either of the two criteria (dielectric puncture or unacceptable monitored property) then the cable system is remediated or repaired and the circuit is retested for the full test time. The inadvisability of using damped ac voltages for withstand purposes is discussed later in Section 10.6.2.

In Figure 1, the schematic represents a monitored withstand test. The critical part of the test is the measurement and interpretation during the "Hold" phase. However, it is clear that the simple scheme in Figure 1 could be modified to allow an evaluation before the start of the withstand test as shown schematically in Figure 2. This approach is valuable in that it enables the field engineers to assess the condition of the cable system before embarking on the monitored withstand test.

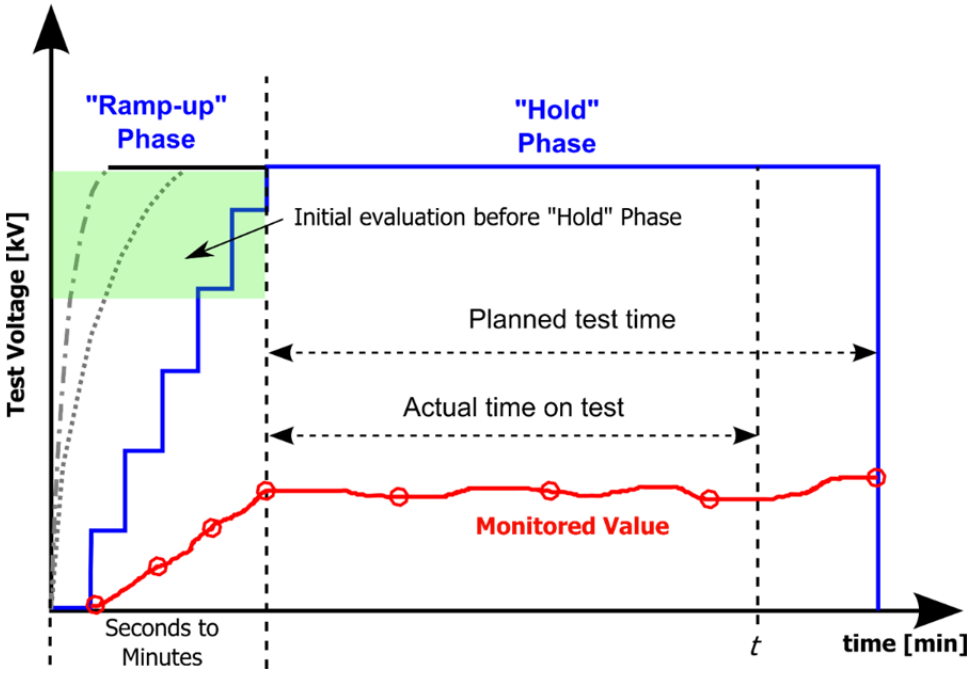

Figure 2: Schematic of a Monitored Withstand Test with Optional Diagnostic Measurement (Monitor)

Like other diagnostic techniques, Simple and Monitored Withstand tests require the application of voltages in excess of the service voltage for extended time periods (up to 60 min). However, unlike many other diagnostic test techniques, a failure on test (FOT) is an acceptable (almost desirable) outcome. The expectation is that the proof stress will cause the weak components to fail without significantly shortening the life of the vast majority of strong components.

The risk of excessive FOTs through unintended degradation of the stronger elements is reduced by using voltages closer to the service level and limiting the duration of the test. Either the number of

cycles or time may be used to measure the length of application. However, the key is to avoid stopping the test *before* an electrical tree within the cable system has grown to the point of failure. Otherwise, the application of the elevated voltage could leave behind electrical trees that might cause a cable system to fail soon after service is restored. The choice of the appropriate property to monitor can help mitigate this risk. Appropriate voltage levels and times for the different energizing voltage sources appear in the Simple Withstand chapter (Chapter 9) of this document.

The advantages and disadvantages of Monitored Withstand testing are summarized in Table 1 and Table 2. These tables focus on the issues associated with the long-term (15 min or greater) monitoring of a given property or characteristic.

When consulting these tabulated summaries, it is assumed that the reader has a working knowledge of each of the diagnostic techniques discussed in earlier chapters. In some cases, the available data are sparse and the resulting summaries include more interpretation by the authors than in previously described diagnostic techniques.

Table 1: Advantages and Disadvantages of Monitored Withstand for All Possible Different Voltage Sources and Monitored Properties			
Voltage Source	**Monitored Value**	**Advantages**	**Disadvantages**
Offline Resonant ac (10 – 300 Hz)	Partial Discharge	• The large number of cycles over the duration of the test increases the probability that a void-type defect will discharge, which increases the likelihood for detection • PD stability can be observed • There is guidance in industry standards on how to interpret results from short and long term PD tests on new HV systems	• There is little or no guidance in industry standards on how to interpret results from long term PD tests on aged systems
	Tan δ	• Not enough information to identify advantages	• There is little or no guidance in industry standards on how to interpret results from a long-term Tan δ test
AC Offline Very Low Frequency (0.1 Hz) Cosine Rectangular	Partial Discharge	Technology recently implemented – no field experience	
	Tan δ	Underlying technical assumptions not yet validated – limited field experience	
AC Offline Very Low Frequency (0.01 – 1 Hz) Sinusoidal	Partial Discharge	• Signals acquired at a slow enough rate that a qualitative interpretation may be made in real time	• There is little or no guidance in industry standards
	Tan δ	• Interpretation possible during the test, allowing for real time adjustments to the test procedure. • Guidance on interpretation available (IEEE and *CDFI* documentation)	• No unique disadvantages for withstand monitoring mode

Table 2: Overall Advantages and Disadvantages of Monitored Withstand Techniques	
Advantages	• Provides additional information over the simple "Pass" or "Not Pass" obtained from a Simple Withstand test. • Allows for the development of trending information during a single test. • Diagnostic stability can be established during the test. • Provides real time feedback so that the test may be adapted (test time increased or decreased) to fit utility objectives. • Cable system population under test can be selected to undergo different test phases (population amendment and risk management). • Many tests can be curtailed after 15 min and so Monitored Withstand requires considerably less total test time when compared to a Simple Withstand approach (40% to 60 % efficiency improvement). • Allows for the integration of outcomes from Simple Withstand test with those from other diagnostic techniques (two diagnostics and thus higher information content). • Less number of FOTs and thus less number of thumper tests for failure location, which results in reduced work and emergency cost.
Open Issues	• Can potentially provide means for estimating a "Pass" margin for cable systems that survive the "Hold" phase of the test. • Selection of the best monitored property (i.e. PD, Tan δ, or Leakage). • Implementation where only level-based assessments (Good/Bad) are available is unclear and may not be useful. • Voltage exposure (impact of voltage/time on cable system) caused by DAC voltages has not been established.
Disadvantages	• Adds complexity (interpretation, set up, and data recording) to Simple Withstand test. • Highly skilled and fast decision-making personnel required.

A critical issue for Monitored Withstand testing, like Simple Withstand, is the application time at the chosen voltage for the test. If the test time is too short then cable systems with localized defects that could cause service failures may be returned to service before the defect has the chance to fail during the test. Equally, a shortened test may not provide enough opportunity for the monitored feature to provide useful information. As an example, an upward trend in a monitored property with time usually indicates a problem. However, if the test time, and thus, the time to observe the trend is too short then it is more difficult to unambiguously identify the trend and make a diagnosis.

The work described in the Simple Withstand chapter (Chapter 9) suggests that 30 minutes should be the usual target test time. This is in accordance with the test time suggested by IEEE Std. 400.2 – 2013. This time may be increased to 60 minutes if the monitored data indicate instability or an upward trend that indicates unsatisfactory performance. The test time may also be reduced to 15 minutes if experience shows that the monitored data definitively confirm good cable system performance. Criteria for test time amendment appears later in this chapter.

10.4 Success Criteria

Monitored Withstand results fall into two classes:

- "Pass" – "No Action Required" and
- "Not Pass" – "Action Required" that may include "Further Study".

Thus, there are two ways a cable system might "Not Pass" a Monitored Withstand test:

1. Dielectric puncture and
2. No dielectric puncture AND non-compliant information from the monitored property as evidenced by:
   - rapid increase in monitored property at any time during the test
   - steady upward trend at a moderate level
   - instability (widely varying data)
   - high magnitude or
   - non-acceptable low "Pass" margin

On the other hand, there is only one way in which a cable system may "Pass" a Monitored Withstand test: no dielectric puncture and monitored data that falls within the pass criteria:

- stable and narrowly varying data and
- low magnitude, and acceptable high "Pass" margin

Figure 3 shows examples of the behavior in a monitored property over the course of a monitored withstand test. With the exception of the "Stable" example, all of the examples in Figure 3 may lead to a "Not Pass" result.

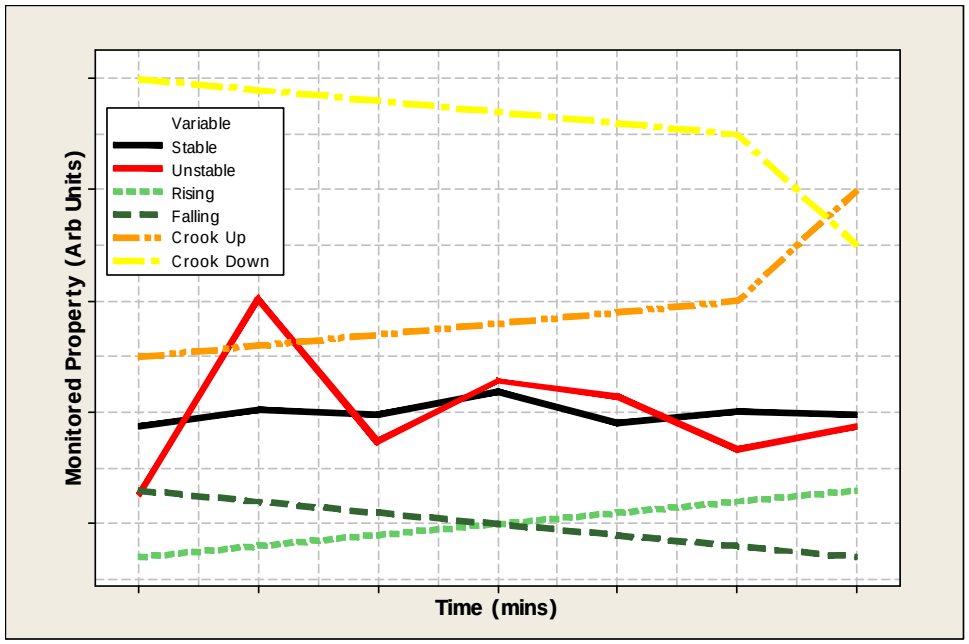

Figure 3: Possible Characteristic Shapes of Monitored Responses

10.5 Estimated Accuracy

If data is available, it is possible to estimate accuracies for Monitored Withstand based on the performance of the component diagnostic techniques (i.e. Simple Withstand plus PD, Tan δ, or Leakage). However, during the *CDFI* no data was available to assess the accuracy of Monitored Withstand testing.

10.6 *CDFI* Perspective

At the start of the *CDFI Phase I*, Monitored Withstand was not seen as a specific diagnostic technique. During the course of the project the advancements in technology (primarily that of VLF Tan δ) meant that this test was now technically possible; hence the concept was discussed and its diagnostic potential was exploited. *CDFI* has undertaken almost all of the fundamental application development work for this technique. Initially, it was also observed that there was virtually no information on the application and interpretation of Monitored Withstand tests. At that time, the limited information was based on "accidental" Monitored Withstand tests. As an example, PD tests at elevated voltages (greater than U_0) for a relatively long period of time *de facto* include a withstand element resulting from the application of the elevated voltage. In contrast, a monitored element can be used when conducting a dc or VLF Withstand test and some dielectric property, such as leakage current or dielectric loss.

During the course of *CDFI Phase I*, a number of Monitored Withstand test programs began and data were provided for analysis. The initial analysis of the data provided a preliminary understanding of the application of Monitored Withstand. This allowed *CDFI Phase I* to provide a preliminary review of this technique. *CDFI Phase II*, on the other hand, continued to study Monitored Withstand testing by gathering large datasets from more mature diagnostic programs. These data and the subsequent analysis have allowed for a more thorough review as compared to *Phase I*. The remaining sections in this chapter discuss the details of this expanded understanding.

10.6.1 Definition of a Withstand Test

To understand the applicability of Monitored Withstand tests, it is important to recall the fundamental elements that define a withstand test; these have been discussed previously in Chapter 9. A withstand test is carefully designed to overstress a cable system to an acceptable risk level and thus to be effective it must include the following three elements:

1. **A Defined Voltage Exposure:** The exposure is characterized by a voltage time waveform (waveshape) that includes a controlled magnitude (voltage metric such as peak or RMS voltage) and time of application (in terms of specified time, number of cycles, shots, or any other convenient time metric).
2. **A Repeatable Voltage Exposure:** The voltage exposure is repeatable. The waveshape is maintained during the voltage application (the same at the end as it was at the start) and that systems with similar characteristics (insulation type, lengths, etc.) experience essentially the same voltage waveshape**.**
3. **A Well-defined Failure Rate:** The failure rate during the withstand test ("Hold" phase for a monitored withstand test) must be higher than the failure rate at normal service voltage.

The "Hold" phase of a monitored withstand test should comply with all three elements for proper applicability.

10.6.2 General Monitored Withstand Framework

All Monitored Withstand tests, independent of the monitored value/parameter, have the same framework, which appears in Figure 4.

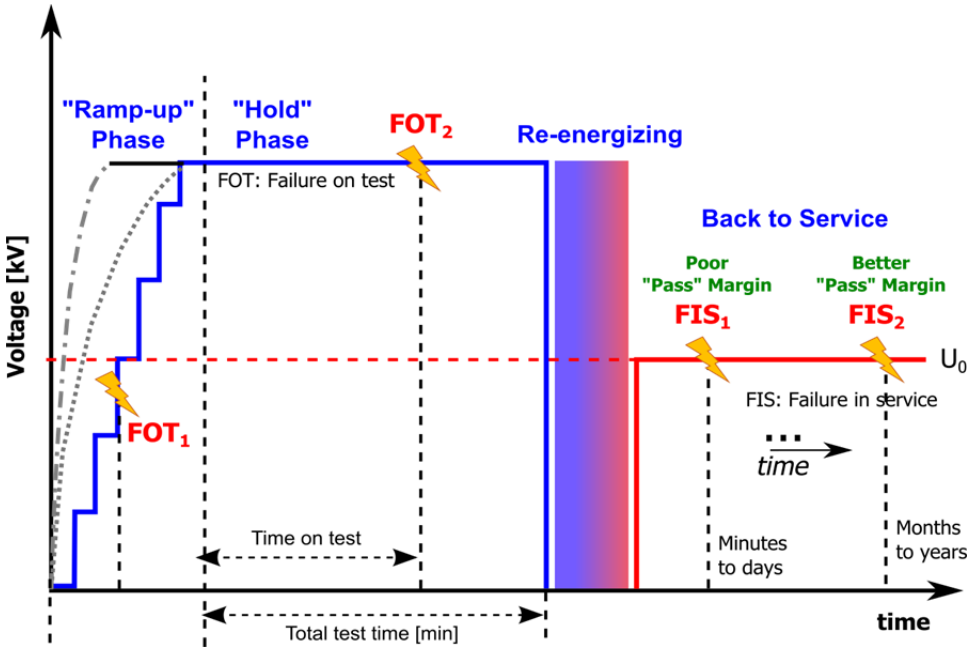

Figure 4: Monitored Withstand Test Framework

In Figure 4, four sequential phases are observed when performing a Monitored Withstand test as follows:

- **"Ramp-up" phase:** This is the initial stage of any Monitored Withstand test (i.e. after a cable system has been taken off-line and properly grounded for testing). This involves raising the test voltage from zero to the required withstand level. The monitored property can be recorded during this stage and may be used to further develop the condition assessment.
- **"Hold" phase:** This stage involves the actual withstand evaluation, the test voltage is held constant and the monitored property is recorded for the duration of the test.
- **Re-energization phase:** This stage involves all the actions and time required to put a cable system back in service once it has successfully completed the monitored withstand test without a FOT.
- **Back to Service phase:** This stage represents operation of the cable system after testing.

There are two possibilities for the timing of a failure during a Monitored Withstand test: (1) during the test itself ("Ramp-up" or "Hold" phases, FOT_1 or FOT_2, respectively, in Figure 4) or (2) after test (Back to Service Phase, FIS_1 or FIS_2 in Figure 4). If the failure occurs on test, then the Monitored Withstand test has successfully failed a weak location in the cable system and thus accomplished its goal. Under this scenario, a Monitored Withstand test does not differ much from a Simple Withstand test because both produce a failure irrespective of the monitored property behavior.

The most useful aspect of the monitoring portion is that it may be used to estimate the "Pass" margin (i.e. the system condition when no dielectric puncture occurred during the test). The concept of "Pass" margin is only possible under the Monitored Withstand framework. At this stage, the monitored property can be used to establish the degree of the "Pass" margin as either "Poor" or "Better". As shown in Figure 4, a "Poor" pass margin is defined as one in which the segment has a high likelihood of failing in service minutes to days after the test concludes, while a "Better" pass margin segment is likely to survive in service without failure months to years after the test. As with all other diagnostic techniques, the key is defining the "likely" part of the previous statement.

The additional information afforded by Monitored Withstand does not come for free because there is added complexity imposed by the diagnostics and decisions of the Monitored Withstand. However, it allows for decision making during test deployment and data analysis for condition assessment during and after the test has concluded. Therefore, in general, decisions and condition assessments can be undertaken at three points as follows:

- **At the end of the "Ramp-up" phase and before the beginning of the "Hold" phase:** The first decisions and condition assessments can be undertaken by evaluating the monitored value/parameters and deciding which systems go to the "Hold" Phase. The reasoning here is simple and is based on the potential that the monitored value/parameter has on detecting extremes on the good and bad conditions. Thus good or bad systems do not need further evaluation because their conditions have already been established and from a condition assessment perspective continuing to the "Hold" phase is not an optimal use of resources (this is Decision 1 on section 10.6.4).
- **During the "Hold" phase:** Decisions can only be undertaken here regarding the duration of the withstand phase. Decisions are then based on 'real time' observation and analysis of the monitored value. If the monitored value shows certain characteristics that can be correlated

to good or bad performance, then the planned test time can be amended to provide a least cost scenario; i.e. reducing total test time or avoiding failures under test on systems that can be remediated later with lower emergency costs (this is Decision 2 on section 10.6.4).

- **After the Monitored Withstand test has concluded:** The potential of a monitored withstand framework is also exploited after the test has concluded; because, additionally to the pass/fail information of the withstand phase, the behavior of the monitored value during the "Hold" phase can be used to determine a final condition assessment for those cable systems that made it to the end of the "Hold" phase without a failure on test (this is Decision 3 on section 10.6.4).

Decision making and condition assessment in the context of a monitored withstand framework are shown in Figure 5. Decision making and condition assessment in the context of a monitored withstand framework using VLF Tan δ measurements appear later in Section 10.6.4.

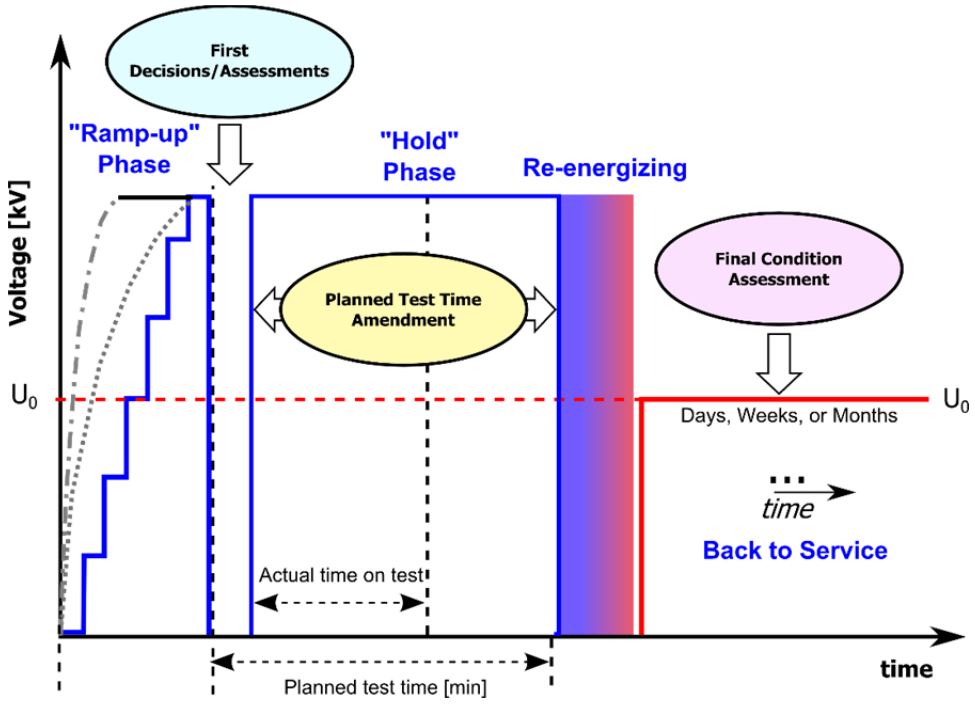

Figure 5: Decision Making and Condition Assessment in the Context of a Monitored Withstand Test Framework

10.6.3 Evolution of VLF Tan δ Monitored Withstand Criteria

CDFI Phase II was able to continue studying the use of VLF Simple Withstand combined with VLF Tan δ. The contributions made during *Phase I* were important; in fact, before the *CDFI*, the concept and application of monitored withstand tests were almost completely unknown to the industry. During *Phase II*, the industry has moved towards smaller and smaller voltage sources with diagnostic assessment tools (based on *CDFI* analyses and recommendations) integrated within them. *Phase I* showed the potential value of Monitored Withstand as a diagnostic tool and laid the groundwork for establishing data-driven assessment criteria. Meanwhile, *Phase II* was able to assemble a large dataset that could be used to define the critical levels for interpreting Monitored

Withstand data. To put this in perspective, the contributions of *CDFI Phases I* and *II*, Table 3 shows the evolution of VLF Tan δ monitored withstand criteria.

Table 3: Evolution of VLF Tan δ Monitored Withstand Criteria for MV Cable Systems

Year	Assessment Hierarchy	Criteria & Issues	Comments (See 10.6.4)
< 2001	None	None	No framework established
2004	***CDFI Phase I***		
2006	1. Trend 2. Stability 3. Level of loss	Initial Discussion	• Contribution of *CDFI Phase I* project based on statistical analysis of data from North American cables • Initial quantitative criteria on **Decision 3** – Final Assessment? Only for paper insulations • Initial quantitative criteria on **Decision 2** – Amend of test time? • First Tan δ Monitored Withstand brochure
2007		Qualitative Experiments	
2008 – 2010		• Criteria based on data • Included in discussions of IEEE Std. 400.2 – 2013	
2011	***CDFI Phase II***		
2011 – 2014	1. Trend 2. Stability 3. Level of loss	• Criteria based on data. • Included in update of IEEE Std. 400.2 – 2013	• Increase the size of the Tan δ monitored withstand database. • Criteria on **Decision 1** – Continue to "Hold" phase? • Criteria on **Decision 2** – Amend of test time? • IEEE Std. 400.2™ – 2013 release. • Continuing update of Tan δ brochure
2015	1. Speeds 2. Stability 3. Level of loss	• Criteria based on data • Verification of Tan δ diagnostic features and hierarchy • VLF Tan δ monitored withstand framework. • Evaluation of the "Ramp-up" Phase • Amendment of test time. • Evaluation of the "Hold" phase & Final Assessment • PCA-based analysis tool	• Contribution of *CDFI Phase II* Project based on statistical analysis of data from North American cables • Criteria on **Decision 1** – Continue to "Hold" phase? • Criteria on **Decision 2** – Amend of test time? • Criteria on **Decision 3** – Final Assessment? • Established complete framework. • Continuing update of Tan δ brochure

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It is important to note the use of the term "Qualitative" in Table 3 is used to describe some of criteria in 2007. This term is used because the understanding in *CDFI Phase I* at the time was limited to which VLF Tan δ measurement values were "really good" and those that were "really bad" but there was not a defined threshold to separate these two categories. Thresholds and criteria were developed later once significant amounts of data were available.

10.6.4 Monitored Withstand Using VLF Tan δ

There are a number of monitored properties that could be utilized during a Monitored Withstand test. They each entail their own difficulties. This section describes the implementation of Monitored Withstand using VLF Tan δ as the monitored property. The basic framework appears in Figure 6.

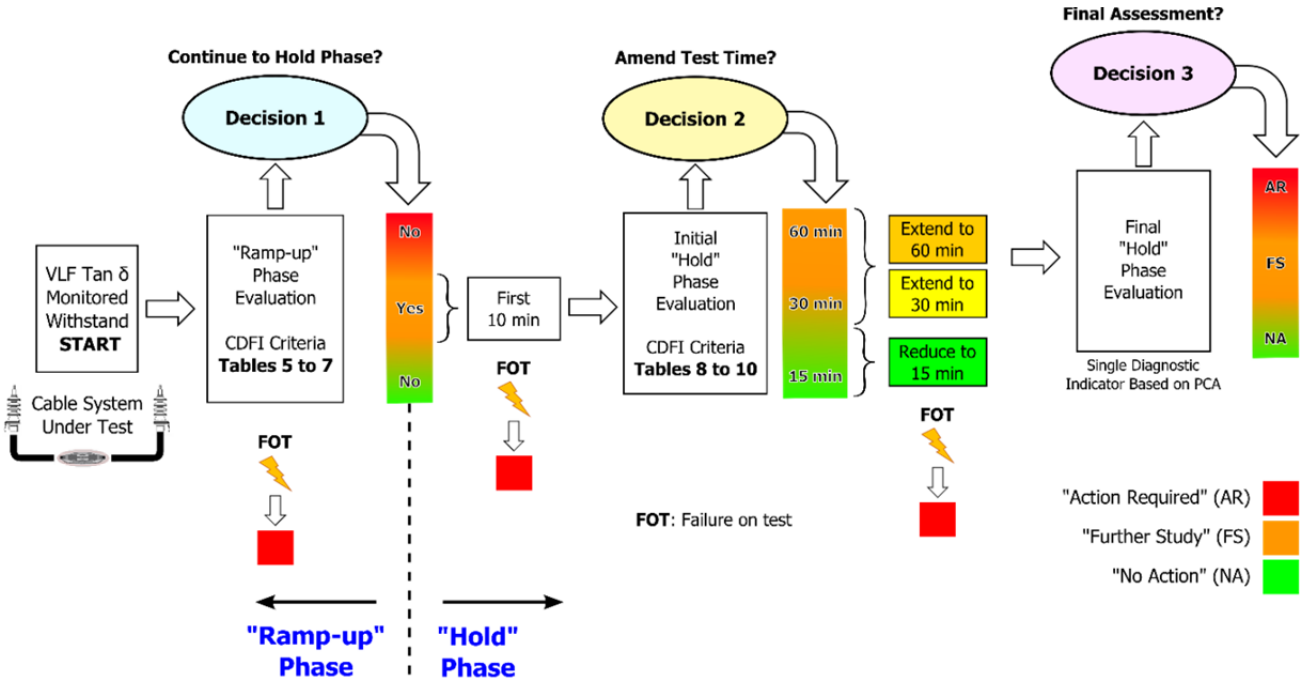

Figure 6: Monitored Withstand Test Framework using VLF Tan δ Measurements

As Figure 6 illustrates, there are three sequential decisions to be made as part of the Monitored Withstand test, namely:

- **Decision 1 – Continue to "Hold" phase?** It is based on the evaluation of the "Ramp-up" phase that can be related to a conventional VLF Tan δ test as described in Chapter 6 (Dissipation Factor – Tan δ). Therefore, Decision 1 can be made by both using reference tables or "Health Index" based on the PCA tool developed in the *CDFI*. Since Decision 1 has to be made on-site during the test, the use of reference tables is preferred over the PCA tool because it is faster and easier to use. Criteria for Decision 1 based on reference tables appear in Table 5 to Table 7 for all insulation types.

- **Decision 2 – Amend test time?** It is based on an initial evaluation of the "Hold" phase to amend test time. Since Decision 2 has also to be made on site during the test, reference table

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based criteria are also used. Criteria for Decision 2 based on reference tables appear in Table 8 to Table 10 for all insulation types.

- **Decision 3 – Final assessment?** If the monitored withstand test has concluded without a FOT, Decision 3 is based on a final evaluation of the "Hold" phase. Since this decision can be made after the test has concluded, it is made by estimating the "Pass" margin using a single diagnostic indicator based on PCA. This complication is not as time sensitive and so does not impact the decision making that must occur during the test.

Each of the above decisions is discussed in detail in Sections 10.6.4.1 through 10.6.4.3. It is important to note that Decision 1 and Decision 2 are made in real time as part of the testing procedure while Decision 3 can be made afterwards. Within each of these sections, criteria are provided for aiding users in making the real time and post-test decisions. These criteria were developed from an extensive VLF Tan δ Monitored Withstand database as summarized in Table 4.

Table 4: Description of the VLF Tan δ Monitored Withstand Database

Insulation Type	Number of Tests		Tested Length	
	Absolute [#]	Proportion [%]	Absolute [mi]	Proportion [%]
PE-based (i.e. PE, HMWPE, XLPE, & WTRXLPE)	618	44.6	366.7	39.4
Filled (i.e. EPR & Vulkene)	237	17.1	110.3	11.9
Paper (i.e. PILC)	513	37.0	409.2	44.0
Hybrid	17	1.2	43.9	4.7
Total	**1,385**	**100.0**	**930.0**	**100.0**

This database includes 1,385 tests on 930 miles of cable system made during 2007 - 2015. The tests encompass a wide variety of cable systems including PILC, PE-based, filled, and hybrid systems. Figure 7 shows the split in terms of both number of tests and length tested for each system type.

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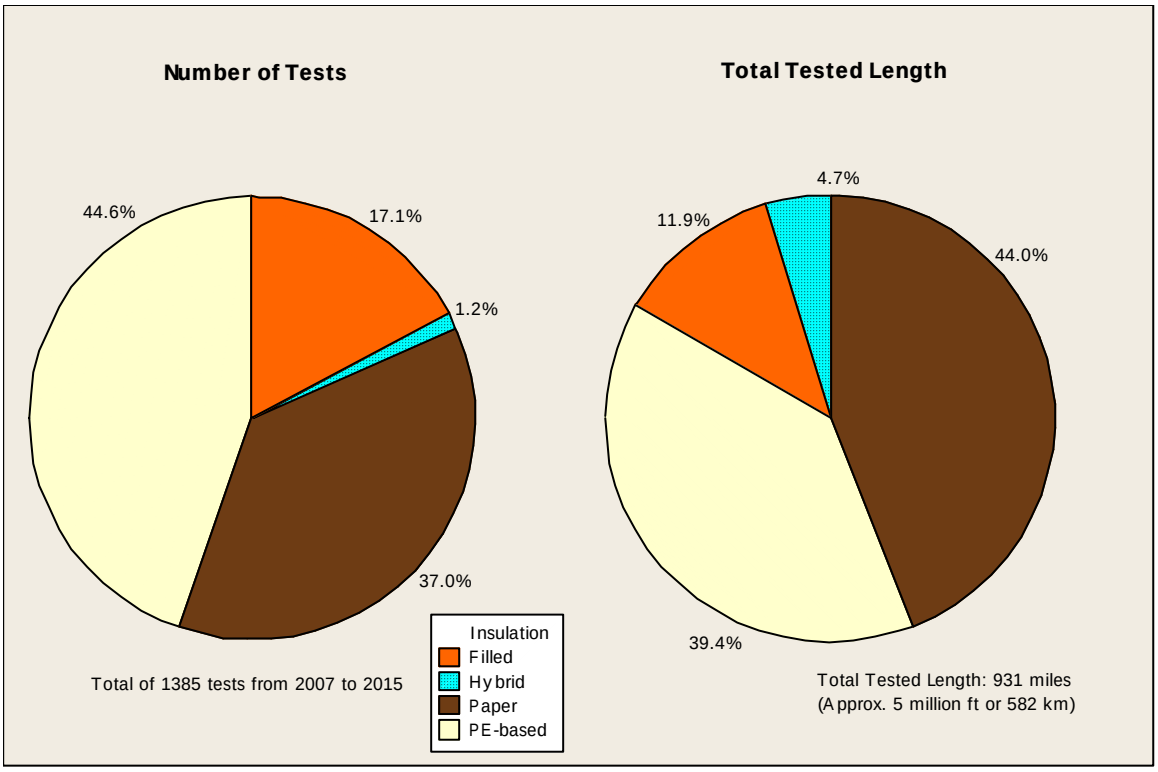

Figure 7: Description of the VLF Tan δ Monitored Withstand Database

Unfortunately, there are too few data to develop criteria for all system types. However, criteria were developed wherever possible as illustrated in the Decision 1 criteria discussed in the next section.

10.6.4.1 Decision 1 - "Ramp-up" Phase Evaluation – Continue to "Hold" Phase?

As seen in Figure 6, Decision 1 is based on the "Ramp-up" phase evaluation. During this phase, the test voltage is increased from zero to the required test voltage level in steps of 0.5 U_0 as the required withstand voltage level is usually greater than 1.5 U_0. The resulting "Ramp-up" phase consists of three steps of 0.5 U_0, U_0, and 1.5 U_0 with Tan δ measurements at each step. It is important to relate the evaluation of the "Ramp-up" phase to a conventional VLF Tan δ test as defined in Chapter 6 Dissipation Factor (Tan δ).

Consequently, the evaluation of the "Ramp-up" phase uses the following Tan δ diagnostic features listed in order of decreasing importance as follows:

- **Tan δ Stability** – This feature represents the time dependence and is normally reported as the standard deviation (STD) of sequential measurements at U_0.
- **Differential Tan δ or Tip Up** – This feature represents the voltage dependence and is normally reported as the simple algebraic difference between the means of a number of sequential measurements taken at two different voltages, in this case the voltage levels are 0.5 U_0 and 1.5 U_0.
- **Tip Up of the Tip Up (TuTu)** – This feature represents the nonlinear voltage dependence and it is reported as the algebraic difference between two Tip Ups: the Tip Up between 1.5

U_0 and U_0 and the Tip Up between U_0 and 0.5 U_0.

- **Level of Tan δ** – This feature represents the level of loss and is normally reported as the mean of a number of sequential measurements (the median of these measurements may also be used) at U_0.

Figure 8 shows examples of measured Tan δ data during the "Ramp-up" phase and the corresponding diagnostic features from a PE-based cable system. The diagnostic features for other insulation types (filled and paper) are the same as the ones described in Figure 8.

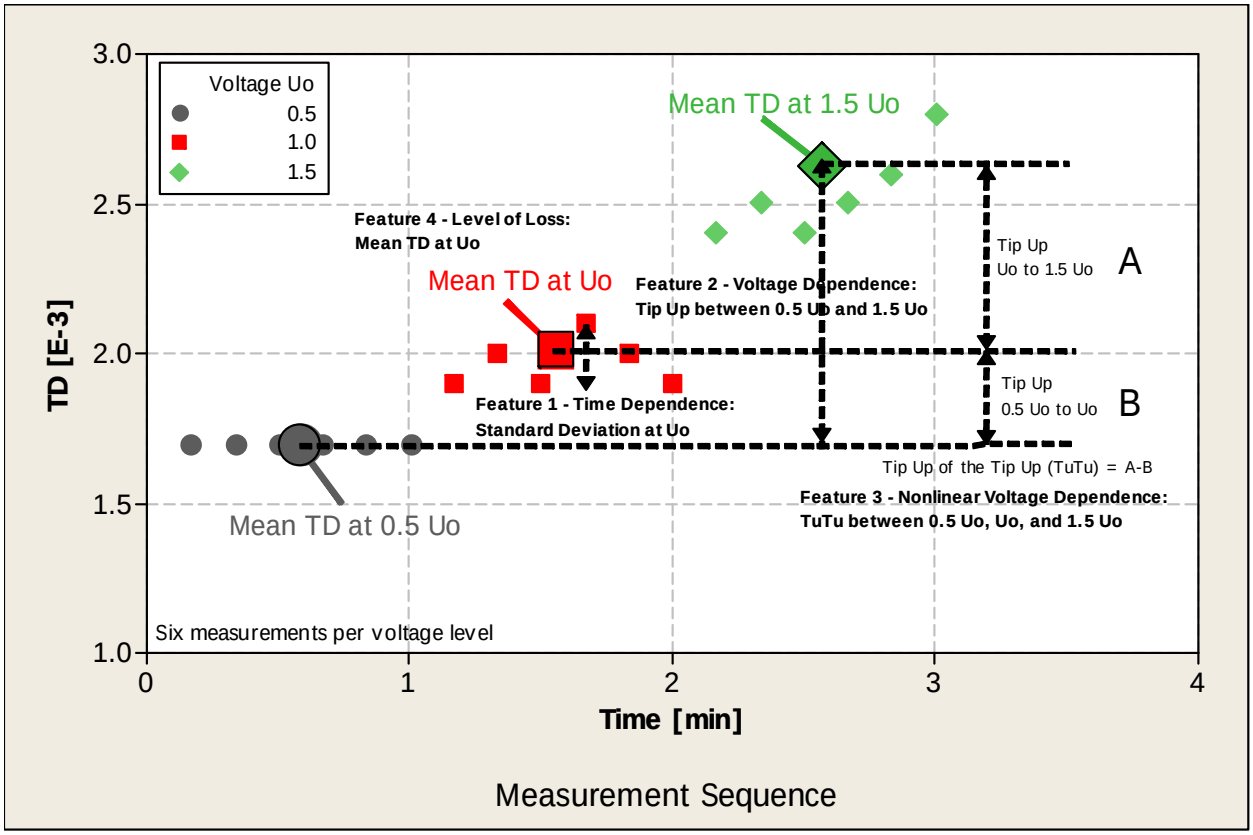

Figure 8: Examples of Measured Tan δ data and Diagnostic features from a PE Cable System during the "Ramp-up" Phase

The criteria for evaluation of the "Ramp-up" phase are the same as those developed in Chapter 6 but reappear in Table 5 to Table 7. In these tables, the typical Tan δ assessment classes of ("No Action Required", "Further Study", and "Action Required") have been replaced with No/Yes to correspond to the Decision 1 question: Continue to "Hold" phase?

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Table 5: *CDFI* Research Criteria for Evaluation of the "Ramp-up" Phase for PE-based Insulations (i.e. PE, HMWPE, XLPE, & WTRXLPE)			
Decision 1 – Continue to "Hold" Phase?			
"Ramp-up" Phase Evaluation [E-3]	**"No"***	**"Yes"****	**"No"*****
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to 1.0	>1.0
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0} – TU$)	<6.7	6.7 to 94.0	>94.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<6.0	6.0 to 70.0	>70.0

* "Green No" – Cable systems condition is assessed as in the best performing 80% and thus it is unnecessary to continue to "Hold" phase because time and resources are saved.

** "Amber Yes" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems are further taken to the "Hold" phase for a final condition assessment.

*** "Red No" – Cable system condition is assessed as in the poorest performing 5% and thus it is unnecessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair costs. Systems in this category can be acted on in a planned manner by managing optimal time and costs.

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Table 6: *CDFI* Research Criteria for Evaluation of the "Ramp-up" Phase of Filled Insulations (i.e. EPR & Vulkene®)			
Decision 1 – Continue to "Hold" Phase?			
"Ramp-up" Phase Evaluation [E-3]	**"No"***	**"Yes"****	**"No"*****
Unidentified Filled Insulations (i.e. EPR, Kerite, & Vulkene®)*			
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to1.2	>1.2
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0} – TU$)	<3.0	3.0 to 30.0	>30.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<1.0	1.0 to 18.0	>18.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<25.0	25.0 to 150.0	>150.0
Mineral Filled Insulations (i.e. EPR) Experience has shown that it is difficult to precisely identify the type of filled insulation in field-installed cable. The issues include: incorrect /missing records, obscured markings on the jacket, indistinct coloring, etc. In these cases, it is recommended to use the criteria for **Unidentified Filled**.			
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to 0.8	>0.8
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0} – TU$)	<2.0	2.0 to 40.0	>40.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<1.0	1.0 to 25.0	>25.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<16.0	16.0 to 75.0	>75.0

* "Green No" – Cable system condition is assessed as in the best performing 80% and thus it is unnecessary to continue to "Hold" phase because time and resources are saved.

** "Amber Yes" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems are further taken to the "Hold" phase for a final condition assessment.

*** "Red No" – Cable system condition is assessed as in the poorest performing 5% and thus it is unnecessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair cost. Systems in this category can be acted on a planned manner by managing optimal time and costs.

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Table 7: *CDFI* Research Criteria for Evaluation of the "Ramp-up" Phase of Paper Insulations (i.e. PILC)			
Decision 1 – Continue to "Hold" Phase?			
"Ramp-up" Phase Evaluation [E-3]	**"No"***	**"Yes"****	**"No"*****
Stability for TD_{U_0} (standard deviation – STD)	<0.2	0.2 to 1.5	>1.5
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0} – TU$)	-30.0 to 22.0	-30.0 to -60.0 or 22.0 to 220.0	<-60.0 or >220.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}– TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<100.0	100.0 to 250.0	>250.0

* "Green No" – Cable systems condition is assessed as good and thus it is unnecessary to continue to "Hold" phase because time and resources are saved.

** "Amber Yes" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems are further taken to the "Hold" phase for a final condition assessment.

*** "Red No" – Cable system condition is assessed as extremely bad and thus it is unnecessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair costs. Systems in this category can be acted on in a planned manner by managing optimal time and costs.

The "Ramp-up" phase evaluation in Table 5 through Table 7 are intended to assist field personnel with deciding whether or not to continue to the "Hold" phase of the Monitored Withstand test. As defined above, cable systems with an evaluation of the "Ramp-up" phase resulting in a "Green No" do not require immediate additional actions and it can be assumed that they have successfully passed the Monitored Withstand test with an acceptable "Pass" margin. In other words, no failures are expected soon after the system is re-energized and returned to service.

Cable systems with an evaluation of the "Ramp-up" phase resulting in a "Red No" require remedial actions in the near future and thus it is assumed that they have not passed the Monitored Withstand test. In this event, the remedial actions following a "Red No" evaluation should be sequentially undertaken as follows:

- review data for a rogue measurement in the sequence – most common in the first voltage cycle
- confirm insulation type to ensure that criteria apply
- verify the integrity of the terminations and if compromised replace them and repeat the test
- retest in the near future and observe trends (6 months to a year) or

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- place on "watch list" and consider system replacement in the near future

When the evaluation of the "Ramp-up" phase is an "Amber Yes," the "Hold" phase of the test is deployed; details on how the "Hold" phase is deployed are discussed in the next section.

The expected outcomes for Decision 1 appear in Figure 9. They are based on the evaluation of all VLF Tan δ data contained in the *CDFI* database. These expected outcomes used later in the chapter through examples of analyses on real data from the field.

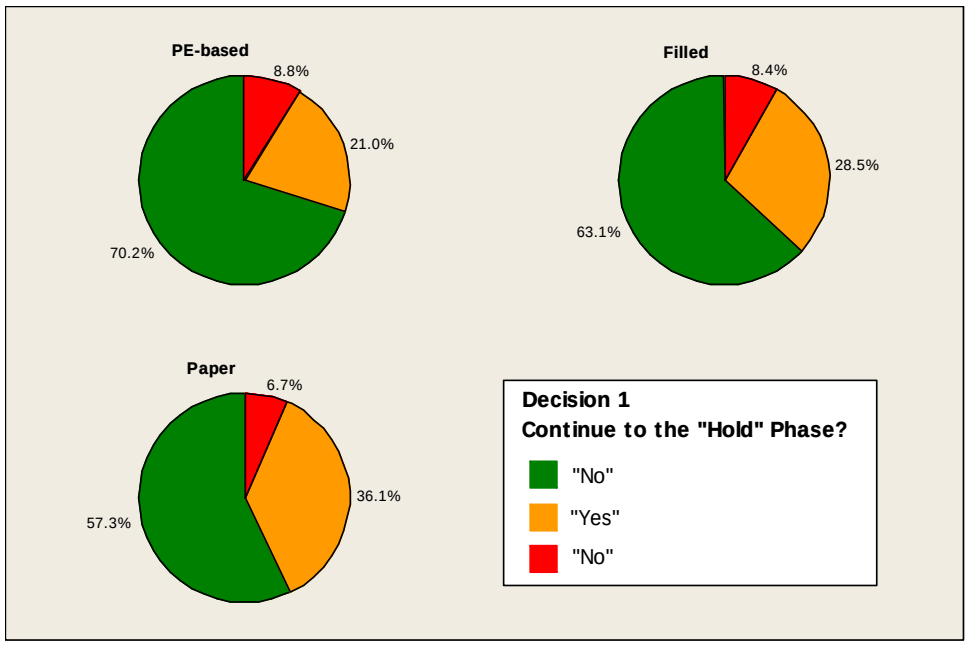

Figure 9: Outcomes for Decision 1 – Continue to the "Hold" Phase?

Once a decision is made to proceed with the "Hold" phase, the next decision (Decision 2) to be made is "how long to test".

10.6.4.2 Decision 2 – "Hold" Phase Evaluation – Amend Test Time?

The recommended test time in IEEE Std. 400.2 – 2013 for the "Hold" phase on field-aged cable systems is 30 min at 0.1 Hz. This time may be extended or reduced if a Monitored Withstand is performed and the monitored property shows specific behavior. Unfortunately, the IEEE guide does not provide a clear indication on how to evaluate the behavior. Thus, the amending of test times is a decision that must be made in the field while the test is underway. This constitutes Decision 2 shown in Figure 6.

As with Decision 1, the available data were analyzed using the same principles to determine those conditions under which the test time can be shortened or extended. This results in a set of criteria that by necessity must be evaluated during the Monitored Withstand test.

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Before reviewing the criteria themselves, it is instructive to examine the differences between the interpretations of Tan δ measurements during the "Ramp-up" phase and those made during the "Hold" phase. As seen earlier, work within the *CDFI* has suggested the following hierarchy for Tan δ measurement interpretation during the "Ramp-up" phase (ranked from most important to least important):

- Tan δ Stability (STD)
- differential Tan δ or Tip-Up (TU)
- Tip Up of the Tip Up (TuTu)
- Tan δ level (magnitude) (TD)

Ideally, these or similar features would be used for Decision 2, However, the constant voltage level during the "Hold" phase does not permit all of the same features (i.e. the TU and TuTu are not available). However, the hierarchy aids in understanding the dependencies that should be considered when characterizing Tan δ measurements even under a constant test voltage. The "Ramp Up" phase approach examines Tan δ variability with time, linear and non-linear variability with voltage, and absolute level of loss. The constant voltage obviously eliminates the possibility of looking at the variability with voltage but the time variability and absolute loss level are still feasible but special attention must be given to the variability in the length of the test (15, 30, or 60 min). Therefore, the need to improve the approach is driven by the long times used for the "Hold" phase and because the user is more likely to be interested in the trend (increasing or decreasing) of the instability and the absolute loss level.

To address these issues, taking into account the above discussion and what is readily available to the user onsite when conducting the test, a set of diagnostic features were defined for the purpose of amending the test time. They are meant to be evaluated test times between 0 and 10 minutes and are as follows:

- **Absolute change in Tan δ:** This feature is quantified by the absolute difference between the Tan δ instantaneous values at 10 and 0 min. It provides information on both time variability and level of loss for the considered time period.
- **Tan δ Stability:** This feature is quantified by the standard deviation (STD) of Tan δ measurements between 0 and 10 minutes and consequently provides the time variability information within the time period.
- **Tan δ level:** This feature is quantified by the mean of Tan δ measurements between 0 and 10 minutes and consequently provides the level of loss information within the time period.

Each of the above features is available for any Monitored Withstand test. The critical levels for each of these features (80^{th} and 95^{th} percentiles) were determined for all insulation types and appear in Table 8 through Table 10. The cumulative distribution functions that were used to generate the critical levels for PE-based insulations (i.e. PE, XLPE, WTRXLPE) appear in Figure 10. For example, in Figure 10, the absolute change in Tan δ between 0 min and 10 min ($|TD_{10}-TD_0|$) can be interpreted as having 80% of the data lie below 0.6 E-3 and thus reducing the planned test time to 15 min is limited by this threshold. Similarly, considering the 95% percentile, the planned test time is extended to 60 min by values of $|TD_{10}-TD_0|$ bigger than 8 E-3.

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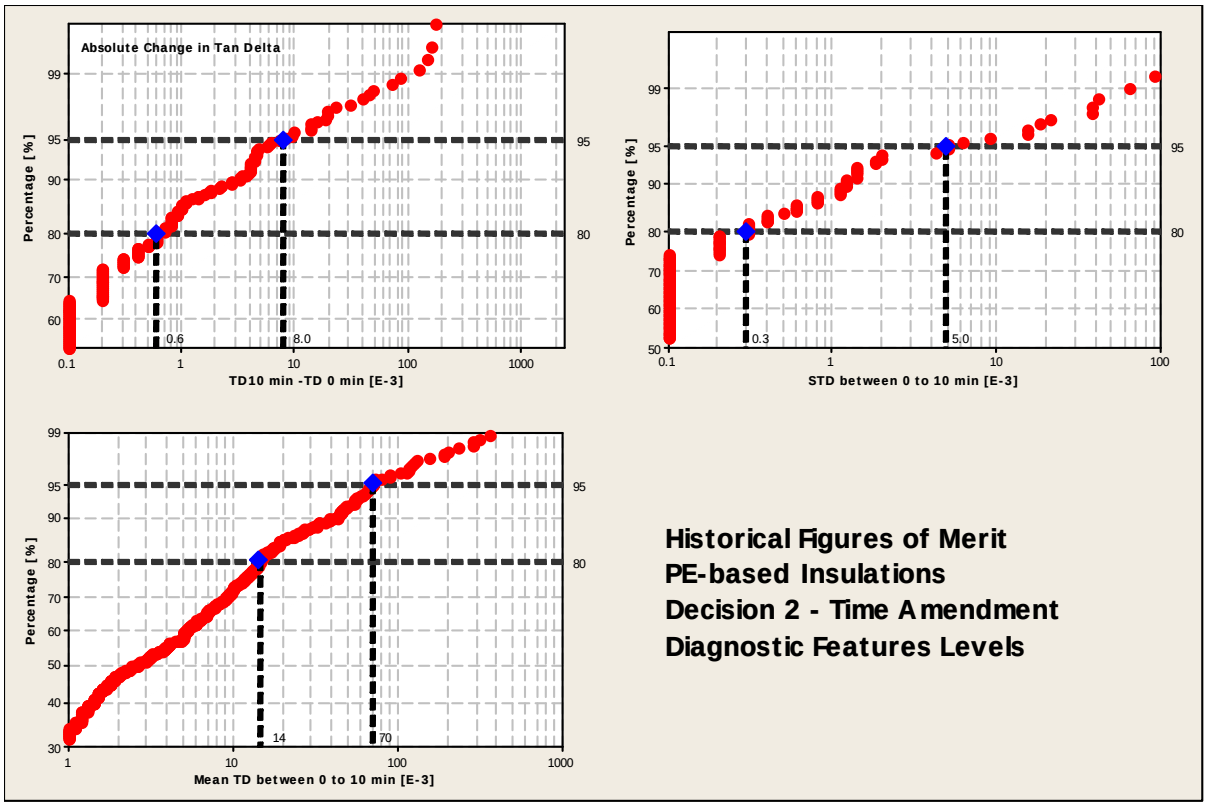

Figure 10: Determining Critical Levels for Diagnostic Features for Test Time Amendment from Research Data (PE-based Insulations)

Subsequently, the criteria for test time amendment for all insulation types are shown in Table 8 through Table 10.

Table 8: *CDFI* Research Criteria for Time Amendment of the "Hold" Phase of PE-based Insulations (i.e. PE, HMWPE, XLPE, & WTRXLPE)*		
Decision 2 – Amend Test Time?		
"Hold" Phase Evaluation [E-3]	**"Reduce to 15 min"**	**"Extend to 60 min"**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0 \rvert$	<0.6	>8
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<14	>70

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* Based on data as described in Table 4

Table 9: *CDFI* Research Criteria for Time Amendment of the "Hold" Phase of Filled Insulations (i.e. EPR & Vulkene)*		
Decision 2 – Amend Test Time?		
"Hold" Phase Evaluation [E-3]	**"Reduce to 15 min"**	**"Extend to 60 min"**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0\rvert$	<0.6	>6
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<13	>105

* Based on data as described in Table 4

Table 10: *CDFI* Research Criteria for Time Amendment of the "Hold" Phase for Paper Insulations (i.e. PILC)*		
Decision 2 – Amend Test Time?		
"Hold" Phase Evaluation [E-3]	**"Reduce to 15 min"**	**"Extend to 60 min"**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0\rvert$	<1.4	>5
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.6	>5.4
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<80	>180

* Based on data as described in Table 4

Using the above criteria, the expected outcomes for Decision 2 appear in Figure 11. These results are used in the case studies that appear in Section 10.6.4.4.

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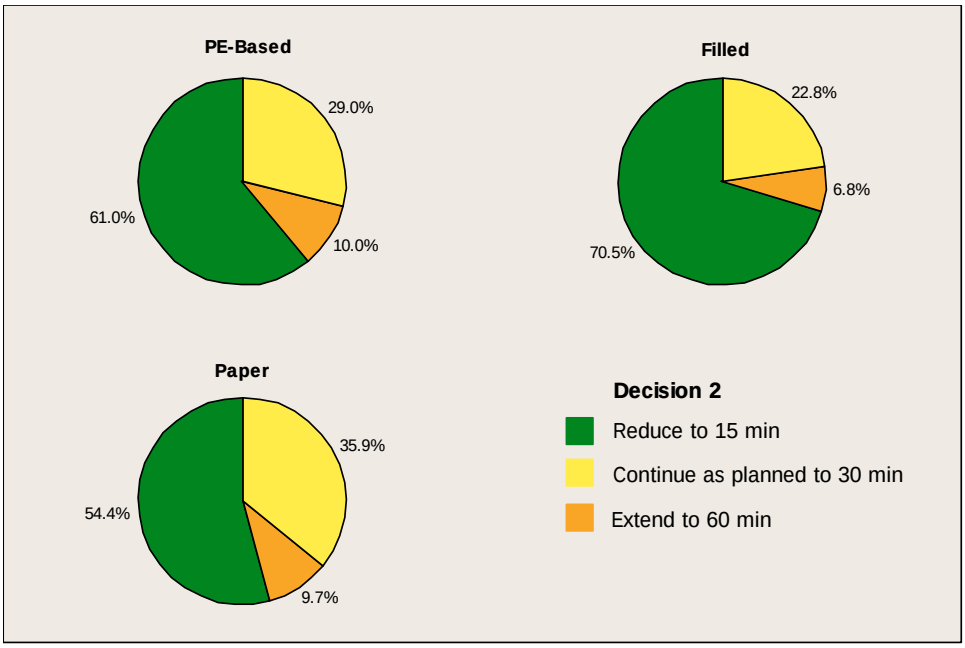

Figure 11: Outcomes for Decision 2 Using *CDFI* Research Data – Amend Test Time?

If the segment under test successfully completes the "Hold" phase without a FOT, then the final step is to provide a condition assessment. The details of how this assessment is conducted are described in the next section.

10.6.4.3 Decision 3 – "Hold" Phase Evaluation – Final Assessment?

Once a VLF Tan δ monitored withstand test has concluded without a FOT, a final evaluation of the "Hold" phase data is required. The utility engineer must then confront a condition assessment that involves a multitude of potential features. This is represented in Figure 6 as Decision 3 – Final Assessment. This assessment can be accomplished by estimating a qualitative "Pass" margin that is derived from diagnostic features obtained from the "Hold" phase. The "Pass" margin is useful to classify cable systems into three categories or classes:

- **"No Action Required"** – Systems in this category are assumed to have aa adequate"Pass" margin and are not expected to fail in the near future. Failures, if any, are expected to appear months or years after testing. Therefore, systems can be returned to service without any major concerns.
- **"Action Required"** – Systems in this category are assumed to have a poor/low "Pass" margin and if no action is taken and these systems are returned to service, failures are expected to appear in the near future minutes to days after testing. Actions following an "Action Required" assessment should include placing the cable system on a "watch list" and considering replacement in the near future.
- **"Further Study"** – This category covers systems in which a clear evaluation of the "Pass" margin cannot be accomplished. Therefore, a final condition assessment is not straightforward. However, actions following a "Further Study" class may aid in finding a final assessment and are described below.

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Cable systems with an evaluation of the "Hold" phase resulting in "Further Study" may require remedial actions in the near future that should be sequentially undertaken as follows:

- review data for a rogue measurement in the sequence – most common during the first few voltage cycles
- confirm insulation type to ensure that criteria apply
- verify the integrity of the terminations and if compromised, clean or replace them and repeat the test
- retest in the near future and observe trends (6 months to a year) or
- place on "watch list" and consider system replacement in the near future

The estimation of the "Pass" margin is not a simple process. The diagnostic features needed to evaluate the "Hold" phase must first be determined and then considered together for the final assessment. Fortunately, irrespective of insulation type, the features can be determined by Cluster Variable Analysis (CVA) [16] and then the grouping of features for the final assessment can be accomplished by Principal Component Analysis (PCA) [16-17]. Both the cluster variable analysis and the PCA are described in detailed in the Appendix A and Appendix B, respectively.

To develop the final assessment, a set of features that built upon those identified during the Tan δ Ramp assessment (Decision 1) were examined. This set was more limited in terms of the types of features (voltage dependence could not be used). As a result, the set used as a starting point for the Cluster Variable and Principal Component Analysis the following feature set:

1. **Tan δ Stability (STD)** – This feature represents the time dependence and is reported as the standard deviation of sequential measurements at the particular test voltage level irrespective of it is a 15, 30, or 60 min test.
2. **Initial Tan δ (Init TD)** – This feature represents the initial measured loss level at the beginning of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
3. **Final Tan δ (Final TD)** – This feature represents the final measured loss level at the end of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
4. **Level of Tan δ (Mean TD)** – This feature represents the average level of loss over the full "Hold" phase irrespective of it is a 15, 30, or 60 min.
5. **Speed (rate of change over time) of Tan δ between 0 and 5 min (SPD 0-5)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the first 5 minutes of the "Hold" phase. More importantly, this feature also provides information about the trend of the measurements during the period under consideration; i.e. positive values indicate an increasing trend and *vice versa*.
6. **Speed of Tan δ between 5 and 10 min (SPD 5-10)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the second 5 minutes of the "Hold" phase.
7. **Speed of Tan δ between 10 and 15 min (SPD 10-15)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the third 5 minutes of the "Hold" phase.
8. **Speed of Tan δ Between 0 and final test time (SPD 0-t_{final})** – This feature represents an estimate of the overall rate of change of the loss level (Tan δ) with time for a completed "Hold" phase irrespective of it is a 15, 30, or 60 min test.

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An example of measured data during the "Hold" phase with the previously described diagnostic features appears in Figure 12.

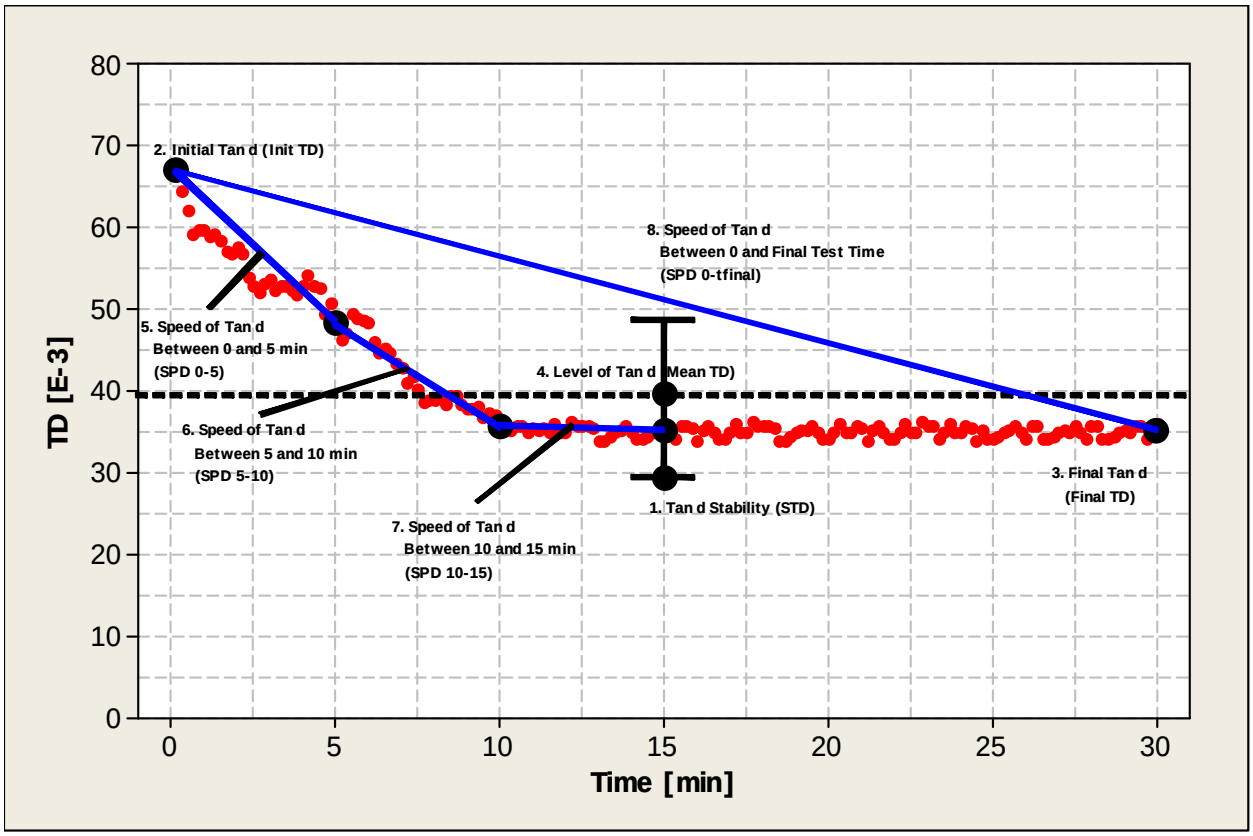

Figure 12: Example of Real Measured Tan δ data and Diagnostic features from a PE Cable System during the "Hold" Phase

As described above, eight features are available for determining the appropriate assessment class. Cluster Variable Analysis (reduces the feature set) and Principal Component Analysis (finds the best combination of features) were used to identify which features to include in the condition assessment. This was done for all three insulation classes (PE-based, filled, and PILC). The details of this feature reduction/identification are discussed in Appendix C, Appendix D, and Appendix E for PE-based, filled, and PILC, respectively. The remaining discussion in this section focuses on the results of these analyses.

Table 11 shows the "recipes" that result from completing the CVA and PCA for each of the insulation types. As this table shows, the features and their positions within the principal components change depending on the insulation type.

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Table 11: Comparison of PCA Results by Insulation Type		
Insulation Type		
PE-based	**Filled**	**Paper**
Number of Principal Components		
4	3	3
Variability Described by Principal Components		
98.0	96.0	94.7
"Hold" Phase Tan δ Diagnostic Features by Principal Component		
PC1 – STD and SPD 0-t_{final} PC2 – SPD 0-5 PC3 – Mean TD PC4 – STD	PC1 – SPD 0-t_{final} and STD PC2 – Mean TD PC3 – SPD 10-15	PC1 – SPD 10-15 and STD PC2 – SPD 0-t_{final} PC3 – Mean TD
"Hold" Phase Tan δ Diagnostic Features Hierarchy of Importance		
Overall and Initial Speeds (SPD 0-t_{final} and SPD 0-5) Variability (STD) Level of Loss (Mean TD)	Overall Speed (SPD 0-t_{final}) Variability (STD) Level of Loss (Mean TD)	Middle and Overall Speeds (SPD 10-15 and SPD 0-t_{final}) Variability (STD) Level of Loss (Mean TD)

With the PCA recipe and the known behavior of a new cable system, it is then possible to compute a PCA distance that essentially quantifies how different a tested cable system is from a new system with similar characteristics. The resulting distributions of these "distances" for the data contained in the *CDFI* database for Monitored Withstand appear in Figure 13. It is important to note that the distributions are different at small distances (i.e. near new) but quite similar at larger distances (poor condition).

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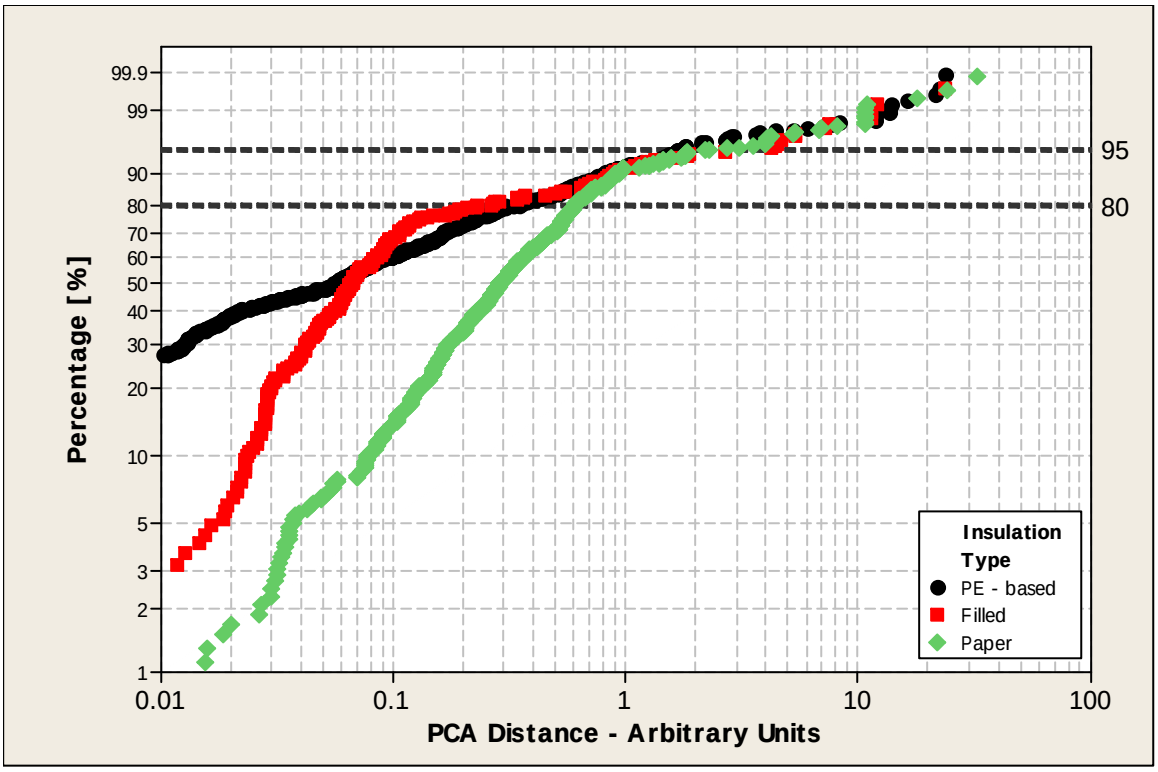

Figure 13: Comparison of Empirical Cumulative Distributions of the PCA Distance used for Evaluation of the "Hold" Phase by Insulation Type

Figure 13 also shows the typical thresholds that were used throughout *CDFI* research and so these define the separations from the different assessment classes for each insulation type. "Action Required" (> 95%) is virtually the same for each of the insulations. There is a more pronounced difference at the "Further Study" threshold (80%). Results from Figure 13 and Table 11 provide indications that when the PCA results are considered together, there are issues to be imparted for all insulation types. These issues appear below:

- The number of diagnostic features used to describe the "Hold" phase can be reduced to four or five features. These features cover more than 95% of the data variability.
- The type and importance of the diagnostic features is generally the same regardless of the insulation type; speeds are the more important features, followed by the variability, and the level of loss.
- The differences observed in the PCA distances (Figure 13) strongly suggest that valuable knowledge of VLF Tan δ Monitored Withstand is gained from collating experience. Furthermore, it shows that the data must be collected separately for different insulation types.

The following section illustrates the use of these results in case studies.

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10.6.4.4 Case Studies

To improve the understanding of the application of the VLF monitored withstand framework, this section presents examples of how the framework is deployed using real data from the field.

- **Case Study 1:** Data for a service-aged XLPE cable system that has been assessed by the framework as "Further Study" at the end of the ramp, but test ultimately curtailed to 15 min.
- **Case Study 2:** Data for a service-aged XLPE cable system that has been assessed by the framework as "Further Study" at the end of the ramp, but test ultimately extended to 30 min.

In both cases, the VLF monitored withstand data are presented graphically in Figure 14 and Figure 15 and the results of employing the Monitored Withstand framework appear in Table 12 and Table 13, respectively.

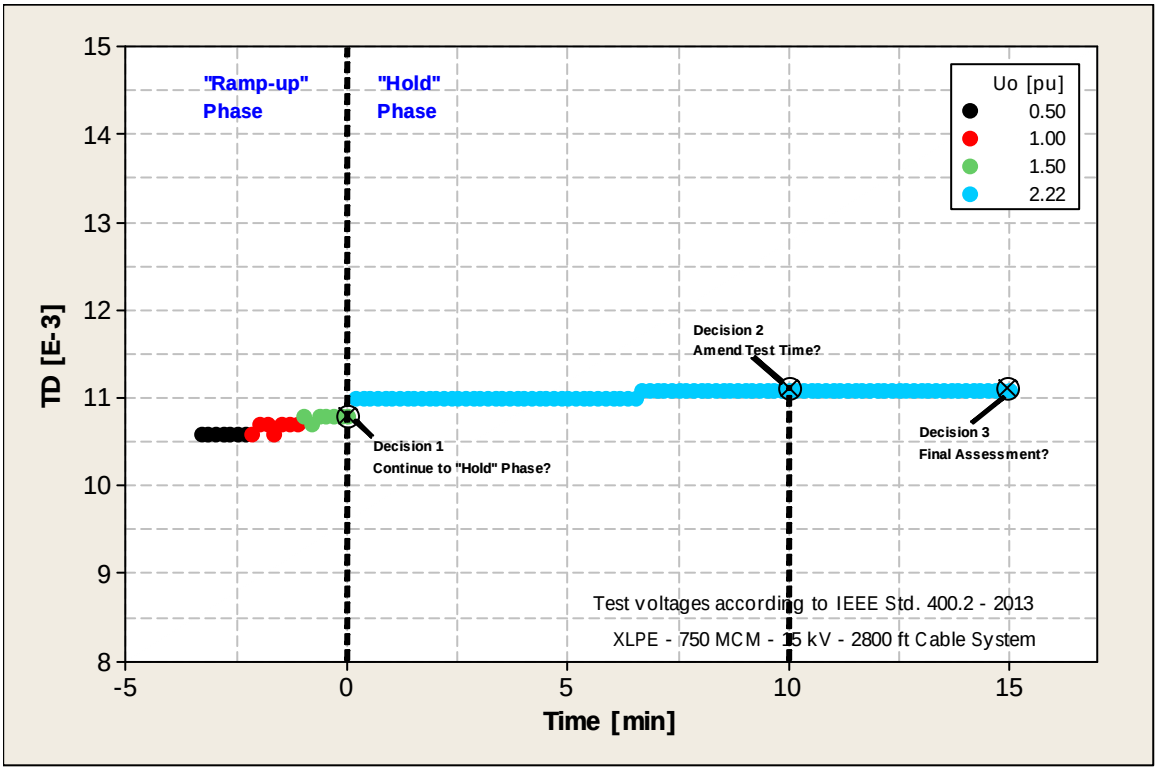

Figure 14: Case Study 1: Field VLF Tan δ Monitored Withstand Data for a Service Aged XLPE Cable System Ultimately Assessed as "No Action"

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Table 12: Case Study 1 - Field VLF Tan δ Monitored Withstand Data and Decision Making Framework for a Service Aged XLPE Cable System Assessed as "No Action" (Tan δ from Figure 14)

Decisions Made On Site				
Decision 1 – "Ramp-up" Phase Evaluation – Continue to "Hold" Phase?				
Diagnostic Feature	**STD [E-3]**	**TU [E-3]**	**TuTu [E-3]**	**TD [E-3]**
Feature Value	0.01	0.3	0.1	10.70
Assessment based on the criteria presented in Table 5				
Individual Feature Assessment	"No"	"No"	"No"	"Yes"
Overall Feature Assessment	"Yes"			
Decision 2 – "Hold" Phase Evaluation – Amend Test Time?				
Diagnostic Feature	**$\lvert TD_{10}-TD_0 \rvert$ [E-3]**	**STD_{10} [E-3]**	**Mean TD_{10} [E-3]**	
Feature Value	0.1	0.05	11.4	
Assessment based on the criteria presented in Table 8				
Individual Feature Assessment	"Reduce to 15 min"	"Reduce to 15 min"	"Reduce to 15 min"	
Overall Feature Assessment	"Reduce to 15 min"			
Decision Taken After Test				
Decision 3 – "Hold" Phase Evaluation – Final Assessment?				
Feature	**SPD 0-5 [E-3/min]**	**SPD 5-10 [E-3/min]**	**SPD 0-t_{final} [E-3/min]**	**STD [E-3]**	**Mean Tan δ [E-3]**	**PCA Distance**	**Percentage Rank [%]**
Feature Value	0.002	0.002	0.002	0.010	11.00	0.12	64.00
Assessment Based on Health Index from PCA (Table 18 and Figure 23)							
Overall Feature Assessment	"No Action"						

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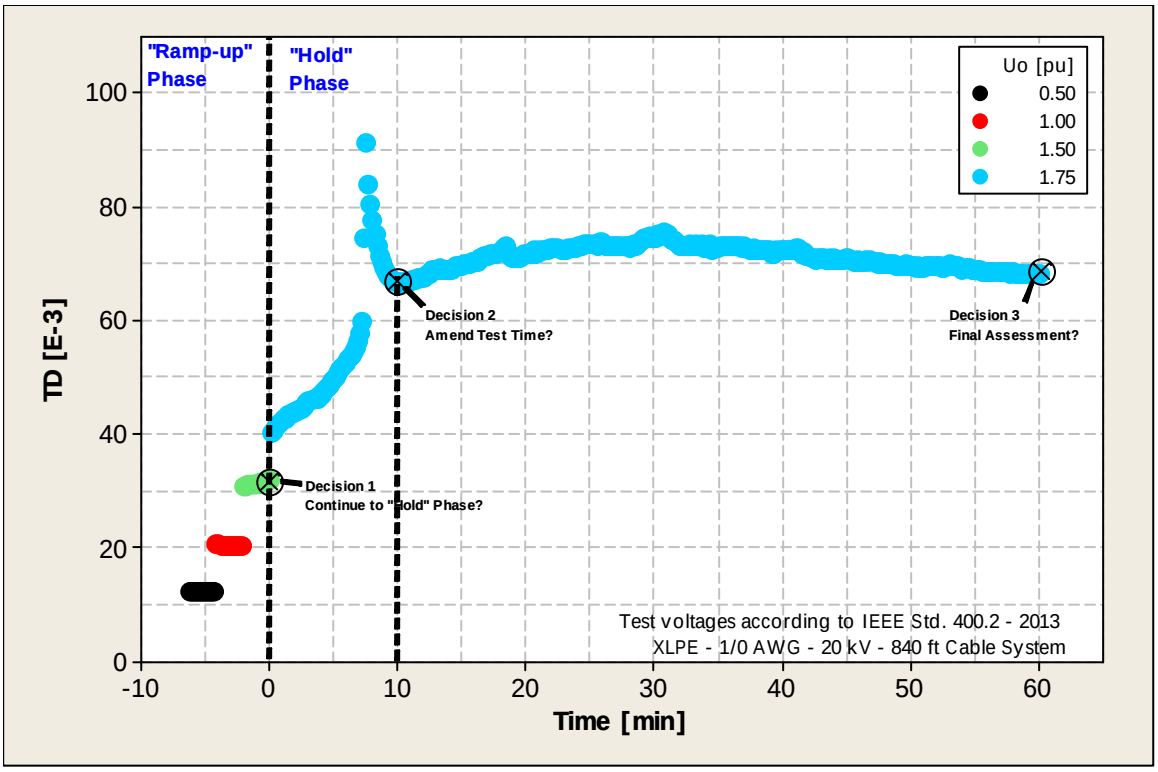

Figure 15: Case Study 2: Field VLF Tan δ Monitored Withstand Data for a Service Aged XLPE Cable System Ultimately Assessed as "Further Study"

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Table 13: Case Study 2 - Field VLF Tan δ Monitored Withstand Data and Decision Making Framework for a Service Aged XLPE Cable System Assessed as "Further Study" (Tan δ from Figure 15)

Decisions Taken On Site				
Decision 1 – "Ramp-up" Phase Evaluation – Continue to "Hold" Phase?				
Diagnostic Feature	**STD [E-3]**	**TU [E-3]**	**TuTu [E-3]**	**TD [E-3]**
Feature Value	0.10	19.00	2.80	20.70
Assessment based on the criteria presented in Table 5				
Individual Feature Assessment	"Yes"	"Yes"	"No"	"Yes"
Overall Feature Assessment	"Yes"			
Decision 2 – "Hold" Phase Evaluation – Amend Test Time?				
Diagnostic Feature	**$\lvert TD_{10}-TD_0 \rvert$ [E-3]**	**STD_{10} [E-3]**	**Mean TD_{10} [E-3]**	
Feature Value	26.40	12.70	55.0	
Assessment based on the criteria presented in Table 8				
Individual Feature Assessment	"Extend to 60 min"	"Extend to 60 min"	"Extend to 30 min"	
Overall Feature Assessment	"Extend to 60 min"			
Decision Taken After Test				
Decision 3 – "Hold" Phase Evaluation – Final Assessment?				
Feature	**SPD 0-5 [E-3/min]**	**SPD 5-10 [E-3/min]**	**SPD 0-t_{final} [E-3/min]**	**STD [E-3]**	**Mean Tan δ [E-3]**	**PCA Distance**	**Percentage Rank [%]**
Feature Value	1.98	3.30	0.47	8.20	68.70	1.44	93.50
Assessment Based on Health Index from PCA (Table 18 and Figure 23)							
Overall Feature Assessment	"Further Study"						

10.6.4.5 Comparison with Simple VLF Withstand

The previous sections have focused on the implementation and interpretation of the Monitored Withstand test. However, the question remains what additional benefit a user gets for the added complication implicit in the Monitored Withstand approach. It is, therefore, useful to compare the monitored withstand framework with its Simple VLF Withstand counterpart in terms of inputs (time) and outputs (subsequent actions). The comparison produces some unintuitive results that are

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worth exploring. This section provides such a comparison assuming that the same group of cable systems was assessed by both Simple and Monitored Withstand frameworks.

Assume that the test population has the following characteristics:

- 1,000 Aged XLPE cable systems
- the average length of a cable system/segment is 1,000 ft
- anticipated FOT rates during the "Hold" phase correspond to the ones estimated during *CDFI Phase I* (2.7% of 1,000 ft segments)

Figure 16 shows the estimated "Hold" phase performance of the Simple Withstand program. In total, 1,000 withstand tests are performed for 30 min each. This produces 27 FOTs corresponding with a failure rate of 2.7 %.

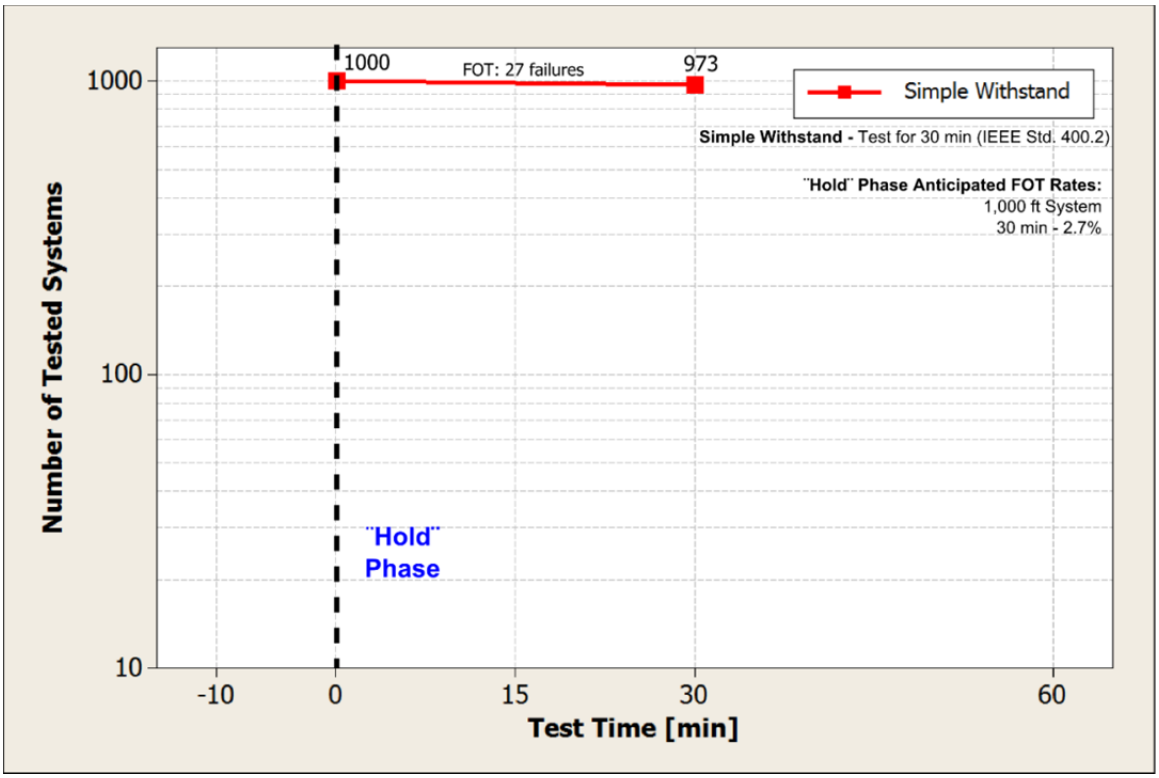

Figure 16: Simple VLF Withstand Framework on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Performance estimates for the Monitored Withstand framework for this set of cable systems appear in Figure 17. In this case, the number of tested systems (blue solid line) declines significantly as a result of Decision 1 (702 "No Action Required" and 88 "Action Required"). This implies that only 210 cable systems proceed to start the "Hold" phase. Stepping back to Decision 1 for this example, it is important to remember that there are two potential implementations of Decision 1:

a) Only "Further Study" ("Amber Yes") systems are considered to move forward to the "Hold" phase or,

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b) Both "Further Study" ("Amber Yes") and "Action Required" ("Red No") systems are considered to move forward to the "Hold" phase.

In the example presented here, the implementation described in (a) above is the one that is considered using the *CDFI* criteria presented in Table 5 to Table 7.

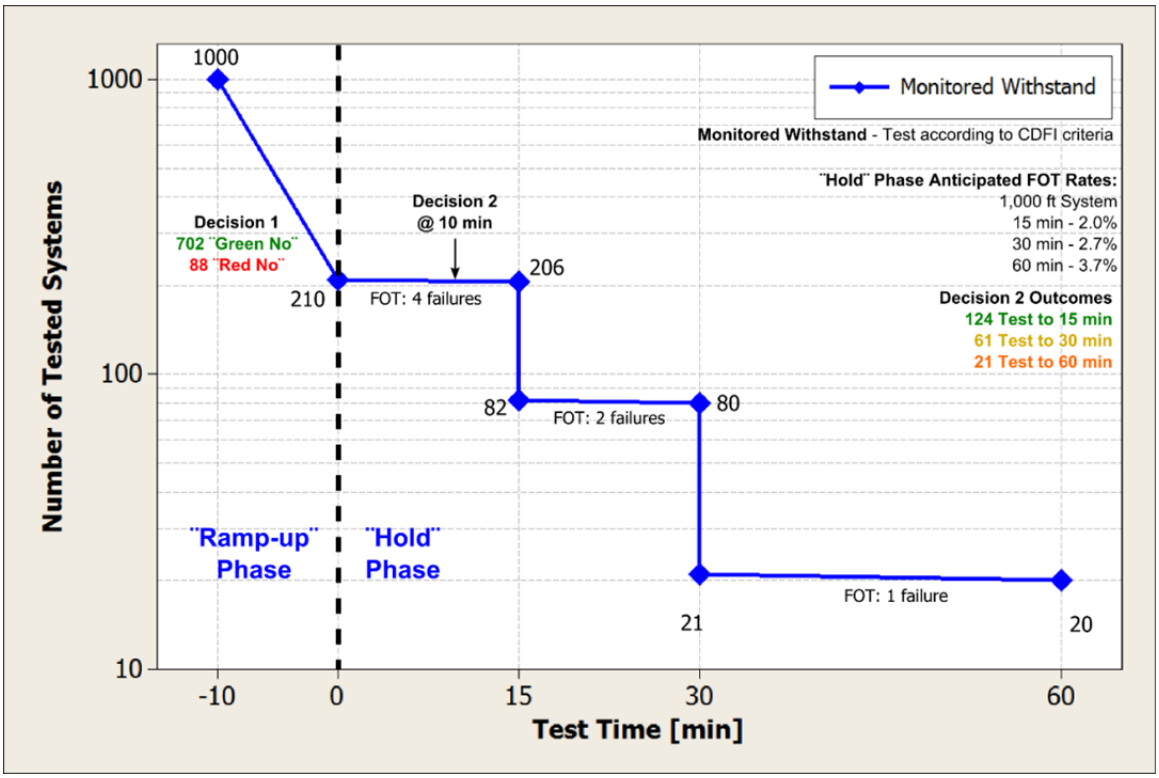

Figure 17: Monitored VLF Withstand Framework on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Figure 17 follows the 210 cable systems that enter the "Hold" phase after passing Decision 1. After the first 15 min, there will have been on average four failures. At this point (Decision 2), 124 of these systems can stop their respective withstand tests while the remaining 82 cable systems must continue. As the systems reach the 30 min point, two cable systems will experience dielectric failures and an additional 59 cable systems will be in position to end their withstand tests. The remaining 21 cable systems will continue to 60 min with one system failing before 60 min. It is worth examining some of these steps in more detail and compare them with the Simple Withstand framework, Figure 18 shows the comparison between Simple VLF (Red) and VLF Tan δ Monitored (Blue) withstand frameworks on the basis of number of tested cable systems and test time for PE-based insulations.

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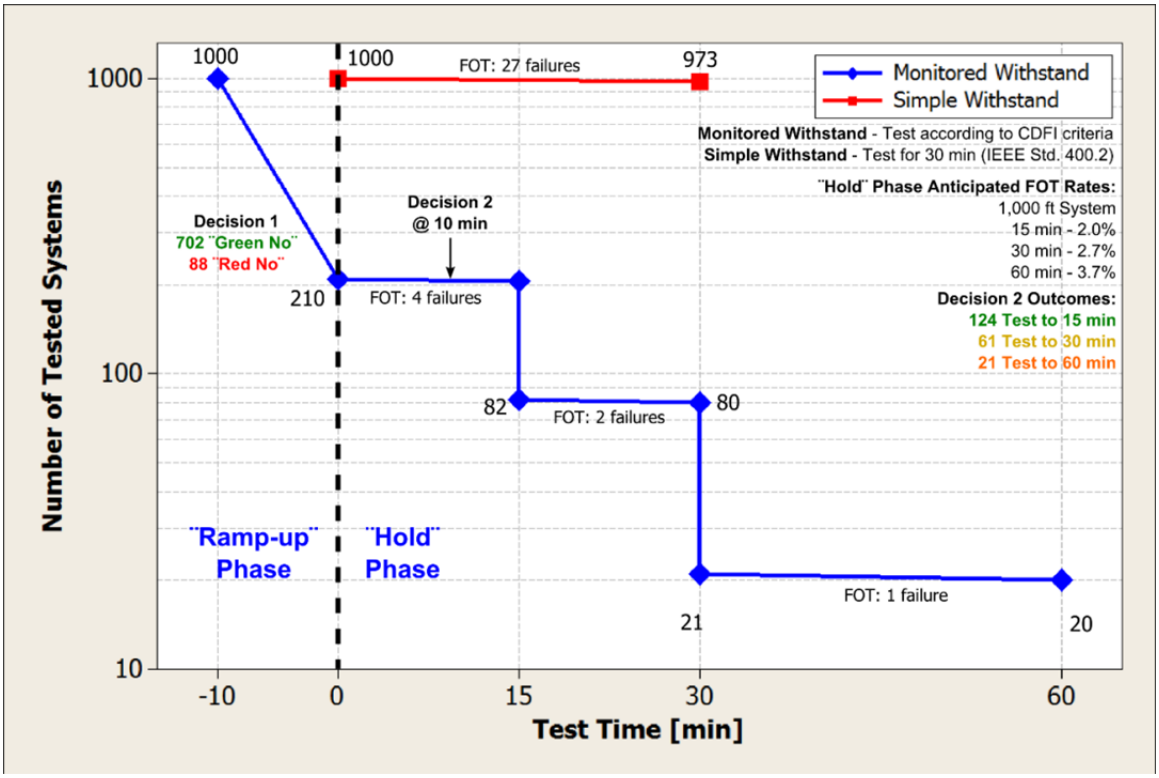

Figure 18: Comparison between Simple VLF (Red) and VLF Tan δ Monitored (Blue) Withstand Frameworks on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Interpretation of Figure 18 reveals that there are considerable differences in how the number of tested systems changes as each framework evolves over test time. In particular, note for the Monitored Withstand framework that the number of tested systems that actually go on to the "Hold" phase is considerably reduced by the diagnostic selection made by Decision 1. A similar effect on the number of tested segments can also be observed at 15 min during the "Hold" phase where again the number of tested systems is considerably reduced by Decision 2. The reduced number of tested segments can have a considerable impact on the total test time of the complete Monitored Withstand test program when compared to a Simple Withstand approach. It is also important to mention that since the number of tested systems is reduced during the test there is also an impact on the number of FOTs and consequently the required emergency actions. In this context, immediate remedial actions refer to actions needed to be undertaken to repair a system that has had a FOT.

The comparison shown in Figure 18 has also been performed for filled and paper insulations and includes additional details such as:

- condition assessment criteria
- number of test set-ups
- expected number of FOTs during the "Hold" phase
- expected number of systems requiring immediate action
- expected number of systems requiring action on a planned basis
- estimation of the "Pass" margin

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- availability of diagnostic information on surviving systems and
- total maximum test times are selected for comparison

Table 14, Table 15, and Table 16 show the comparisons for PE-based, filled, and PILC cable systems, respectively.

As seen in Table 14, the VLF Tan δ Monitored Withstand framework improves upon all aspects of the Simple VLF Withstand framework. In particular, the Monitored Withstand approach leads to a reduction in the total required test time (30,000 min (500 h) versus 15,009 min (250 h)). This represents a 50% reduction in the required time. In addition, the number of systems that require immediate or planned action is 95 (7 immediate and 88 planned) for Monitored Withstand as compared to 27 immediate actions for Simple Withstand. This can be viewed a number of ways but is not unexpected since the Monitored Withstand framework classifies systems with unusual estimated "Pass" margins as systems that require action on a planned basis. It is somewhat utility dependent as to the relative importance of immediate and planned actions.

Table 15 shows a similar difference when Monitored Withstand and Simple Withstand are employed on a set of filled cable systems.

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Table 14: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for PE-based Insulations		
Comparison Issue	**Framework**	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in IEEE Std. 400.2 – 2013	*CDFI Phase II* evaluation of "Ramp-up" and "Hold" phases: • **Decision 1** – Continue to "Hold" phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the "Hold" phase	27	7*
Availability of Survival Information from Withstand ("Hold" Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 203 Systems
Total	1,000 Systems	210 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the "Pass" Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 206 Systems **Decision 3** – 203 Systems
Surviving Systems	None on 973 systems that passed "Hold" Phase	Yes on 993 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	7
Planned	0	88**
Total	27	95
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	15,009 min (250 h)***

* Estimation based on the anticipated FOT rates from *CDFI Phase I* and shown in Figure 18.

** 88 cable systems are assessed as "Red No" from the evaluation of the "Ramp-up" phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 50% of the total maximum test time for the Simple VLF Withstand framework.

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Table 15: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for Filled Insulations		
Comparison Issue	**Framework**	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in the IEEE Std. 400.2 – 2013	*CDFI Phase II* Project evaluation of "Ramp-up" and "Hold" phases: • **Decision 1** – Continue to "Hold" phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the "Hold" phase	27	7*
Availability of Survival Information from Withstand ("Hold" Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 276 Systems
Total	1,000 Systems	283 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the "Pass" Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 279 Systems **Decision 3** – 276 Systems
Surviving Systems	None on 973 systems that passed "Hold" Phase	Yes on 993 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	7
Planned	0	84**
Total	27	91
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	16,105 min (268 h)***

* Estimation based on the anticipated FOT rates from the *CDFI Phase I* and shown in Figure 18.

** 84 cable systems are assessed as "Red No" from the evaluation of the "Ramp-up" phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 54% of the total maximum test time for the Simple VLF Withstand framework.

Table 16 illustrates that paper systems have somewhat unique differences as compared to either

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extruded insulation type.

Table 16: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for Paper Insulations		
Comparison Issue	**Framework**	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in the IEEE Std. 400.2 – 2013	*CDFI Phase II* Project evaluation of "Ramp-up" and "Hold" phases: • **Decision 1** – Continue to "Hold" phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the "Hold" phase	27	12*
Availability of Survival Information from Withstand ("Hold" Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 349 Systems
Total	1,000 Systems	356 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the "Pass" Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 354 Systems **Decision 3** – 349 Systems
Surviving Systems	No for 973 Systems	Yes on 988 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	12
Planned	0	67**
Total	27	79
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	18,940 min (316 h)***

* Estimation based on the anticipated FOT rates from the *CDFI Phase I* and shown in Figure 18.

** 67 cable systems are assessed as "Red No" from the evaluation of the "Ramp-up" phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 63% of the total maximum test time for the Simple VLF Withstand framework.

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Finally, a comparison between VLF Tan δ Monitored Withstand frameworks between insulation types is shown in Table 17 based on the expected number of condition assessment decisions on site and after test, expected number of systems requiring action after test, and total maximum test time for the test program example considered in this section.

Table 17: Comparison between VLF Tan δ Monitored Frameworks Including all Insulation Types

Comparison Issue	PE-based	Filled	Paper
Expected Number of Condition Assessment Decisions			
On Site			
Decision 1 Continue to "Hold" phase?	1,000	1,000	1,000
Decision 2 Amend test time?	206	279	354
After Test			
Decision 3 Final Assessment?	203	276	349
Expected Number of Systems Requiring Action after Test			
Immediate	7	7	12
Planned	88	84	67
Total	95	91	79
Total Maximum Test Time			
Total Test Time	15,009 min (250 h)	16,105 min (268 h)	18,940 min (316 h)
Relative to a Simple Withstand Framework	50%	54%	63%

10.6.5 Monitored Withstand Using Partial Discharge

The quantities of field data provided or gathered where PD is the monitored property for the Monitored Withstand test were not sufficient for developing condition assessment decisions. While technically feasible, the actual implementation of such a program, confirmed by *CDFI* tests/experience, is complicated by the intrinsic difficulties of the PD test setup and analysis (see Chapter 7 and Chapter 8 for details on PD testing). As a result, although conceptually possible, the *CDFI* has not developed a perspective on this technique. Additional suggestions are discussed in Section 10.7.1.

10.6.6 Monitored Withstand with Damped ac (DAC) Voltage Sources

Damped ac voltage sources have often been mentioned in the industry for use in withstand testing. However, as DAC has proven ineffective for withstand tests (see Section 10.6.1); then the inadvisability of DAC voltage sources for monitored withstand tests becomes evident.

Therefore, at the present time, DAC voltage sources do not meet the definition of a withstand test (Simple or Monitored) and thus are not recommended. Field data are needed to show the pass and fail capability and to provide evidence for the third element that defines a withstand test.

10.6.7 Monitored Withstand Using DC Leakage Current

Leakage Current data are primarily gathered during withstand tests utilizing dc voltage sources. The use of dc withstand tests for aged-cable extruded cable systems has been highly discouraged for the last two decades because of the accumulated space charge and its impact on system performance once the cable system is re-energized with 60 Hz. At least one utility continued to utilize dc for its withstand program during the *CDFI* and recorded some leakage current data. These data were limited in scope and thus could not be analyzed in the same manner as the available VLF Tan δ data. As a result, the *CDFI* has not developed a perspective on this technique. Additional suggestions are discussed in Section 10.7.1.

10.7 Outstanding Issues

Monitored Withstand came into existence during the term of the *CDFI* research and so is one of the "younger" techniques available. As such, there remain a number of outstanding issues of which the more important are discussed below.

10.7.1 Monitored Withstand Framework – PD and Leakage Current

During the *CDFI Phase II*, it was not possible to collect enough data for PD and dc leakage current during a Monitored Withstand test to properly establish a framework for these two monitored properties. However, the *CDFI* perspective considers that it is likely that, the hierarchy observed and confirmed by data from Monitored Withstand programs employing dielectric loss measurements, could be generalized for any other monitored property. This is due to the fact that all the levels of the monitored property hierarchy are logically correlated with system performance (i.e. steeper trends, bigger variability, and increased absolute magnitude of the monitored property all should indicate poorer cable system condition). Therefore, the hierarchy for PD and Leakage Current could be conceptualized as follows:

1. Trends within the monitored period. These are likely to be categorical attributes: flat, upward trend, downward trend, etc. They can also be characterized by speeds (e.g. average change per unit time of the monitored property for a pre-established period within the test time.).
2. Stability or scatter of the monitored property for a pre-established period within the test time.
3. Absolute level of the monitored property for a pre-established period within the test time.

Therefore, the Monitored Withstand frameworks for PD and Leakage Current remain as open issues that may be addressed by future research programs.

10.7.2 Criteria Based on Local and Global Data

The criteria for VLF Tan δ Monitored Withstand as well as those developed for other diagnostic techniques are intended, by the nature of this project, to be industry-wide criteria that include test results from as many utilities as possible. This provides a global perspective on each diagnostic technique. This perspective does not distinguish between the variety of system designs, environmental conditions, and installation practices used by the utilities supplying the data. The result is a large dataset that represents the experience of many utilities. At present, criteria are segregated only by insulation type.

Unfortunately, there could be cases where the criteria cannot be ideally applied to a particular case of an individual utility. Indeed, this is specifically recognized in IEEE Std. 400.2 – 2013 where a local utility perspective is advocated. This is due to the many factors that can contribute to system aging such as the manufacturer, vintage, cable/accessory design, operating environment, and operating conditions. In such cases, it would be necessary to generate local data and thus criteria that are based solely on an individual utility's cable system.

The process of developing local criteria is the same as that used to determine global criteria within *CDFI* (see previous quarterly reports and the *CDFI Phase I* final report for more information). The challenge is having enough data from the specific utility to facilitate this process. Therefore, local criteria cannot be developed unless a significant effort is expended during the test. A utility just starting a diagnostic program must rely on the global criteria until they can generate enough data for local criteria to be useful.

10.8 References

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10.9 Relevant Standards

- IEEE Std. 400 – 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.1 – 2007: *IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage*
- IEEE Std. 400.2 – 2004: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)*
- IEEE Std. 400.2 – 2013: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)*
- IEEE Std. 400.3™ – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*
- IEEE Std. 400.4™ – 2014: *Omnibus - IEEE Draft Guide for Field-Testing of Shielded Power Cable Systems Rated 5kV and Above with Damped Alternating Current Voltage (DAC)*
- IEEE Std. 404™ – 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*

10.10 Appendix

10.10.1 Details of Feature Elimination Using Cluster Variable Analysis

One of the problems that occur when considering a large number of Tan δ diagnostic features is how to organize these features (stability, changes with time/voltage at various levels, and magnitudes) into meaningful groups or clusters. Cluster variable analysis is useful because it identifies key variables that explain the principal dimensionality (not variability) of the data. It is used to classify the data into groups when the groups are initially unknown. One important reason to cluster the variables is to reduce their number but, more importantly, it is used in this research to understand the taxonomy and meaning of the Tan δ diagnostic features.

The analysis is an agglomerative hierarchical method that begins with a separate treatment of all features, each forming its own cluster. In the initial step, the two features closest together are joined. In the next step, either a third feature joins the first two (now considered as a stand-alone cluster) or another feature is joined with a different cluster. This process continues until all clusters are joined into one. The complete process, from the initial cluster variable analysis to the final feature selection, is explained later in the chapter for all insulation types.

The agglomerative hierarchical method uses the distances between variables when forming the clusters. These distances are based on a single dimension that uses the absolute Pearson correlation coefficient [17] between features. The correlation coefficient can be translated to a level of similarity between clusters. The level of similarity can be used as a tool to compare the relationship between features or clusters.

The similarity level between two features or clusters, e.g. features or clusters *i* and *j*, is given by the following equation,

$$S_{ij} = \frac{100(1 - d_{ij})}{d_{max}} \qquad \textbf{Equation 1}$$

where,

S_{ij}: Similarity level between features or clusters *i* and *j*,
d_{ij}: distance measure between features or clusters *i* and *j*, based on the absolute Pearson correlation coefficient,
d_{max}: Maximum distance between the initial set of features before starting the clustering procedure.

The interpretation of the level of similarity is quite straightforward. The level of similarity is a number that ranges from 0% to 100%. A similarity level approaching 100% indicates that the features or clusters under investigation are redundant, i.e. they carry essentially the same information. In other words, the features or clusters are highly correlated; thus, they contribute little to solving an eventual classification problem. In contrast, a level of similarity approaching 0% indicates that the features or clusters under investigation are complementary or uncorrelated. Thus, the likelihood of using these features or clusters in an eventual classification problem with good

results is higher than using redundant features or clusters.

There are several algorithms available for the clustering of the Tan δ diagnostic features and each of them may yield different results. However, here, the group average and the furthest neighbor methods are used in the cluster variable analysis of the Tan δ diagnostic features. Specifically, the group average method is used in the agglomerative procedure during clustering. The clustering process is as follows:

1. Initially each feature is declared a cluster and all distances between clusters are calculated.
2. Two clusters with the smallest distance between them are fused together and declared to be a new cluster. This is the beginning of the agglomerative process.
3. All distances between clusters are again calculated and the agglomerative process continues until the number of clusters is one.
4. Once one cluster is left, the number of clusters to be considered for the final feature selection is determined by choosing a similarity level.

The results of the clustering procedure can be represented graphically in a tree-like plot, also known as a dendrogram plot. The dendrogram plot for the cluster variable analysis represents the features under analysis on the x-axis and the level of similarity between features and clusters on the y-axis. The clusters are represented by vertical and horizontal lines between the features.

Determining the number of clusters for the final feature selection can be termed as "cutting the dendrogram". Cutting the dendrogram is akin to drawing a line across the dendrogram to specify the final grouping at a particular similarity level. There is no pre-established procedure on choosing the similarity level for cutting the dendrogram. However, a good similarity level to cut the dendrogram is that level at which a sudden change in the number of initial clusters is observed.

Examples of dendrograms appear in Appendix C, D, and E.

10.10.2 Single Diagnostic Indicator Based on Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a method that combines diagnostic features to create a single diagnostic indicator that puts any set of measurements in context with the "Hold" phase Tan δ measurements database. Therefore, through the single diagnostic indicator, the "Pass" margin can be estimated.

The PCA technique is useful because it takes a given set of points in a high dimensional space and then reduces the dimensionality to a more manageable number. In other words, the PCA technique summarizes the data with several assumed independent variables to a smaller set of derived variables without sacrificing the potential for classification. In fact, the classification capability is enhanced by the PCA [16-17].

The technique provides a predictive model with guidance on how to interpret or "weigh" the primary measurement features. It also allows a physical meaning to be ascribed to the resulting composite factors, i.e. the Principal Components. The PCA approach identifies linear combinations of factors and generates the principal components that better represent the data. The first component has or describes the largest portion of the variance, followed by the second, and then the third, and so on. The PCA redistributes the variance in such a way that the first *k* components explain as much as possible of the total variance of the data. It must be noted that the higher the variance the higher the potential for better classification.

Another important reason for choosing the PCA technique is that in many data analysis/mining scenarios, seemingly independent variables are highly correlated, which affects model accuracy and reliability. PCA is able to detect such correlations and then essentially exclude the redundant information; however, some of the redundancy has been previously filtered by the cluster variable analysis discussed earlier.

To illustrate and easily understand the essentials of the PCA technique, Figure 19 shows a qualitative explanation of the technique. The circles represent a dataset in which there are two features (axes) and the variance within this dataset with respect to these features is represented by the area of the rectangle denoted as Area 1. The PCA method attempts to reduce the variance by generating new axes that are linear combinations of the available two features. This causes a rotation/translation of the original axes from F1-F2 to PC1-PC2. The new variance can then be thought of as the area of the rectangle represented by Area 2. Comparing the areas clearly shows that area 2 is smaller and, therefore, has less variance than the original configuration in Area 1. As mentioned above, this process reduces the dimension of a dataset to as few or as many principal components as are needed.

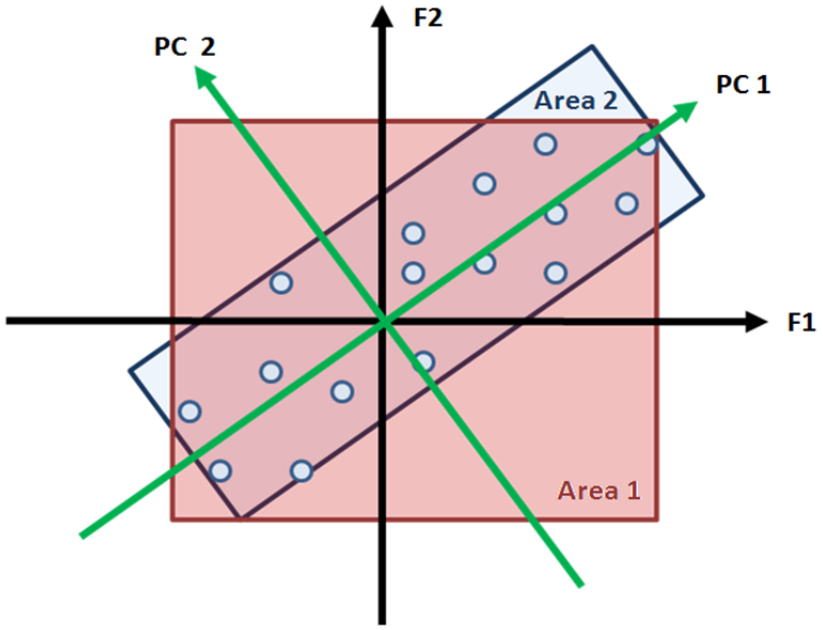

Figure 19: Graphical Interpretation of Principal Component Analysis (PCA)

Once the dimensionality has been reduced, the selected principal components can be used to compute a PCA distance from a known set of PCA transformed diagnostic features providing in this way the single diagnostic indicator. The process to compute the single diagnostic indicator appears in Figure 20.

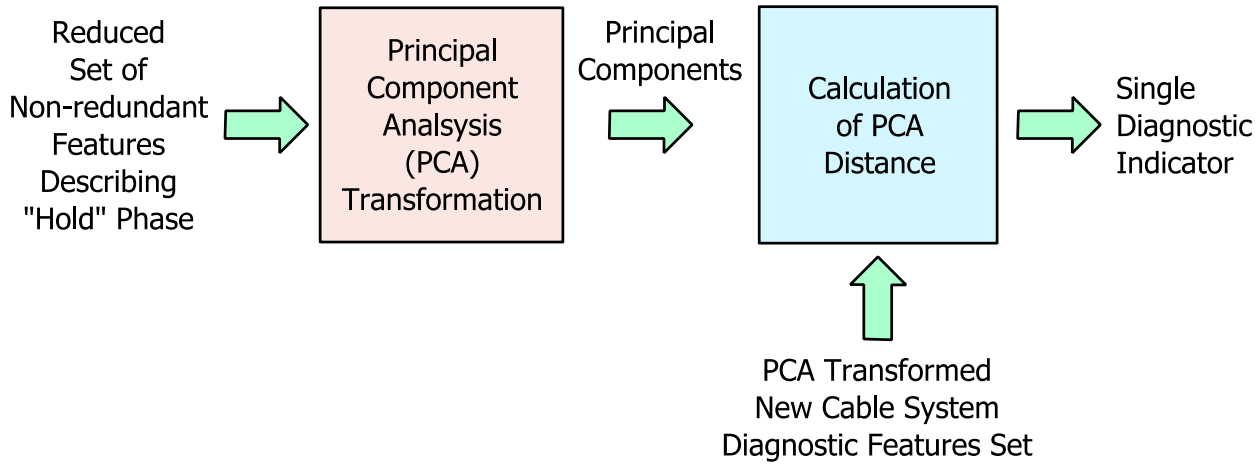

Figure 20: Calculation of the Single Diagnostic Indicator from PCA

As seen in Figure 20, the known set of PCA transformed diagnostic features corresponds to features of a new cable system and this allows for establishing a critical diagnostic for the single diagnostic indicator and its corresponding "Pass" margin. In this case, the critical levels are also determined using the Pareto Principle [17], for two critical levels at the 80th and 95th percentiles of the data. The interpretation of the single diagnostic indictor based on PCA distance and its corresponding "Pass" margin (Decision 3 on Figure 6) is as follows

:

- Cable systems showing a PCA distance bellow the 80th percentile have a good "Pass" margin and thus are classified as "No Action Required."
- Cable systems showing a PCA distance between the 80th and 95th percentiles have an uncertain "Pass" margin and thus are to be classified as "Further Study."
- Cable systems showing a PCA distance beyond the 95th percentile have a poor "Pass" margin and thus are classified as "Action Required."

The interpretation of the single diagnostic indicator based on PCA distance completes the picture of the Monitored Withstand test framework using VLF Tan δ measurements and it is one of the more important contributions of the *CDFI*. The next sections show results of the "Hold" phase evaluation for all insulation types.

10.10.3 PE-Based Insulation Final Assessment

This appendix describes the analysis process employed on the available VLF Tan δ Monitored Withstand data to develop criteria for making the condition assessment for PE-based cable systems. Also discussed are the test cases used to validate the approach.

Results of the cluster variable analysis of the diagnostic features used to characterize the "Hold" phase for PE-based insulations appear in Figure 21. As a reminder, the feature descriptions are also below:

1. **Tan δ Stability (STD)** – This feature represents the time dependence and is reported as the standard deviation of sequential measurements at the particular test voltage level irrespective of it is a 15, 30, or 60 min test.
2. **Initial Tan δ (Init TD)** – This feature represents the initial measured loss level at the beginning of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
3. **Final Tan δ (Final TD)** – This feature represents the final measured loss level at the end of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
4. **Level of Tan δ (Mean TD)** – This feature represents the average level of loss over the full "Hold" phase irrespective of it is a 15, 30, or 60 min.
5. **Speed (rate of change over time) of Tan δ between 0 and 5 min (SPD 0-5)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the first 5 minutes of the "Hold" phase. More importantly, this feature also provides information about the trend of the measurements during the period under consideration; i.e. positive values indicate an increasing trend and *vice versa*.
6. **Speed of Tan δ between 5 and 10 min (SPD 5-10)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the second 5 minutes of the "Hold" phase.
7. **Speed of Tan δ between 10 and 15 min (SPD 10-15)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the third 5 minutes of the "Hold" phase.
8. **Speed of Tan δ Between 0 and final test time (SPD 0-t_{final})** – This feature represents an

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estimate of the overall rate of change of the loss level (Tan δ) with time for a completed "Hold" phase irrespective of it is a 15, 30, or 60 min test.

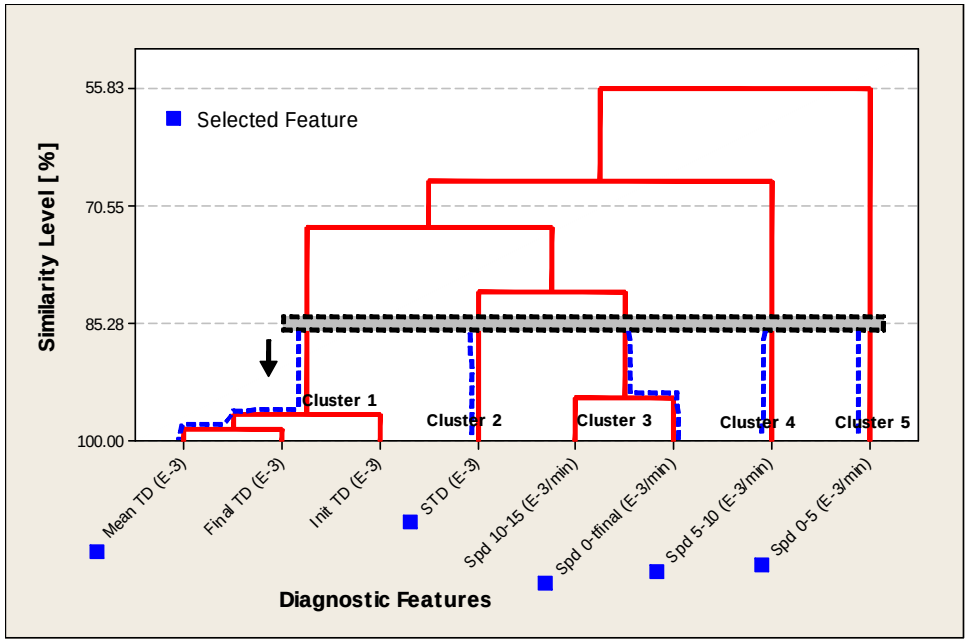

Figure 21: Cluster Variable Analysis Results for PE-based Insulations (Based on data as described in Table 4)

As Figure 21 shows, when a similarity level of approximately 85% is chosen to cut the dendrogram, five clusters result:

- Cluster 1 – Mean TD, Final TD, and Init TD
- Cluster 2 – STD
- Cluster 3 – SPD 10-15 and SPD 0-tfinal
- Cluster 4 – SPD 5-10
- Cluster 5 – SPD 0-5.

In the approach presented here, each cluster may be represented by one single diagnostic feature from within that cluster. The selection of the diagnostic feature to represent each cluster appears in Figure 21 by the blue dashed lines and thus the final selected set of features is indicated by the blue squares.

The cluster variable analysis results also provide insight into the types of features applicable for the PCA as well as their relative importance. The assumption here is that features that are more dissimilar may be more important. Following this logic, the more important features are the speeds (clusters 3, 4, and 5); particularly at the beginning of the "Hold" phase when higher speed magnitudes are generally observed, followed by the STD (cluster 2) and loss level (cluster 1). The results of the cluster variable analysis shown in Figure 21 indicate that five of the initial set of eight diagnostic features should be considered for the PCA.

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PCA was applied to the "Hold" phase monitored withstand database of PE-based insulations. Figure 22 shows the transformation from two Tan δ diagnostic features (STD and SPD 0-t_{final}) to the first two principal components (PC1 and PC2). As mentioned previously, the PCA reduces the dimensionality; however, this technique does not directly provide a single diagnostic indicator by itself. It does enable the construction of simplified and appropriate feature maps that may enhance the classification potential of the diagnostic features when they are appropriately combined. The principal component feature maps provide a single condition assessment descriptor. The transformation can be observed in Figure 22 in which the application of the PCA transformation reveals a clearer connection between PC1 and PC2 (right side of Figure 22) as compared to the original data (STD and SPD 0-t_{final} shown on the left side of Figure 22).

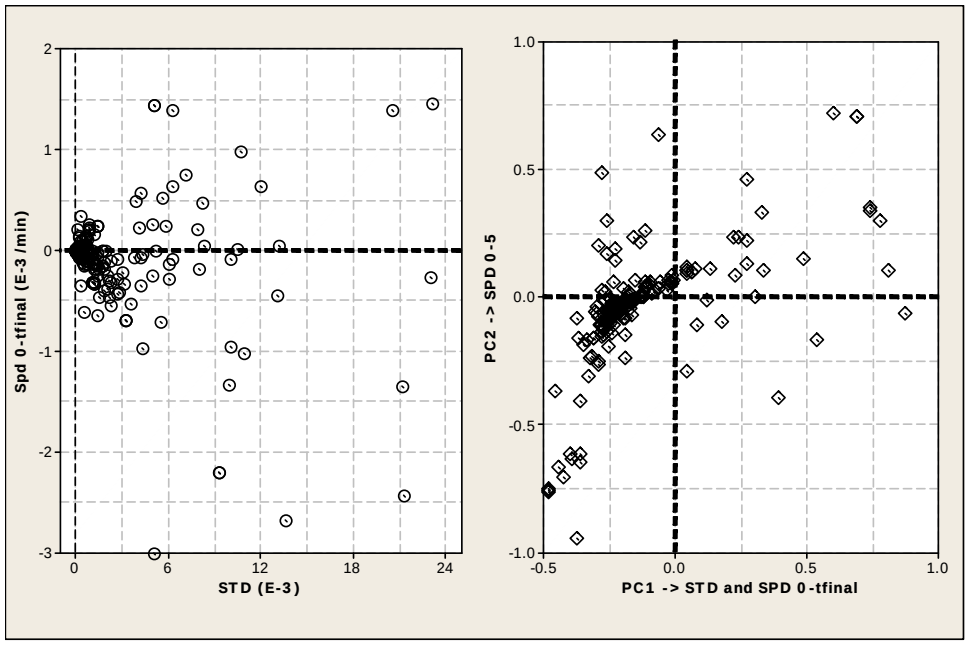

Figure 22: STD vs. SPD 0-t_{final} (left) and PC1 vs. PC2 (right) – PE-based Insulations

Applying PCA to the full database yields the principal components shown in Table 18. This table shows the percentage of variance accounted for by each principal component (i.e. the variability) as well as the diagnostic features that contribute the most to each component. Results from Table 18 indicate that only four principal components are required to describe 98% of the data variance. It is, therefore, reasonable to utilize four principal components.

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Table 18: PCA Variances and Component Composition for PE-based Insulations			
Principal Component	**Variance Described by Component [%]**	**Cumulative Variance [%]**	**"Hold" Phase Tan δ Diagnostic Features**
PC1	49	49	STD and SPD 0-t_{final} (Variability and trend)
PC2	28	77	SPD 0-5 (Trend)
PC3	12	89	Mean TD (Level of Loss)
PC4	9	98	STD (Variability)
PC5	2	100	Not relevant

The main observation from the PCA results in Table 18 is that they also give an indication of the importance and relevance of the "Hold" phase Monitored Withstand Tan δ diagnostic features. The features can be ranked in importance as:

1. trend of the measurements (SPD 0-t_{final} and SPD 0-5)
2. time dependence (STD) and
3. loss level (Mean TD)

The overarching question is - How to combine all diagnostic features into a single indicator?

The identification of suitable Principal Components also allows these components to be combined together to form a set of coordinates. The approach adopted elsewhere within *CDFI* has been to calculate the Euclidean distance between the data point and a reference point. The greater the distance, the less like the reference point is to the newly acquired data point. Applying this principle to these data, the best choice for a reference point is a new cable system. As a result, the distance calculated essentially quantifies the gulf between a new cable system and an aged system.

Figure 23 shows the combined PCA distance of the four principal components for all the available Monitored Withstand data from PE-based cable systems. If all the data are ranked from smallest (most like new) to largest (least like new) this gives the rank position, which can easily be converted to a percentage. In practice, the resulting graph might conveniently be regarded as the "Pass" margins for the population of cable systems tested. The interpretation is straightforward as the higher rank positions represent those cable systems that are least "like new" while the low rank positions correspond to those systems that most "like new".

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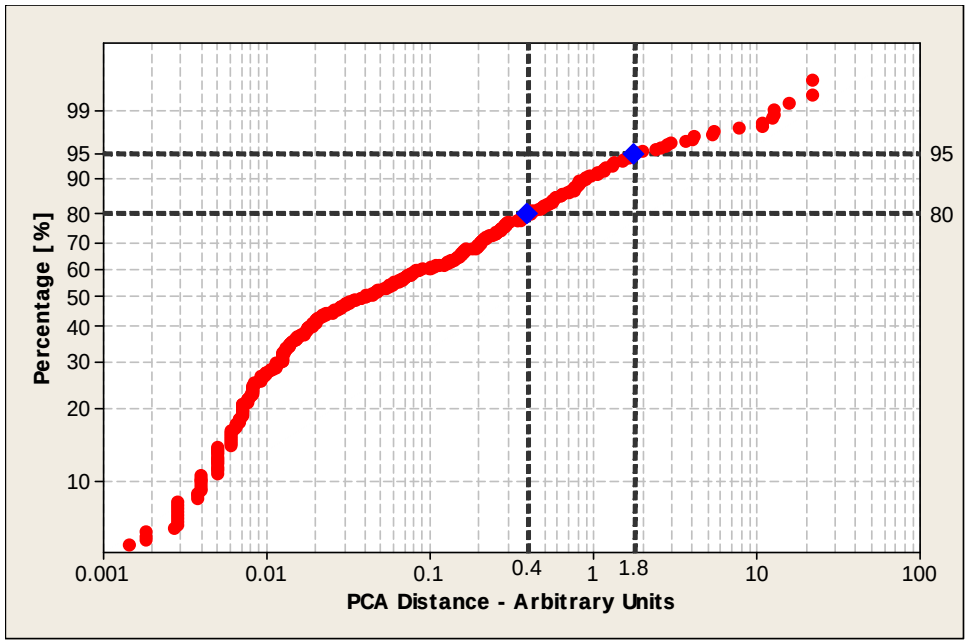

Figure 23: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for PE-based Cable Systems

Critical level for the single diagnostic indicator can be established using the same Pareto Principle as before. The 80th and 95th percentage ranks appear in Figure 23 and they correspond to PCA distances of 0.4 and 1.8, respectively. The critical levels for the single diagnostic indicator are then used to establish the final condition assessment and thus address Decision 3, "Hold" Phase evaluation, of the Monitored Withstand framework. The critical levels for the single diagnostic indicator and corresponding condition assessment categories appear in Figure 24.

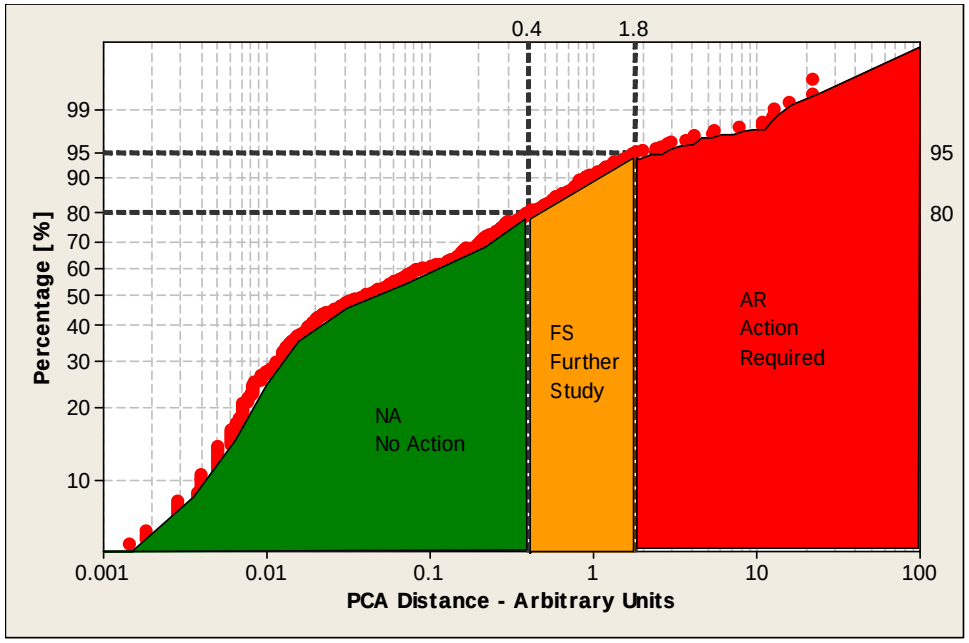

Figure 24: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for PE-based Cable Systems with Condition Assessment Categories

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Several case studies using experimental data/features illustrate the application of the research PCA to the evaluation of the "Hold" phase of a Monitored Withstand test. The summary of these case studies appears in Table 19.

Table 19: Cases Studies for "Hold" Phase Evaluation for PE-based Insulations

Case No.	Description	SPD 0-5 [E-3/min]	SPD 5-10 [E-3/min]	SPD 0-t_{final} [E-3/min]	STD [E-3]	Mean Tan δ [E-3]	Percentage Rank [%]
1	New System	0.002	0.002	0.002	0.01	0.1	2.9
2	Features at 80% level and Pos. Speeds *	0.350	0.350	0.350	15.00	0.3	76.0
3	Features at 80% level and Neg. Speeds *	-0.350	-0.350	-0.350	15.00	0.3	74.0
4	Features at 95% level and Pos. Speeds *	3.000	3.000	3.000	5.00	70.0	95.0
5	Features at 95% level and Neg. Speeds *	-3.000	-3.000	-3.000	5.00	70.0	94.0
6	Utility Test 1	0.420	0.140	0.227	0.80	10.1	69.0
7	Utility Test 2	2.500	-0.480	0.067	5.20	6.3	89.0
8	Utility Test 3	3.960	2.480	1.460	23.10	200.0	96.0

* The 80% and 95% diagnostic feature levels correspond to level of the diagnostic features for "Hold" phase" Evaluation – Decision 2 – Amend Test Time? as shown in Table 8 considering constant speed values during the period under evaluation.

In Table 19, the following examples are included:

- **Case 1:** New PE cable system that lies within the 0.03st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 25 by the solid black circle symbol.
- **Case 2:** All diagnostic features set to their respective 80% levels (black square symbol in Figure 25) with positive speeds. It is important to note here that all the features at the 80% level yield a percentage of 76.0%. Therefore, there is an acceptable correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features are at their respective 80% levels with negative speeds. In this case all of the features set at the 80% level yield a percentage of 74.0%. Therefore, there is again good correlation between the feature levels and the overall condition assessment.
- **Case 4:** All diagnostic features are set at their 95% levels (black triangle symbol in Figure 25) with positive speeds. In this case, the percentage is exactly 95.0%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all

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features together.

- **Case 5:** All diagnostic features set at their 95% levels with negative speeds. In this case, the percentage is 94.0%. Note again the good correlation between the features levels and the overall condition assessment.
- **Case 6:** Real case and represents one of the low to mid performers. The PCA indicates that in 2014 the cable system is within the upper "No Action" category with a rank of 69.0%.
- **Case 7:** Real case and represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 89.0%.
- **Case 8:** Real case and represents one of the poorest performer in a cable system (black diamond symbol in Figure 25). The PCA indicates that in 2013 the cable system is within the poorest 4% of all PE-based cable systems.

The symbols in Figure 25 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 19.

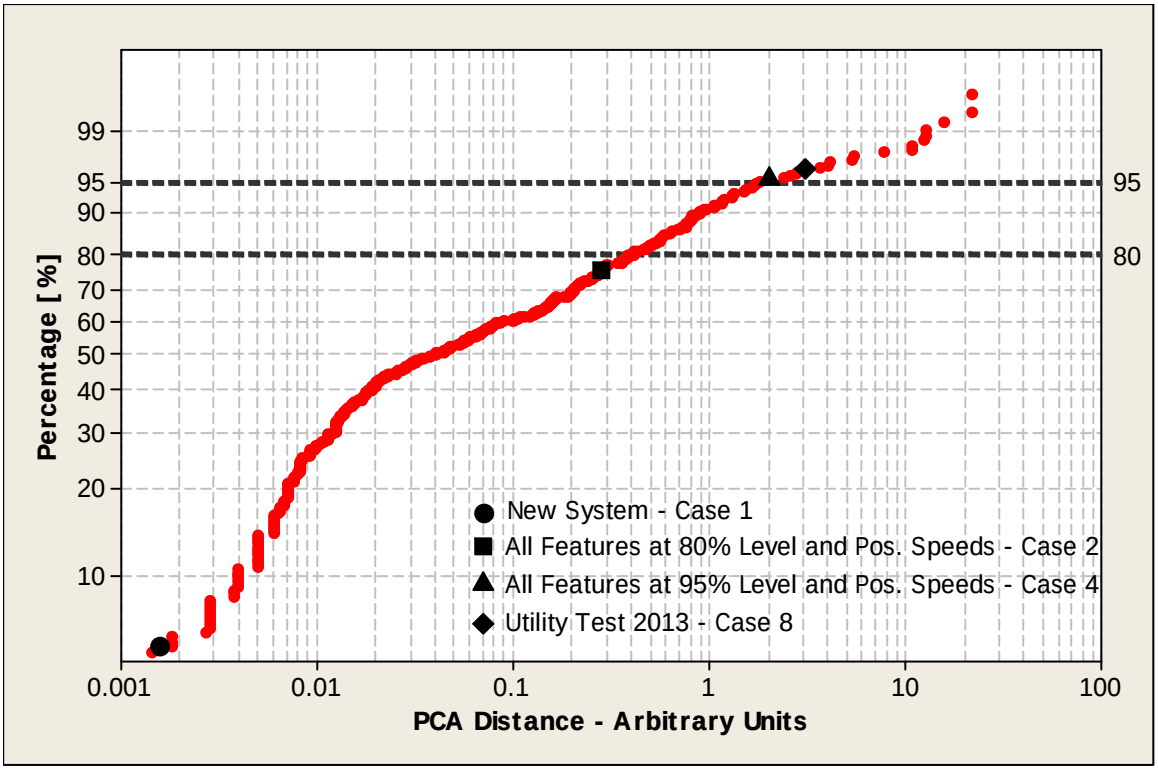

Figure 25: Empirical Cumulative Distribution of the PCA Distance from CDFI Research Used for Evaluating the "Hold" Phase for PE-based Cable Systems with Relevant Case Studies from Table 19

Observe that in Table 19 there are only small differences between the ranks of Cases 2 and 3 and Cases 4 and 5. This is because the distance approach only considers the magnitude of the trend and not its direction (i.e. positive speeds (not vectors) compared to negative speeds). At first glance, this may be perceived as a disadvantage of the PCA distance approach. However, even though negative trends (negative speeds) generally indicate better system conditions than systems with positive

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trends (positive speeds) to date there is no theoretical nor experimental basis to support this belief, however reasonable, for PE-based insulations.

10.10.4 Filled Insulation Final Assessment

This appendix describes the analysis process employed on the available VLF Tan δ Monitored Withstand data to develop criteria for making the condition assessment for filled cable systems. Also discussed are the test cases used to validate the approach.

Results of the cluster variable analysis of the diagnostic features used to characterize the "Hold" phase for filled insulations appear in Figure 26. Note that the same feature set as was used in Appendix A is used in Figure 26.

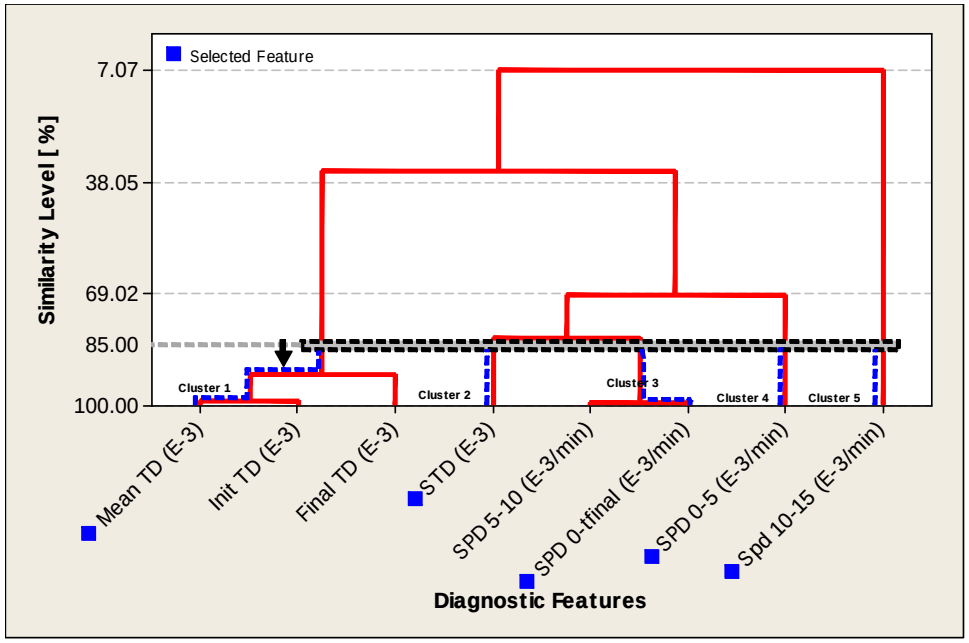

Figure 26: Cluster Variable Analysis Results for "Hold" Phase Features for Filled Insulations (Based on data as described in Table 4)

Using the same approach as was used for PE-based insulations, the dendrogram can be reduced to four clusters. In fact, the same features are identified for Filled insulations as PE-based insulations.

Applying PCA to the filled insulations database yields the principal components shown in Table 20. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features that contribute the most to each component. Results from Table 20 indicate that only three principal components are required to describe approximately 96% of the data variance.

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Table 20: PCA Variances and Component Composition for Filled Insulations			
Principal Component	**Variance Described by Component [%]**	**Variance Described by Component Cumulative [%]**	**"Hold" Phase Tan δ Diagnostic Features**
PC1	51.8	51.8	SPD 0-t_{final} and STD (Trend and Variability)
PC2	25.9	77.7	Mean TD (Level of Loss)
PC3	18.3	96.0	SPD 10-15 (Trend)
PC4	3.7	99.7	Not relevant since these components only describe 4% of the variability
PC5	0.3	100.0	

Figure 27 shows the combined PCA distance of the three principal components for all the available filled insulation Monitored Withstand data. The approach is again the same as the PE-based insulation example in Appendix C. However, the features and feature order used is quite different. Furthermore, the distances that correspond to the 80th and 95th percentiles are quite different at 0.4 and 2.7, respectively.

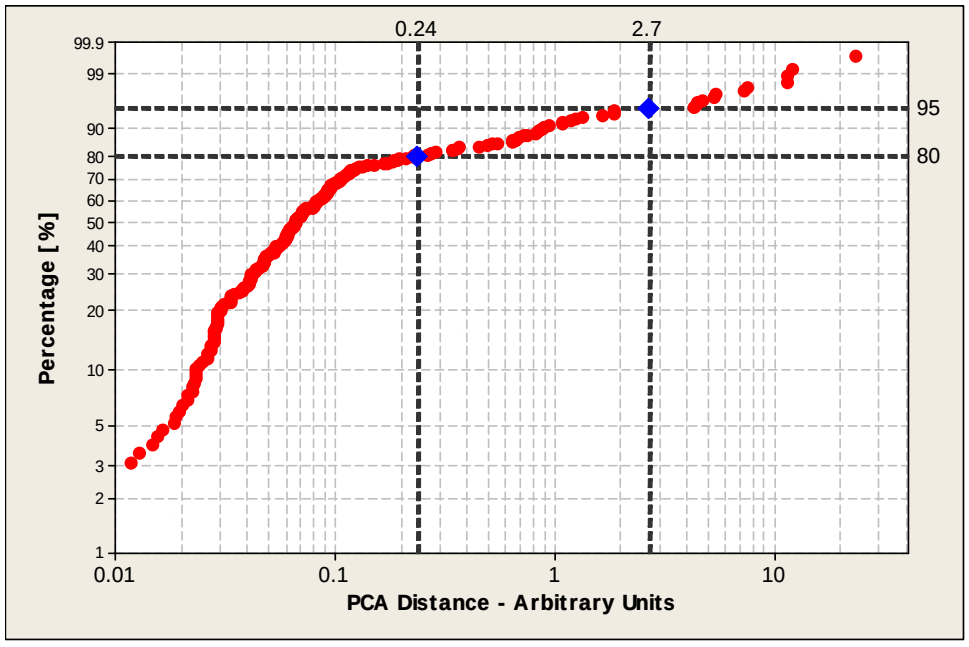

Figure 27: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Filled Cable Systems

Several case studies using experimental data/features illustrate the application of the PCA to the evaluation of the "Hold" phase of a monitored withstand test and they appear in Table 21.

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Table 21: Cases Studies for "Hold" Phase Evaluation for Filled Insulations							
Case No.	**Description**	**SPD 10-15 [E-3/min]**	**SPD 0-5 [E-3/min]**	**SPD 0-t_{final} [E-3/min]**	**STD [E-3]**	**Mean Tan δ [E-3]**	**Percentage Rank [%]**
1	New System	0.002	0.002	0.002	0.01	3.5	2.5
2	Features at 80% level and Pos. Speeds *	0.060	0.060	0.060	0.30	13.0	77.0
3	Features at 80% level and Neg. Speeds *	-0.060	-0.060	-0.060	0.30	13.0	79.0
4	Features at 95% level and Pos. Speeds *	0.600	0.600	0.600	5.00	105.0	94.0
5	Features at 95% level and Neg. Speeds *	-0.600	-0.600	-0.600	5.00	105.0	94.0
6	Utility Test 1	-0.040	-0.040	-0.033	0.30	5.3	72.0
7	Utility Test 2	-0.520	-0.100	-0.287	1.70	22.8	93.0
8	Utility Test 3	1.680	1.120	0.470	5.20	130.7	96.0

* The 80% and 95% diagnostic feature levels correspond to the level of the diagnostic features for "Hold" phase Evaluation – Decision 2 – Amend Test Time? as shown in Table 9 considering constant speed values during the period under evaluation.

In Table 21, the following examples are included:

- **Case 1:** New Filled cable system lies at the 0.03st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 28 by the solid black circle symbol.
- **Case 2:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 28) with positive speeds. Note here that all the features at the 80% level yield a percentage of 77.0%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features set at their respective 80% levels with negative speeds. Note here that all the features at the 80% level yield a percentage of 79.0%. Therefore, there is again good correlation between the features levels and the overall condition assessment.
- **Case 4:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 28) with positive speeds. In this case, the percentage is 94%. This implies good correlation between the feature levels and the overall assessment considering all features together.
- **Case 5:** All diagnostic features set at their 95% levels with negative speeds. In this case, the percentage is again 94.0%. There is once again good correlation between the feature levels and the overall condition assessment.

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- **Case 6:** Real case that represents one of the mid to high performers. The PCA indicates that the cable system is within the mid to higher "No Action" category with a rank of 72.0%.
- **Case 7:** Real case that represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 93.0%.
- **Case 8:** Real case that represents one of the poorest performers (black diamond symbol in Figure 28). The PCA indicates that the cable system is within the poorest 4% of all filled insulated cable systems.

The symbols in Figure 28 represent selected test cases used as examples and their computed PCA distance (Percentage) results appear in Table 21.

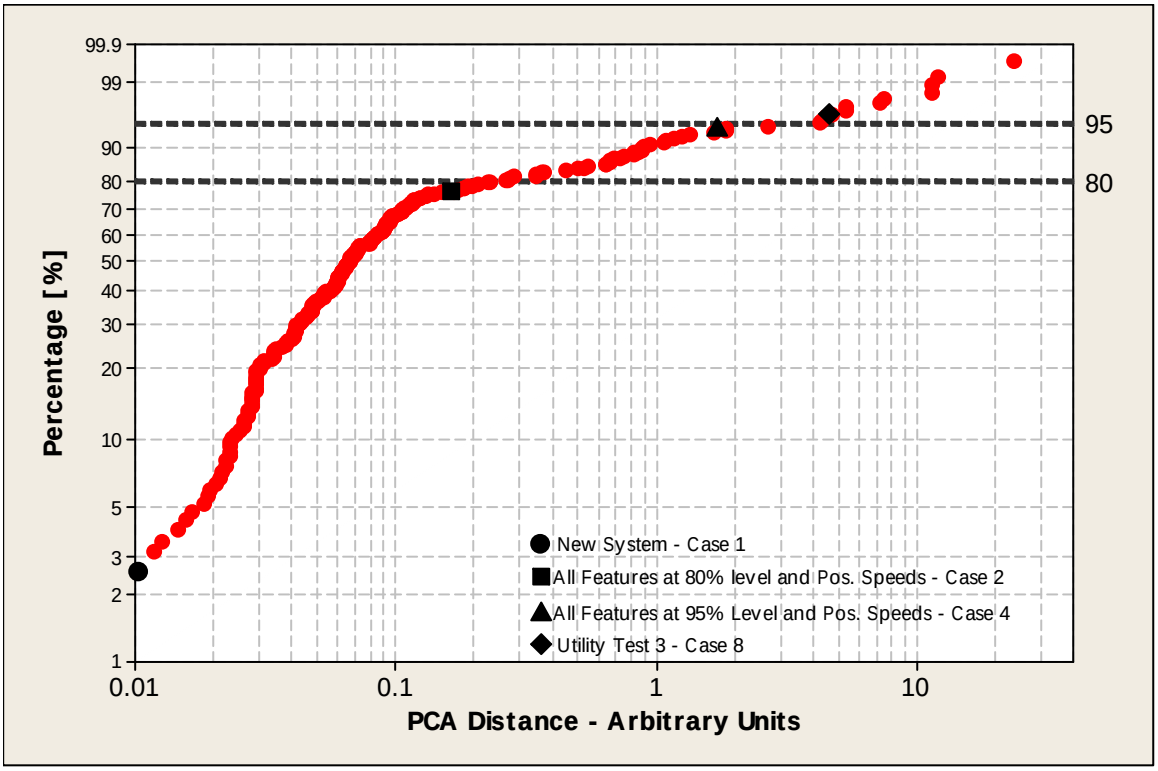

Figure 28: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Filled Cable Systems with Relevant Case Studies Presented in Table 21

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10.10.5 PILC Insulation Final Assessment

The set of diagnostic features used to characterize the "Hold" phase for paper insulations is the same set used for PE-based insulations as described earlier in Figure 12. Consequently, results of the cluster variable analysis of the selected set of diagnostic features appear in Figure 29. Note that the feature set is identical to the filled and PE-based studies.

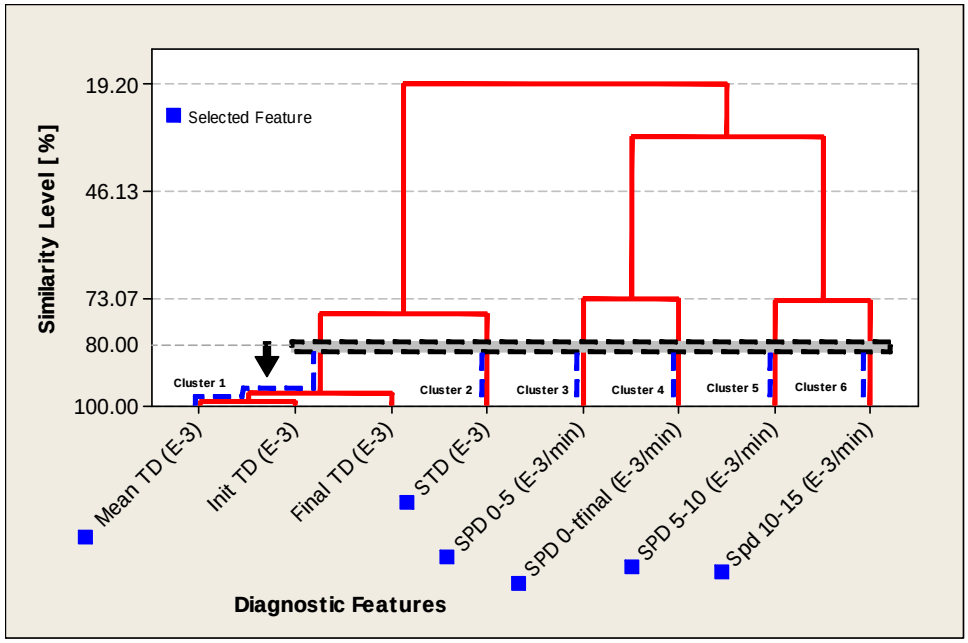

Figure 29: Cluster Variable Analysis Results for the Diagnostic Features Selected to Characterize the "Hold" Phase for Paper Insulations (Based on data as described in Table 4)

The results of the cluster variable analysis shown in Figure 29 indicate that six of the initial eight diagnostic features should be included in the PCA.

Applying PCA to the paper insulation database yields the principal components shown in Table 22. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features that contribute the most to each component. Results from Table 22 indicate that only three principal components are required to describe approximately 95% of the data variance.

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Table 22: PCA Variances and Component Composition for Paper Insulations			
Principal Component	**Variance Described by Component [%]**	**Variance Described by Component Cumulative [%]**	**"Hold" Phase Tan δ Diagnostic Features**
PC1	44.4	44.4	SPD 10-15 and STD (Trend and Variability)
PC2	29.0	73.4	SPD 0-t_{final} (Trend)
PC3	21.3	94.7	Mean TD (Level of Loss)
PC4	3.0	97.7	Not relevant since these components only describes approximately 5% of the variability
PC5	2.0	99.7	
PC6	0.3	100.0	

In the same manner as PE-based and filled insulations, the use of the PCA technique has allowed developing a combined diagnostic indicator scheme in which all independent diagnostic features are considered together for a final condition assessment.

Figure 30 shows the combined PCA distance of the three principal components for all the available Monitored Withstand data of paper insulated cable systems.

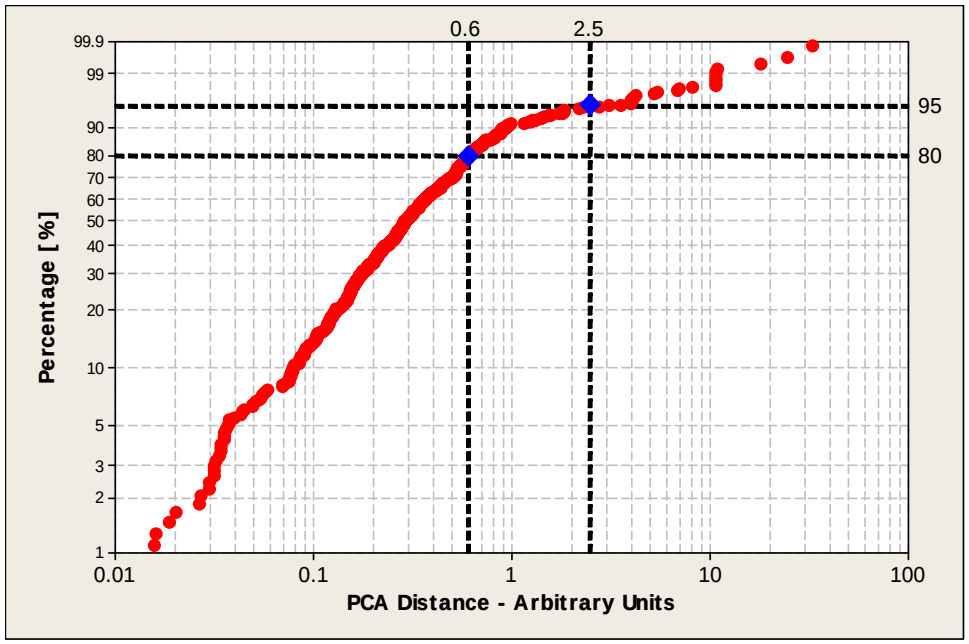

Figure 30: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Paper Cable Systems

Critical levels for the single diagnostic indicator can be established in the same manner as shown before by considering the critical level located at the 80th and 95th percentage ranks. The 80th and

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95th percentage ranks appear in Figure 30 and they correspond to PCA distances of 0.6 and 2.5, respectively. Several case studies illustrate the application of the PCA to the evaluation of the "Hold" phase of a monitored withstand test and they appear in Table 23.

Table 23: Cases Studies for "Hold" Phase Evaluation for Paper Insulations

Case No.	Description	SPD 10-15 [E-3/min]	SPD 5-10 [E-3/min]	SPD 0-t_{final} [E-3/min]	SPD 0-5 [E-3/min]	STD [E-3]	Mean Tan δ [E-3]	Percentage Rank [%]
1	New System	0.002	0.002	0.002	0.002	0.01	12.0	1.9
2	Features at 80% level and Pos. Speeds *	0.140	0.140	0.140	0.140	0.60	80.0	74.6
3	Features at 80% level and Neg. Speeds *	-0.140	-0.140	-0.140	-0.140	0.60	80.0	74.6
4	Features at 95% level and Pos. Speeds *	0.500	0.500	0.500	0.500	5.40	180.0	93.1
5	Features at 95% level and Neg. Speeds *	-0.500	-0.500	-0.500	-0.500	5.40	180.0	93.1
6	Utility Test 1	0.040	0.080	0.100	0.180	0.40	32.7	30.1
7	Utility Test 2	-0.040	-0.060	-0.100	-0.200	0.40	131.5	89.6
8	Utility Test 3	-4.640	-17.70	-0.750	20.100	32.10	169.0	98.7

* The 80% and 95% diagnostic features levels correspond to level of the diagnostic features for "Hold" phase Evaluation – Decision 2 – Amend Test Time? as shown in Table 10 considering constant speed values during the period under evaluation.

In Table 23, the following examples are included:

- **Case 1:** New paper cable system that lies within the 0.02st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 31 by the solid black circle symbol.
- **Case 2:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 31) with positive speeds. Note here that all the features at the 80% level yield a percentage of 74.6%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 31) with negative speeds. Note here that all the features at the 80% level yield a percentage of 74.6%. Again, there is good correlation between the feature levels and the overall condition assessment.
- **Case 4:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 31) with positive speeds. In this case, the percentage is 93.1%.

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- **Case 5:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 31) with negative speeds. As before, the percentage is 93.1%.
- **Case 6:** Real case and represents one of the low to mid performers. The PCA indicates that the cable system is within the lower to mid "No Action" category with a rank of 30.1%.
- **Case 7:** Real case and represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 89.6%.
- **Case 8:** Real case and represents one of the poorest performers (black diamond symbol in Figure 31). The PCA indicates that the cable system is within the poorest 2% of all paper insulated cable systems.

The symbols in Figure 31 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 23.

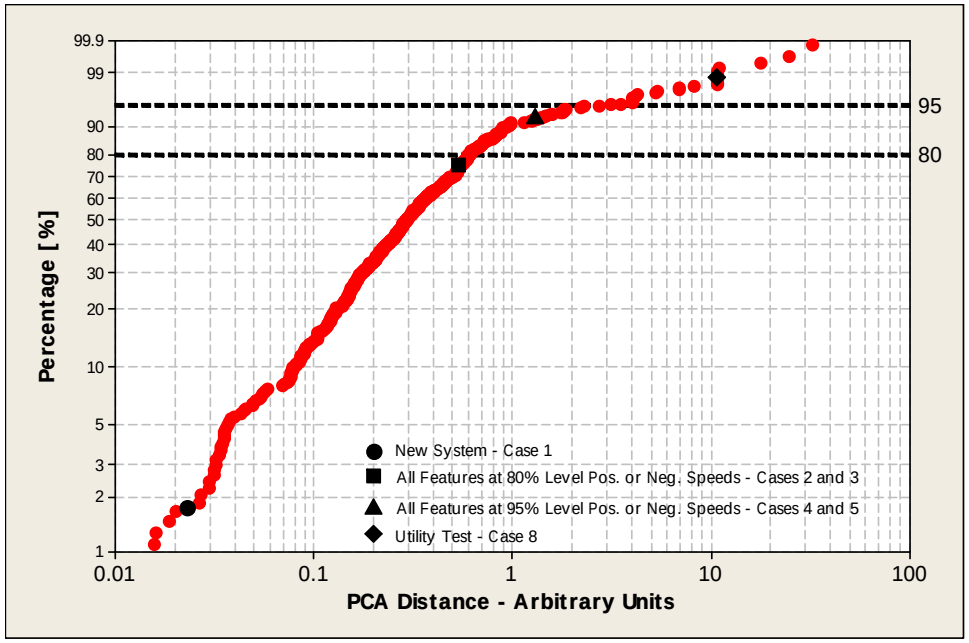

Figure 31: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Paper Cable Systems with Relevant Case Studies Presented in Table 23

CHAPTER 11

Metallic Shield Assessment

Jean Carlos Hernandez-Mejia and Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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11.0 METALLIC SHIELD ASSESSMENT

Most US electric utility companies installed thousands of miles of unjacketed, bare concentric neutral cables during the 1960s and 1970s. Analysis of early, unexpected failures revealed issues with neutral corrosion and many utilities decided to add an overall jacket to the cable construction. The jacket serves to protect the metallic shield and cable core from outside elements (moisture, rocks, etc.). Current experience indicates that jackets are effective at reducing moisture ingress and subsequent corrosion of the metallic shield. But a substantial installed population of unjacketed concentric neutral cable remains in service and shield corrosion has led to stray voltage and safety problems as well as cable failures.

As problems due to metallic shield corrosion increase, utilities are faced with making the decision whether to repair or replace these systems. Most diagnostic techniques investigated during CDFI focused on the condition of the dielectric system. This chapter focuses on techniques for assessing the condition of the metallic shield, which is also referred to as the cable neutral.

11.1 Test Scope

The application of cable diagnostic techniques to estimate the condition of the metallic shield of a power cable system is based on the following:

- **Cross Sectional Area Loss:** This condition is usually progressive with time and is due to corrosion. A reduced metallic shield cross sectional area diminishes the cable system capacity to safely carry normal operating and fault currents that may pose a risk to personnel and equipment.
- **Continuity Break:** This condition could be the result of poor workmanship, localized corrosion, or fault current at one location affecting the metallic shield at other locations of the cable system. A cable system with a degraded metallic shield is not able to withstand fault currents it was originally designed to handle and thus the fault current may mechanically and electrically stress degraded locations, resulting in breaks that can go undetected.
- **Loss of Contact with Cable Insulation Shield:** Metallic shield no longer makes good (sufficient) contact with the insulation shield as a result of cable corrosion or insulation shield degradation. A poor electrical contact between the metallic shield and cable insulation shield distorts the designed cable core electric field profile. The distortion may lead to surface arcing, damaging the cable core. While uncommon, mineral deposits at the metallic shield/insulation shield interface can also cause the loss of contact between these components.

The main application for diagnostic techniques for assessing metallic shield integrity is on unjacketed, concentric neutral cables. Figure 1 to Figure 5 show examples of the corrosion problems observed on unjacketed concentric neutral cables.

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Figure 1: Unjacketed Concentric Neutral Cable with Corroded Neutral Wires (#14 AWG)

Figure 2: Corrosion of Concentric Neutral Wire Resulting in Loss of Metallic Shield Cross Sectional Area and Contact with Cable Insulation Shield (#14 AWG)

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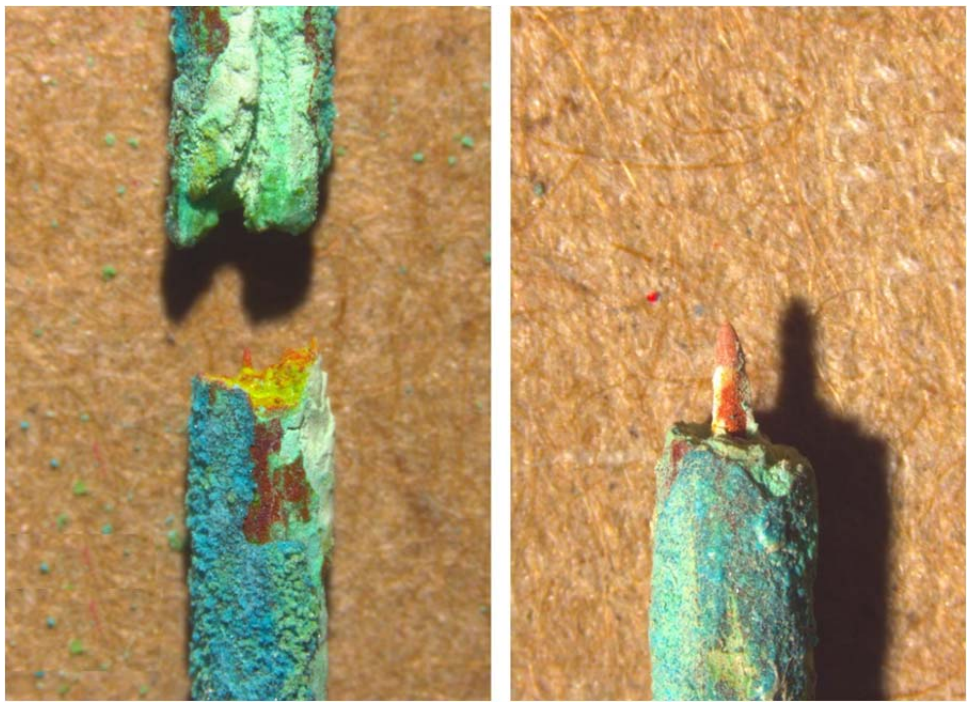

Figure 3: Corrosion of Concentric Neutral Resulting in a Wire Break (#14 AWG)

Figure 4: Metallic Shield Loss of Contact with Cable Insulation Shield Due to Mineralization

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Figure 5: Exterior Arcing Due to Corrosion and Neutral Wire Break Causing Degradation to the Cable Core

11.2 How It Works

Two methods are used in field assessments of metallic shields: Time Domain Reflectometry (TDR) and ac resistance (also known as Ω-Check).

The TDR method works much the same way as is described in Chapter 5. A handheld unit sends an energy pulse of as little as 2 ns in width down the cable conductor. Each time this pulse experiences a change in impedance, a portion of the energy is reflected back to the pulse source. Depending on the magnitude and polarity of this reflection, the anomaly causing the impedance change (in the cable conductor or in the neutral) may be characterized. The TDR technique has been used for many years to detect the presence of cable joints and cable system failures, but its use in detecting the presence and relative severity of neutral corrosion is primarily used was initially used by companies involved in cable rejuvenation.

The Ω-Check test method involves measuring the resistance of a neutral path either with or without isolating the cable from the service. The condition of the neutral under test is determined by comparing the measured resistance to the manufacturer published resistance of a new neutral of the same type and configuration.

11.3 How It Is Applied

11.3.1 Time-Domain Reflectometry (TDR)

Typically, this technique is performed offline. A fast rise time, low voltage pulse is applied between the conductor and the metallic shield of a cable system at an elbow or termination. As the pulse travels through the cable system, reflections are produced by discontinuities that change the local impedance. The initial and reflected pulses are displayed against time on an oscilloscope display and interpreted by the operator. The pulse travel time can be converted to distance or location using an assumed velocity of propagation (VoP). An experienced operator can often determine the source (cause) of an impedance discontinuity by the shape and magnitude of the reflected signal. The test duration (including interpretation) is 5-10 min once the TDR and the cable system are connected. Overall advantages and disadvantages of TDR measurements are shown in Table 1.

Table 1: Overall Advantages and Disadvantages of TDR Measurements

Advantages	• Testing is easy to employ. • Test equipment is small and inexpensive. • Test equipment uses low test voltage (much less than U_0). • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Information of location of corrosion or break may be available. • Complete breaks in the entire metallic shield can be clearly identified.
Open Issues	• Unclear whether the test may be performed online. • Detailed knowledge of the cable system construction needed for interpretation. • It is difficult to interpret some impedance discontinuities. • It is difficult to interpret results on tape-shielded cables. • Selecting the pulse width for optimal resolution and distance can be problematic. • Interpreting results on circuits with multiple taps is challenging if not impossible. • Length measurement requires that the start of the TDR pulse be identified, and this can be difficult.
Disadvantages	• Not designed for metallic shield assessment. • Skilled operators are required for testing and post analysis. • There are “blind spots” due to the ringing effect that occurs near the pulse injection end. The length of cable within the blind spot depends on the injection method and pulse width. • Electrical noise may interfere with the low voltage TDR signal. • Successful location of an impedance discontinuity depends on having the correct velocity of propagation for the tested cable system. • Generally only detects significant localized corrosion. • There is no way to determine the cause of “bad” signal responses not related to neutral breaks.

One of the more important issues to note when performing TDR measurements is that the length reading on the TDR unit is related to the cable system conductor length and not the surface distance between the near and far ends of the system under test. This fact causes two challenges that are addressed in detail later in this chapter (see Section 11.6). The first challenge is related to the relationship between how the power cable system was laid underground and its impact for pinpointing an accessory or anomaly. The second is the error in the velocity of propagation, which directly affects the length readings and thus TDR trace interpretation results. An illustration for different power cable system layouts is shown in Figure 6.

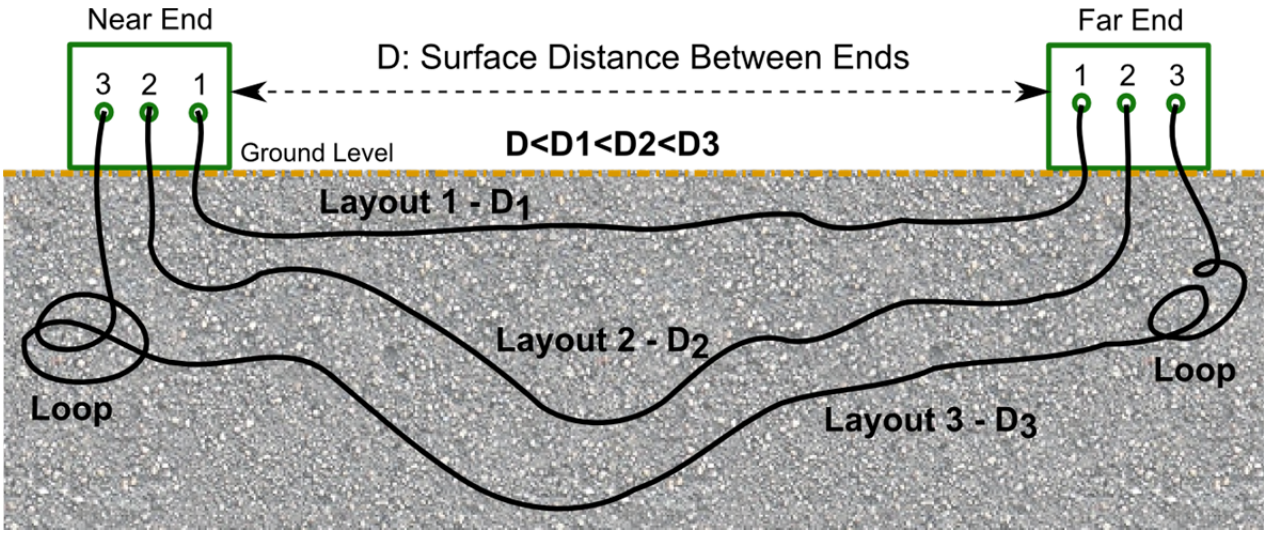

Figure 6: Illustration for Different Path Possibilities for Underground Cable Systems

As shown in Figure 6, there are different paths a cable segment can take between two devices such as transformers or switchgear. The route directly affects the ability of the operator to identify the location above ground. The relationship between the conductor lengths for all layouts (D_1, D_2, and D_3) and the surface distance separation between the ends (D) is also shown in Figure 6. Note that there are also extreme cases that could include loops in the cable system. Obviously, D3 is the worst case scenario since the cable is coiled at both ends.

As indicated, the selected velocity of propagation (VoP), which can be adjusted by the operator, directly affects the distance reading from the TDR and thus will also impact digging location. The VoP depends on the cable geometry and insulation material. Table 2 contains a number of **calculated** VoP's for different cable designs with nominal dimensions. The conductor size and insulation wall affect the VoP by 3-6% and up to 11%, respectively.

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Table 2: VoP Guidelines for Different Cable Designs							
Conductor Size/ Insulation	**Class/ Insulation Thickness**	**Inductance**		**Capacitance**		**Characteristic Impedance Z_0 [Ω]**	**VoP[1] [%]**
		mH/m	**mH/ft**	**pF/m**	**pF/ft**		
1/0[2] AWG XLPE[3]	15 kV/175 mils	171	56	211	69	28	55
	15 kV/220 mils	193	63	178	59	33	57
	25 kV/260 mils	211	69	159	52	36	58
	35 kV/345 mils	244	80	132	43	43	59
1/0[2] AWG EPR[4]	15 kV/175 mils	171	56	257	84	26	50
	15 kV/220 mils	193	63	217	71	30	51
	25 kV/260 mils	211	69	193	63	33	52
	35 kV/345 mils	244	80	160	52	39	53
1,000[2] MCM XLPE[3]	15 kV/175 mils	101	33	505	166	14	47
	15 kV/220 mils	112	37	414	136	16	49
	25 kV/260 mils	121	40	359	118	18	50
	35 kV/345 mils	140	46	284	93	22	53
1,000[2] MCM EPR[4]	15 kV/175 mils	101	33	615	202	13	42
	15 kV/220 mils	112	37	504	165	15	44
	25 kV/260 mils	121	40	437	143	17	46
	35 kV/345 mils	140	46	346	113	20	48

[1]: Velocity of propagation (50% ~ 0.5 ft/ns or 0.16 m/ns)
[2]: Compressed stranded round conductor
[3]: XLPE dielectric relative permittivity of 2.3
[4]: EPR dielectric relative permittivity of 2.8

11.3.2 AC Resistance (Ω-Check)

This test method involves measuring the ac resistance of a cable metallic shield (or neutral path) with or without isolating the cable from the service. The condition of the neutral under test is determined by comparing the estimated ac resistance to the resistance of a new neutral (calculated) of the same type.

This method is primarily used for concentric neutral cable systems where estimates of the neutral resistance have been made. Typically, these segments are installed between two padmount

transformers or switching cubicles. However, the test method could also be used for overhead neutrals or shield wires.

The test system injects a 60 Hz current (0-30 A) through the neutral system between the two ends. A portion of injected current returns through the neutral that is being tested and the balance returns through other parallel paths. The device measures the current flowing in the neutral under test, the voltage drop across the neutral and the phase angle between them. It then calculates the resistance of the neutral using following equation.

$$R_n = \frac{V cos\theta}{I} \qquad \textbf{Equation 1}$$

Where:

R_n = Resistance of the neutral under test, Ohms
V = Voltage across the neutral, Volts
I = Current in the neutral, Amperes
θ = Phase angle between V and I, Degrees

In the case of an online test, the unbalanced current may be flowing in the neutral during the test. This current will add/subtract to the test current depending on the phase angles involved. In addition to measuring the resistance of the neutral, the theoretical resistance of a new neutral of the same type, size and length is used for comparison. The theoretical resistance of new neutral is calculated using Equation 2.

$$R_{ref} = \frac{R_s K_1 L}{n} \qquad \textbf{Equation 2}$$

Where:

R_{ref} = Resistance of a new neutral, Ohms
R_s = Resistance of one neutral strand per foot, Ohms
L = Length of the cable, feet
n = Total number of strands in the neutral
K_1 = Lay factor accounting for additional length of spiral neutral strand (the device assumes a lay factor of 1.1)

11.3.2.1 Field Application - Online Test

The main advantage of this method is that the test does not require an outage or switching. However, the operator is required to perform the test by making connections to the neutral system at each end as shown in Figure 7. The equipment requires 120 volts (60 Hz) power supply which typically is obtained from the secondary side of the transformer. For sites consisting of vaults and switching cubicles, the source power must be obtained remotely. The remote source may include a nearby distribution transformer, an exterior house receptacle or a vehicle mounted power inverter (about 2 kW). A portable generator can also be used, if available. During testing, the device

continuously changes the polarity of the test current to account for any phase difference between the test current and unbalanced or stray currents that may be flowing in the neutral. However, the test results may be influenced by a source current that has significant harmonic contents. Power sources with clean sinusoidal waveforms are preferred.

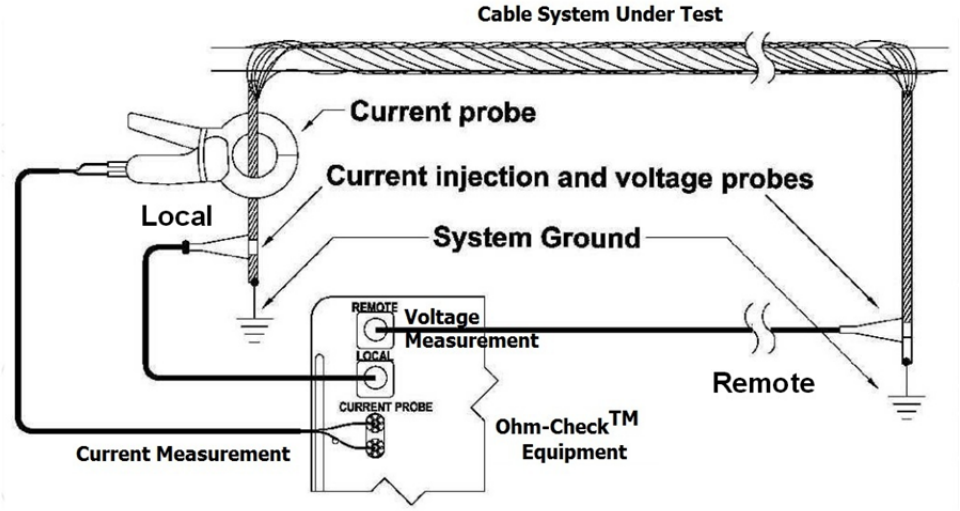


Figure 7: Ω-Check™ Connections for Online or Offline Testing

11.3.2.2 Field Application - Offline Test

For more accurate results, the Ω-Check test should be performed in offline mode. To perform the test in offline mode, the subject cable is disconnected at each end. The test current is injected in the loop formed by the cable conductor and the neutral under test. The main advantage of this application is that the operator does not have to lay the test leads along the cable span. The local and remote test leads from the device are connected only at one end as shown in Figure 8. At the other end the de-energized cable conductor and the neutral are tied together with a short, low-impedance conductor. During offline operation, the system neutral needs to be temporarily disconnected from the cable neutral at the local end (Figure 8). The disconnection of the neutral is not required if the system neutral dead ends on the opposite end of the cable segment.

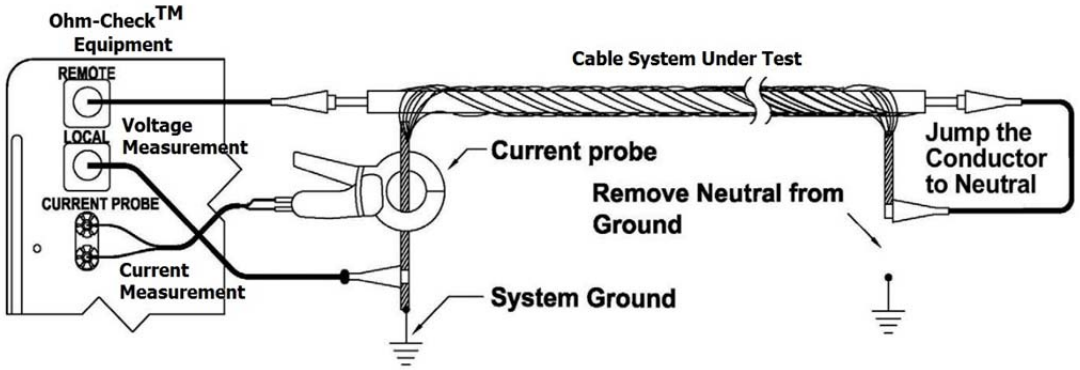


Figure 8: Ω-Check Connections for Offline Testing Using Conductor Back Path

After completing the test connections as shown in Figure 8, the operator turns on the machine and waits for the display to initialize. Unlike online operation, the only information that the operator keys in is the length of 100 ft in the place of span length. For the purpose of keying in, the information regarding neutral is not required. However, the information regarding neutral, cable conductor and cable length is required to compute various resistances external to Ω-Check device (see Equation 4).

The test consists of injecting the current in the loop made by the cable conductor and neutral and measuring the current, voltage and phase angle. The Ω-Check device then determines the total resistance of the loop as described by Equation Equation 3).

$$R_{n+c+t} = \frac{V \cos\theta}{I\left(\frac{L}{100}\right)} \qquad \textbf{Equation 3}$$

Where:

R_{n+c+t} = Measured resistance of the loop (neutral + conductor + termination), Ohms
V = Loop voltage, Volts
I = Loop current, Amperes
θ = Phase angle between V and I, degrees
L = 100 feet

The resistance of neutral under test is externally calculated by using Equation 4).

$$R_n = R_{n+c+t} - R_c - R_t \qquad \textbf{Equation 4}$$

Where:

R_n = Resistance of neutral under test, Ohms
R_c = Resistance of new cable conductor of the same type, size and length as the test conductor (from manufacturer's specifications), Ohms
R_t = Resistance of termination cable at the far end, Ohms (For short termination cable, this resistance can be ignored), Ohms

Other parameters such as the "resistance ratio" or the "% of neutral strands intact" can be determined by comparing against the resistance value of the new neutral wire of the same type and size from Equation 2). Overall advantages and disadvantages of Ω-Check techniques appear in Table 3.

Table 3: Overall Advantages and Disadvantages of Ω-Check Techniques	
Ω-Check Online	
Advantages	• Specifically designed for metallic shield assessment. • Testing is easy to employ. • Test equipment is small. • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Results are numeric and easy to understand. • Easy to deploy, no expert operator required. • Neutral isolation not required. • Segment does not need to be de-energized for testing. • Detects a wide range of degradation due to corrosion as well as breaks in the neutral. • Immune to high frequency electrical noise on the neutral. • Presence of breaks can be clearly identified (but not located).
Disadvantages	• Requires running a cable to the far end of the tested segment, which can be a challenge for long segment lengths. • Requires an accurate segment length estimate. • The returning current lead and the metallic shield form a loop and thus induced currents may become impact the measurement. • Accurate knowledge of cable metallic shield design is required. • Reference database for neutral resistance is required. • Difficult to apply for metallic shields that are not concentric neutral wires. • Information of location of corrosion or break is not available.
Ω-Check Offline	
Advantages	• Specifically designed for metallic shield assessment. • Testing is easy to employ. • Test equipment is small and inexpensive. • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Numeric easy to understand results. • Easy to deploy no expert operator required. • No risk of failure during test. • Does not require running a cable to the far end of the tested segment. • Induced currents are generally not an issue, which can improve accuracy. • Detects a wide range of degradation due to corrosion as well as breaks in the neutral. • Immune to high frequency electrical noise. • Presence of breaks can be clearly identified (but not located).
Disadvantages	• Requires temporary neutral isolation at far end. • Long lengths are challenging because of long lead length and potential voltage drop issues as well as the uncertainty of the cable conductor resistance if using the cable conductor as the return path.

Table 3: Overall Advantages and Disadvantages of Ω-Check Techniques	
	• Requires an accurate segment length estimate. • Accurate knowledge of cable metallic shield design is required. Reference database is required. • Information of location of corrosion or break is not available. • Difficult to apply for metallic shields that are not concentric neutral wires.
Both Ω-Check Online & Offline	
Open Issues	• Impact of splices and connectors on measurements difficult to establish. • Impact of induced currents for offline procedure is unknown. • Exact lay lengths are generally unknown. • Applicability to EHV, HV including subsea cable systems and armor evaluation is not verified.

11.4 Success Criteria

11.4.1 TDR

Typically, a TDR sends a narrow pulse (2 ns in duration) of approximately 20 V down the cable. Localized changes in impedance like those that would appear because of corroded neutral wires, reflect energy back to the TDR and they appear as positive peaks on the graphical display where corrosion or open neutral conditions exist. A decrease in impedance, below 50 Ω, will cause a negative reflection. After a pulse passes several imperfections it may lose a significant portion of its energy dues to reflection. In this case, a wider pulse (10 ns) must be sent. However, the shorter pulse widths give much cleaner reflections and minimize the blind spot at the near end while the longer pulse widths are able to travel greater distances. On-screen cursors can be adjusted so that the TDR can display the distance along the conductor to the area of interest.

IEEE 1617 – 2007, IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables, addresses TDR testing and adopts a severity approach where the most severe degradation of signal occurs for increasing loss of neutral. The severity of neutral corrosion is divided into four levels. These levels are determined by comparing the peak of the anomaly reflection (+ve) with the far end reflection and any joints in the cable system. There is an implied requirement that a joint should be present in the span. The corrosion levels and how they are defined within IEEE 1617 are listed below:

- **Level-I:** 0%-25% neutral corroded, peak is too small to be recognized.
- **Level-II:** 25%-50% neutral corroded, the +ve peak is less than the splice.
- **Level-III:** 50%-75% neutral corroded, the +ve peak is larger than the splice and smaller than the cable end.
- **Level-IV:** 75%-100% neutral corroded, the +ve peak is larger than magnitude of the reflection at a discontinuity is calculated as the reflection coefficient or ρ. It is calculated as:

$$\rho = \frac{Z_d - Z_o}{Z_d + Z_o}$$ **Equation 5**

Where:

Z_o is the characteristic impedance of the cable and
Z_d is the impedance of a discontinuity.

The value of ρ ranges from 1 (open circuit) to -1 (short circuit). A reflection coefficient of zero indicates there is no reflection. This can only occur if there is no change in impedance. Thus, for the bulk of a cable system, the reflection coefficient is zero along the length since the pulse propagates down the cable with uniform impedance. This process continues along the full length unless there is a change caused by an accessory or neutral discontinuity.

TDR units can generate pulses as much as 100's of microseconds wide or as narrow as 1 nanosecond. For neutral assessment, the pulse width should be as narrow as possible to gain the best spatial resolution while still enabling the pulse to traverse the full circuit length.

11.4.2 Ω-Check

The resistance measured by the Ω-Check device is compared to the theoretical resistance of a new neutral (see Equation 2). This comparison is made available to the user in terms of "resistance ratio, R_n / R_{ref}" or in terms of "% of strands remaining intact" as shown in Equation 6.

$$\%\ \boldsymbol{of\ Strands\ Remaining\ Intact} = \left(\frac{R_{ref}}{R_n}\right)100$$ **Equation 6**

Once the condition of the neutral is determined, a decision to replace the cable can be made on the basis of pre-determined replacement criteria established by the user. Although the cable replacement criteria can vary from one utility to another, it is generally based on short circuit and/or steady-state performance of corroded neutrals. A typical threshold value for replacement used by utilities and cable rejuvenation providers is 50% or less of strands remaining intact.

11.5 Estimated Accuracy

Estimated accuracies are established by comparing test results with actual findings. Therefore, it is not possible to establish accuracies for TDR and Ω-Check as tools to assess the condition of the metallic shield of cable systems. Some of the more important reasons are as follows:

- The amount of TDR and Ω-Check data available is extensive; however, in most cases no follow up is undertaken to determine what in fact happened to these systems.
- TDR and Ω-Check results are not provided in pass/fail terms, but rather as general information concerning the tested cable system.
- When a cable system failure occurs, little or no attention is given to the system's previous

testing or performance history and thus the information and correlation with test data are lost.

11.6 *CDFI* Perspective

Much of the research work within *CDFI* was focused on assessing the condition of the cable system dielectric. However, as the analysis/testing proceeded, it became increasingly clear that the metallic shield impacts diagnostic measurements on the dielectric. As discussed, both the TDR and Ω-Check methods are used for assessing cable metallic shields and like the other diagnostic techniques, they are not without their deployment challenges. The following sections discuss some of these issues.

11.6.1 TDR Based Neutral Assessment

The TDR assessment method involves equipment and set up issues that were not necessarily critical when TDR was only used to identify joints and cable lengths. Figure 9 show a TDR with an impedance grading coupler and regular TDR leads. The impedance coupler is often used in the field when a neutral assessment is performed. The goal of this arrangement is to inject the "cleanest" signal possible while using a very narrow pulse. Unfortunately, the connection of the TDR unit to the cable system requires great care if meaningful results are to be obtained. Figure 9 shows two connections options. The first utilizes standard leads (right side of Figure 9) while the second is the impedance coupler (left side of Figure 9)

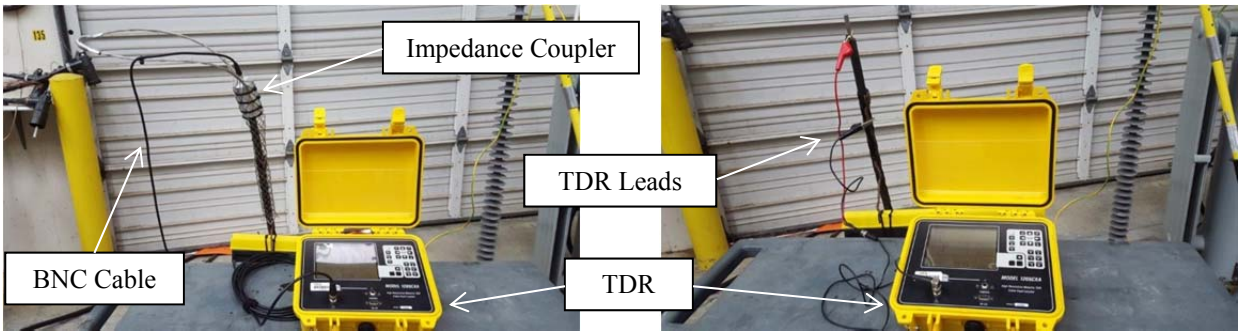


Figure 9: TDR Connections – BNC & Impedance Coupler (left) and BNC & Leads (right)

The impedance grading coupler shown in Figure 9 significantly reduces the magnitude of the reflection resulting from the connection of the TDR to the cable. It is important to note for this device to work on a cable system with elbows, at least one elbow must be removed. This coupler could be used with an indoor or outdoor termination left in place, although the results presented below are for the case of an elbow that is removed. Figure 10 shows an example of signal injection with a TDR with (----) and without (—) impedance grading. Clearly the large reflection at the connection point is virtually eliminated when impedance grading is employed. As a result, more energy is transmitted to the cable system.

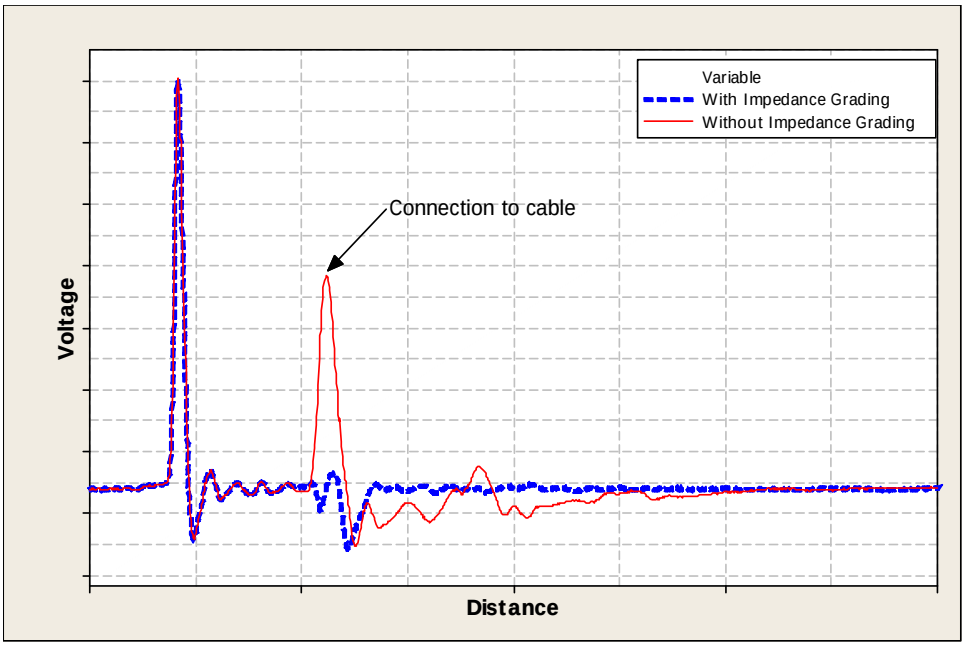


Figure 10: TDR Traces with and without Impedance Grading

By interpreting apparent noise and the reflections in a TDR trace, a trained operator can provide a qualitative assessment of the amount of neutral corrosion and its location within a circuit. The apparent noise on the trace is typically indicates uniform neutral corrosion while the reflections are indications of significant localized neutral corrosion or neutral breaks. As an illustration, Figure 11 shows examples of the types of signals that may be seen in a TDR trace for both uniform and localized corrosion.

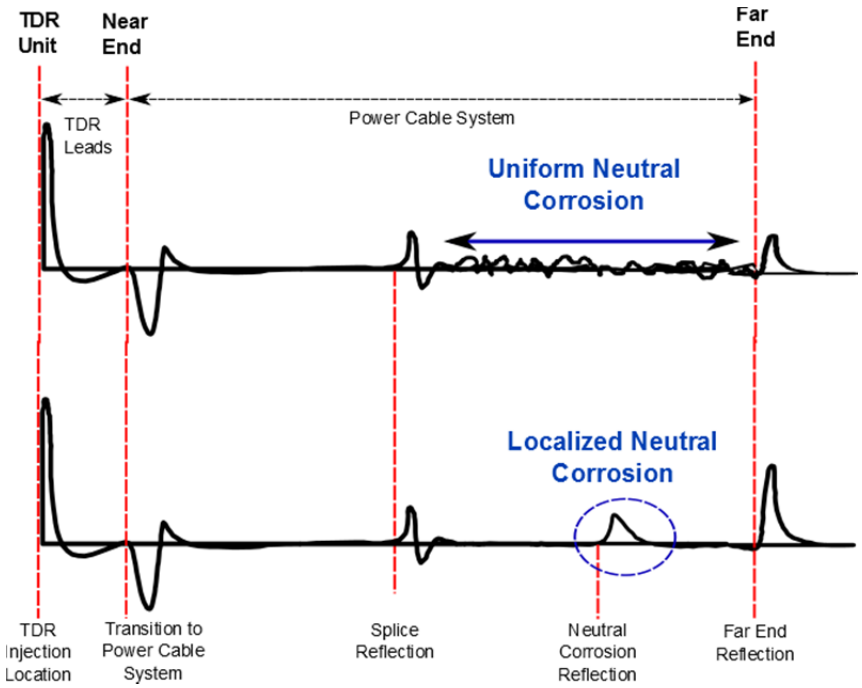


Figure 11: TDR Trace Showing Uniform and Localized Neutral Corrosion

Observe also in Figure 11 that uniform neutral corrosion causes high noise levels in the trace and so the amplitude resolution decreases since smaller reflections cannot be seen in the trace. The noise has the added side effect of reducing the pulse energy such that the far end reflection itself is also lower in amplitude and could be difficult to distinguish from the noise. In the field, both issues could be present in a cable system and one could dominate the other. It is up to the skilled operator to reach a neutral condition assessment.

IEEE 1617 describes how the relative heights of the "bumps" (reflections) in the TDR trace coming from localized neutral issues may be used to assign a condition level to the neutral under test. Instead of expressing the level of corrosion in terms of the percentage of the remaining neutral, IEEE 1617 uses the percentage of wires broken or percent neutral loss. Four levels are considered; however, given the levels, the guide does not provide a prognosis. Guidelines are shown in Table 4. It is unclear in the guide how the correlation of these heights to different degrees of neutral loss was determined.

Table 4: Summary of IEEE Std. 1617 – 2007 Metallic Shield TDR Assessment Levels

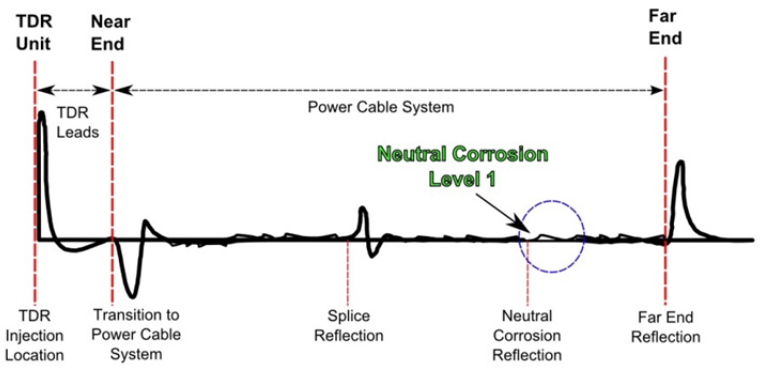
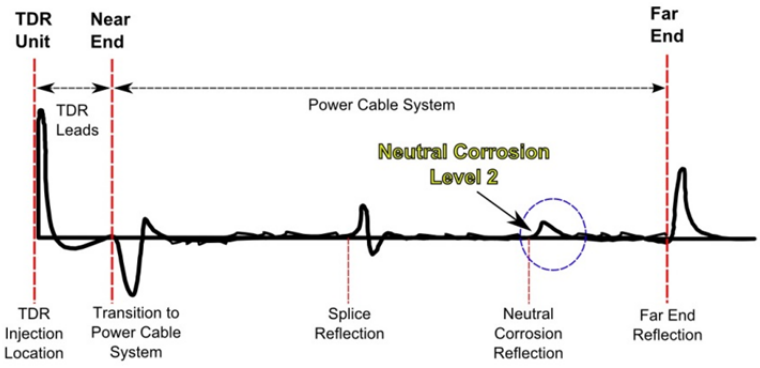
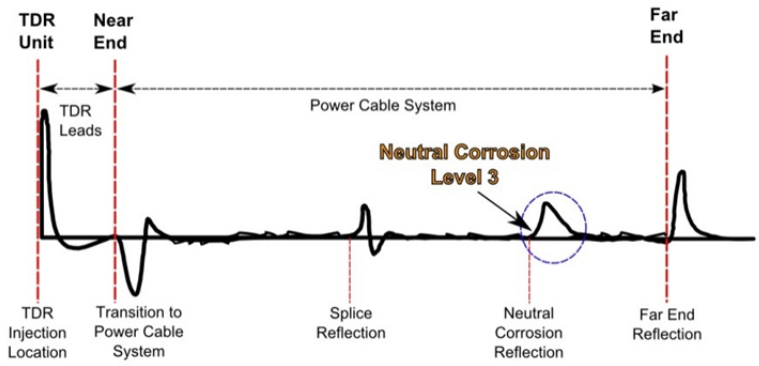
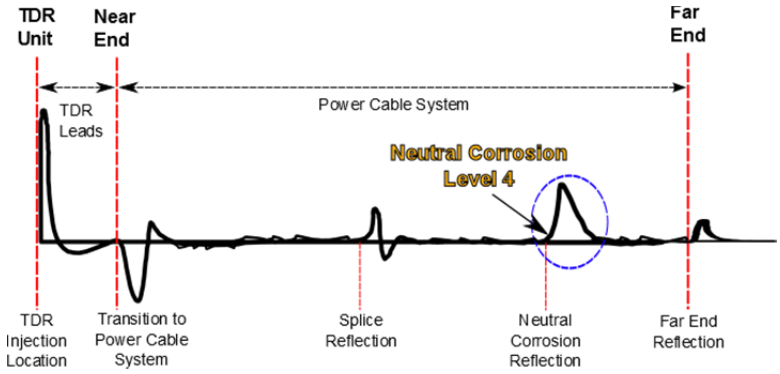
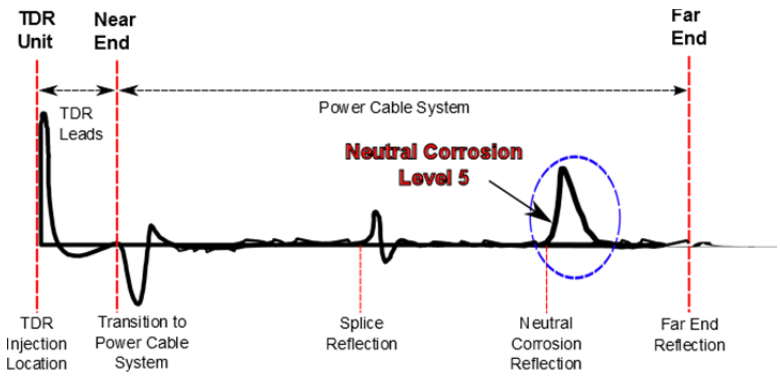
Wires Broken	Condition	Illustrated from Assertions in IEEE Std. 1617 – 2007
Level 1 - No recognizable reflections		
0 – 25%	**Good (<< splice reflection)**	
Level 2 – Recognizable reflection but smaller than a splice		
25 – 50%	≤ splice reflection	

Table 4: Summary of IEEE Std. 1617 – 2007 Metallic Shield TDR Assessment Levels		
Wires Broken	**Condition**	**Illustrated from Assertions in IEEE Std. 1617 – 2007**
Level 3 – Reflection larger than a splice but smaller than the end of the cable		
50 – 75%	> splice reflection < end reflection	
Level 4 – Reflection larger than the end of cable reflection		
75 – 99%	> end reflection	
Level 5 – Far end reflection location closer than expected[§]		
100%	**Bad**	
§ - Not presently described in IEEE Std. 1617 – 2007		

A number of issues exist that are believed to limit the usefulness of the guidelines shown in Table 4:

- Not all cable segments have splice locations that can be used as a reference; guidelines

should be established in order to handle such cases.

- Distance from the TDR unit affects the amplitude of the received reflection – a splice located far away creates a lower amplitude reflection than an identical splice located near the sending end.
- Signal amplitudes depend on several factors – system length, pulse injection method, pulse width, and number of splice locations.

11.6.3 TDR Experimentation at NEETRAC

A 400 ft length of 15 kV XLPE insulated, jacketed cable with six metallic shield wires was modified with switches (two locations approximately 50 ft apart) on each neutral wire so that the effect of different neutral loss conditions could be observed with a TDR. Figure 12 shows one of the locations with the switches in place.

Figure 12: Cable Segment with Switches on Each Neutral Wire

The following figures show measurements that were completed using an impedance grading device as shown in Figure 9. Figure 13 shows the TDR trace for the entire segment with the location of the switch box. The "near end" or injection point is shown on the left while the "far end" is shown in the right of Figure 13. All switches were closed (all neutral wires intact) in this figure.

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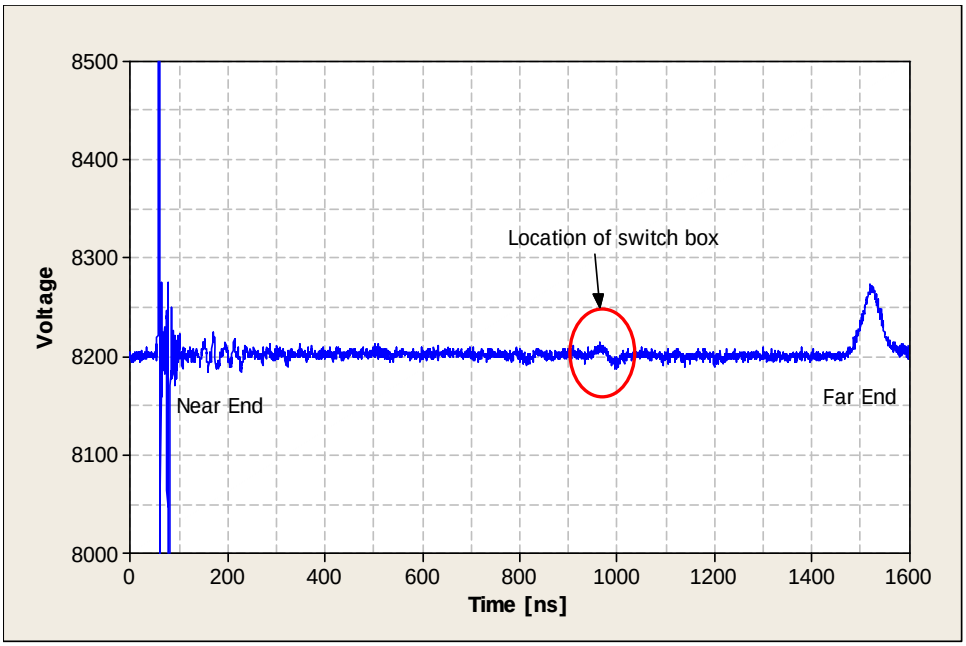

Figure 13: TDR Trace of Full Cable Segment

As switches are opened in the switch box, the size of the reflection generated at switch location increases while the far end reflection decreases in size because more energy is reflected at the switch box location. Figure 14 shows an enhanced view of the TDR trace at the switch box location for different percentages of remaining neutral (66%, 50%, and 17%).

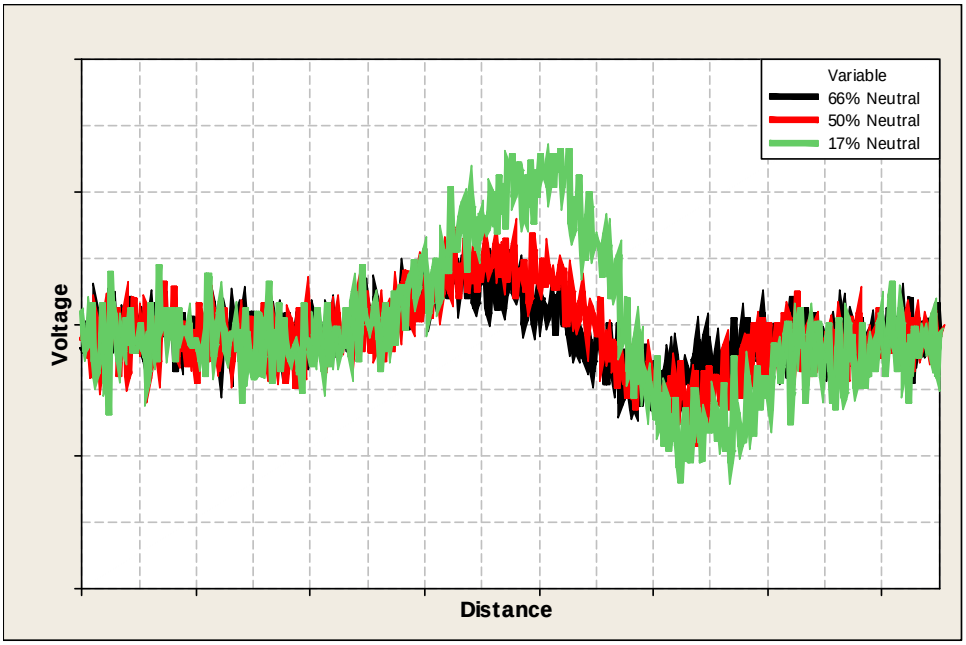

Figure 14: Reflections Resulting from Different Levels of Remaining Neutral for One Cable System (Less Neutral = Larger Reflection)

As Figure 14 and Figure 15 illustrate, the difference between 66% and 50% remaining neutral is difficult to distinguish. However, with only 17% remaining neutral, the difference is quite large as

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compared to the other two cases. A similar effect can be seen at the far end except the far end reflection reduces as more neutral wires are switched out.

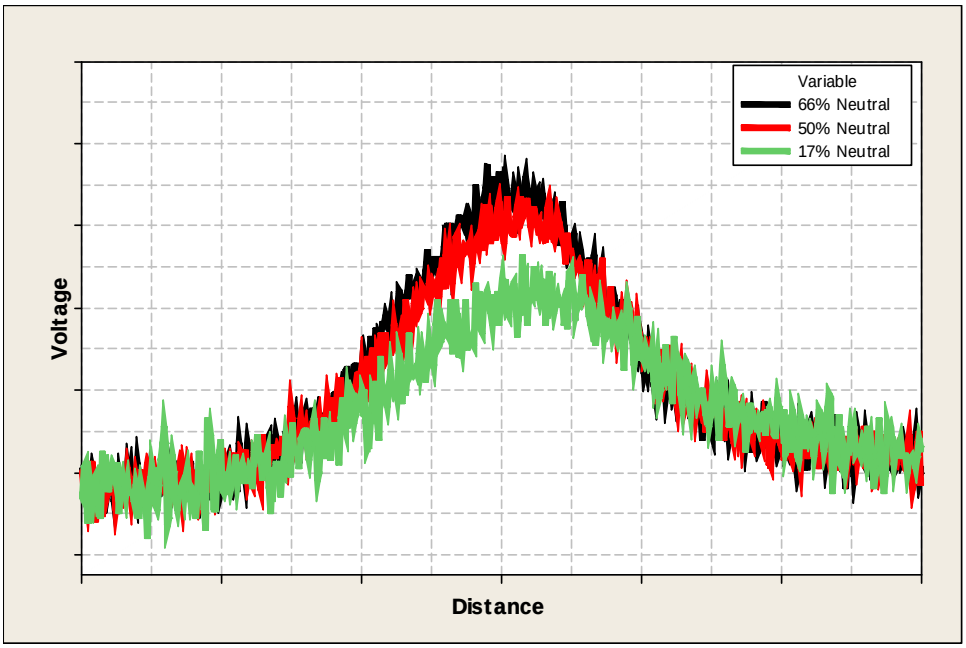

Figure 15: Far End Reflections Resulting from Different Levels of Remaining Neutral for One Cable System (Less Neutral = Smaller Reflection)

As the above figures illustrate, it is possible to see reflections at locations where the metallic shield is, in this case, discontinuous. However, the locations of the switches were known and so it was clear where to look for the changes. This situation would not occur in the field so one must be cautious to keep the above findings in context.

11.6.4 AC Resistance-Based Neutral Assessment

It is estimated that over 1.5 million feet of cable has been assessed using the Ω-Check approach. This approach, however, is not without its own challenges as the test leads must be laid along the segment length if an online test is to be performed (Figure 7). At times, this task can be difficult, particularly for longer spans and for the spans where leads cross the roads. Additionally, there are factors that may influence the accuracy of the test results particularly when the test leads are spread out to connect across the neutral span. A number of such issues exist and are discussed below.

11.6.4.1 Online or Offline Testing

Lay Factor, K_1

The lay factor constant of 1.1 in Equation 2 accounts for the additional length of the neutral strands due to spiraled application of the neutral wires over the cable. For most applications, this factor may

range from 1.05 to 1.13, causing some error in the computation of the resistance of a good neutral. In other neutral designs, the lay factor does not apply since longitudinally corrugated tape (LCT) shields (when in good condition) form essentially continuous tubes with corrugations around the cable core. As a result, care must be taken when using Ω-Check to determine the remaining metallic shield since there are no base numbers for the newer shield designs.

Cable Length, L

Similar to the lay factor constant, the length of the cable being tested is used in Equation Equation 2) to compute the resistance of the new neutral for comparison to the measured results. This length should be determined as accurately as possible, though it is often impossible to know precisely the cable route.

Some of the methods used for measurement of length include:

1. installation records, if available;
2. visual inspection of drawings (allow for additional length at each termination);
3. measuring Wheel (allow for additional length at each termination);
4. laser and ultrasonic distance finder (straight line only, allow for additional length at each termination); and
5. Time-Domain Reflectometry.

11.6.4.2 Online Testing

As shown in Figure 7, the online testing requires spreading and connecting the test leads along the cable segment. In some cases, this task is time consuming, especially for longer spans or where the area between the two padmount transformers or switchgear is difficult to access.

Unbalanced Current in the Neutral

Sometimes there is current flowing in the neutral being tested due to unbalanced phase currents (in the case of three phase systems), neutral return current (in the case of single phase systems) and possible stray currents. To minimize the influence of current in the neutral on the measurement, the Ω-Check device may reverse the polarity of the test current and averages the measured current and voltage.

Induced Voltage on Voltage Measuring Lead

During online testing, the current carrying lead and voltage measuring lead run together between the measurement locations. The magnetic loop made by the neutral and the current carrying lead induces voltage on the voltage measuring lead, which may influence the voltage measured across the neutral. Experience has shown that the induced voltage influence on the voltage measuring lead is typically subtractive, indicating somewhat less degraded neutral than actually exists. This could potentially lead to an overly optimistic assessment. To minimize this effect, the test leads should be kept as close to the cable as practical.

11.6.4.3 Offline Testing

Offline tests can be carried out if the cable segment can be de-energized. This helps to alleviate some of the known sources of "interference" as described above.

11.6.5 Comparison of TDR and Ω-Check Data

TDR and Ω-Check data were collated as part of the research work in *CDFI Phase II*. The goal of this analysis was to determine the differences and similarities between these two techniques from the assessment perspective. Both techniques seek to measure/assess the same cable "illness", but data comparing the two techniques is not available in the literature.

Figure 16 shows the cumulative distribution functions (CDF's) of remaining neutral for all collated data during the *CDFI* from cable circuits assessed in North America. The TDR assessments were performed according to the conventions in IEEE 1617 – 2007 and are, by definition, based on discrete condition levels (level-based). These levels correspond to different neutral loss ranges and are primarily for unjacketed MV cable systems.

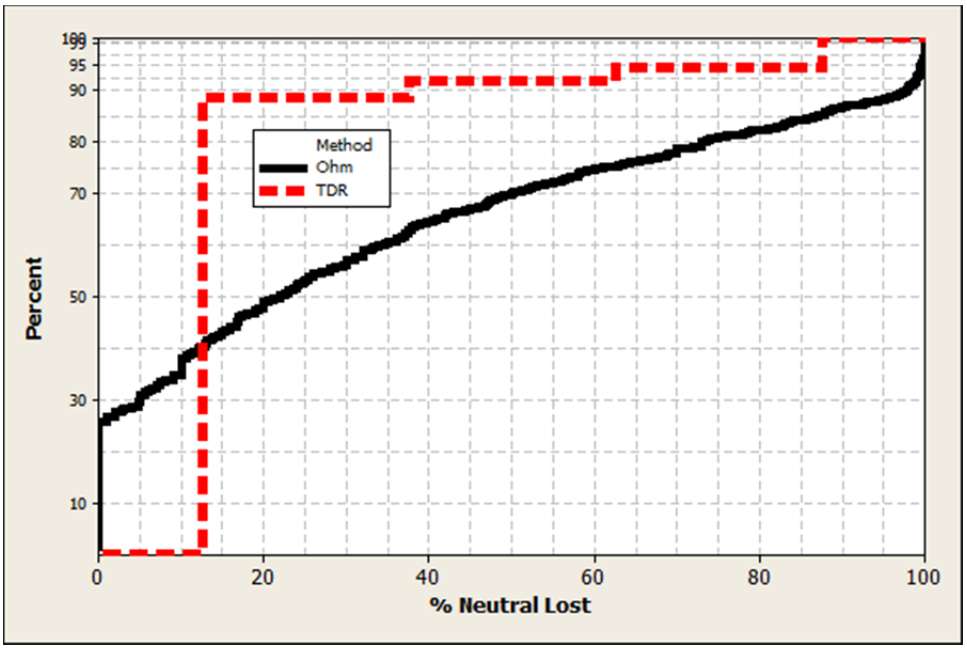

Figure 16: Cumulative Distributions of Ω-Check and TDR Neutral Loss Data [14]

As Figure 16 shows, the data from Ω-Check measurements form a smooth curve since these data are numeric in nature rather than level-based as discussed above. It is useful to compare percentiles as the Ω-Check data appear to paint a more pessimistic picture of the condition of cable neutrals throughout North America. Table 5 shows a comparison of the cumulative distribution percentiles for Ω-Check and TDR. Clearly, there are some significant differences between the estimated neutral loss for the two methods.

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Table 5: Comparison of Distribution Percentiles from Figure 16			
Neutral Loss [%]	**Remaining Neutral [%]**	**Ω-Check Cum. Percentile [%]**	**TDR Cum. Percentile [%]**
0	100	27	-
< 25	> 75	53	88
< 50	> 50	70	91
< 75	> 25	82	94

As neutral degradation is generally an aging phenomenon, it is worth examining the neutral loss data as a function of cable system age. Figure 17 shows the cumulative distributions for different age classes (top) as well as the corresponding age distribution for circuits with 25% or less remaining neutral (bottom).

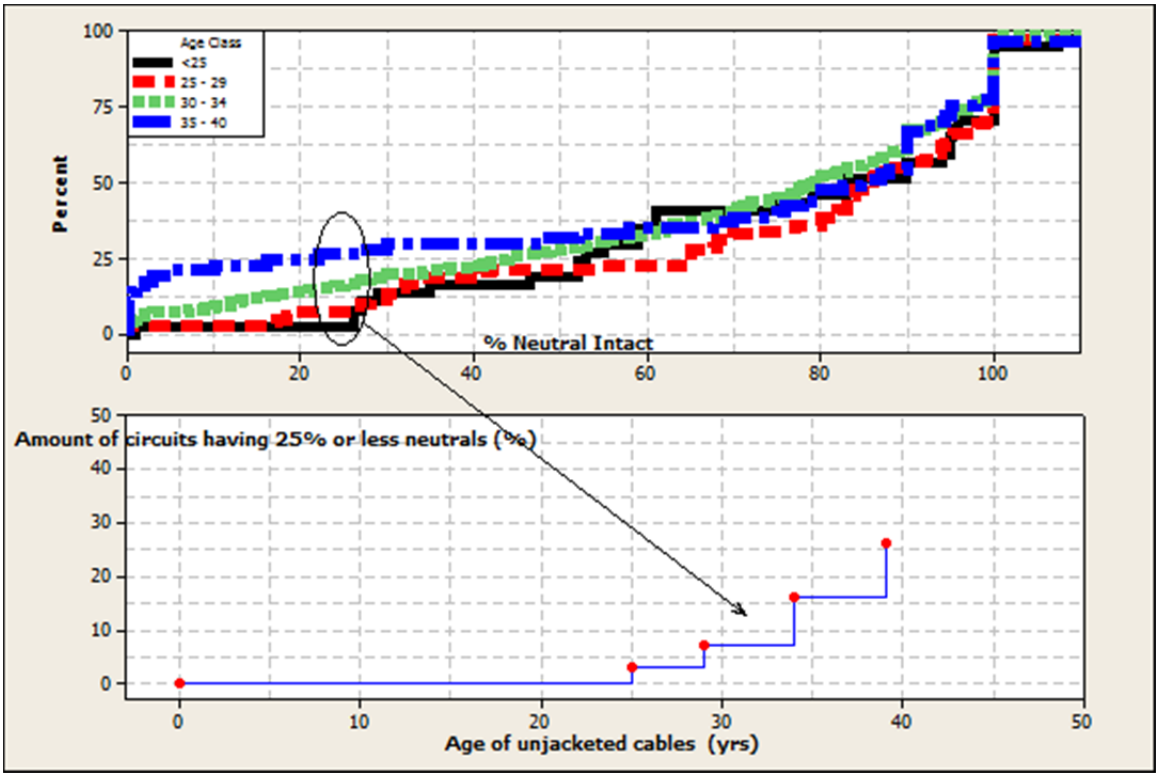

Figure 17: Neutral Integrity as Function of Cable System Age Using Ω-Check Data

Figure 17 illustrates that as unjacketed cable systems approach 35-40 years in service, the likelihood of finding significant neutral corrosion increases significantly. In the case of systems younger than 25 years, the data indicate that none have less than 25% remaining neutral. On the other hand, for systems approaching 40 years of age, there is a 25% chance that an individual segment will have 25% or less remaining neutral.

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The industry has tended to refer to 50% loss as a critical threshold for replacement as various safety related issues can arise with additional degradation. Assuming the 50% threshold then for Pass and Not Pass the data in Figure 17 can be re-analyzed. Figure 18 shows the results of re-interpreting the data from Figure 17. This figure shows that systems less than 32 years of age are unlikely to have less than 50% remaining neutral. That percentage increases quite sharply as these cable systems approach 40 years of age – approximately 50% have 50% or less remaining neutral. It is important to note that the data are quite sparse in this age region as most 40 year and older cable systems have been replaced with newer jacketed systems.

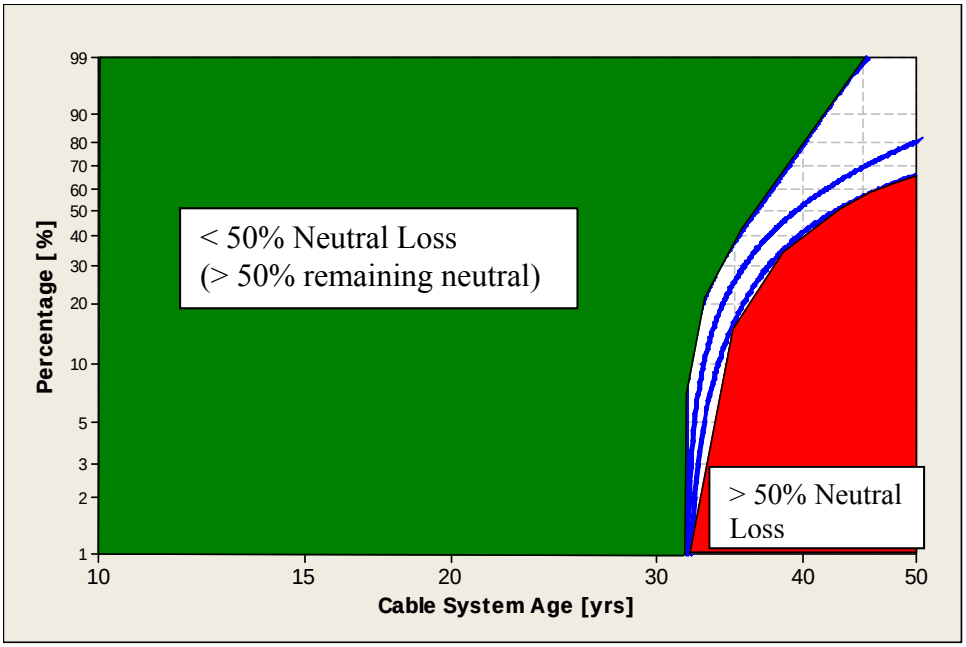

Figure 18: Cable System Neutral Life Expectancy for Full Neutral Cable Systems

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Additional Comments

The above use of the 50% remaining neutral (or 50% neutral loss) criterion is commonly used within the industry. The origin of this criterion is not known. It likely evolved as an expedient level from the experience of practitioners for establishing a pass/fail condition assessment for neutral loss. The fact that many unjacketed cables had substantial neutrals with a conductance that was equal to the conductance of the cable conductor (full neutral) also contributed to the choice of 50%. In at least the last 20 years, there has been a move within the industry to reduce the cross sectional area of the metallic shield to reduce circulating current losses, lower cable cost, and enhance the thermal/ampacity performance of the cable. Today's cables may have, when new, as little as a "1/6 neutral" on each phase of a triplex jacketed cable (50% neutral when combined).

This observation presents utility engineers with several questions that currently remain unanswered for the cable system life, chief among them being: *What level of neutral loss should utilities consider as critical for cable systems with "reduced neutral" designs?* In other words: *Is 50% loss for a 1/6 neutral an appropriate threshold?*

The question identified above cannot be addressed with the currently available field data. The vast majority of neutral assessments are not performed on jacketed systems as these systems are believed to have very limited if any corrosion. Although there is some evidence that neutral corrosion can occur on some cable designs, implying that the industry will ultimately need to establish threshold limits based on solid, engineering principals, rather simple expedience.

11.7 Outstanding Issues

11.7.1 TDR

There are a number of outstanding issues for the TDR assessment of metallic shields. These are discussed below.

11.7.1.1 TDR Leads

When using TDR, it is always advisable to be consistent with the TDR leads. When the TDR leads are simply a pair of wires attached to the unit, there is variability in the measurement since the capacitance between leads changes according to how they are placed for the test (see Figure 9). Therefore, using a BNC cable with leads (right side of Figure 9) that are as short as possible is advisable whenever an impedance coupler (left side of Figure 9) is not available.

Another issue for the TDR leads is their length. If short leads are used, the ringing effect at the near end of the cable system might make this portion blurry. The location of the near end is important for accurate location/pinpointing of accessory and anomalies. To overcome this issue and always have a clear position for the near end on the TDR trace, the use of long (15 ft – 50 ft) coaxial (BNC) leads is recommended. In field tests, a length of 30 ft or more has proven useful for achieving a clear near-end signal. Once this length is chosen, it should be used for all tests. Figure 19 shows an illustration for comparing the use of short and long TDR leads.

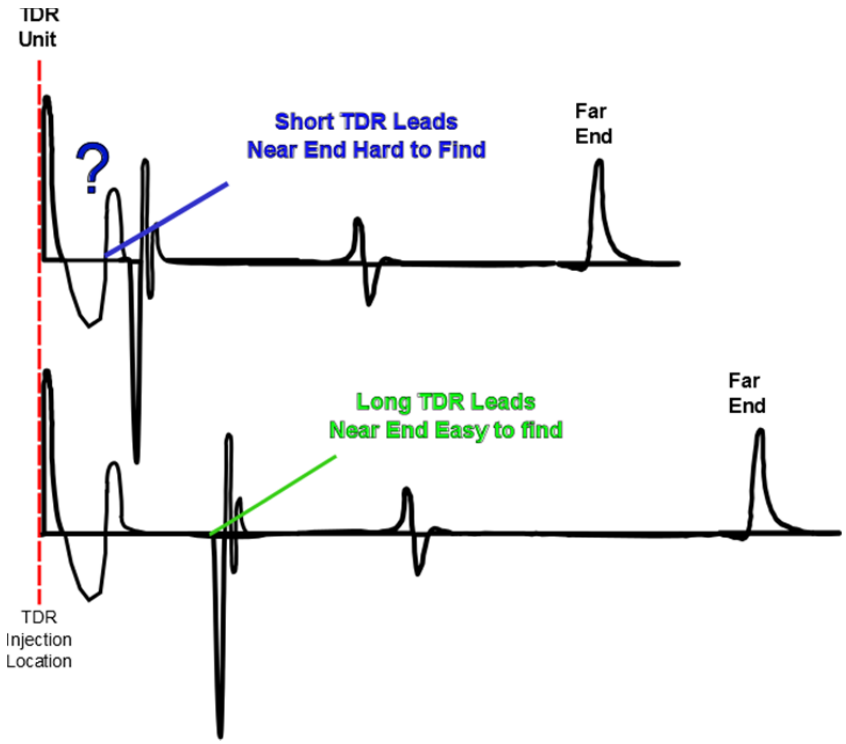

Figure 19: Illustration for Comparing the Use of Short and Long TDR leads

11.7.1.2 Identifying the Far End

Of equal importance to locating the near-end on the TDR trace is the ability to identify the far-end of the cable system. If there is a doubt, comparing TDR traces for the far end grounded and then ungrounded is a useful method. The grounding and ungrounding of the far end produces a polarity reversal for the far-end reflection without affecting any of the other reflections along the cable system. This technique is illustrated in Figure 20 where a comparison between TDR traces for the same cable system for grounded and ungrounded set ups at the far end.

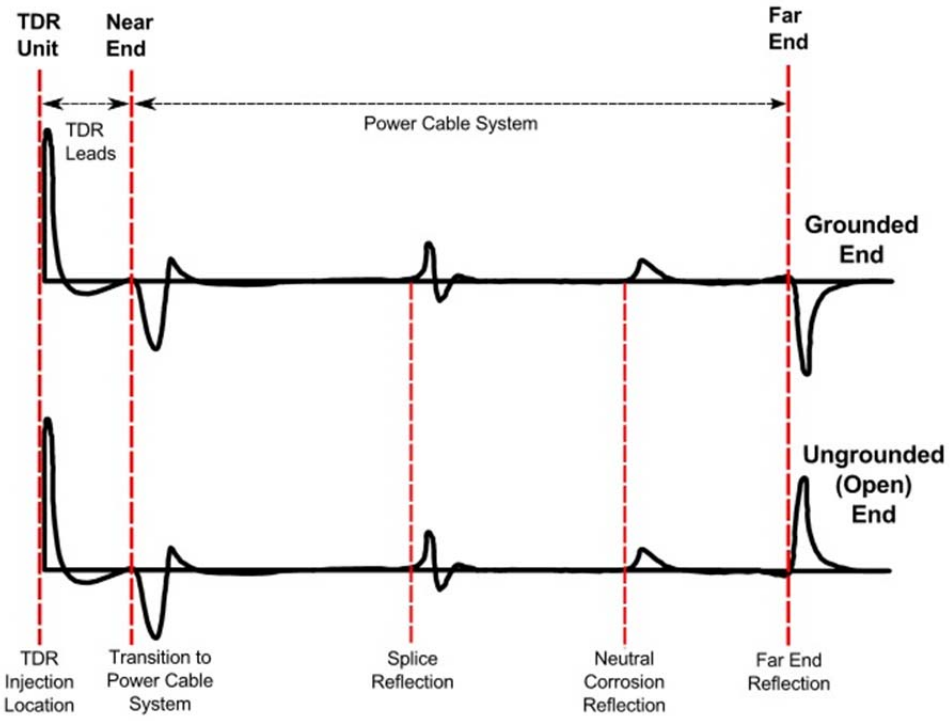

Figure 20: Comparison between TDR Traces for the Same Cable System for Grounded and Ungrounded Far End.

11.7.1.3 TDR "Ghost" Reflections

Even though TDR is a useful tool for diagnosing potential cable system problems, there are some issues when interpreting the TDR trace. One of the key issues is the potential for reflections of reflections (otherwise known as "ghost" reflections) to occur in systems with multiple joints. This can also occur in systems with a single joint located close to the near end of the system.

"Ghost" reflections are signatures that appear on the TDR trace that do not correspond to any actual joint or anomaly present in the system. They are the result of the reflected and re-reflected TDR pulses travelling along the system in both directions, i.e. from near to far end and vice versa. The TDR "ghost" reflections are a function of three variables:

1) the location of joints or anomalies;
2) the number of joints or anomalies; and

3) the difference in characteristic impedance between the joints and cable.

There are a large number of potential situations that could create "ghost" reflections, so it is impossible to cover and understand all of cases. However, an understanding of TDR ghost reflections can be attained through the analysis of basic case studies. This knowledge should lead to improved interpretation in real field scenarios. Six case studies are presented below (see Table 6):

Case 1: Cable system with no splices or anomalies.
Case 2: Cable system with one splice located farther than 50% of the cable system length as measured from the near end.
Case 3: Cable system with one splice located at the exact midpoint of the cable system length.
Case 4: Cable system with one splice located between the near end and midpoint of power cable system length.
Case 5: Cable system with two splices located at arbitrary positions.
Case 6: Cable system with two splices located at arbitrary positions but includes the use of impedance coupling at the near end.

Keeping track of the TDR pulse reflections as they travel back and forth in the cable system is tedious. However, this analysis can be accomplished graphically using bounce diagrams. The bounce diagram is a graphical analysis technique that greatly simplifies the analysis of transients on a "transmission" line and thus provides a tremendous amount of clarity regarding how transients are perceived at any point in the system. (Note that in this case, a "transmission" line is a model for a distributed impedance network that is used to characterize the propagation or transmission properties of signals and not a high voltage power line.) In other words, the bounce diagram provides a pictorial tool showing clearly how incident TDR pulses reflect, transmit, and combine along the length of the cable system over time. To draw a bounce diagram for these different pulses a series of parameters must be considered including:

- The characteristic impedance of the cable used in the cable system.
- Knowledge of the reflection coefficients at the cable system ends, joint, and anomaly locations.
- Number of expected joints in the cable system.
- Expected length of the cable system.

The bounce diagram has the following basic structure:

- X-axis represents the position along the cable system.
- Y-axis represents the elapsed time from the initial injected TDR pulse at the near end.
- Near end is shown on the left side, whereas the far end is shown on the right side of the bounce diagram.
- The initial injected TDR pulse starts at X=0 (near end position) and Y=0 (time zero), and travels to the far end.
- Slopes/gradients represent the velocity of propagation of the TDR pulses through the system; lower gradients equal higher propagation velocities.

Using the above structure and knowledge of the cable system, the following observations generally hold:

- The first reflected TDR pulse occurs at the first joint or anomaly that produces a change on the cable characteristic impedance.
- The amplitudes of the reflected and transmitted TDR pulses decrease as they travel due to the attenuation and dispersion phenomena.
- The TDR trace as seen in the near end can be determined from the bounce diagram by following the vertical line that goes through X=0 (near end position).

The case studies, their corresponding bounce diagram and TDR traces appear in Table 6.

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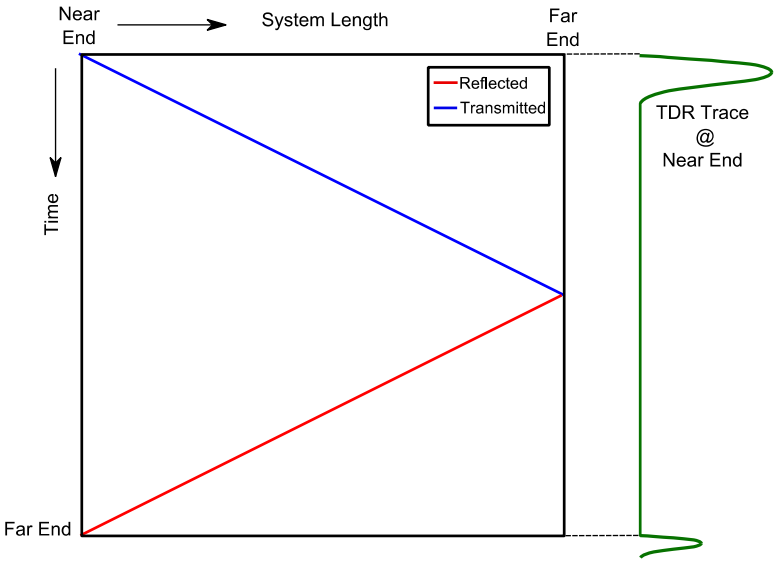
Table 6: Illustrative Case Studies for TDR "Ghost" Reflections

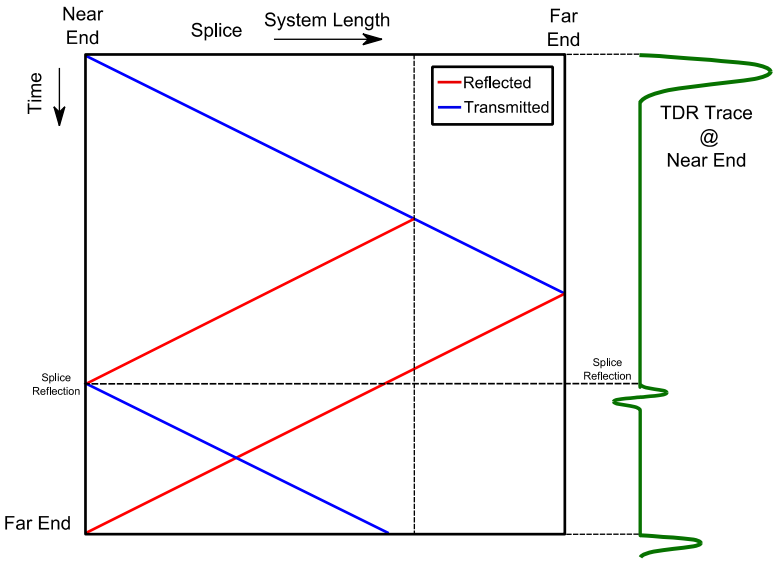
Case 1: Cable System with no Splices or Anomalies

- No TDR "Ghost" reflections observed.



Case 2: Cable System with One Splice Located Farther than the 50% of the Power Cable System Length as Measured from the Near End

- No TDR "Ghost" reflections observed before the far end reflection.
- "Ghost" reflections arrive after far end reflection and are ignored.



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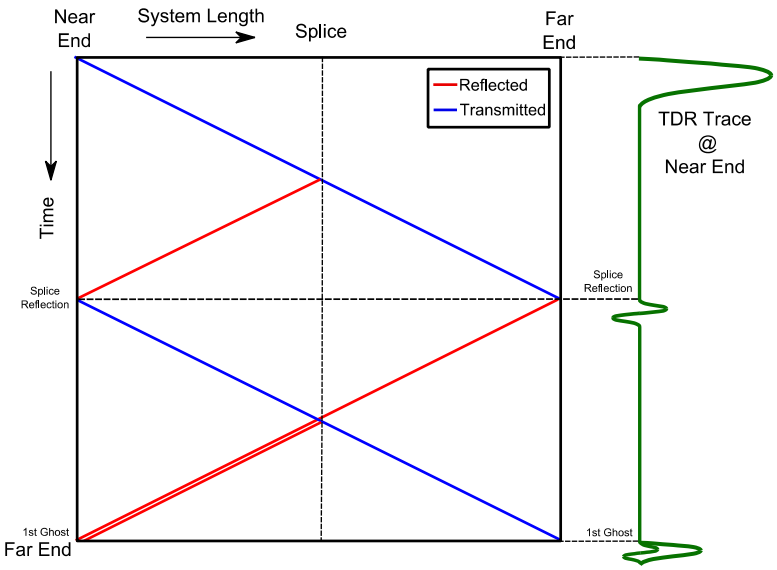
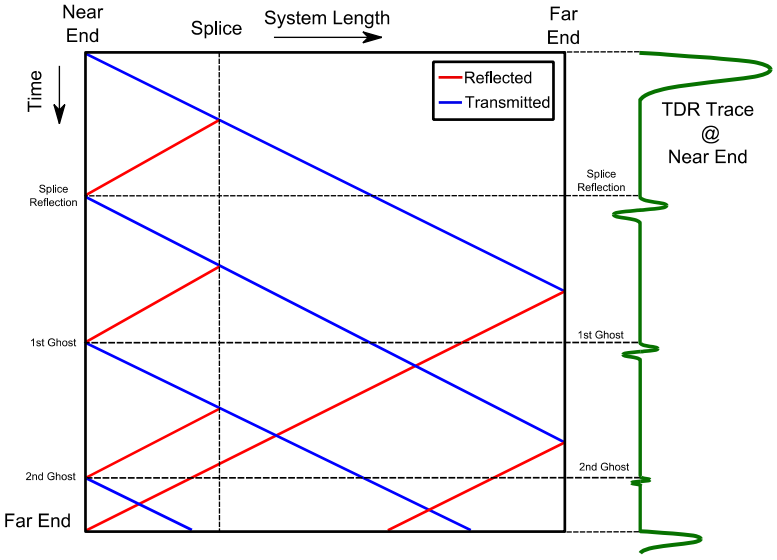
Case 3: Cable System with One Splice Located at the Exact Midpoint of the Power Cable System Length

- No TDR "Ghost" reflections observed before the far end reflection.
- Critical location for splices or anomalies for not having "Ghosts."
- First splice "Ghost" superimposes the far end reflection.



Case 4: Cable System with One Splice Located between the Near End and the Midpoint of the Power Cable System Length

- At least one TDR "Ghost" reflection observed before the far end reflection.
- Generally easy to interpret taking into account the attenuation and dispersion.



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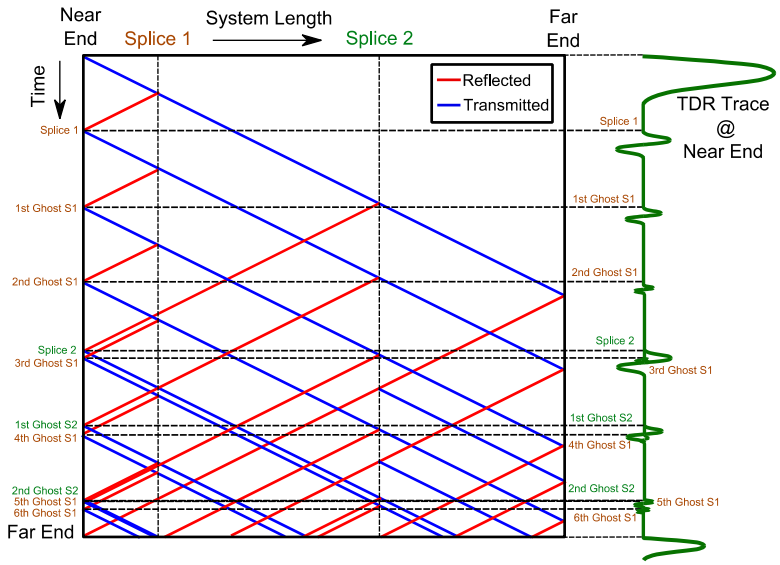
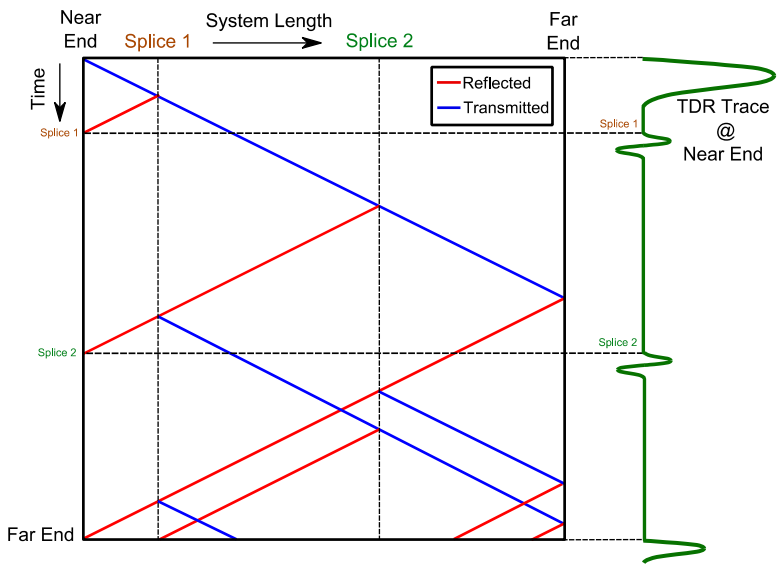
Case 5: Cable System with Two Splices Located at Arbitrary Positions	
• At least one TDR "Ghost" reflection observed • Generally challenging to interpret even by taking into account the attenuation and dispersion	

Case 6: Same as Case 5 Considering the Use of Impedance Coupling at Near End	
• All TDR pulse reflections are absorbed at the near end. • No "Ghosts" are observed on the TDR trace before far end reflection. • The presence of "Ghosts" is still possible depending on splice/anomaly location and separation.	

As seen in Table 6, when dealing with TDR "Ghost" reflections, the following points are important:

- The first reflection captured by the TDR unit always corresponds to a joint or anomaly irrespective of where the joint/anomaly is located.
- When one joint or anomaly exists beyond 50% of cable system length, then TDR "ghost" reflections are not an issue. It may, therefore, be advantageous to measure from the other end if there is a doubt.
- The TDR "ghost" reflections start to appear only if the joints or anomalies are located within the first 50% of the cable system length.
- Care must be taken when interpreting TDR traces with "ghost" reflections, since the

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"ghosts" might be interpreted as nonexistent joints or additional anomalies.

- The attenuation and dispersion effects as well as spacing between "ghost" reflections can help in the identification.
- The issue can be partially addressed by perfectly matching the cable system characteristic impedance. In this case, any additional reflections from the near end would be absorbed and this could avoid many TDR "ghost" reflections.
- The TDR "ghost" reflections between joints or joints and anomalies are impossible to control and are always present at some level.
- When dealing with "ghost" reflections, it is always advisable to perform a far end TDR deployment; a discussion on far end TDR deployment is contained in the next section.

The TDR "ghost" reflections have been observed in the field, see Figure 21, for a 25 kV WTRXLPE URD cable system approximately 5,211 ft long with two splices. A 100 ns TDR pulse was injected without an impedance matching device. The cable system structure (splice locations) was known beforehand.

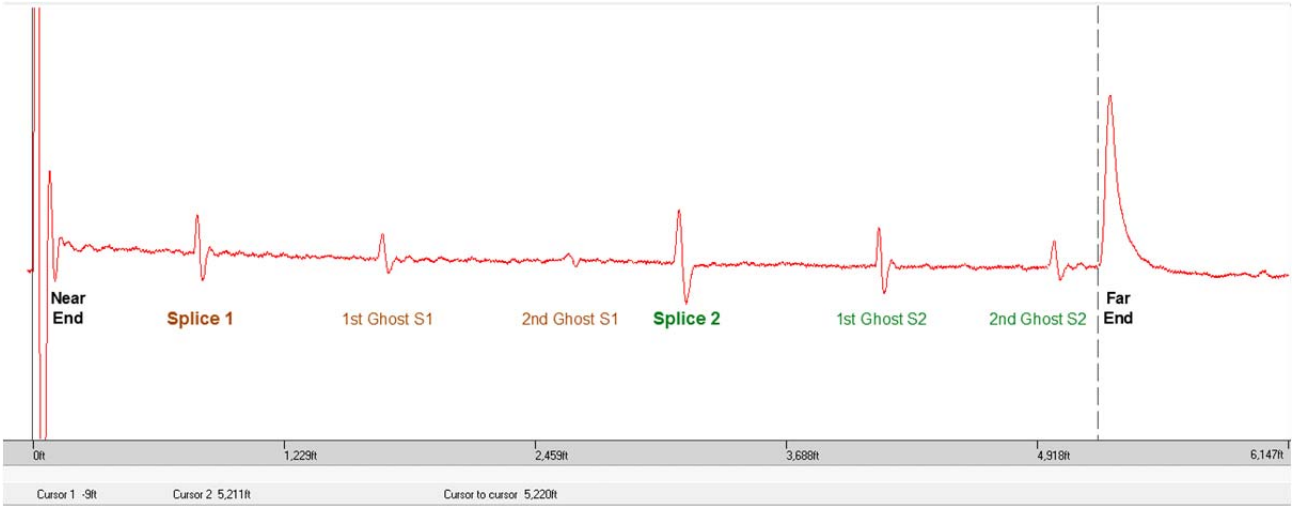

Figure 21: Splice and Ghost Reflections as seen in a TDR Unit from Field Tests of a 25 kV XLPE Cable System with Two Splices (TDR pulse of 100 ns) (See Case 5 in Table 6)

As seen in Figure 21, two "ghost" reflections appear in the TDR trace. The "ghost" reflections can be easily identified in this trace because of the spacing pattern. For example, the distance between "1st ghost S1" and "splice 1" is the same as the distance between "1st ghost S1" and "2nd ghost S1"; conversely, "2nd ghost S1" was more attenuated/dispersed than "1st ghost S1" and "1st ghost S1" more attenuated/dispersed than "splice 1". The same also holds true for "Splice 2" and its "ghost" reflection. In fact, the bounce diagram presented in Table 6 for two splices corresponds to the TDR trace shown in Figure 21; however, the other predicted "ghost" reflections for "splice 1" are not observed in the TDR trace. This is due to attenuation and dispersion that causes them to fall below the noise level and thus making them undetectable by the TDR unit.

The interpretation of the TDR trace shown in Figure 21 is relatively straightforward once some configuration assumptions are made based on known cable system configuration parameters (e.g. standard reel lengths, consistent spacing between "ghost" reflections, other local knowledge, etc.).

Without these assumptions, then an operator could easily conclude that the system has six joints - an erroneous assessment as verified by the utility when they attempted to find the joints.

11.7.1.4 TDR Far End Deployment

In most cases, TDR is only deployed from one end (near end) of the cable system. This is generally enough for determining the system structure and possible existing anomalies; however, in some cases, there is benefit to deploy the TDR test from both ends. It is advisable to repeat TDR measurements from the far end if:

- The far end is not visible on the TDR trace or there is a mismatch between the TDR trace length and the estimated actual length.
- There is doubt about the presence and type of an anomaly.
- There is a need to pinpoint an accessory or anomaly.

Figure 22 shows the near and far end deployment of TDR.

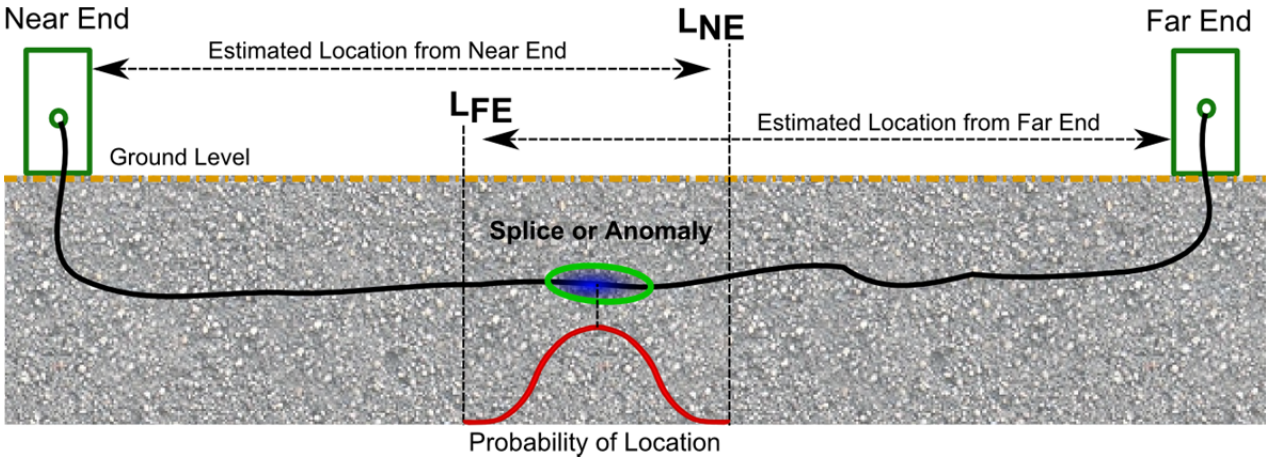

Figure 22: Conundrum for Pinpointing a Splice or Anomaly based on TDR Measurements

As seen in Figure 22, the TDR is deployed from both ends and in each case the joint or anomaly location is over estimated; however, the TDR pinpointing has the advantage that the limits L_{NE} and L_{FE} are identified, the joint would be located with a high degree of certainty between them. In Figure 22, the probability of the location of the splice or accessories occurring between the limits is represented by the red curve. It is important to note that the probability has its maximum at the midpoint of the range established by L_{FE} and L_{NE}; therefore, if digging for repairs is required, this location is the best choice. If the joint or anomaly is not found at that location; then repair crews should start digging in both directions until it is found.

It is important to mention that to increase the accuracy in pinpointing splices or anomalies, the TDR technique can be used in combination with other locating methods. There are several methods to achieve the aim and the previously specified benefits. However, some of them (especially those based on high voltage testing) can diminish the integrity, or even worse, be destructive to the cable system. Some of these might require equipment that is not easy to handle and deploy, or some might

involve detection methods that are unfamiliar to the utility cable engineer. There is no question that an understanding of all available methods is essential to maximizing the effectiveness of successfully locating a splice or anomaly; however, such a comprehensive study falls beyond the scope of the research and practical work considered in the *CDFI*.

11.7.1.5 Pinpointing an Accessory or Anomaly

From a financial and reliability perspective, the importance of pinpointing an accessory or anomaly in a cable system is very important, thus knowing the cable system structure with some level of certainty is of great value. As seen in the previous section, the TDR technique, when deployed from both ends, can effectively pinpoint an accessory or anomaly in a cable system. However, there are several factors to consider when maximizing the benefits of the TDR results.

- Influence of the velocity of propagation (VoP): As mentioned earlier, different cables have different VoP's. To assure the most accurate conductor distance measurements, the cable VoP must be determined. Therefore, the CDFI perspective provided in this chapter is only valid if the correct VoP has been selected.
- System layout: The layout is directly related to the conductor length and thus affects the TDR results. Figure 23 is the same as Figure 6 and shows different cable system layouts that could be encountered in the field. Figure 24 shows the corresponding illustrative TDR traces for the different layouts in Figure 23.

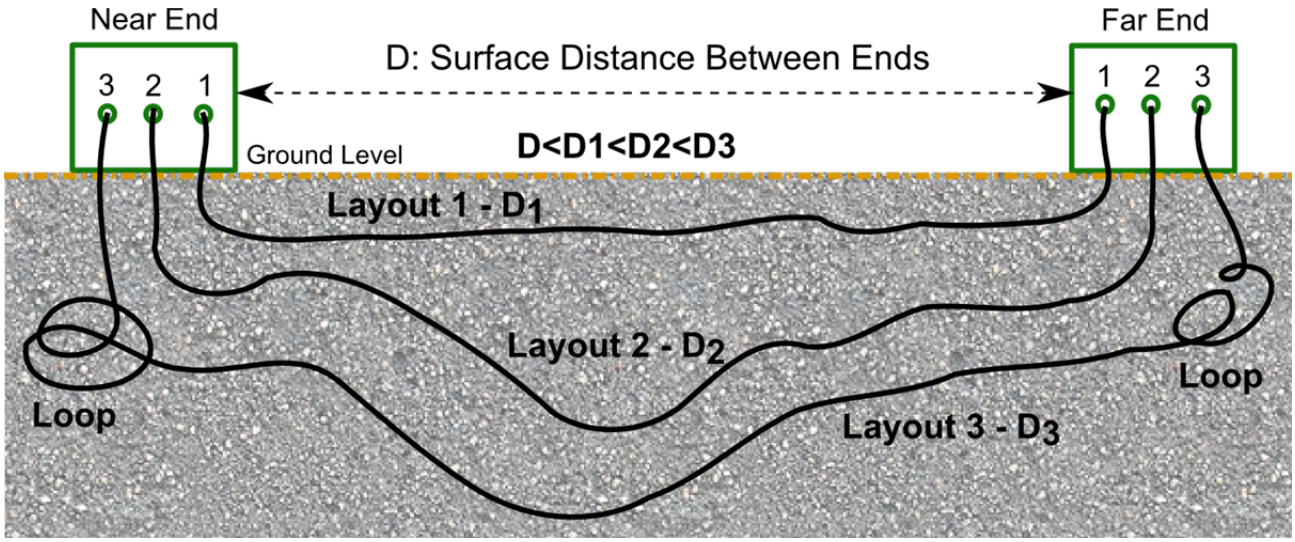

Figure 23: Different Underground Power Cable System Layouts

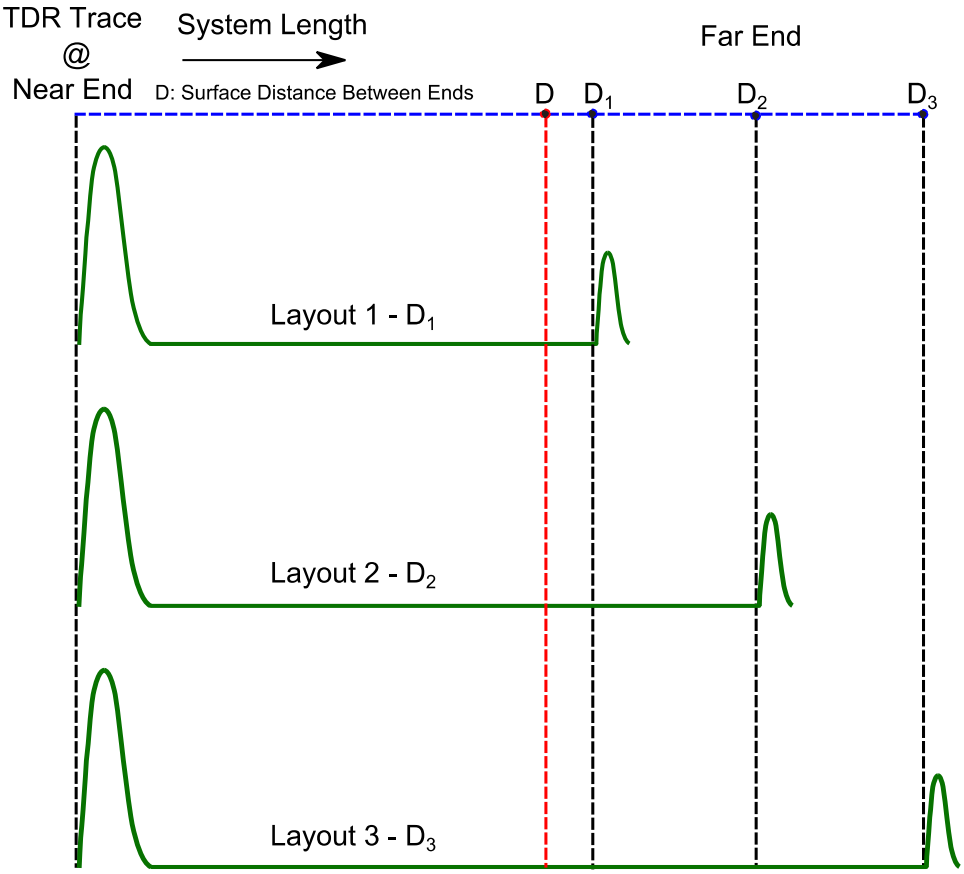

Figure 24: Illustrative TDR Traces for the Different Underground Power Cable System Layouts Shown in Figure 23

As seen in Figure 24, when the correct VoP is used, the estimated distance of the far end, as compared to the surface distance between ends, is always over estimated. This situation intensifies for layouts 2 and 3 as more buried cable and thus conductor length is present. One obvious solution to this issue is to adjust (increase) the VoP up to the level that causes the TDR measured distance to be the same as the surface distance between ends. While this could be a good practice for layout 1 (small difference between D and D_1), it does not work for layouts 2 and 3. It is, therefore, best practice not to assume the cable system follows the shortest path. The VoP has to be determined or estimated according to the cable system under test. Fortunately, basic cable parameters are relatively easy to identify based either on cable markings or utility installation practice.

11.7.1.6 Operator Training

Beyond hardware and software, the success of power cable condition assessment using TDR relies on the skill of the operator. Therefore, an excellent operator training program would provide a higher probability for correctly assessing the cable systems. Training should not be over simplified. Initially the operator must understand the basic concepts of transmission lines and how a high frequency signal travels through them. The concepts of frequency components, attenuation, dispersion, noise coupling, and filtering are also important. The operator must study and develop a

command of the TDR unit hardware and software. Next would be learning acquired from the basic accessory or anomaly TDR signatures. Hands-on experience would then become paramount. Tailored solutions appropriate for their specific system would be learned and correlated with the TDR measurements. Finally, heuristic rules and procedures would be developed. This would round out training and should result in the development of a skilled operator.

11.7.2 Ω-Check

11.7.2.1 Application to other Types of Metallic Shield other than Concentric Neutral

The Ω-Check method was initially designed considering only cable systems with bare concentric neutral wires. However, the principles of the technology can be applicable to any other cable metallic shield types. Therefore, problems with copper tape, wire, LCT, other metallic shield types could potentially be identified if proper databases and procedures are developed. This requires an expansion of the capabilities of this diagnostic technology, which is outside the scope of the *CDFI*.

11.7.2.2 Impact of Joints and Connectors on Measurements

The presence of joints and/or connectors in a cable system can influence Ω-Check results, specifically if they pose high resistances at the connection interfaces with the metallic shield. These high resistances may be interpreted as corrosion issues and thus they may lead to incorrect assessment results, though a poor metallic shield connection at a joint is good information to have. It is also important to consider that the likelihood of metallic shield breaks is increased when joints are present in the system.

11.7.2.3 Applicability to EHV, HV Cable Systems Including Subsea Cable Systems and Armor Evaluation

During the last two decades, a considerable increase in the number of EHV and HV cable systems including subsea applications have occurred in the electric power industry. There is no question that over time these systems will start to degrade and eventually fail. Given their importance, diagnostic techniques will be needed to assess all of their elements of these systems, including their metallic shields and even the cable armor, if present. The Ω-Check technology has the potential to be adapted to provide this capability through the development of proper databases and test procedures.

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11.9 Relevant Standards

- IEEE Std. 81 - 2012: *IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Grounding System*.
- IEEE Std. 400 – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*.
- IEEE Std. 1617 – 2007: *IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium-Voltage Underground Cables*.

11.10 Appendix A

11.10.1 VoP Error in TDR Measurements

It may be thought that variations in VoP would make it almost impossible to locate an accessory or anomaly accurately. Fortunately, there are ways to minimize the error in the VoP when testing, resulting in very accurate distance measurements. The most common technique used to reduce VoP error is to test the system from both ends (TDR dual-ended deployment) to establish two lengths thereby localizing the accessory or anomaly between the two ends. The procedure is as follows:

- Determine the path of the cable system. With a measuring wheel, estimate the length of the cable system being tested. Set the VoP to 50%, test the cable from one end, and record the distance reading to the accessory or anomaly. Next, using the same VoP setting, test from the opposite end of the cable system and also record the distance reading. If the sum of the readings is the length of the cable system that was initially estimated, the VoP is correct and the fault has been located with some good degree of certainty.
- If the sum of the two readings is more than the initial estimated distance, reduce the VoP setting and re-test. This process can be repeated until a match between the computed and estimated distances is found.
- Similarly, if the sum of the two readings is less than the measured distance, increase the VoP setting. This process can be repeated until a match between the computed and estimated distances is found. However in this case, the operator must also consider the possibility of two accessories or anomalies.
- Same results can be obtained mathematically. Take the estimated power cable system length and divide by the sum of the two TDR readings obtained by the tests from each end. This gives the adjustment factor. Then multiply each of the TDR readings by the adjustment factor. These results will be the corrected length readings.

CHAPTER 12

Other Diagnostic Techniques

Jean Carlos Hernandez-Mejia & Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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12.0 OTHER DIAGNOSTIC TECHNIQUES

This chapter describes other diagnostic techniques infrequently used in the U.S. and Canada but might potentially be used for condition assessment of MV or HV power cable systems. The diagnostic techniques are as follows:

- Dielectric Spectroscopy.
- DC leakage current.
- Recovery voltage.
- Polarization/depolarization current or isothermal relaxation current (IRC).

These techniques have all been described in the past (prior 2005); however, during the last decade, they have mainly been used on laboratory and/or pilot studies not for making decisions regarding the condition assessment of real power cable systems. Thus, their application is still limited. Detailed descriptions of each technique follow.

12.1 Dielectric Spectroscopy

12.1.1 Test Scope

Dielectric Spectroscopy is a similar technique to Tan δ; however, the Tan δ is established by measuring the real and imaginary components of a cable system current at a range of applied voltage frequencies, typically 0.001 to 100 Hz [1-9]. The benefit of this process is that it supplies additional information about the cable system insulation. In general, the Tan δ varies inversely with frequency (since the capacitive current is directly proportional to the applied ac frequency) and will therefore be larger and more easily measured at lower frequencies (Figure 1 [9] and Figure 2 [5]). The loss current, on the other hand, remains constant with frequency unless there is degradation present in the cable system.

The data that result from dielectric spectroscopy measurements are essentially frequency spectra that contain considerable information, and consequently require more careful interpretation than Tan δ measurements made at one frequency. It is instructive to note the strong frequency and voltage stress dependencies in Figure 1 and the strong frequency and age dependencies (Cable 1 – 20 yrs., Cable 2 – 50 yrs.) [5] in Figure 2.

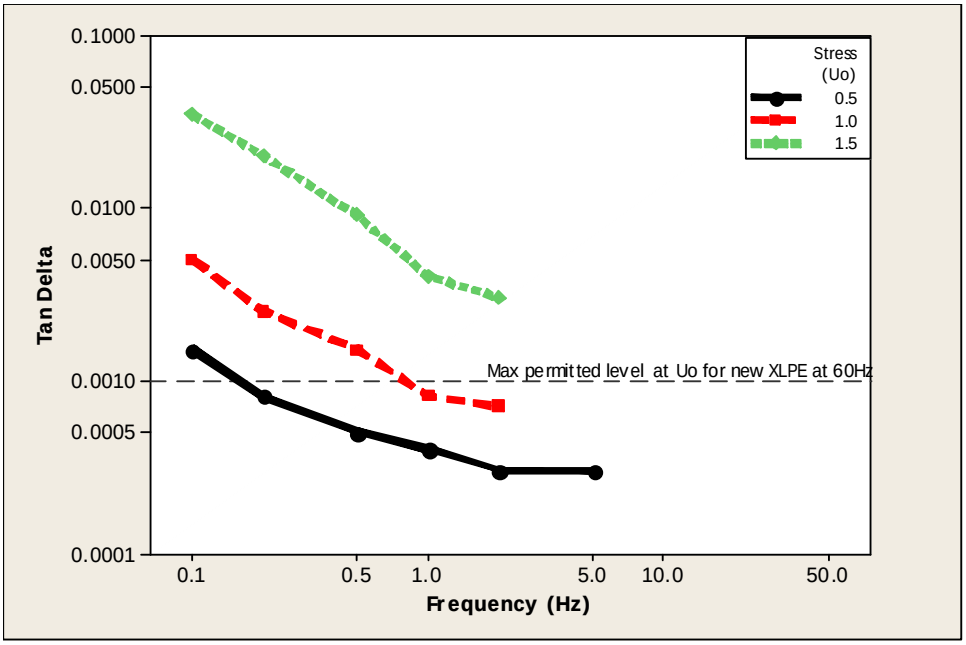

Figure 1: Dielectric Spectroscopy of Aged XLPE Cables [9]

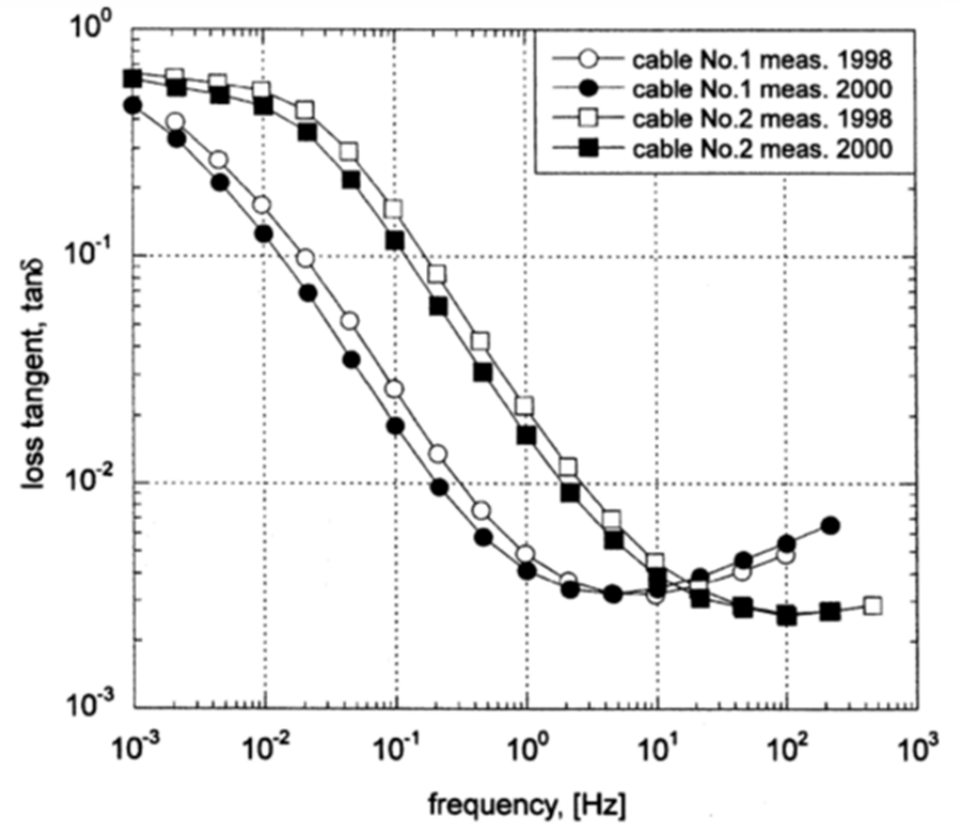

Figure 2: Dielectric Spectroscopy of Aged Paper Cables [5]

12.1.2 How It Works

There are two ways to obtain the dielectric loss spectra:

- Frequency Domain Spectroscopy (FDS) – Employ a variable frequency source and perform conventional current measurement and phase angle calculation
- Time-Domain Spectroscopy (TDS) – Measure a number of DC currents as a function of time and then transform to the frequency domain using the Hamon approximation [4]

The variable frequency/conventional data (FDS approach) are obtained by applying voltages at discrete frequencies and then calculating the real and imaginary parts of the current at that frequency. The Tan δ is then the ratio of these two parts. The frequency is then stepped to cover the complete frequency range. The data may be interpreted as frequency spectra [9] or via equivalent circuit models [2, 9]. The equivalent circuit model translates the measured "complex" current into a "complex" permittivity where the real part of the permittivity represents the direct capacitance and the imaginary part represents the resistive or loss component. The Tan δ then becomes the ratio of the imaginary permittivity to the real permittivity. The effects of age, moisture, and temperature can then be analyzed using either of these approaches. Figure 3 shows examples of frequency domain permittivity measurements on paper cables with different moisture contents.

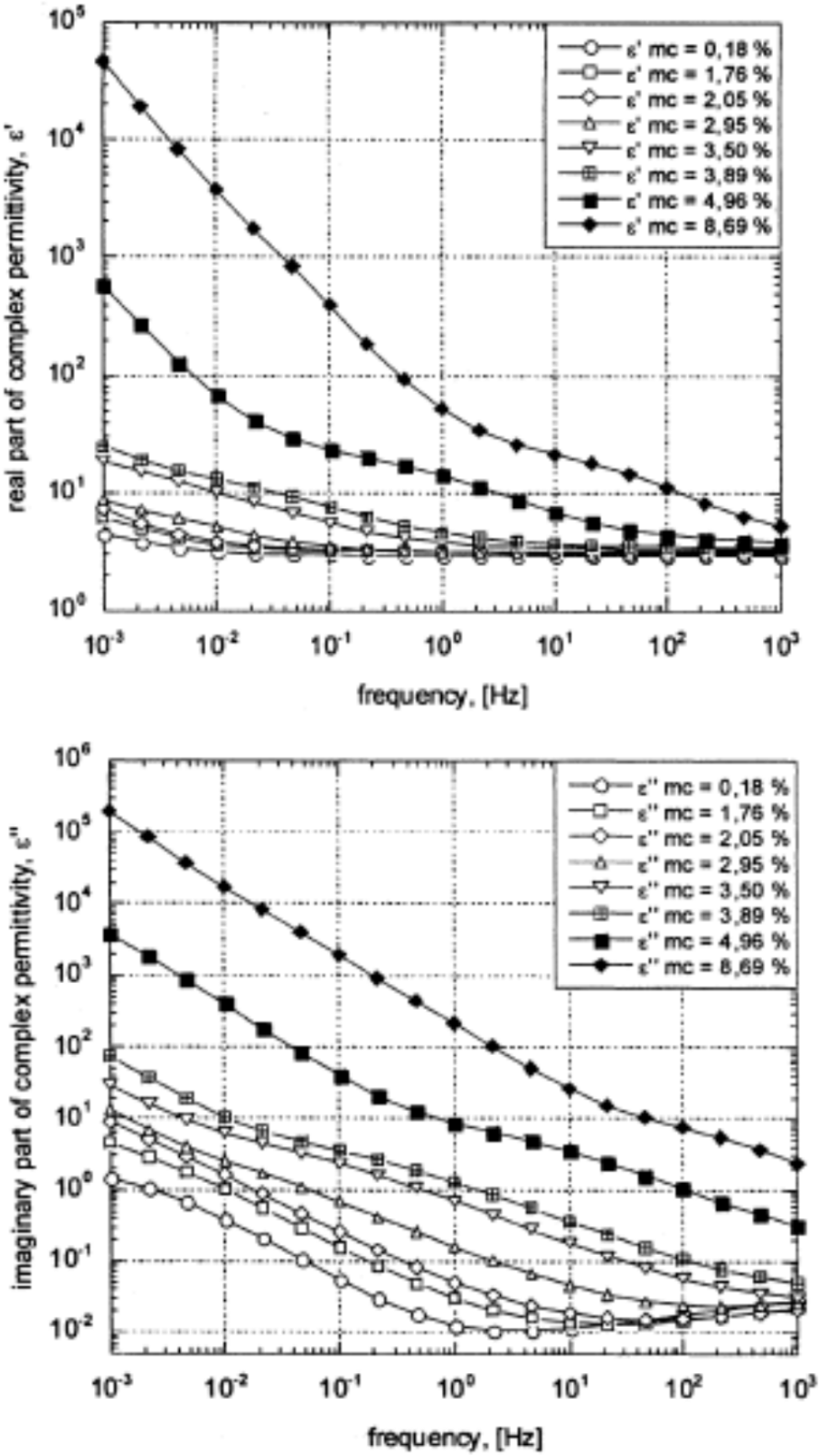

Figure 3: Real (top) and Imaginary (bottom) Parts of Complex Relative Permittivity for Paper Cables with Different Moisture Contents

The TDS approach, as compared to the FDS approach, uses a DC voltage applied for sufficient time to obtain measurements of the cable system loss current as a function of time. These measurements are subsequently transformed to the frequency domain using the Hamon approximation. The basic approach to TDS with the contributing currents is set out in Figure 4. As this figure shows, measurements are made both with voltage (polarization mode) and without voltage (depolarization mode) applied. Three current components make up the currents measured with voltage (i_{pol}) and without voltage (i_{depol}):

- i_{cap} – capacitive current (charging current)
- i_{abs} – absorption current (loss current)
- i_{qc} – space charge/quasi-conduction current

Equation 1 shows i_{pol} and i_{depol} as functions of the above current components.

$$i_{pol} = i_{cap}(t) + i_{abs}(t) + i_{qc}(t)$$
$$i_{depol} = -i_{cap}(t) - i_{abs}(t)$$

Equation 1

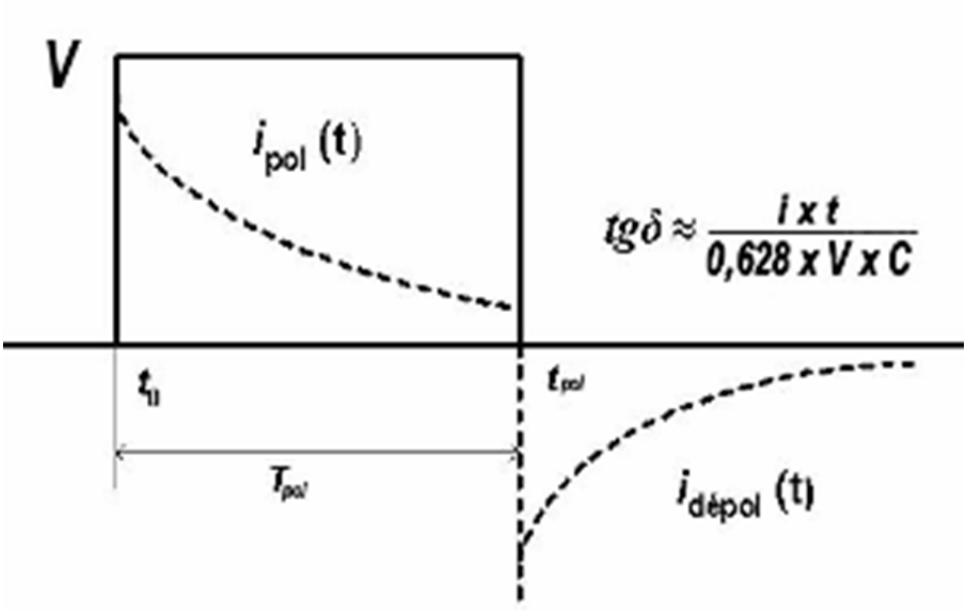

Figure 4 Currents and Voltages for Tan δ Estimation using TDS

An estimate of the Tan δ is given by the Hamon approximation once the capacitance (C) and the absorption (i_{abs}) current are measured. Figure 4 shows that two currents can be derived from the application of DC (polarization and depolarization) thus giving two ways to estimate Tan δ via the two formulas shown in Figure 4. In theory, the polarization and depolarization absorption currents should be equal for the case where the charging time is infinitely long. Such long test times are not practical and so the charging and discharging times are selected to allow for reasonably complete charging and discharging of the dielectric, the actual charging and discharging currents end up appearing similar in shape but different.

12.1.3 How It Is Applied

Figure 5 shows a TDS unit with the typical voltage application protocol used in the field. Note that the voltage protocol uses a polarization and depolarization period for each voltage step. Furthermore, the time duration of the depolarization phase is significantly longer than that of the polarization phase.

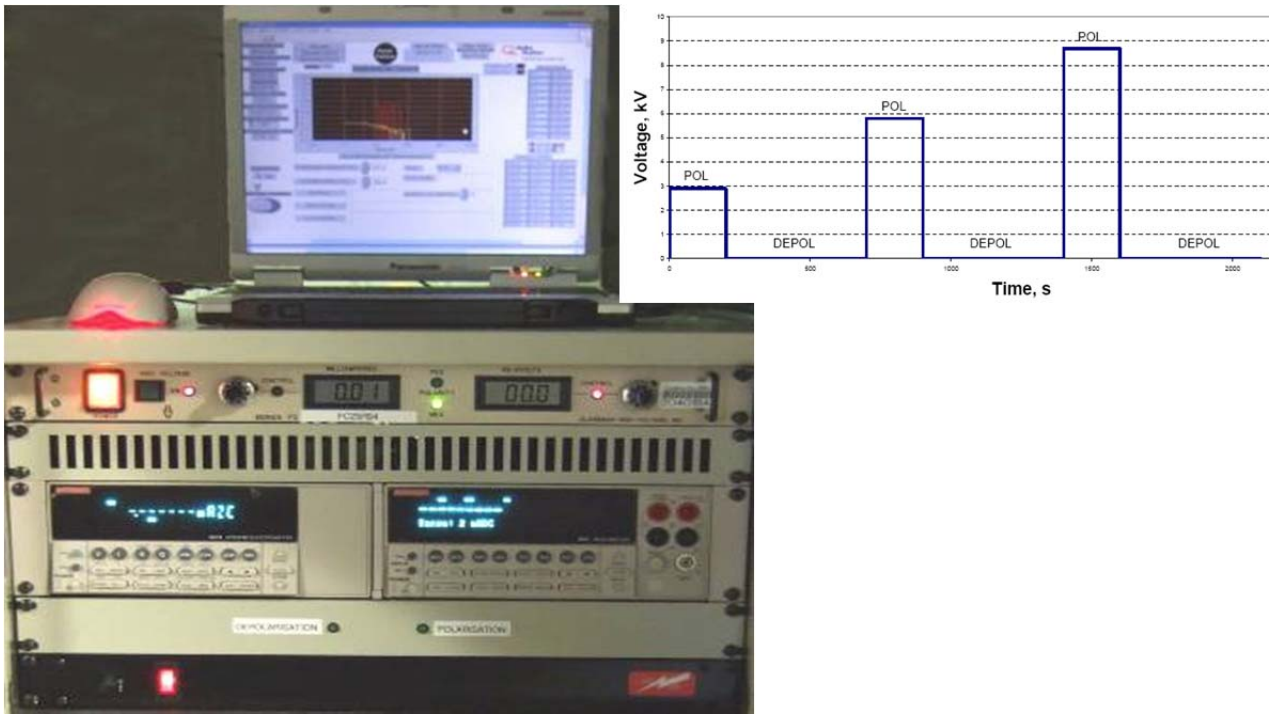

Figure 5: TDS Unit and Voltages Used for the step tests

Figure 5 shows the setup of power supply (top) and digital meters (bottom) for the measurements; not shown is a capacitance meter. The data obtained using the TDS approach are presented as current versus time and Tan δ versus frequency graphs as shown in Figure 6 and Figure 7. These figures show the measurements made during both polarization and depolarization modes.

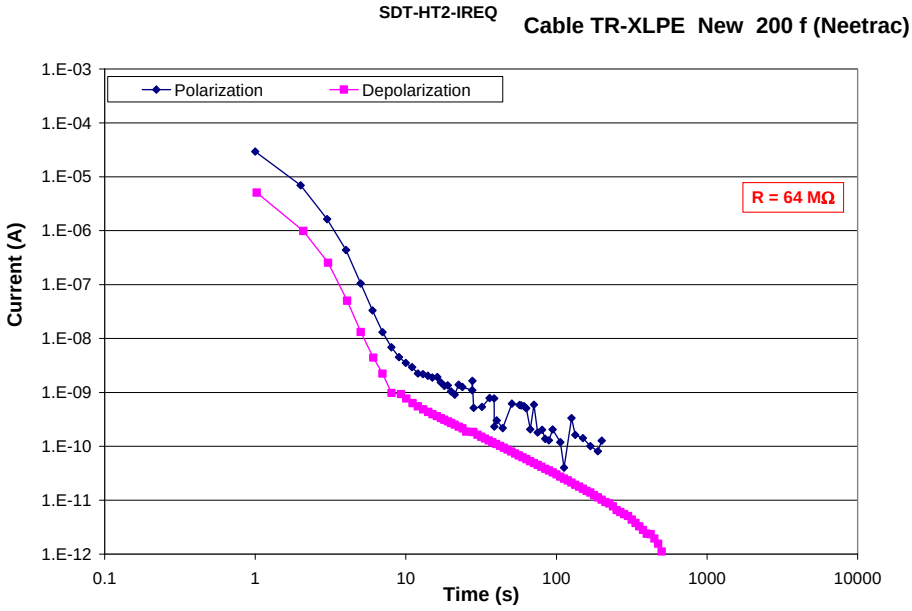

Figure 6: Time-Domain Current Measurements Using TDS Approach

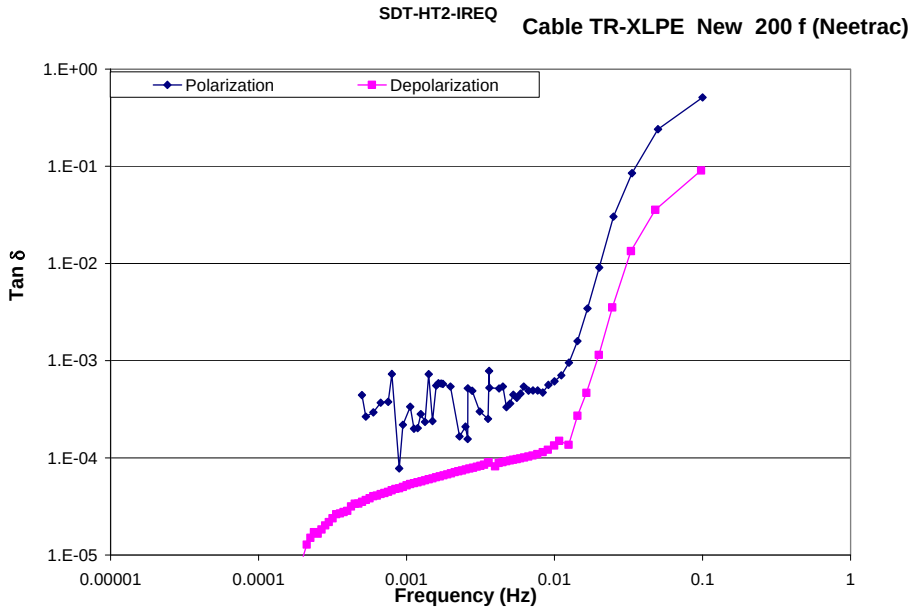

Figure 7: Transformed Tan δ Spectra from Figure 6

As the above figures show, the transformation from the time-domain to the frequency-domain is a one-to-one mapping of the data points. The currents and their components appear in Figure 6. Currents measured at short times (< 10 sec in Figure 6) are dominated by the capacitive current (i_{cap}) while currents measured at long times (>10 sec) are dominated by the absorption current (i_{abs}). The absorption current is the current that is of interest for determining the Tan δ. When these currents are transformed to the frequency domain using the Hamon approximation ($f = 0.1/t$),

shorter times correspond to higher frequencies and longer times to low frequencies so the absorption current becomes dominant at frequencies generally below 0.01 Hz. The practical consequence is that currents at higher frequencies have considerable capacitive components that mask the absorption current. This means that Tan δ measurements using the Hamon approximation at higher frequencies (>0.01 Hz) and shorter times may not be accurate estimations of the Tan δ since the capacitive current is likely still masking the absorption current. Cable system length (capacitance) determines the precise cut off frequency for the capacitive current.

The advantages and disadvantages of Dielectric Spectroscopy appear in Table 1 and Table 2.

Table 1: Advantages and Disadvantages of Dielectric Spectroscopy for Different Voltage Sources

Source Type	Advantages	Disadvantages
DC (Time Domain)	• Testing equipment is small and easy to handle. • Multiple voltage levels up to and above U_0 can be applied. • Tip Up can be easily computed. • Comparing polarization and depolarization Tan δ provides an additional diagnostic feature not available in other Tan δ diagnostics.	• Long Test Times (> 10 minutes per voltage step) are required to charge and discharge the cable circuit. • Requires very low current measurements on the order of nano and pico amps. • May inject space charge at the higher voltages (>20 kV/mm and times longer than 100 sec). • The polarization and depolarization estimates of Tan δ complicate interpretation since there are two estimates of Tan δ for every frequency.
Variable Frequency AC Sinewave (Frequency Domain)	• Testing equipment is small and easy to handle. • Waveform is the same shape as the operating voltage waveform.	• Test voltages may be limited to a fraction of U_0 due to the difficulty of synthesizing frequencies >0.1 Hz. • Long test times are associated with frequencies below 0.01 Hz (i.e. times >100 sec per cycle) • May inject space charge at low frequencies (<0.01 Hz) and higher voltages

The application of voltages above U_0 for a long period (defined by either cycles or time) may cause further degradation of an aged cable system. The impact of this effect warrants consideration for all the methods of Dielectric Spectroscopy described in this section. The precise degree of degradation will depend upon the voltage level, frequency, and time of application. Thus, when undertaking spectroscopic measurements, a utility should consider that a circuit can fail during the test and may want to have a repair crew on standby.

Table 2: Overall Advantages and Disadvantages of Tan δ Dielectric Spectroscopy Techniques	
Advantages	• Adds Tan δ frequency dependence as a diagnostic feature. • Measurements on a given phase are comparable to adjacent phases, so long as the phases have the same configuration (Also applies to T-branched or other complex circuit configurations). • Periodic testing provides numerical data that can be compared with future measurements to establish trends. • Indicator for the overall degree of water treeing in XLPE cable. • Data obtained at lower voltages ($<U_0$) are generally as useful as data at higher voltages. • Test results are simple numerical values that can easily and quickly be compared to other measurements or reference values. • Simple numeric results enable a quick risk assessment to be made prior to proceeding to higher test voltage levels.
Open Issues	• The relationship between the measured loss on the entire system and the loss at a specific location (such as an accessory or cable defect) needs to be established. • Development of the equivalent circuit from the data. • Identification of defects from the loss measurements. • The importance of differentiating between the loss characteristics of different EPR insulation materials needs to be established. • Methods to interpret results for hybrid circuits need to be established. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • May be possible to determine the equivalent electrical circuit. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC has not been established. • Effect of single or isolated long water trees on the Tan δ. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable must be taken out of service for testing. • Not an effective test for commissioning newly installed cable systems. • Few data sets are available to determine the usefulness of this approach. • Accurate Pass / Not Pass levels not yet established. • Test at different voltage levels require longer test times.

To enhance the effectiveness of Tan δ measurements at variable frequencies, the measurements should be made periodically, preferably over several years. In general, an increase or shift in the spectra in comparison to previously measured values indicates that additional degradation has occurred.

It is important to bear in mind that some accessories employ stress relief materials with non-linear loss characteristics (dielectric loss changes nonlinearly as a function of voltage). Some have suggested that these materials might have an influence on the measured loss values. However, the

evidence available indicates that the type of stress relief may have a smaller effect on the overall loss measurement for the circuit than losses associated with severely degraded or improperly installed accessories. Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Tan δ over time.

12.1.4 Success Criteria

There is insufficient data to provide definitive success criteria. However, the success criteria provided earlier for measurements made at 0.1 Hz are applicable for data developed at the same frequency. However, there are no guidelines on how to interpret frequency dependent Tan δ data.

12.1.5 Estimated Accuracy

The *CDFI* lacks sufficient dielectric spectroscopy data to estimate the accuracy of this measurement technique.

12.1.6 *CDFI* Perspective

12.1.6.1 Comparison with other Techniques

Collaborative research work between NEETRAC and IREQ [7] has shown that, within comparable frequency ranges, 0.1 Hz VLF-sinusoidal Tan δ and DC dielectric spectroscopy (TDS) give very comparable data. Figure 8 shows results from the TDS and standard variable frequency VLF Tan δ measurement techniques on a heat shrink joint. The upper group of curves comes from the TDS polarization current measurement whereas the lower group comes from the depolarization current measurement. This finding held true for EPR, WTRXLPE, and XLPE cables and for joints as well. The data developed in the *CDFI* show that the Tan δ values estimated using the TDS polarization technique agree with measurements made on the same cable using the standard VLF Tan δ measurement technique. It is also possible to derive Tip Up (or differential dielectric loss data) by applying different polarization voltage levels. Note that dielectric loss estimates from depolarization (discharge measurements) do not directly follow the polarization results. In fact, this difference is useful as a diagnostic feature because the depolarization loss is a "voltage off" estimate. In a lightly degraded and, hence, linear cable system the two measurements should be in close agreement. If these measurements differ from each other, then this indicates a non-linear cable system that must have some form of degradation present to generate this behavior.

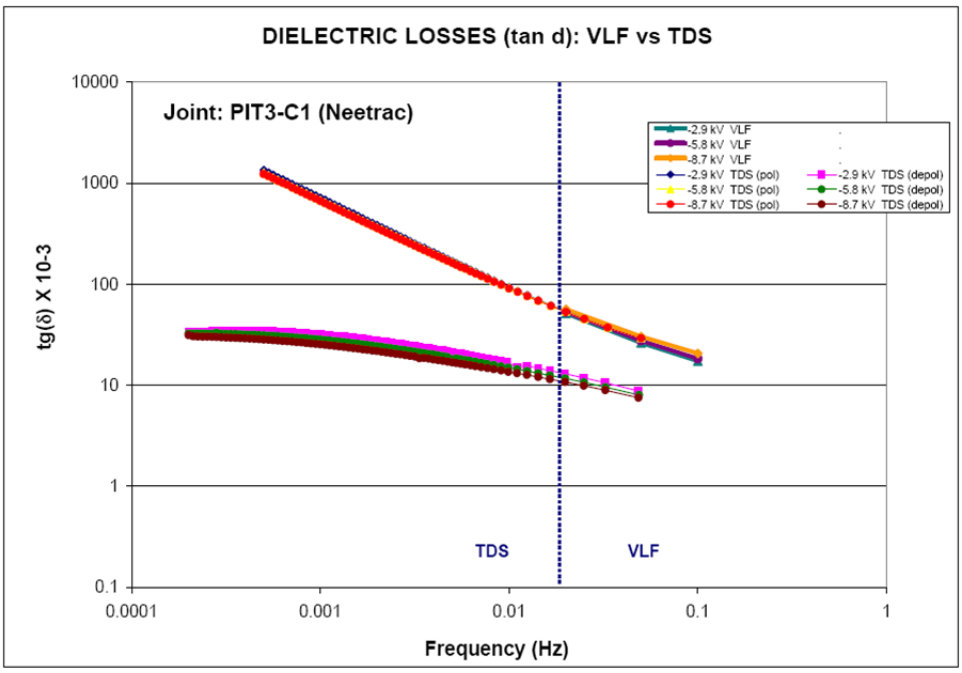

Figure 8: Frequency Spectroscopy on a Heat Shrink Joint using Variable Frequency VLF and TDS Dielectric Loss Measurement Equipment

12.1.6.2 Diagnosis for Paper Cable

Work undertaken in Sweden [5] using variable frequency Dielectric Spectroscopy provides data for paper insulated cables as shown in Figure 9. The authors of this work have suggested that the loss results are correlated to the moisture content of the cables to the extent that the loss measurements may be used to determine the moisture content directly. In this case, the magnitude of the minimum loss, measured over a wide frequency band (0.001 Hz to 1 kHz), is determined, and related to the moisture content via Equation 2.

$$Moisture = \alpha + \beta \ln(Tan\delta_{Min}) \qquad \textbf{Equation 2}$$

where,

α, β – Constants to be determined empirically

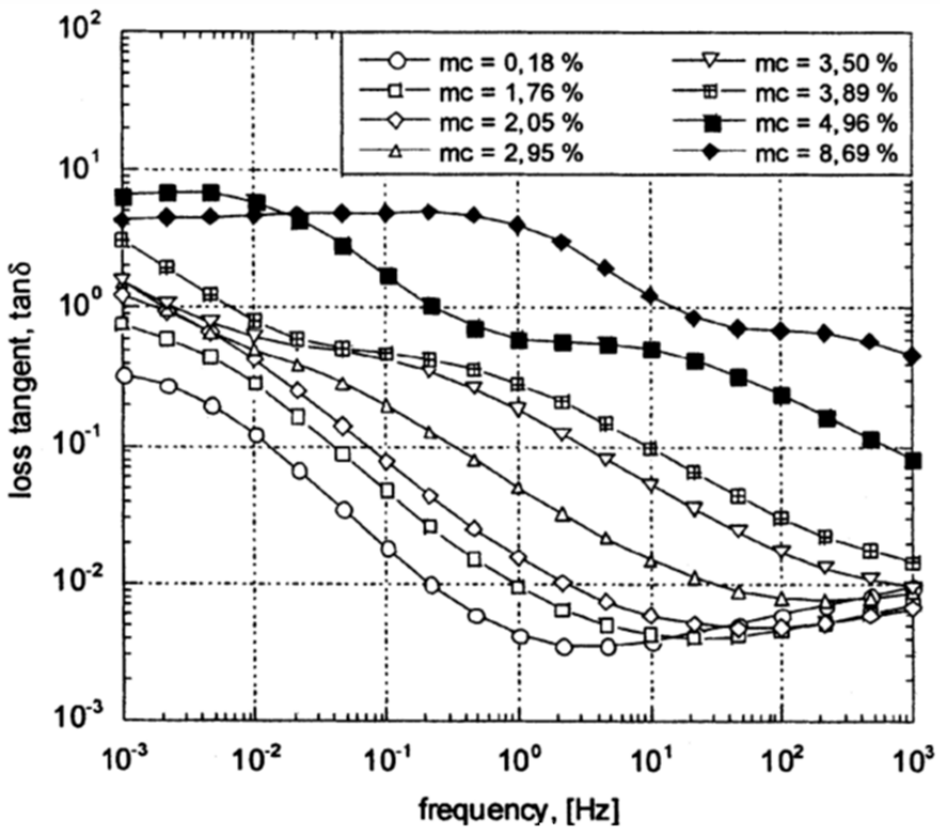

Figure 9: Relationship between Loss and Frequency for Selected Moisture Contents

This proposed correlation [5] may be practical at low moisture contents as the minima are expected to be within the low frequency range. This is not the case for higher moisture contents. Thus, it was decided to investigate the relationship of the absolute loss measured at 0.1 Hz since this frequency is commonly employed in field measurements of Tan δ. It was found that the Tan δ versus moisture data could be modeled so that Tan δ could be used to ascertain the average moisture content of the cable system. Using the data shown in Figure 9, the corresponding Tan δ/moisture content model appears in Figure 10. The data in Figure 2 were then used to test the usefulness of this model since these measurements originated from different cable systems. The reference lines on Figure 10 show the Tan δ and moisture contents measured for Cable 1 and Cable 2 from Figure 2. The model appears to be valid since these data points fall on the curve.

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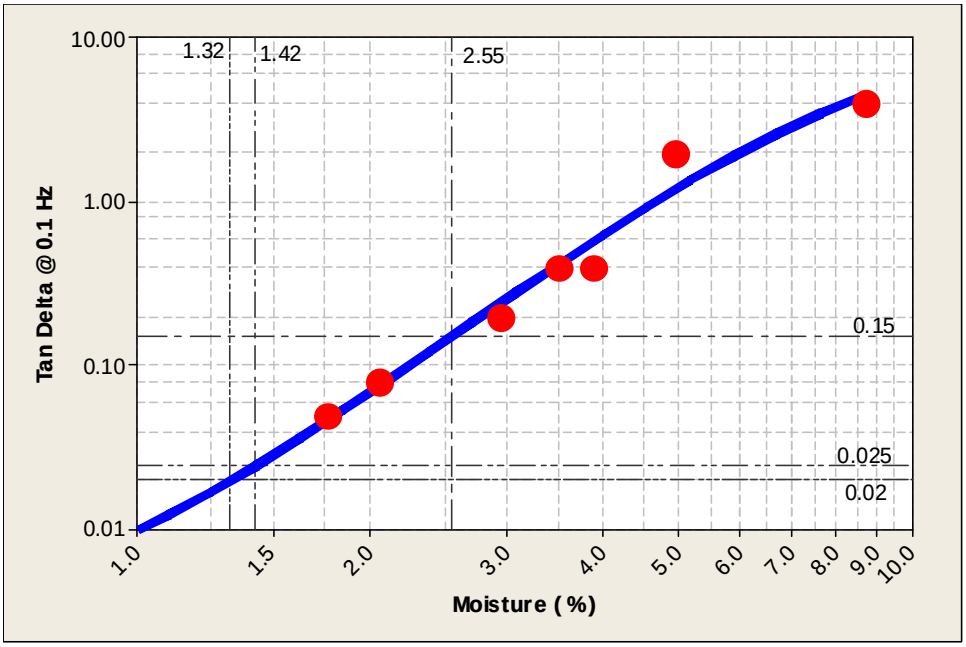

Figure 10: Relationship between Tan δ at 0.1 Hz (from Figure 9) with Moisture Content

12.1.7 Outstanding Issues

Outside of laboratory research, this technique is not used in the U.S. or Canada and so additional data is needed to fully evaluate its validity.

Section 6.6.14 of Chapter 6 discusses the use of Dielectric Spectroscopy for subsea and HV cable systems.

12.2 DC Leakage Current Measurement Technique

12.2.1 Test Scope

DC leakage current tests consist of the application of dc voltage (lower than that used in dc withstand tests described in Chapter 9) with the simultaneous measurement of leakage current. It can be applied to all cable circuits. However, research has shown that the application of dc voltage to aged XLPE insulated cables can cause premature failure by injecting space charge into degraded regions of the insulation [10 - 14]. This trapped charge, if not discharged from the cable system leads to enhanced stress within the insulation once the circuit is re-energized with 60 Hz ac.

12.2.2 How It Works

A dc voltage is applied to the circuit. Once at steady state, the dc current required to maintain a given cable circuit at a specified voltage is measured.

12.2.3 How It Is Applied

This technique is performed offline. Its intent is to measure the global condition of the cable system insulation, but it can also be used for measuring tracking currents at insulation interfaces or on the external surface of terminations. A dc test voltage is applied between the conductor and the insulation shield and the resulting current is measured. The test voltage is increased stepwise. Each step usually takes 30 seconds. The total test duration is approximately 10 minutes. The maximum voltage is typically twice the peak value of the rated line-to-ground voltage of the cable. For new circuits, as an acceptance test, the voltage may be as high as 6 U_0.

The advantages and disadvantages of the dc leakage current measurement technique appear in Table 3.

The application of high voltages for a long period (defined by either cycles or time) may cause further degradation of an aged cable system. The impact of this effect warrants consideration for all the methods of dc leakage current described in this section. The precise degree of degradation will depend upon the voltage level and time of application. However, there are numerous studies that show that the rate of degradation is heightened when dc voltages are used – see discussion in Chapter 2. Thus, when applying elevated voltage to a cable system, a utility should have a repair crew on standby to address possible failures.

It is important to note that some accessories employ stress relief materials with non-linear loss characteristics. There have been suggestions that these materials might influence the measured values. *CDFI* has not explored dc leakage testing or data analysis to any significant degree, so the impact of these materials on dc leakage measurements is unknown.

Table 3: Overall Advantages and Disadvantages of Leakage Current Technique	
Advantages	• Provides a general (though simplistic) condition assessment of a cable system. • The technique can be automated. • Test equipment is small, inexpensive, and easy to deploy. • Periodic testing provides historical data that enhances future testing by establishing trends.
Open Issues	• DC leakage tests may not be able to detect dirty terminations.
Disadvantages	• DC voltages (>U_0) create space charge accumulation that can cause aged XLPE insulated cables to fail prematurely after returning to service. • Before and after each test, cable must be completely discharged – these times can be long; > 4 times the length of the test. • The duration of voltage application is not well established. Typical times range from 15-60 minutes. • The cable system must be taken out of service for testing. • DC only detects severe cable system defects.

DC leakage testing has been deployed for many years and it is still used today, though mostly for industrial cable applications. In many cases, this appears to be a legacy issue from the previous common practice of dc hipot testing, rather than the proven efficacy of the technique.

12.2.4 Success Criteria

Leakage current results are reported in terms of the basic data.

Table 4: Pass and Not Pass Indications for Leakage Current Measurements		
Cable System	**Pass Indication**	**Not Pass Indication**
HMWPE WTRXLPE XLPE	No uniform criteria established	No uniform criteria established
EPR		
PILC		

There are no unified success criteria for leakage current measurements (Table 4). Establishing such criteria is complicated in that the values depend not only on the cable system quality, but also on the cable/accessory technologies employed, the applied voltage, the circuit length, and the humidity (which may impact the measurement equipment and terminations) at the time of the test.

Although no unified criteria are available, a number of references indicate some useful features that form a basis for diagnostic conclusions (Table 5).

Table 5: Useful Judgment Criteria for the DC Leakage Current Technique [13]

Observed Characteristic	Judgment		
	No signs of deterioration	**Middle signs of deterioration**	**Marked signs of deterioration**
Leakage current changes with time during test	Current tends to decrease	Current tends to decrease	Current tends to increase
Rate of change of current changes during test	Rate of change decreases	Constant Rate	Rate of change increases
Leakage current (relative to reference cable)	Same as reference	2 to 10 times reference	>10 times reference

12.2.5 Estimated Accuracy

The *CDFI* does not have sufficient dc leakage current data to estimate the accuracy of this measurement technique.

12.2.6 *CDFI* Perspective

The *CDFI* does not have sufficient dc leakage current data to establish a *CDFI* perspective.

12.2.7 Outstanding Issues

This technique was historically utilized as part of a withstand program (see Chapter 10 – Monitored Withstand). To date, only one utility is known to have used it in North America. Data has not been collated in a coherent manner thus no research was possible within *CDFI*.

12.3 Recovery Voltage Technique

12.3.1 Test Scope

This diagnostic technique can be applied to any single cable insulation type (not hybrid circuits) with conventional or non-linear stress relief accessories. However, the availability of success criteria has effectively limited its use to paper insulated cables.

12.3.2 How It Works

This technique is sensitive to the level of water tree degradation in the insulation [14 - 18], or moisture ingress in PILC cables. It measures the increase in voltage caused by the release of trapped charges within the insulation. Absorbed moisture within the insulation likely causes charges to be trapped. The voltage measured across the cable system dielectric after the applied test voltage is removed is called the recovery voltage.

12.3.3 How It Is applied

This technique is conducted offline and measures the global condition of the insulation. Very little Recovery Voltage testing was performed in the *CDFI* so the following discussion is based on information from the literature.

The procedure follows the scheme shown in Figure 11. The cable circuit is charged using dc voltage for a given time. Typical values range from 1 to 2 kV. Charging time is usually 15 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a ground resistor. The open circuit voltage is then measured. This voltage is known as the recovery voltage.

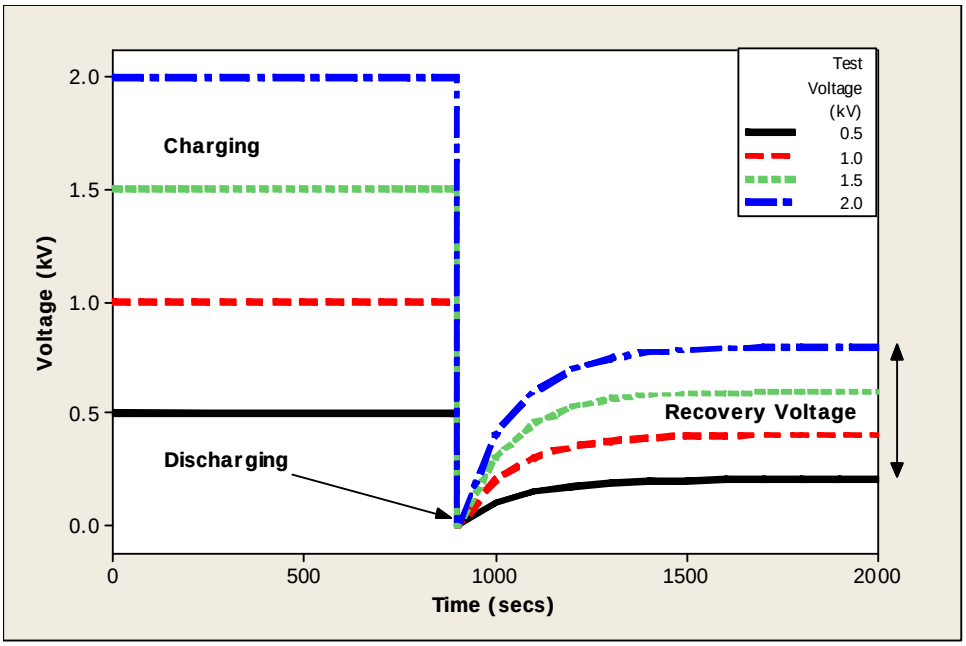

Figure 11: Schematic Representation of the Recovery Voltage Measurement Technique

Data from Kuschel et al. [13] (Figure 12) display the magnitudes expected from tests on new (unaged) cables. Figure 11 shows the different discharging characteristics and that the Recovery Voltages are in the range of 0.1% to 0.2% of the dc charging voltage. These data used the following test protocol:

- charging voltage: 3 kV dc
- charging time: 15 min (900 sec)
- discharge time: 5 sec

The data appear in Figure 12 for the maximum measured voltage and the result after a decay time of 10,000 sec.

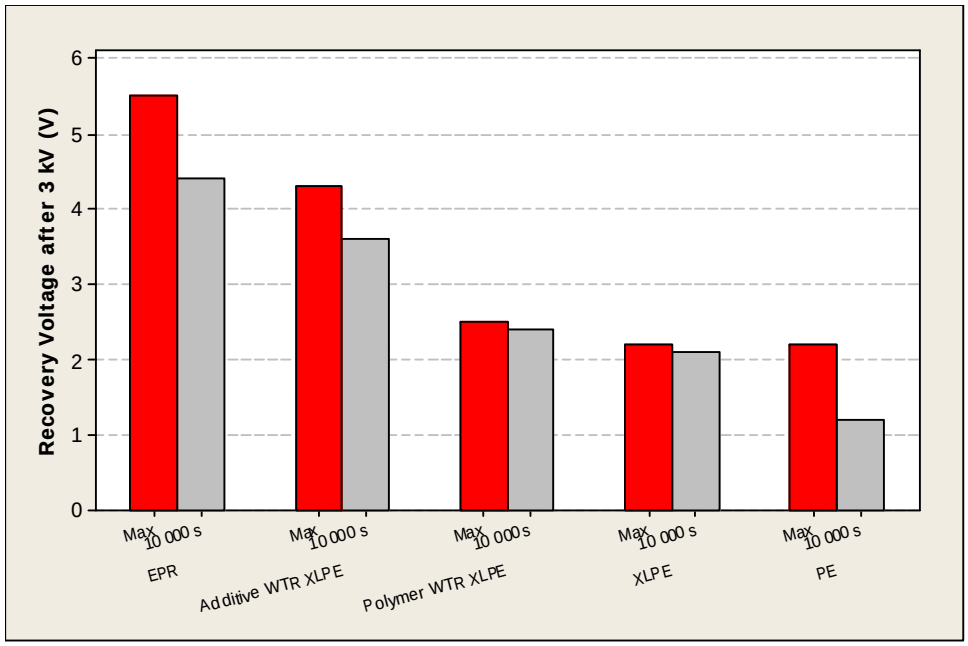

Figure 12: Recovery Voltage Data [13]

In the recovery voltage technique, the diagnostic factor D describes the level of damage to the cable. The diagnostic factor D is the ratio between the maximum recovery voltage with U_0 as the charging voltage and the maximum recovery voltage with 2 U_0 as the charging voltage. This ratio appears in Equation 3.

$$D = \frac{\text{Recovery Voltage}_{\text{Max}}(2U_0)}{\text{Recovery Voltage}_{\text{Max}}(U_0)} \qquad \textbf{Equation 3}$$

Where:

D - Diagnostic factor
Recovery Voltage$_{Max}$ *(2*U_0*)* - Maximum recovery voltage recorded for 2 U_0
Recovery Voltage$_{Max}$ *(*U_0*)* - Maximum recovery voltage recorded for U_0

The standard diagnostic criterion is the "non-linearity" of the return voltage at its maximum value. For unaged (undamaged) cables, D should equal two. That is, if the charging voltage doubles then the recovery voltage should also double as there is a one-to-one correspondence between the recovery and charging voltages. A heavily aged cable system will not behave linearly and so the diagnostic factor (D) for such a system would be different from the ratio of the two charging voltages [15 - 17].

Although the nonlinearity of the dielectric response seems to be a good diagnostic parameter for water tree detection, a false diagnosis is possible if the degree of non-linearity is exclusively described by a single numerical value, i.e. the value of D established using measurements at U_0 and $2U_0$. Thus, better discrimination may be attained if D is computed for a range of voltages and thus shown to be linear or near-linear.

Advantages and disadvantages for the Recovery Voltage technique appear in Table 6.

Table 6: Overall Advantages and Disadvantages of Recovery Voltage Technique	
Advantages	• Provides a general condition assessment of cable system insulation. • Test equipment is small.
Open Issues	• Historically applied to all cable types but currently recommended only for paper cables. No data on paper cables are available. • Accessory behavior must be considered to properly assess cable system insulation condition. • Cable must be completely discharged after each test.
Disadvantages	• No application guidelines are available. • Cannot detect localized defects. • Cannot be applied to hybrid circuits due to the responses of different insulation materials. • Cable must be removed from service for testing.

It is important to bear in mind that some accessories specifically employ stress relief materials with non-linear loss characteristics, that is, their dielectric loss does not vary linearly with the applied test voltage. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available to date for dielectric loss measurements (Chapter 6), which are related to Recovery Voltage, shows that the type of stress relief is likely to show a smaller effect than either:

a) the aging of the accessory or

b) incorrect installation depending on the tested segment length

Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Recovery Voltage values.

12.3.4 Success Criteria

Recovery Voltage results are reported in terms of basic recovery voltage measurements as a function of charging voltage.

There are some success criteria for recovery measurements (Table 7) that provide a hierarchy of levels. General criteria for all cable types are used but it is expected that the criteria depend on not only the quality of the cable system, but also on the cable and accessory technologies employed and the stress associated with the application (charging) voltage.

Table 7: Pass and Not Pass Indications for Recovery Voltage Measurements		
Cable System	**Pass Indication**	**Not Pass Indication**
HMWPE WTRXLPE XLPE	No unified criteria	No unified criteria
EPR		
PILC		

Although no unified criteria are available, a number of references indicate some useful features to form a basis for diagnostic conclusions (Table 8).

Table 8: Interpretation Rule of Diagnostic Factor D Obtained From Maximum Recovery Voltages at U_0 and $2U_0$ [15]		
Diagnostic Factor D	**Evaluation**	**Action**
2.0 – 2.5	Insulation in good condition	No action
2.5 – 3.0	Insulation in fair condition	Other tests are recommended to identify isolated weak areas
> 3.0	Severely damaged	Replace cable

Figure 13 graphically illustrates the criteria shown in Table 8.

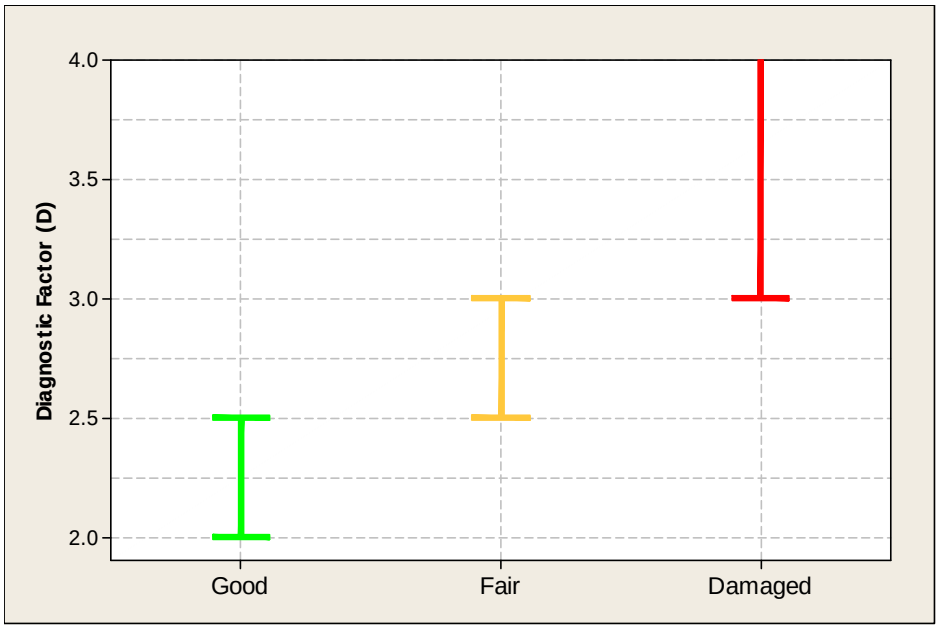

Figure 13: Interpretation of the Diagnostic Factor D

12.3.5 Estimated Accuracy

No information is available to *CDFI* to make this assessment.

12.3.6 *CDFI* Perspective

This technique is not used in the U.S. or Canada so no significant data have been provided to the *CDFI*. Thus no perspective on this technology was developed.

12.3.7 Outstanding Issues

This technique is not used in the US or Canada and so additional data is needed to fully evaluate its validity.

12.4 Polarization/Depolarization Current Or Isothermal Relaxation Current (IRC) Technique

12.4.1 Test Scope

This test involves the short-term application of low dc voltages to extruded cable circuits having only one type of insulation material. Very little IRC testing was performed in the *CDFI* so the following discussion is based on information from the literature.

12.4.2 How It Works

It measures the time constant of trapped charges within the insulation as they relax by measuring the discharge current over time after the application of a prescribed dc voltage [18 - 19].

12.4.3 How It Is applied

This technique is performed offline. The measured results relate to the global condition of the insulation and the presence of water trees. The procedure is as follows: The cable circuit is charged using dc voltage (1 kV) for a given time. The charging time is usually 5 to 30 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a resistor to ground. The discharge current is then measured for 15 to 30 minutes. This current is known as the depolarization or Isothermal Relaxation Current (IRC). The voltage application is similar to that described for Recovery Voltage in Figure 11, but the measured parameter is a current, not a voltage. The measured current appears schematically in Figure 14.

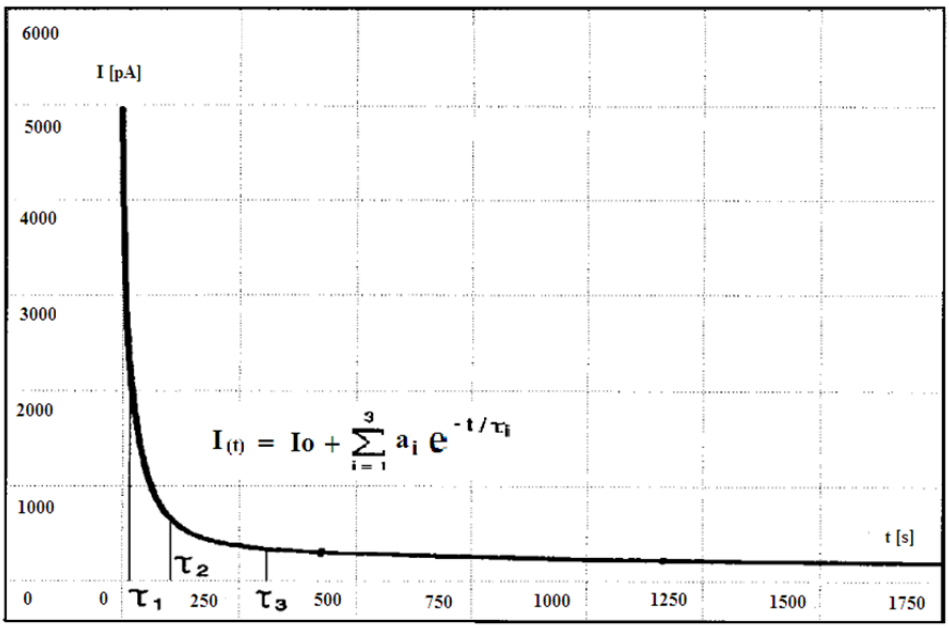

Figure 14: Schematic Representation of Measured Current from the IRC Technique [18]

It is assumed that the measured discharge current is comprised of three current components (similar to the discussion on Dielectric Spectroscopy in earlier in the chapter), which must be separated and compared. The separation applies an assumed model that considers three exponential currents, each with a different time constant. These three currents are computed and identified as -

a) current related with the cable insulation
b) current related with the semi conductive layer and
c) current related with insulation defects

Each current has a corresponding duration and, thus, represents a certain amount of charge: Q1, Q2, and Q3. The current of most concern is that which generates Q3. In fact, the larger the peak of Q3 as compared to Q2 or Q1, the worse the condition of the cable insulation [17]. Figure 15 shows these principles graphically. See [18] for definitions of the terms used in this figure.

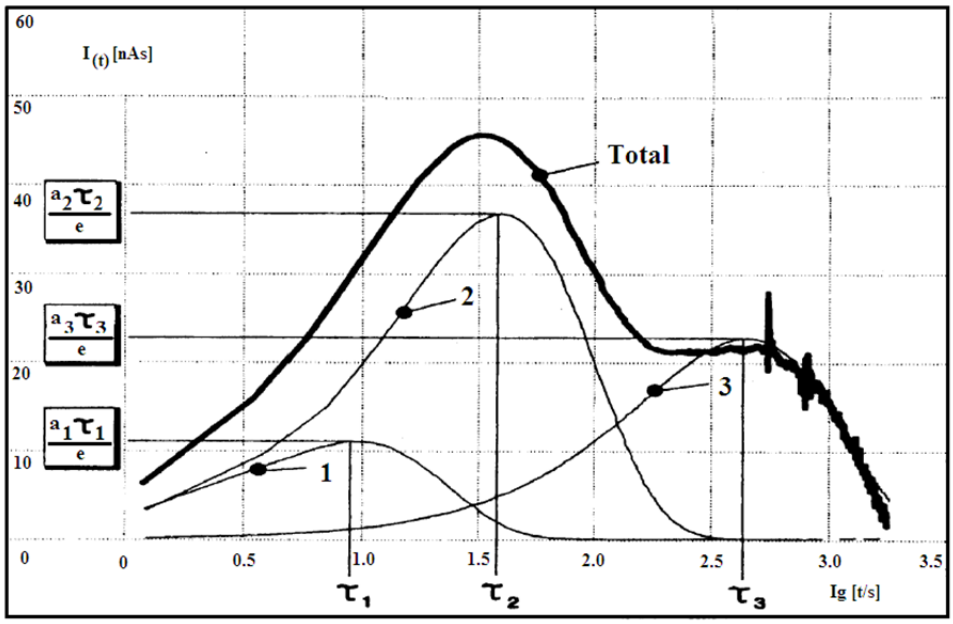

Figure 15: Principles of IRC Current Separation and Charge Calculation [18]

Advantages and disadvantages for the IRC approach to diagnostic testing appear in Table 9.

Note that some accessories specifically employ stress relief materials with non-linear loss characteristics. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available for dielectric loss, which is related to the IRC measurement, shows that the type of stress relief is likely to show a smaller effect than either -

a) the aging of the accessory or
b) incorrect installation depending on the tested segment length

Therefore, the best practice is to perform periodic tests at the same voltage level(s) while observing the general trend in IRC values.

Table 9: Overall Advantages and Disadvantages of Polarization/Depolarization Current Technique	
Advantages	• There are well-established criteria for evaluating German XLPE cable systems against accelerated laboratory endurance tests. • Test equipment is small.
Open Issues	• No assessment criteria for U.S. cables. • Criteria not established for WTRXLPE or EPR cable systems. • Accessory behavior may need to be included to properly assess cable system condition. • Assumes a three time constant model. This model may not be appropriate. • Reproducibility of measurement for very small currents on the order of nano amps. • Stability of the mathematical separation techniques for the current. • Cables need to be energized prior to testing to ensure adequate polarization. • The technique is apparently sensitive to the presence of water trees.
Disadvantages	• Difficult to measure new extruded cables due to presence of crosslinking byproducts. • The small currents measured are very sensitive to the test environment. • Cannot detect localized defects. • Cable must be completely discharged after each test. • Cable must be taken out of service for testing. • Cable neutral must be ungrounded. • Computationally difficult to extract model parameters. • Long length required to get sufficiently large signal.

In the IRC technique, the aging factor (IRCA) describes the level of damage to the cable. The aging factor is the ratio between the trapped charge in the insulation defects and the trapped charge in the semiconductor layers of the cable [18]. This ratio appears in Equation 4.

$$IRCA = \frac{Q_3}{Q_2}$$ **Equation 4**

Where:

$IRCA$ - Aging factor

Q_3 - Trapped charge in the insulation

Q_2 - Trapped charge in the semiconductor layers

12.4.4 Success Criteria

General criteria depend on the cable system quality, the cable and accessory technologies employed, and the stress associated with the application voltage. Table 10 and Table 11 show the interpretation of IRCA.

Table 10: Pass and Not Pass Indications for Recovery Voltage Measurements		
Cable System	**Pass Indication**	**Not Pass Indication**
XLPE	See Table 11	See Table 11
HMWPE WTRXLPE	No unified criteria	No unified criteria
EPR		
PILC		

Table 11: Correlation Between Aging Class and Aging Factor for XLPE Cables [18]	
IRCA	**Aging Class**
Less than 1.75	Good
Between 1.75 and 1.90	Middle
Between 1.90 and 2.10	Aged
More than 2.10	Critical

12.4.5 Estimated Accuracy

This technique is not used in the USA or Canada and thus no extensive data are available for analysis.

12.4.6 *CDFI* Perspective

No *CDFI* perspective exists due to the limited information available on this technology.

12.4.7 Outstanding Issues

This technique is not used in the USA or Canada and so additional data is needed to fully evaluate its validity.

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CHAPTER 13

Benefits of Diagnostics

Nigel Hampton and Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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13.0 BENEFITS OF DIAGNOSTICS

Chapter 4 details the results of some research that determines how many of diagnostic techniques are used within utility programs. This work was conducted in late 2014 and indicates that between 56% and 74% of utilities currently do not use diagnostics. Although this figure may appear discouragingly large, when it is taken in context with the results of the 2006 research it shows that there has been an increase in the use of diagnostics throughout the course of this project. Thus before examining the sort of benefits that accrue for the 44% to 26% of utilities that undertake diagnostics it is useful to examine that baseline (no diagnostic) case.

If cable system diagnostics are not employed then there are essentially two options used to manage the reliability of the cable system; one major and one minor (the two right-hand columns of Figure 1):

1. Major: Run To Failure (RTF) – between 54% & 72%
    a. With use of outage data and simple heuristics i.e. “three strikes and out”
    b. Without use of outage data
2. Minor: Service Failure Modelling - use service failure data (accurate outage data segregated at the component level) to develop robust trends – approx. 2%

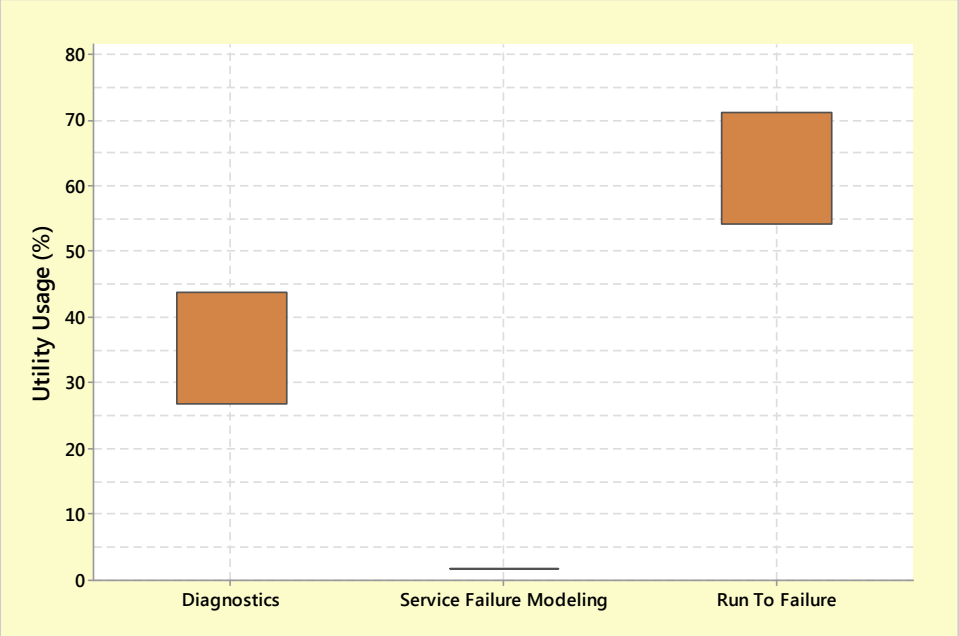

Figure 1: Methods Used To Manage MV Cable System Assets – the results of the research are imprecise, the boxes represent the most likely range of values

Generally speaking utilities face increasing pressure to maintain / improve reliability, and seek to do this with constrained resources (Operations & Maintenance (O&M) and Capital). Thus in the course of numerous discussions with utilities it is clear that twin goals / concepts have evolved:

A. Resource optimized Reliability - - Total Outage Cost reduction per dollar, SAIFI reduction per dollar, SAIDI reduction per dollar
B. Needs based resource forecasting - - how much resource will be required by the year 20xx, how much will I be able to do with today’s resource in the year 20xx

Consequently it is useful to view the goals contained in A&B above in the context of the majority of utilities that do not undertake cable system diagnostics (the two right-hand columns of Figure 1). In most cases the metrics available to a utility are outage data and approximate age data. Thus for a utility which does not undertake cable system diagnostics:

I. The utility will not be able to establish the health of their assets in an unbiased way
II. The utility will not be able to establish how the health of their assets change with time or as the result of any repair / replacement / rehabilitation programs
III. In the absence of a) health data and b) how the asset health changes with time, the utility will not be able to accurately forecast
    a. Future resource needs (O&M and Capital) needs
    b. How far current resources will reach
    c. Efficacy of funded programs – determine if specific programs are optimal
    d. Determine the optimal portfolio of programs by running efficacy assessments for various "what if" scenarios

The remainder of this chapter will focus on

- How the cost / benefit of a diagnostic system might be estimated
- The ways in which diagnostics have assisted different utilities or the industry as a whole to address the shortcomings of the Run to Failure approach outlined in I to III above.

In addition the sections will introduce / discuss the useful basic concepts in this area.

13.1 Background/State of the Art

This section discusses the current state-of-the-art approaches to managing cable systems.

13.1.1 Hazard Curves

Hazard functions or rates have recently become of interest to asset managers as they work to predict future cable system reliability. The hazard rate is defined mathematically using conditional probability theory but is more concisely described as follows:

> *The hazard rate is the probability of failure in the next time interval given that the cable system has survived up to the present time.*

Hazard rates can be defined for any parametric distribution, but are most commonly discussed from the perspective of the Weibull distribution. The Weibull Distribution utilizes two (or three if desired) parameters, namely: the shape parameter (β) and scale parameter (α). These parameters are estimated using either a Least-squares or Maximum Likelihood approach using the actual time to failure data. The resulting estimates for α and β are then used to estimate the hazard function. The hazard model for Weibull-distributed data is shown in Equation 1.

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \qquad \textbf{Equation 1}$$

The changes in hazard rate with age forms the basis for the often referenced "bathtub" curve. A sample bathtub curve is shown Figure 2. As this example shows, the bathtub curve is composed of three general regions each with its own Weibull and, hence, hazard curve:

1. Infant Mortality or Burn-In (Weibull gradient < 1)
2. Normal / Reliable Operation (Weibull gradient = 1)
3. Aging or Wearout (Weibull Gradient > 1)

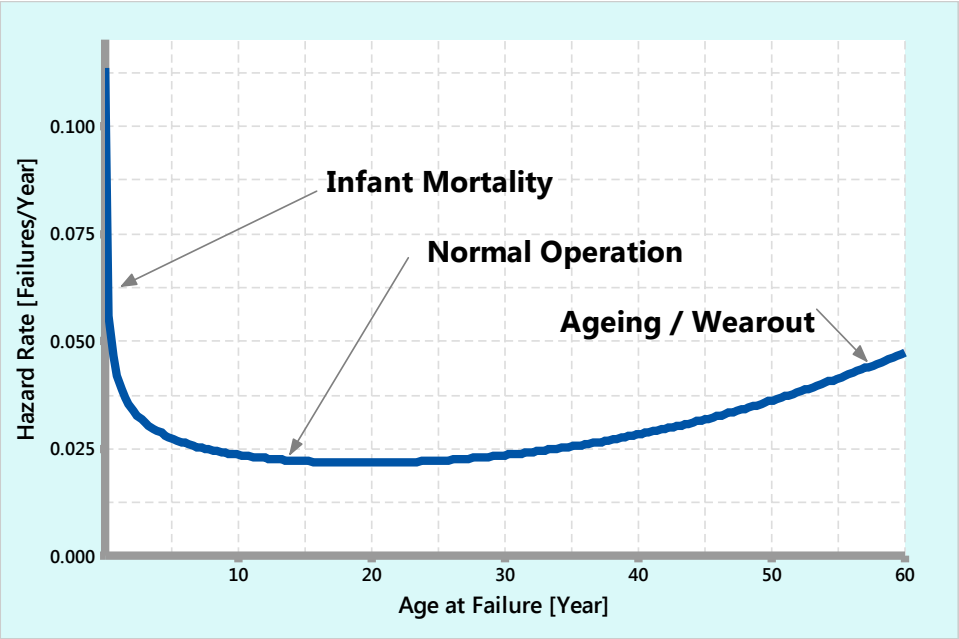

Figure 2: Example Bathtub Curve

The *infant mortality* stage represents only a small percentage of the total operational life of the cable system but can account for a high number of failures over a short period of time. Hence, these are very often "visible" issues. Such failures are sometimes termed as "burn-in" failures since the system reliability improves with time as defects are removed. During this stage it is better to leave things alone as older units are generally more reliable than newer ones.

Once the system passes the infant mortality stage, it operates normally with a low failure rate (purely random failures that are time independent) as represented by the *normal operation* region. Failures that occur during this period are not related to aging, in fact, this is the most reliable period in the system's lifetime. In practice, cable systems should spend the majority of their lifetimes in the *reliable operation* region.

On the other hand, as the cable system ages it moves from *normal operation* into the *aging* stage. This last region is the period during which most aging related failures occur as the failure rate continues to increase with time from this point forward. The actual onset of the aging stage is difficult to identify until the system is well into this stage.

The current state of the art views the bathtub curve and associated hazard rates as essentially deterministic for a given cable system and the age correlates to a single precise failure rate i.e. age

is everything. The full curve is constructed from the available population and performance data for the entire utility system. At least three failure modes (regions with different Weibull gradients) should be identified during the analysis for a full bathtub curve to be constructed. Each of these failure modes will have their associated confidence intervals, thereby indicating the presence of several different possible bathtub curves for the same data. This gives rise to families of bathtub curves as illustrated in Figure 3. It is important to note that these curves were generated from the same three distributions using the familiar Monte Carlo approach.

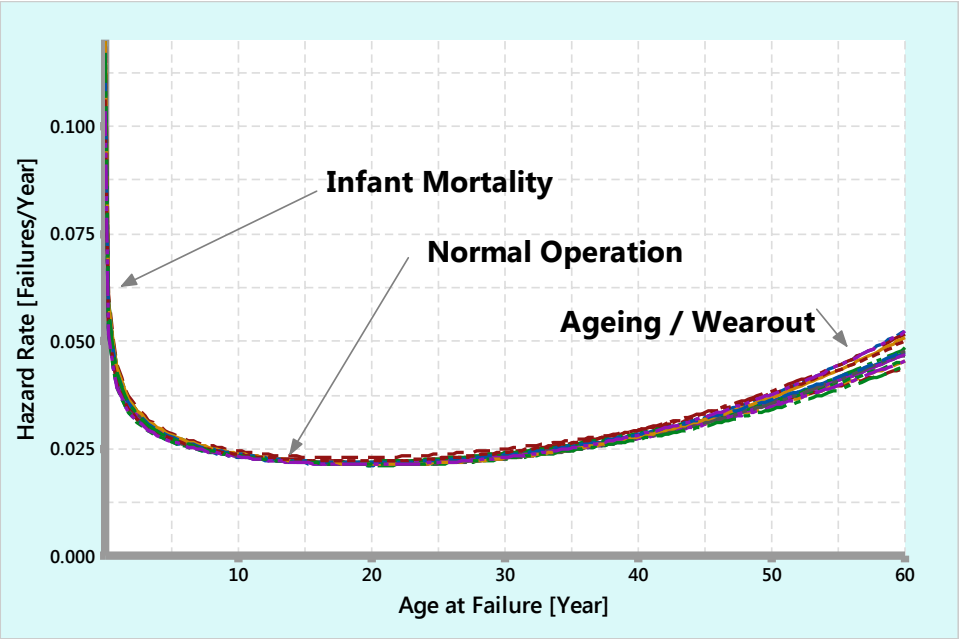

Figure 3: Family of Bathtub Curves for Randomized Data

The challenge where most effort has been focused in the industry is the data mining required to amass enough age-related performance data to be able to construct a complete or partial bathtub curve. Utility performance data rarely includes the age of the cable system at the time of failure and even less often identifies whether the failure occurred in the cable or an accessory. This is an ongoing problem that will continue to be a challenge for the industry.

Multiple Hazard Plots or Bathtub Curves are most often shown as examples. This leads to the question of whether this framework exists in reality of is just a theoretical construct. Many projects within the Reliability Group at NEETRAC has shown that the Bathtub Curves do exist and the areas are identifiable - Figure 4 & Figure 5 are two examples of where Bathtub Curves are valuable in understanding MV & HV / EHV cable system ageing respectively.

If a hazard plot is successfully constructed from field data, then the issue becomes how to assign a dollar value to each failure. In principle, there is a cost associated with each cable system failure.

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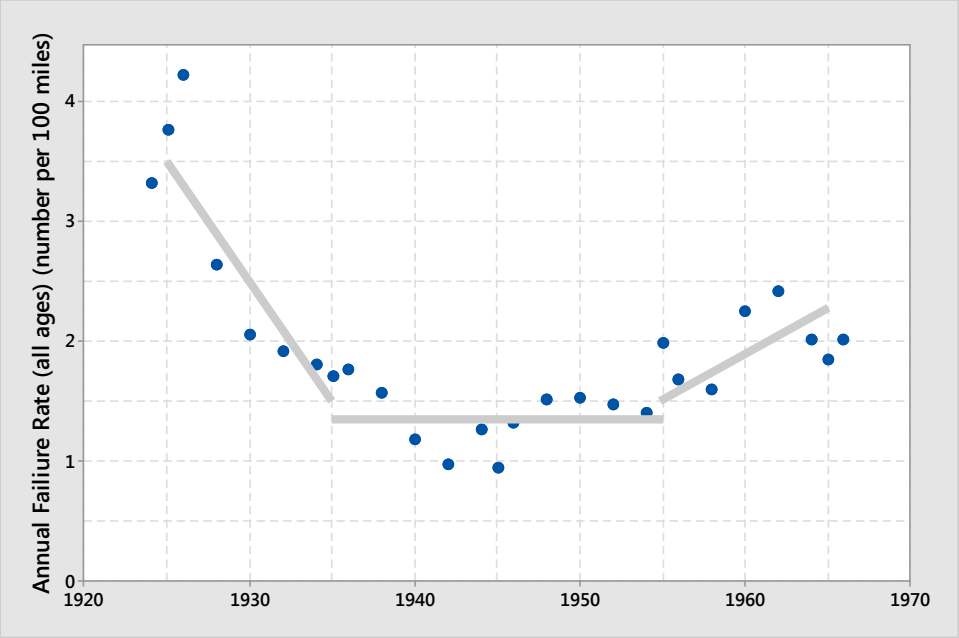

Figure 4: Bathtub Curve for PILC Cable Systems – Thue & Lawson

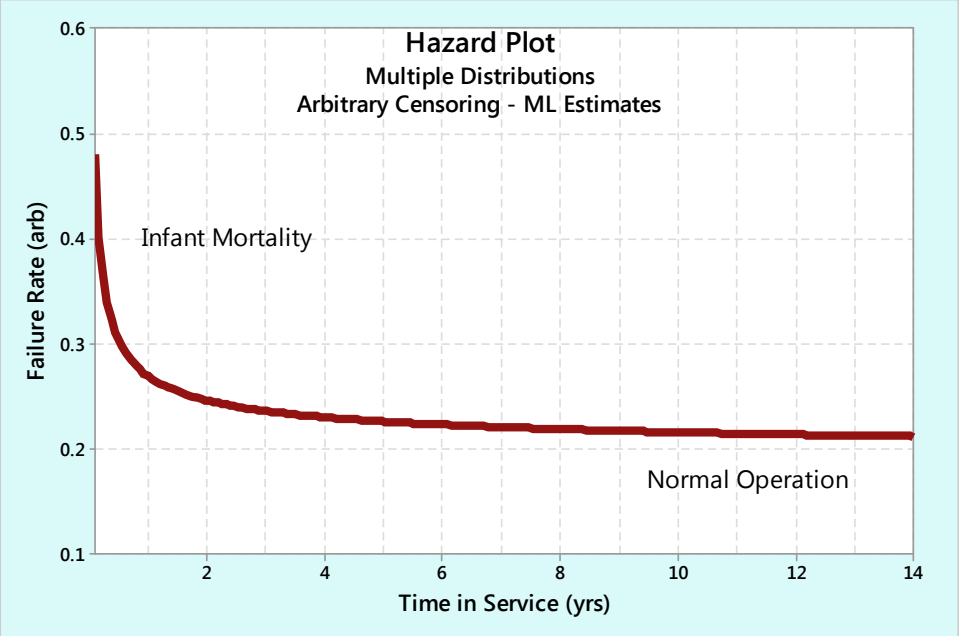

Figure 5: Bathtub Curve for HV and EHV Cable Systems – NEETRAC Member Research

13.2 Cost Elements for Life Costs

There are many costs associated with cable systems (MV and HV / EHV); the terminology and relationships used in this work is provided in Table 1. Rather than provide dollar estimates on the values as these vary widely between utilities, this section attempts to provide the cost components in terms of the costs of the cable. It is important to note that this table takes the perspective of "total cost of ownership" rather than the more commonly discussed installed cost

Table 1: High Level Definitions of Cost Terms				
Cost Terms		**Cost Element**		**Approx. Cost Multipliers (where input has been received) – rel to cable = 1**
"Total Cost of Ownership"	"First" or "Installed" Cost	Standards		?
		Supplier Oversight		?
		Permitting / Approvals		?
		Cable	Accessories	1.1 – 1.3
		QA		.001
		Installation		10
		Commissioning		.1
		TOTAL		>12
	"Cable System Operational Life" Costs {excl cost of losses}	Maintenance	Diagnostics	See later
			Cost of Outage [$]	See later
			Service Restoration	See later
			Repair / Replace	See later
	Reliability Upgrade Costs	Diagnostics		See later
		Rehabilitation		3 – 6 (25% to 50% of "First Costs")
	"End of Life" Costs			?

$ experienced by the customer
? Costs are not known but they are incurred by utilities

The cost elements that comprise the "Cable System Operational Life" Costs (Table 1) are set out in Table 2 for both the Proactive (Diagnostics Used) and Reactive (Run to Failure) options. Where appropriate the differences in the costs associated with the two options are identified. This table again looks at relative costs but shows the relationships between the different elements. As an example, the number of outages for the Reactive Case will be larger than those experienced in the Proactive Case - denoted by X and x respectively.

Clearly the Costs most relevant for this work are those that comprise "Cable System Operational Life" Costs. Ultimately what we are, looking to compute is the difference between the "Proactive" and "Reactive" approaches to failures. The elements of these two costs are detailed in Table 2. It is generally assumed that Proactive Costs are lower than the Reactive Costs. If this hypothesis is true then D (the cost of a diagnostic program) must be less than the cost of unplanned outages to the customer and the cost of unplanned repairs.

Table 2: Definitions of the components within Proactive (Diagnostics Used) and Reactive (Run To Failure) elements of "Cable System Operational Life" Costs			
Cost Terms	**Cost Element**	**Proactive Approx. Cost Indications for x outages**	**Reactive Approx. Cost Indications for X outages (where X>x)**
"Cable System Operational Life" Costs	Maintenance	M	M
	Diagnostics	D	
	Cost of Outage[$]	O*x	*O**X more failures in service X>x at a higher cost *O*>O
	Service Restoration	S*x	S*X more failures in service X>x
	Repair / Replace	R*x	R*X more failures in service requiring attention in an unplanned (expensive) manner X>x

$ experienced by the customer

During both CDFI phases, attempts were made to obtain cost data for each of the utility participants. The most challenging cost to understand was the impact a service failure or sequence of failures have on a utility's SAIDI, SAIFI, etc. as well as their customer impact. Through discussions with a number of participants, it is clear that these costs exist and are quite substantial but are difficult to quantify as they are not directly paid or identified by the utility. Crew, cable replacement, cable rejuvenation, switching, etc. costs are far more tangible and for purposes of this discussion will be termed as "Tangible" costs (Section 13.2.1). The other costs mentioned above may then be referred to as "Intangible" costs (Section 13.2.2). The interaction of these cost elements is somewhat similar to that of real and reactive power. Our ac systems cannot operate without both types of power even though reactive power is a far more abstract concept than real power. The Tangible and Intangible costs are similar in this respect.

13.2.1 Tangible Costs

The Tangible Costs have been garnered and estimated from a variety of sources. The ranges shown in Table 3 are judged to be a reasonable consensus from the variety of sources. It is not particularly useful to look for a single cost as this changes with technology, location, accounting practices, time acceptance of risk, etc. Thus it is best to accept that there is uncertainty and consider the ranges.

As shown in Table 3 there are different ways of describing the costs in terms of either "per foot" or "per segment" (length independent). This is an important distinction to be aware of as the cost of any remediation (repair / replacement / rehabilitation) will be driven by length. The diagnostic testing on the other hand is generally by segment – thus a 500 ft segment will cost the same as a 200 ft or a 4000 ft segment.

Table 3: Tangible Cost Elements for "Cable System Operational Life" Description and Guidelines		
Cost Element	**Description**	**CDFI Cost Range [$]**
Emergency Switching (assuming looped system)	Cost of identifying failed cable run and switching loop from normal condition to abnormal condition so that service is restored. This activity effectively determines SAIDI in the case that there is no second failure before the first is repaired	$400 – $800 per event
Repair Cost	Locating failure site within cable run and repairing with 1-2 repair splices as needed.	$1,500 - $2,500 per event
Replacement Cost	Install new run of cable	$15 - $25 per ft (single phase)
Rejuvenation Cost	Rejuvenate a single cable run	$4 - $13 per ft (single phase)
Diagnostic Testing Cost	Diagnostic testing by service provider	$3,400 - $6,700 per day or $850 - $1,600 per segment
	Diagnostic testing by utility	$1,600 - $2,500 per day or $400 - $650 per segment

13.2.2 Intangible Costs

Like reactive power, Intangible costs are essential to the estimation of the "Cable System Operational Life" cost. Yet these elements are the most difficult to understand in terms of value and impact. These costs are related to SAIDI, SAIFI, CAIDI, etc. and therefore quantify the effect of outages on customers. Thus, it is important to understand their numbers, types, locations, and importance in order to estimate the impact of unscheduled outages. Each cable run, if it were to fail, impacts a different group of customers which means its "Do Nothing" curve will look quite different from other similar cable runs in other areas.

The Department of Energy provides an "Interruption Cost Estimate" (ICE) Calculator to enable estimates to be made – upgraded in 2015. The ICE Calculator is a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. Thus it is a useful tool for this work – specifically estimating the Cost of Outage in Table 2. In this case the Proactive Cost O would be associated with low values of SAIDI and SAIFI, whilst Reactive Cost *O* would be associated with higher values of SAIDI and SAIFI (see Table 2). The ICE tool requires cable system performance data (SAIDI etc.), location, load mix & income data (median income &

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multiplier to median income). It is important to realize that the ICE Calculator only covers outages up to 16 hours; it is not intended to model sustained outages or blackouts.

In order to determine suitable customer impact values for use in the estimates in this document, a designed experiment was developed and executed which used the Interruption Cost Estimate (ICE) tool to estimate the impact of SAIDI and SAIFI on customers in different states. These data and the subsequent analyses were used to determine, for the US, the importance of the selected factors outlined above. The factors that are statistically significant are shown in Table 4. It is interesting that the Region / State did not show as a significant factor.

Table 4: Significant Factor Analysis for the Cost of an Outage Based on the ICE Calculator for Different Load Mixes

Importance of the Factors	Cost of Residential Customer Outages	Cost of Outages Small Industrial Customers	Cost of Outages Medium to Large Industrial Customers
First in Importance	Multiplier to Median Income		
Second in Importance	SAIFI	SAIDI	
Third in Importance	SAIDI	Interaction between SAIDI & SAIFI	Median Income

Each analysis resulted in an equation that may be used to estimate the cost of an outage. Considerable arithmetic simplification results if the Region / State can be omitted. In addition any estimates that are made can be assumed to be valid for any part of the US if the appropriate values for Median Income and / or Income Multiplier are used. The equations that resulted from the analysis are shown in Table 5.

Table 5: Outage Cost Estimate Equations from Analysis of ICE Calculator Output

Value Calculated	Best Fit Equation
Cost Residential [$/1000 Customers]	0.2941 Median Income+3228.9 Median Income Multiplier+5544 SAI FI+33.6 SAIDI [Min]+1.7 SAIFI*SAIDI [Min]-28470
Cost Small Commercial & Industrial [$/1000 Customers]	179924+0.10 Median Income+93380 Median Income Multiplier+157 632 SAIFI+5226 SAIDI [Min]-1323 SAIFI*SAIDI [Min]
Cost Medium & Large Commercial & Industrial [$/1000 Customers]	46.2 Median Income+579098 Median Income Multiplier+919131 SA IFI+29613 SAIDI [Min]-6655 SAIFI*SAIDI [Min]- 3827412

Figure 6 to Figure 10 present a graphical representation of the results of the analyses for the main cost elements and provides a final summary.

Inspection of the curves shows that the SAIDI & SAIFI relationships to cost are very different for Commercial & Industrial installations when compared to Residential. Interestingly in Commercial

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& Industrial installations the SAIFI has little effect (one plausible explanation is that there is no escalation factor the cost for interruption 1 is high and is equally high for interruption 3), whilst there is a clear SAIFI / SAIDI interaction in the Residential arena. Furthermore, the magnitudes of the associated outage costs are very different for the different installations.

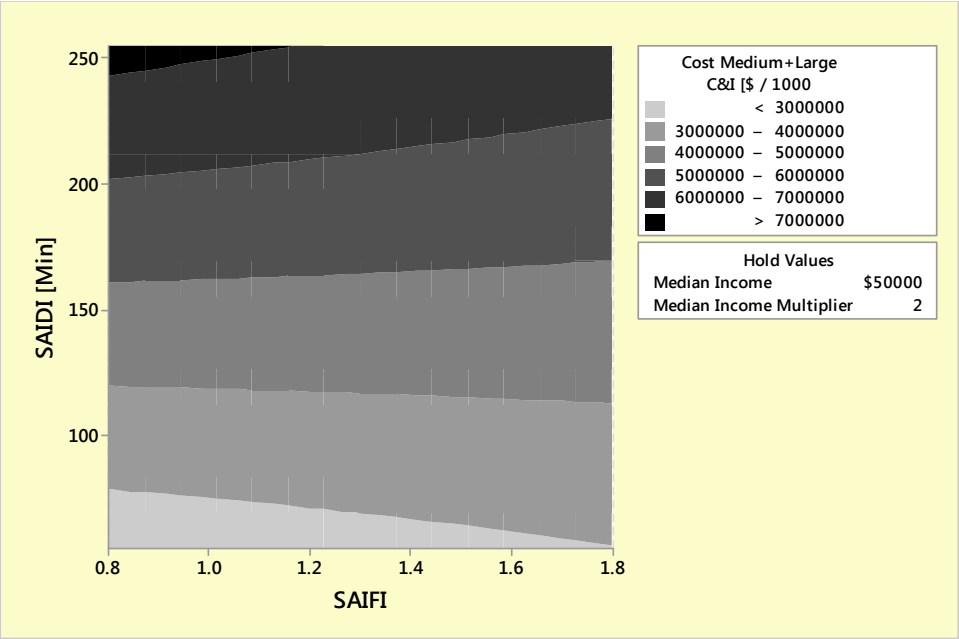

Figure 6: Impact of SAIDI & SAIFI on the outage Cost Medium & Large Commercial & Industrial [contours are $/1000 Customers] – median income = $50,000, median income multiplier = 2

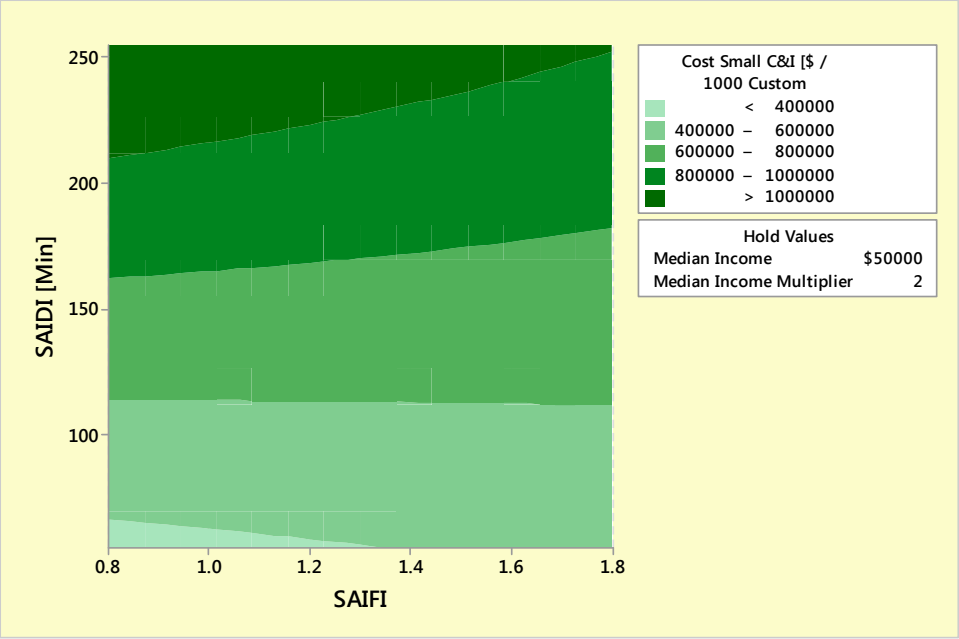

Figure 7: Impact of SAIDI & SAIFI on the outage Cost Small Commercial & Industrial [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 2

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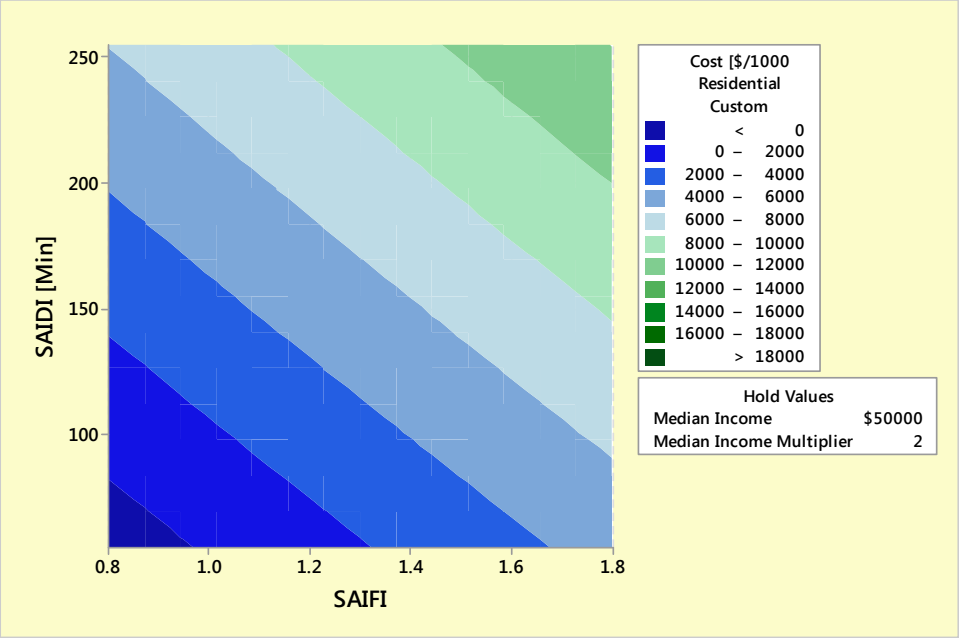

Figure 8: Impact of SAIDI & SAIFI on the outage Cost for Residential [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 2 – the same levels are used for the contours in Figure 8 & Figure 9

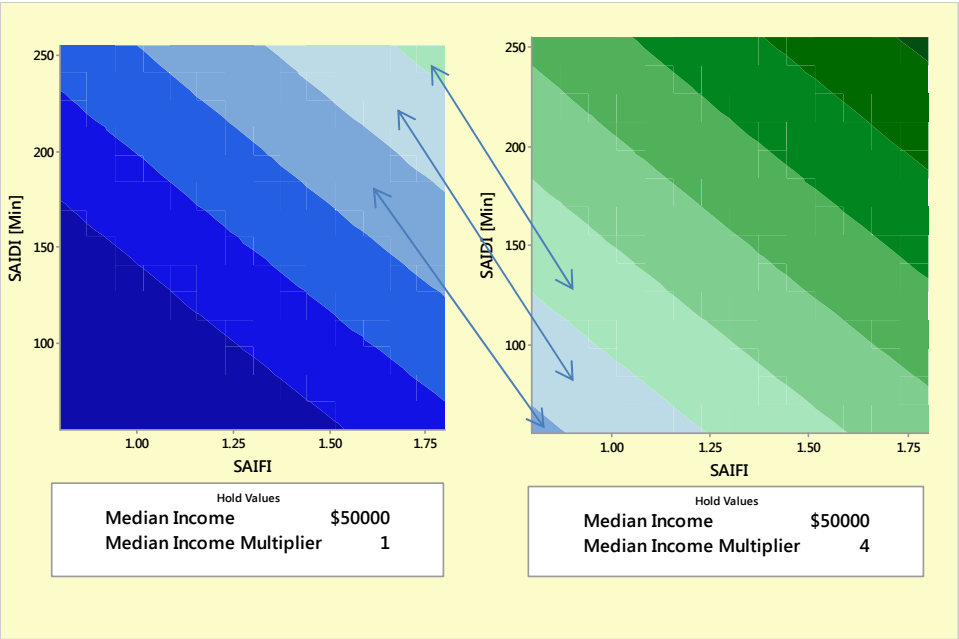

Figure 9: Impact of SAIDI & SAIFI on the outage Cost for Residential [contours are $ / 1000 Customers] – median income = $50,000, median income multiplier = 1 & 4 – the same levels are used for the contours in Figure 8 & Figure 9

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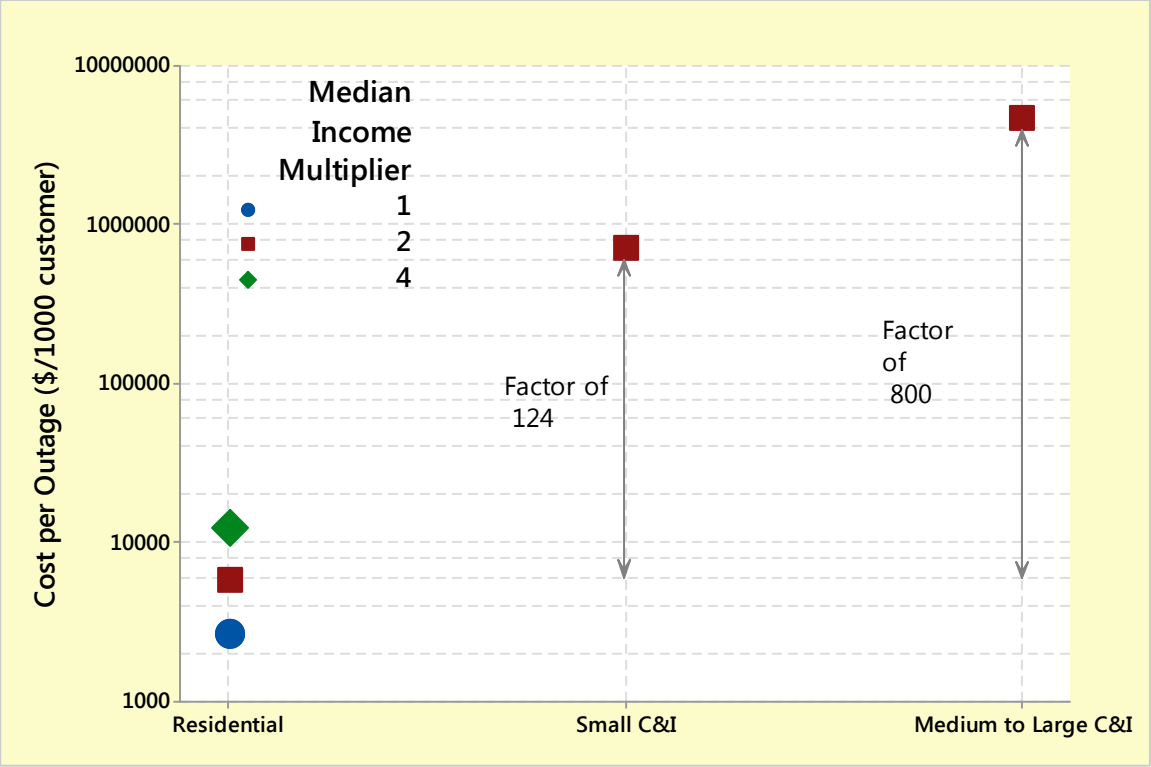

Figure 10: Impact of Median Income Multiplier and the Type of Customer Served on the Outage Cost [$ / 1000 Customers], Factors Estimated for Twice Median Income – Median income = $50,000, SAIFI=1.4, SAIDI=155mins

13.3 Selected Examples of Benefit Estimation

This section provides examples of benefit estimation and thereby sets out a framework whereby the benefits of conducting Diagnostics can be estimated. The basic premise is that the employment of a diagnostic is compared in terms of cost (tangible and intangible) with the default case which, for these examples, is "Run to Failure" (RTF).

The basic steps in the methodology deployed here are:

1. "Build" a typical cable system
2. Determine appropriate Diagnostic and Remediation Scenario
3. Use results from CDFI studies on real Utility systems to estimate
    a. Likely outages as a function of time
    b. Likely diagnostic outcomes
4. Determine likely classifications to guide subsequent remediation activities
5. Estimate Failures on Test (FOT)
6. Estimate costs of undertaking diagnostics
7. Estimate the cost of remediation resulting from diagnostic outcomes
8. Estimate costs associated with outages
    a. Cost of remediation
    b. Customer Cost
9. Accumulate Costs

10. Display Benefits
    a. Avoided Costs (Costs without diagnostics (RTF) – Costs with diagnostics)
    b. Avoided Outages

It is useful to reconfirm some definitions that are particularly useful:

Outages – failures that occur at unanticipated times which interrupt customer supply and where the full system fault is experienced by the cable system

Failures on Test – failures that occur at an anticipated time (during the test) which does not interrupt customer supply and where only the fault current available from the test equipment (much less than the full system fault) is experienced by the cable system

The scenarios considered are:

- New 132kV cable system commissioning test – 13.3.1
- Aged MV cable system Diagnostic Test – 13.3.2
    - Withstand Diagnostic conducted by a Utility
    - Diagnostic Tests conducted by a Service Provider

13.3.1 Commissioning Test Estimations

As noted in earlier chapters Commissioning Tests are generally conducted in HV / EHV cable systems with the goal of reducing infant mortality (Figure 5). Figure 5 shows the early life reliability prognosis for modern (installed since 2000) HV & EHV cable systems. Clearly the issue is to conduct an effective commissioning diagnostic program so that the service failures may be avoided by addressing them whilst the cable system is in the control of the contractor rather than the responsibility of the utility.

It is possible to estimate the effects and hence the benefit of a commissioning diagnostic tests by examining a utility case. The details of the utility case (modeled on http://www.pesicc.org/iccwebsite/subcommittees/C/Presentations/2010Spring/C1-SpringHVandEHVCableSystemsforAbuDhabi.pdf) are given below; here the utility has been installing a considerable amount of HV XLPE cable system in the 2010 to 2012 time frame

Voltage:	132 kV
Length:	325 km / 225 cable segments
Accessories:	114 terminations, 675 joints

In this scenario we have chosen to consider a near power frequency resonant test voltage (DAC is not considered resonant) of 1.7 U_0 for 60 min (based on IEC recommendations) with Partial Discharge (PD) monitoring. This approach is acknowledged (CIGRE B1.28) to be effective with no outages having been reported following this test. The alternative IEC voltage levels (1.4U_0 or U_0 for 24 h) are not considered for this scenario as it is known that these voltages are not effective (outages are reported) at reliably eliminating outages.

NEETRAC research suggests that a reasonable failure rate in the early years of a cable system is of the order 0.0016 failures per km per year, recognizing the uncertainty in these estimates. Within this

rate, 67% of the failures are likely to be associated with accessories. In addition Figure 5 shows that the likely infant mortality failure rate is 2 to 3 times that of normal operation.

Thus for a given cable system architecture the outages with and without Infant Mortality failures may be estimated. In this system, assuming a 15 year horizon, with and without Infant Mortality failures are 3-5 (X in Table 2) and 2-3 (x in Table 2), respectively. This scenario assumes that the Infant Mortality (early) failures are completely avoided and that the remedial actions result in a lower (25% lower) failure rate for normal operation.

The repair of accessory or cable failures requires considerable effort and resources and their cost (S from Table 2) are estimated at between 0.5 % and 0.8 % of the "First Cost" (Table 1) per event. These are lower (conservative costs) as they assume that a failure only require remediation to that phase i.e. that there is no collateral damage. The cost for a three phase repair is unlikely to be three times the single phase cost as the civil / construction work is unlikely to be tripled. Furthermore the estimates are for the size of system under study here; as the size of the system decreases then the cost of the remediation increases as a percentage of the "First Cost". On very short systems it can approach 20 – 30%. In all the estimates that follow the lower cost has been used.

Thus the benefit (S*(X-x) from Table 2), using the avoided outage model, is 0.5 to 1.6% of the "First Cost" (Table 1) **plus** the "Cost of Outage" (O*(X-x) from Table 2). Clearly the "Cost of Outage" depends upon the number of customers but a conservative estimate can be obtained from Figure 6 to Figure 9. Using a conservative approach for customer numbers (low) and residential / industrial mix (highly residential); then the ICE models estimate that benefit is between 1.3 & 2.6 $M (unadjusted for inflation) over the 15 year horizon. These benefits are represented by the "difference arrow" in Figure 11.

It may be argued that in many cases at HV, no outages occur due to the fact that there are alternate feeds. Thus the ICE costs estimated above are best considered as a "Risk Cost" as should a second fault occur then the outage cannot be recovered without the full repair of one of the two faults. Furthermore the repair time is much longer than the 16 hours covered by the ICE estimates; thus it is likely that the true Risk Cost will possiblly be significantly higher than used in these estimates. Thus if there is a benefit with diagnostics using these lower ICE estimates then there will certainly be a benefit with the true value.

Figure 11 shows the cost difference between the commissioning test program and the alternate (no commissioning test) program. The size of the bubbles represents the number of outages. Clearly the commissioning test case yields fewer outages each of whoich is less expensive.

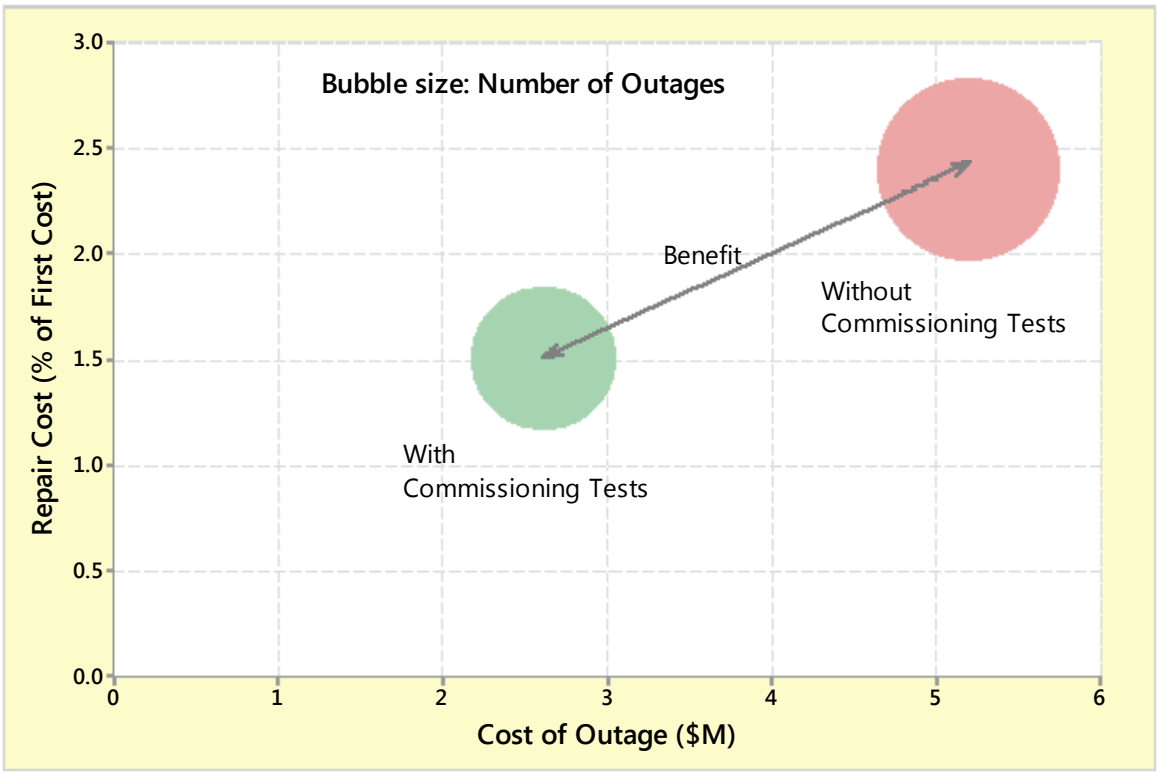

Figure 11: Graphical Representation of the Costs (see Table 2) for a Selected Utility HV System With and Without Commissioning Diagnostics

13.3.2 Diagnostic Test Estimations

Previous chapters have noted that diagnostic testing is mainly carried out on aged MV assets. Thus it is convenient for us to use this common scenario to investigate the benefits of diagnostics as it is possible to postulate the differences between the with and without diagnostics cases.

The scenario we have chosen is a cohort of 100 segments with an average segment length of 400ft. These are aged cable systems which have shown reliability issues in the past; hence are viable candidates for testing (recall that diagnostic testing is not recommended to be carried out on new systems as there is little benefit to be derived). The basic parameters for the diagnostic performance model in are provided in Chapter 9.

The tangible cost estimates are taken as single values from within the ranges given in Table 3.

The intangible costs are drawn from the ICE Calculator (Figure 6 to Figure 10) for 1000 customers (980 residential) and a SAIDI of 120 minutes. The cost for a SAIFI of 1.2 is taken as a single value and is $54/customer/per outage. This cost has been used for both of these analyses. There has been no estimate for the risk cost that results from the difference in the time it takes to isolate the fault (120 min) and to complete a final remediation (7 days). This is a “Risk Cost” as should second fault occur then the outage cannot be recovered without the full repair of one of the two faults.

Two further cases can be considered:

a) Testing carried out by the utility
b) Testing carried out by a Service Provider

Case a): Testing carried out by the utility

Earlier chapters (Chapter 4) have identified that the most commonly used diagnostic by utilities is a VLF Withstand. In this approach the general premise is that failures on test are preferable to outages as although they have the same cost to repair, the failure on test does not expose the cable system to the full fault current and does not incur the cost of the outage. In this scenario we have chosen two test applications, each two years apart. The cable system performance and hence benefits are considered over a four year period. It is assumed that a segment is replaced should it fail in service or on test.

The scenario is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- VLF Withstand Diagnostics conducted by a Utility
- Withstand Diagnostics applied at year 0 and year 2
- Repair is made by replacing the cable segment with new cable

The evolution of failures (outages and failures on test) is shown in Table 6 for the two testing scenarios. Inspection shows that the total number of failures is higher when diagnostics are employed, though the number of outages is lower: 9 & 19 for the "with" and "without" cases respectively. In this model the 4 year time scale has been selected as this is reasonably short and thus we can assume that the population does not significantly age. Any longer term scenarios would need to address this extra sophistication.

Table 6: Failures (Failures On Test and Outages) for a MV Scenario for Test Programs With and Without Diagnostics
Testing Conducted by the Utility

	With Diagnostics			Without Diagnostics		
	Outages	**Failures on Test**	**No of surviving segments**	**Outages**	**Failures on Test**	**No of surviving segments**
Start			100			100
End of 1st test period		13	87			
End of Year 2	5		82	10		90
End of 2nd test period		10	72			
End of Year 4	4		68	9		81
TOTALS	**9**	**23**	**68**	**19**		**81**

The failures detailed in Table 6 are shown graphically in Figure 12. At first sight the lower number of failures (higher number of surviving segments) would be expected to be correlated with the lowest cost. This is not the case as the costs of an outage is not the same as the cost of a failure on

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test – the failure on test has a lower cost because in the vast majority of cases no customer outage occurs. The costs associated with these failures are detailed below in Figure 12.

Table 3 identifies the ranges for the tangible costs. This estimate uses the lowest values in the ranges. A more complete analysis would employ Monte Carlo simulations using the identified ranges. As the goal of this chapter is to demonstrate the methodology and typical values, there is no need to expand the sophistication of the analysis at this stage. Customers with this style of system typically replace a segment upon failure.

Thus for this analysis we assume:

- The repair costs for a failure on test are 400 ft*15 $/ft per failure on test: $6,000
- The repair costs after an outage are $400+400 ft*15 $/ft per outage: $6,400
- Test costs are 100*400 $/segment: $40,000
- The Outage Costs 1,000 customers*$54 per outage per customer: $54,000/outage

The detailed buildup of costs over the 4 years considered here are shown as waterfall diagrams in Figure 13 and Figure 14.

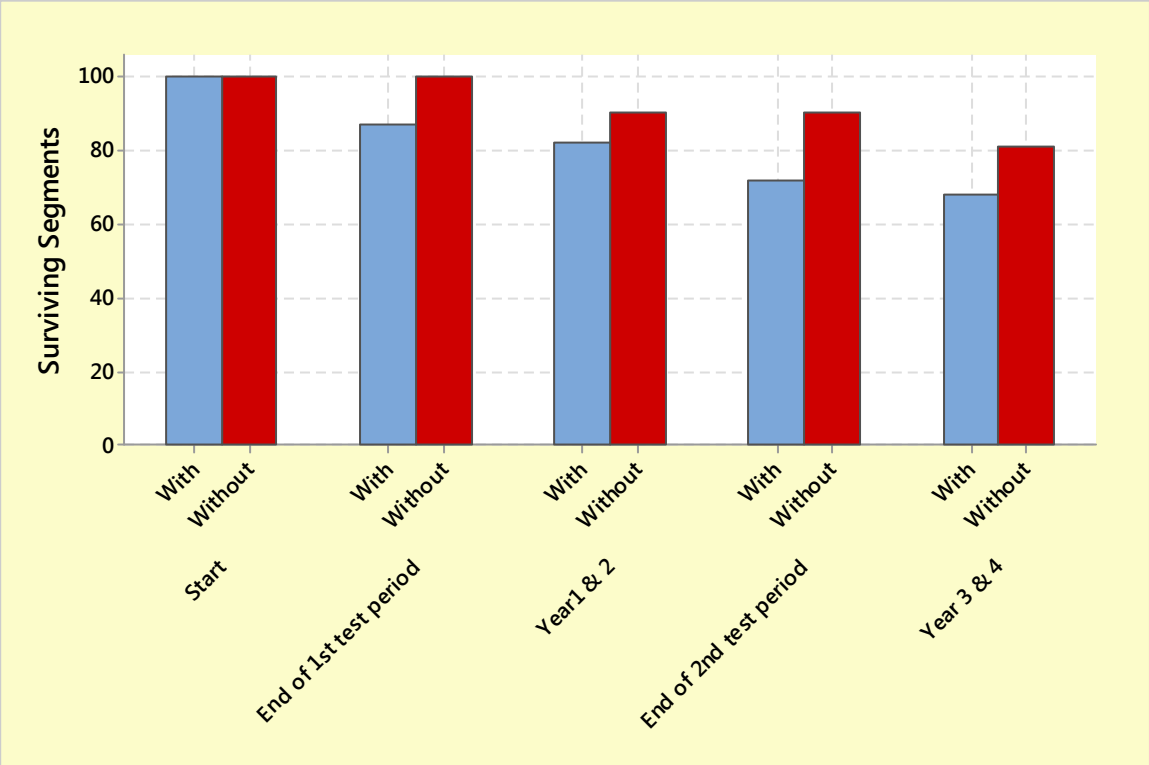

Figure 12: Reduction of Original Segment Population over Time for Programs Detailed in Table 6

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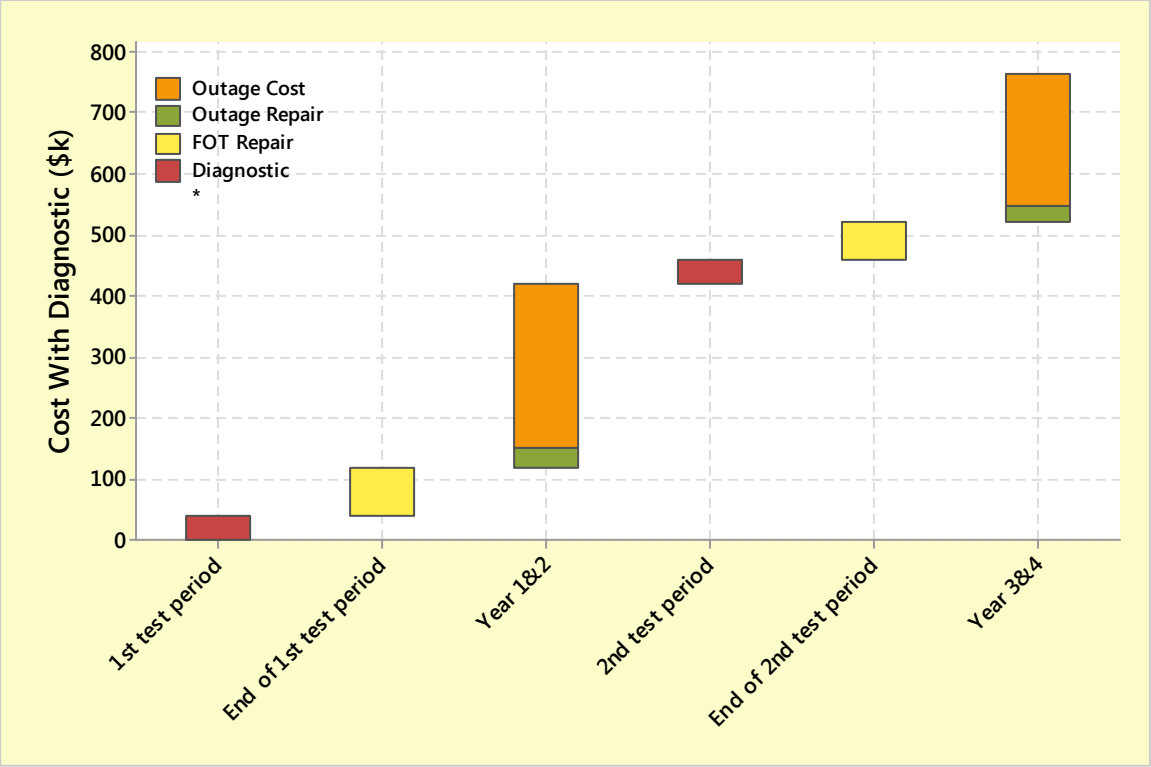

Figure 13: Diagnostic Program Cost - Uses Failure on Test and Outage Data in Table 6 – Testing Conducted by the Utility (9 Outages, 9 Outage Repairs and 23 Test Repairs)

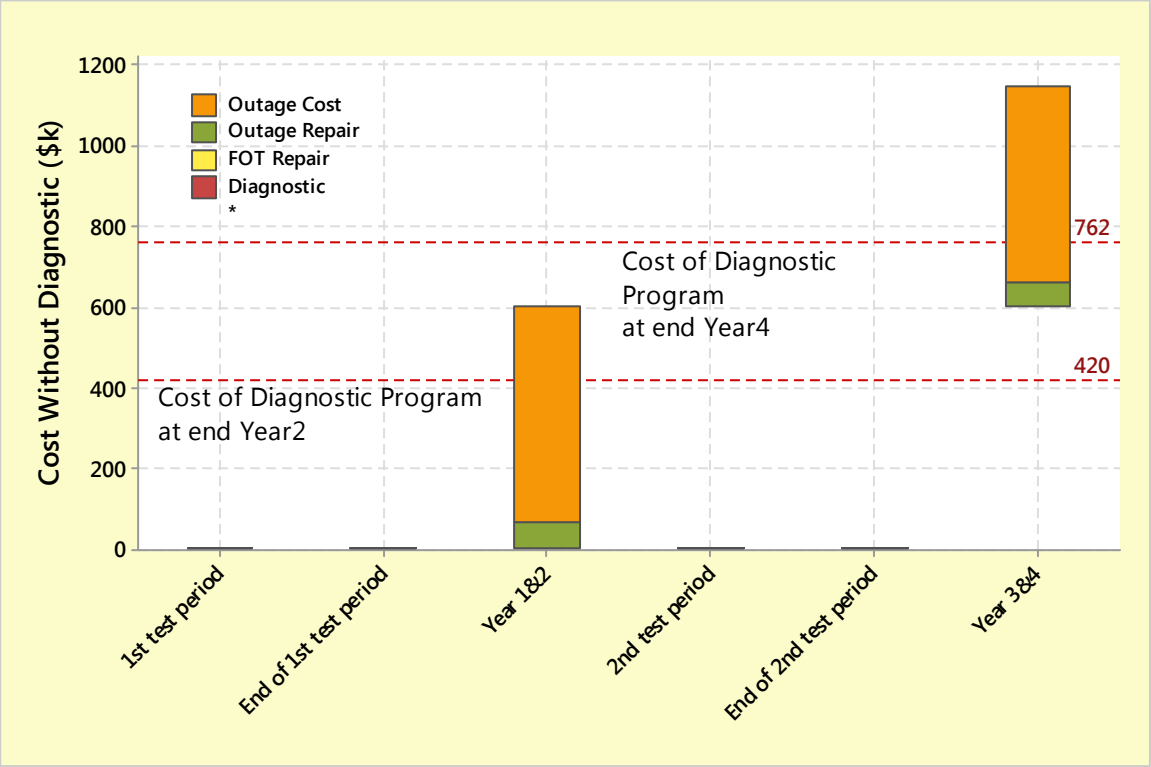

Figure 14: Cost Build Up Without Diagnostics - Uses Failure on Test and Outage Data in Table 6 – Testing Conducted by the Utility (19 Outages and 19 Outage Repairs)

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Examination of Figure 14 and Figure 15 shows that, for this case, the VLF diagnostic program yield lower costs than the Run to Failure approach: approximately $350 k or four to five times the cost of the diagnostic testing. The benefits of lower outages (9 vs 19 for with and without respectively) are in addition to the reduced cost of outages and can easily be described (lower amounts of system shock due to fault currents, extra degradation due to locating / thumping etc), however ascribing a financial value to then is not straightforward. We content ourselves with noting that these benefits are in addition to the decreased costs.

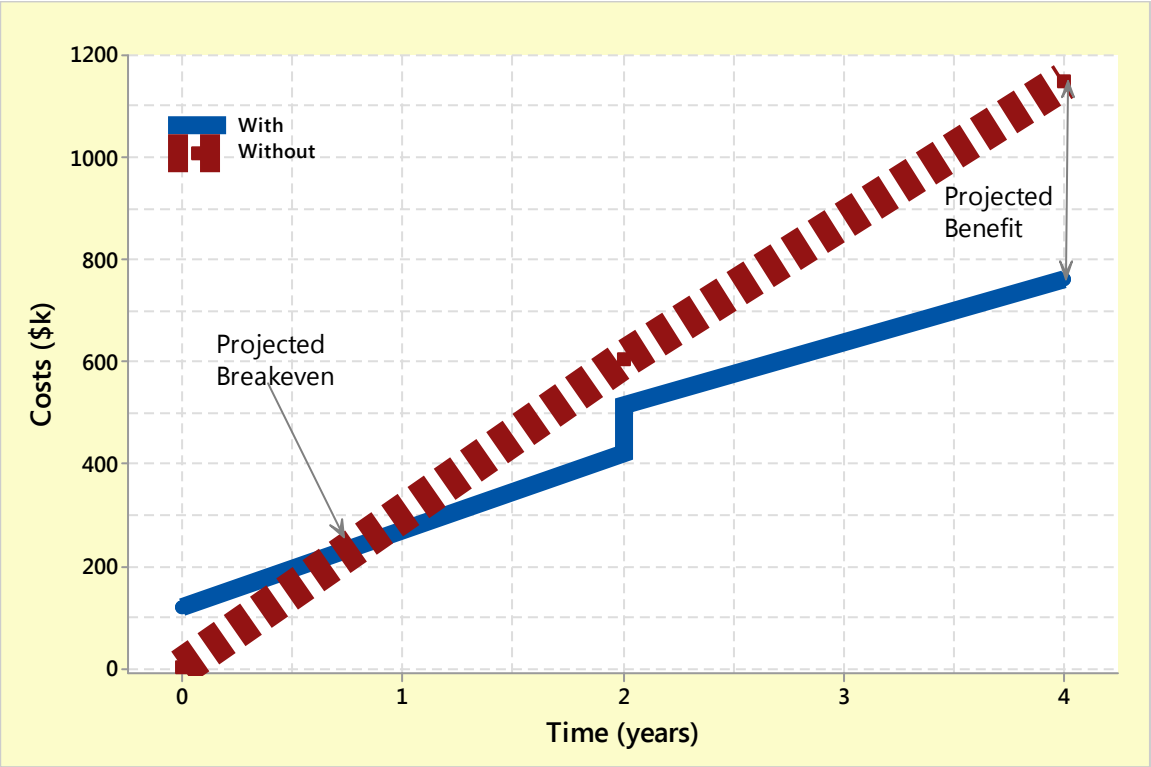

Figure 15: Cost Evolution With and Without Diagnostics
Width of Lines Represents the Number of Outages (9 and 19, respectively)

The scenario represented in Figure 15 above is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- VLF Withstand Diagnostics conducted by a Utility
- Withstand Diagnostics applied at year 0 and year 2
- Repair is made by replacing the cable segment with new cable

Case b): Testing carried out by the Service Provider

Earlier chapters have identified that some utilities use a Service Provider to perform their diagnostics. In these cases it is uncommon to undertake a withstand diagnostic. It is most common for PD or Tan Delta diagnostics to be used. In these approaches the general premise is that failures on test are very rare and that repairs are carried out at the time of a utility's choosing, thereby

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avoiding outages. Thereby they have the same cost to repair, but the cable system is not exposed to the full fault current and does not incur the cost of the outage; both of which are advantageous.

In this scenario we have elected to consider 30 year old segments as the aged population and to replace only those cable systems in the Action Required (AR) class as these have the highest risk (20% see Outcome Lines in Chapter 6) of leading to an outage in a five year horizon. The members of the Further Study (FS) and No Action (NA) classes are not repaired as these have lower risks of leading to outrages (13 and 6% respectively). Thus at age 30 the segment population is comprised of 5 AR / 25 FS / 70 NA. The utility elects to replace the 5 AR with the expectation of avoiding one outage (i.e. 20% of 5 AR) and chooses not to replace the 25 FS thereby deciding not to avoid three outages. At age 35 the original population of 100 is reduced to 88 (100 – 5 (proactively replaced) – 7 (outages)). If both AR and FS classes were proactively replaced at age 30 then the population at age 35 would be 66 (100 – 30 – 4).

The scenario is

- 30 year old cable system serving 1,000 customers (98% residential)
- 100 segments of average length 400 ft
- SAIDI = 120 min and SAIFI =1.2
- PD (online or offline) diagnostics conducted by a Service Provider
- PD (online or offline) diagnostics applied at year 30 and year 35
- Repair is made by replacing the cable segment with new cable

The evolution of failures (outages and repairs due to test results) is shown in Table 7 for both the "with diagnostics" and "without diagnostics" scenarios.

Inspection shows that the total number of repairs (due to tests and outages) is higher when diagnostics are employed, importantly however the number of outages is lower for the diagnostic program: 13 and 19 for the with and without cases, respectively. In this scenario the 10 year time scale (age 30 to age 40) has been selected, this is too long to assume that subsequent cable system degradation is insignificant. Thus a suitable age line for diagnostic data (Chapter 6) has been used to model the changes with time. Information received from PD practitioners indicates that this approach is a reasonable alias for the PD results. The failures in service have been modeled using the outcome lines (Chapter 6), again these model the PD world reasonably well. The outcome lines are used for the diagnostic case as well as the no diagnostic case.

The failures detailed in Table 7 are shown graphically in Figure 16. At first sight the lower number of failures (higher number of surviving segments) would be expected to be correlated with the lowest cost. This is not the case as the cost of an outage is not the same as the cost of a repair due to a test. The repair for a failure on test has a lower cost because, in the vast majority of cases, no customer outage occurs. Furthermore, no upstream equipment (transformers, overhead lines, substation equipment, etc.) are subjected to the additional stress of providing the resulting fault current.

The costs associated with outages are detailed in Table 7.

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Table 7: Failures (Failures On Test and Outages) for a MV scenario Programs With and Without Diagnostics *Testing Conducted by a Service Provider*						
	With				**Without**	
	Number of Outages From classes FS + NA	**Class Membership** Segregated by class AR / FS / NA	**Repairs undertaken due to the Test Outcome** Segregated by class AR / FS / NA	**No of segments surviving**	**Outages** From classes AR + FS + NA	**No of segments surviving**
Start Age 30				100		100
End of 1st test period		5/25/70	5/0/0	95		
Age 35	7 (3+4)			88	8 (1+3+4)	92
End of 2nd test period		18/26/44	18/0/0	70		
Age 40	6 (3+3)			64	11 (5+3+3)	81
TOTAL	**13**		**23**	**64**	**19**	**81**

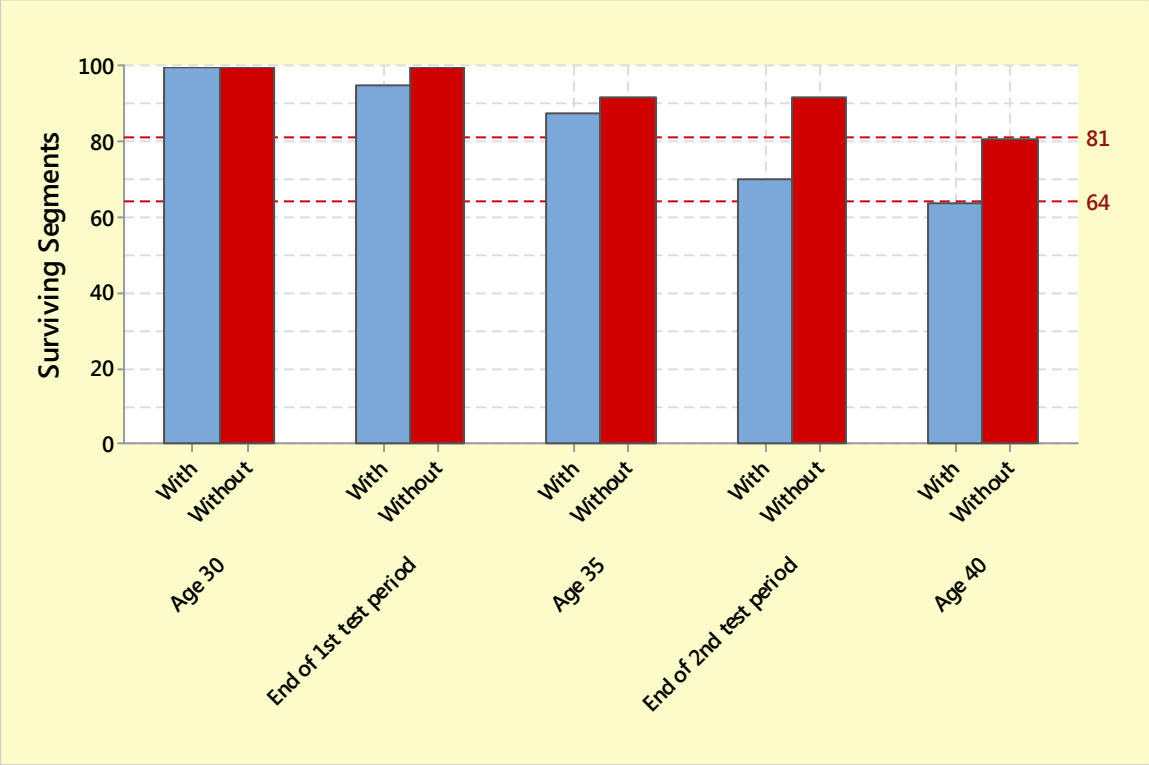

Figure 16: Reduction of Original Segment Population over Time for Programs Detailed in Table 7

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Table 3 identifies the ranges for the tangible costs. This estimate uses the lowest values in the range. A more complete analysis (Section 13.4.4) would employ Monte Carlo simulations using the identified ranges. As the goal of this chapter is to demonstrate the methodology and typical values, there is no need to expand the sophistication of the analysis at this stage. Customers with this style of system typically replace a segment upon failure.

Thus for this analysis we assume:

- The repair costs for work indicated by a test are 400 ft*15 $/ft per segment: $6,000
- The repair costs after an outage are $400 + 400 ft*15 $/ft per outage: $6,400
- Test costs are 100 * 850 $/segment: $85,000
- The Outage Costs 1,000 customers*$54 per outage per customer: $54,000 per outage

The detailed evolution of costs over the 10 years considered here are shown as waterfall diagrams in Figure 17 and Figure 18.

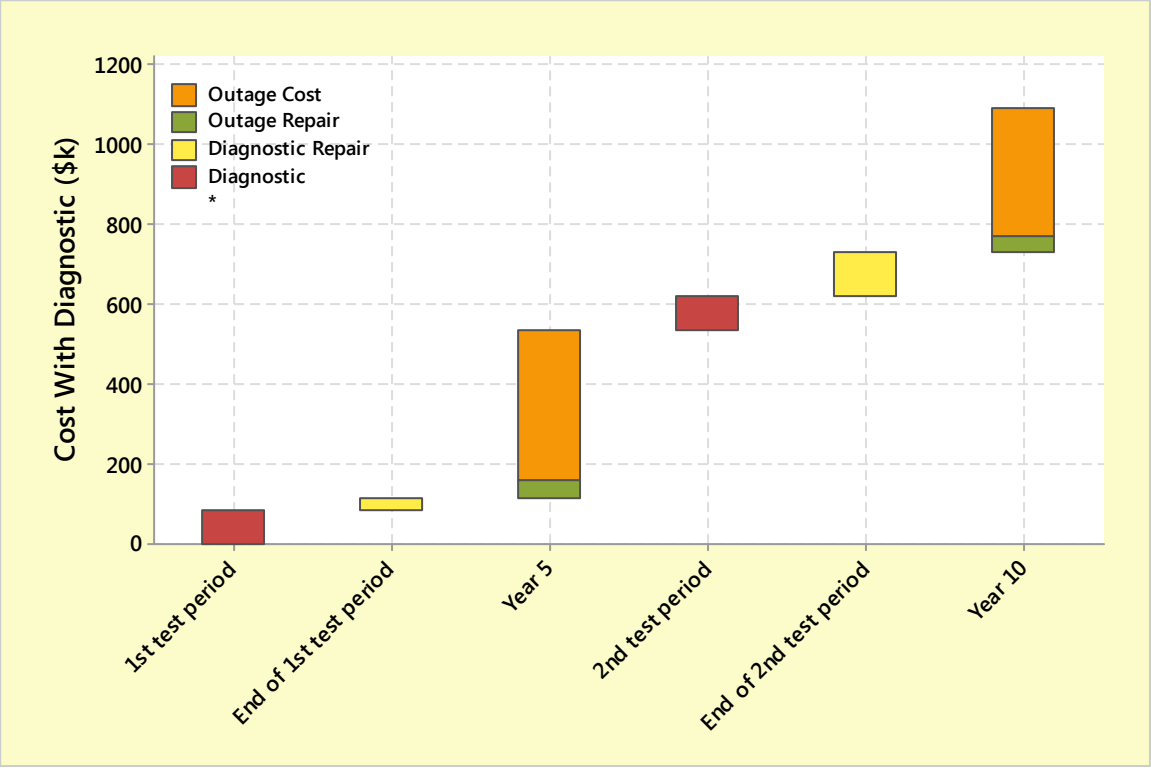

Figure 17: Diagnostic Program Cost - Uses Failure on Test and Outage Data in Table 7 Testing Conducted by a Service Provider (13 Outages, 23 Proactive Repairs and 13 Outage Repairs Over 10 Years)

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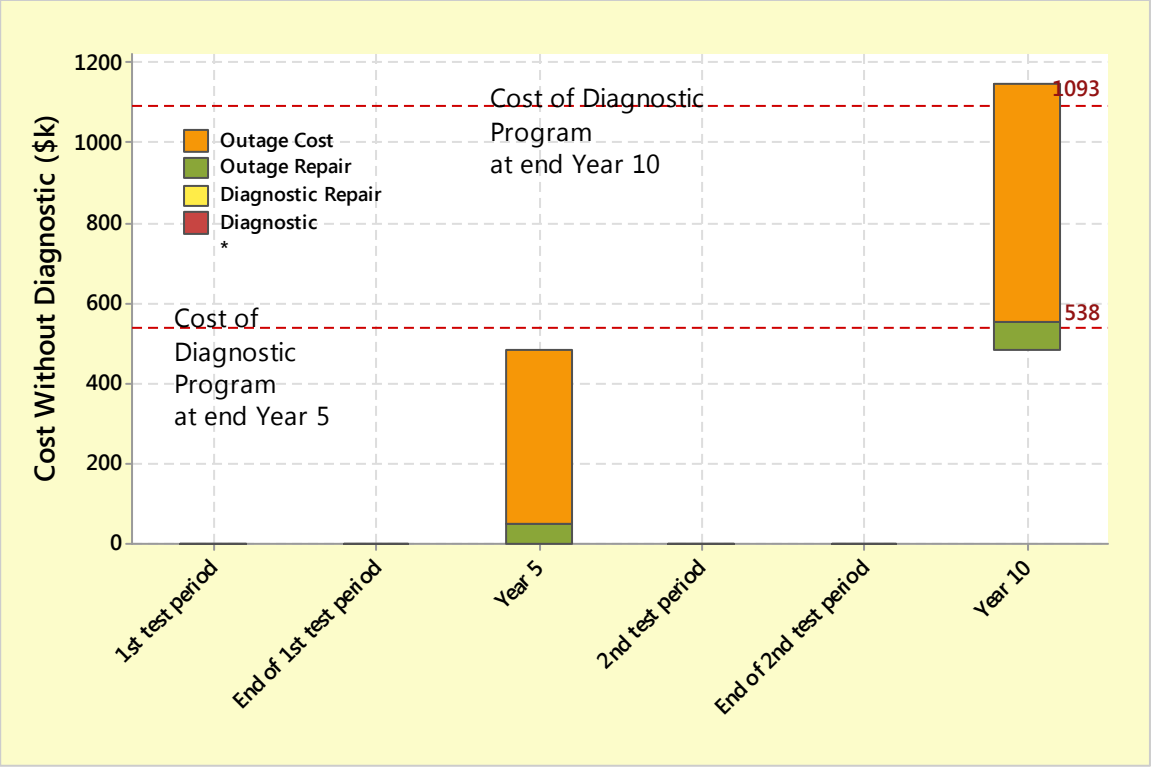

Figure 18: Cost Build Up Without Diagnostics - Uses Failure on Test and Outage Data in Table 7 (19 Outages and 19 Outage Repairs Over 10 Years)

Examination of Figure 18 and Figure 19 shows that for this case the diagnostic program yields lower costs than the Run to Failure approach by Year 10 (Age 40). Figure 19 shows and increase in slope for the Run To Failure (without) case after age 35; this is due to the fact that the cable system is smaller (there have been replacements between 30 and 35) but that the remainder age such that there are more in the Action Required and Further Study categories.

The benefits of fewer outages (13 vs 19 for with and without, respectively), in addition to the cost of outages can easily be described: lower amounts of system shock due to fault currents, extra degradation due to locating / thumping. However ascribing a financial value to this is not straightforward. We content ourselves with noting that these benefits are in addition to the costs that are already included.

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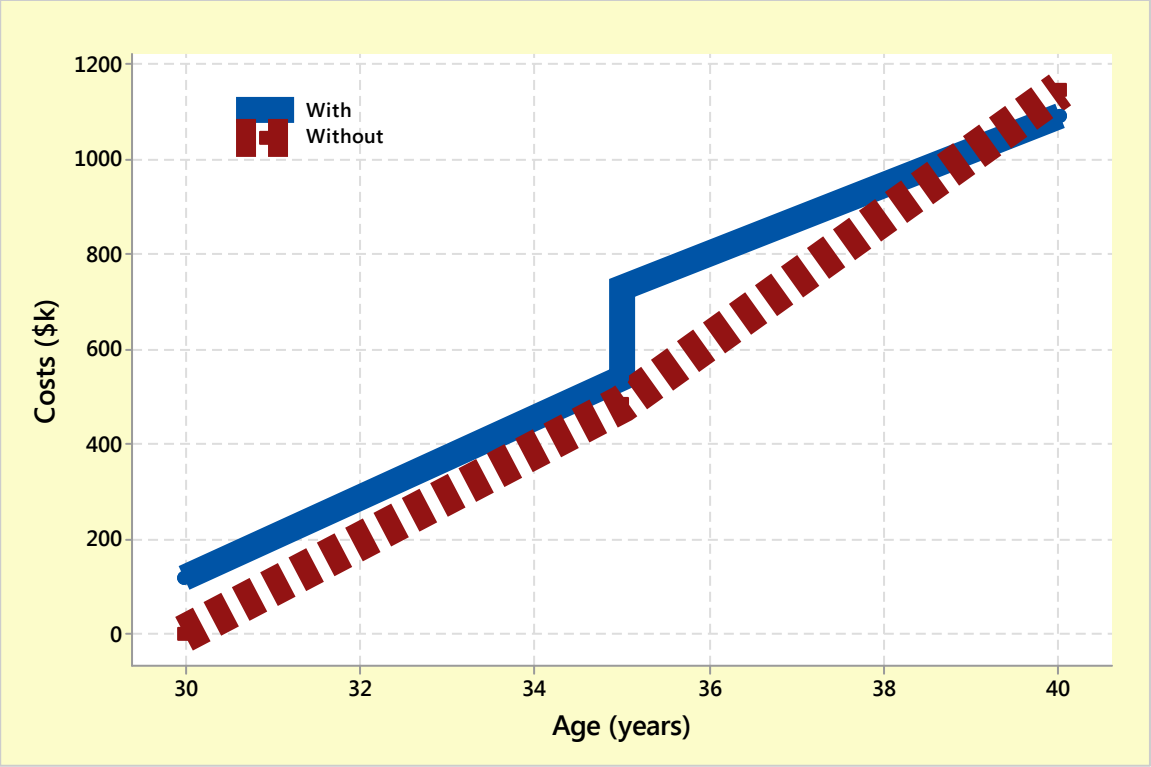

Figure 19: Cost Evolution With and Without Diagnostics
Width of Lines Represent the Number of Outages (13 and 19 respectively Over 10 Years)

13.3.3 Impact of Repair Methods on Aged Cable Systems

Figure 17 through Figure 19 show the different components of cost for diagnostics and Run to Failure (RTF). It is interesting to note that there are other default solutions rather than just RTF. Figure 20 shows the situation when the cases for Complete Replacement and Complete Rejuvenation are included.

In these analyses it has been assumed that

- Complete Replacement results in a new system with a zero failure rate.
- Complete Rejuvenation is assumed to
  - return the accessories to age 0 where the likelihood of failure is vanishingly low and
  - return the dielectric system of the cables to age 20 (where the likelihood of AR is very low) and
  - that the metallic neutrals have aged at a slower rate than the dielectric system.

The alternate case where the dielectric system is rehabilitated but the metallic neutrals become the life limiting factor has not been considered but it is likely to result in some case in between RTF and the Rejuvenation considered herein.

Based on the estimated total costs that include both Tangible and Intangible elements the most attractive is Complete Replacement followed by Rejuvenation, Diagnostics, and Run to Failure.

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Clearly this assumes that complete replacement within a one year period is financially and technically feasible.

Based on the estimated total costs that include only Tangible elements the most attractive is Run to Failure, followed by Rejuvenation, Diagnostics, and Complete Replacement.

These estimates show the importance of the Intangible Costs associated with an Outage. Without them Diagnostic Programs are not beneficial. Even though there may be little consensus as to what these intangible costs are, they are clearly real and close to the values used in this study. If they were not real and significant then there would be no techno economic basis for diagnostic programs and we know that between 26% and 44% of utilities undertake diagnostics and that these figures have grown since 2006.

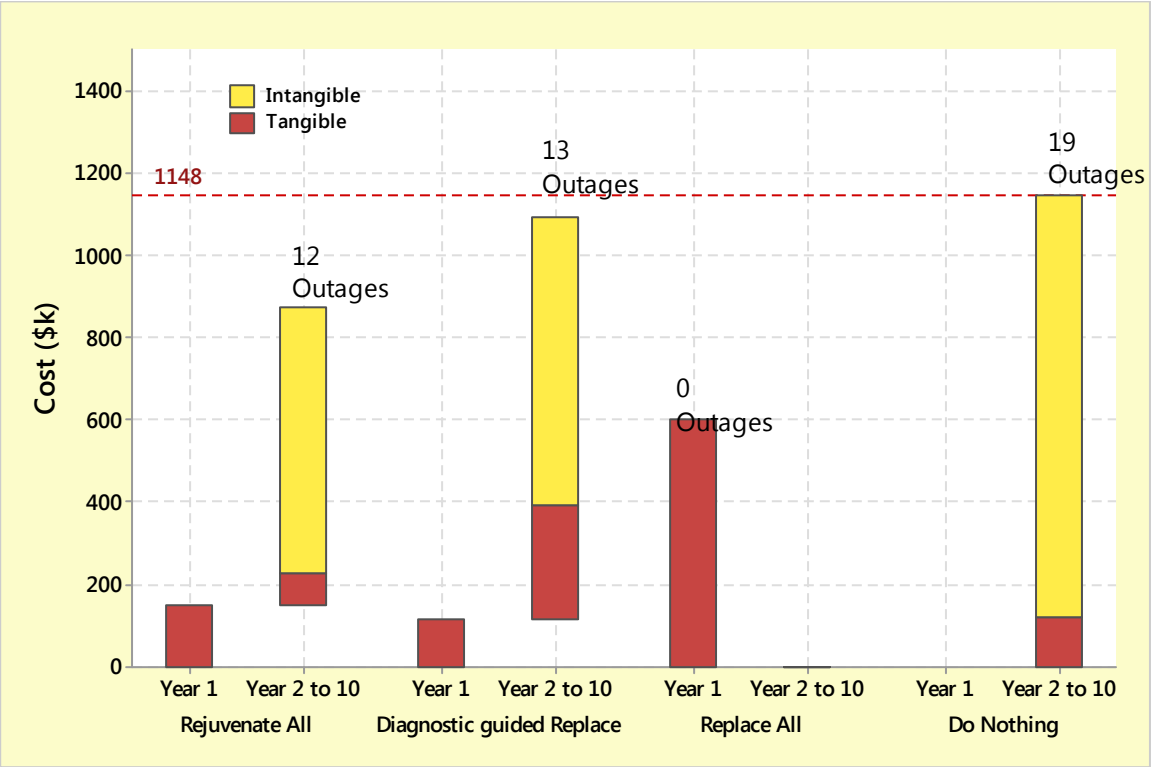

Figure 20: Cost Comparison between Several Remediation Approaches – Costs Separated by Program Year and Type (Tangible or Intangible)

13.4.4 Range of Diagnostic Estimates

The estimates presented in the preceding sections have made deterministic (we assume that we know the cost of repairs / outages / etc.) and conservative (low values selected) assumptions. Thus the benefits that accrue are the largest that may reasonably be expected. However as noted in and the ICE Calculator modeling, there are ranges associated with the input variables. We have chosen not to undertake the preceding estimates using Monte Carlo methods but we have decided to make some calculations to examine how the large uncertainties in costs impact the the benefits.

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Cost of an Outage

The first example is the "cost per customer per event" that comes from the ICE Calculator. The calculator provides estimates for different US locations and a single value ($54 per customer per event) has been used in the preceding sections (13.4.4.2 and 13.4.4.3) – the amount of variability the location accounts for. Thus a number of simulations were undertaken to establish the appropriate statistical distribution and thence the uncertainty of this $54 estimate. The results are shown in Figure 21. This graph shows that the uncertainty (90%) in the chosen cost per outage is between 44$/customer/event and 68$/customer/event.

Thus given the sensitivity of the diagnostic benefits to the intangible costs which derive from the cost per customer per event it is possible that the same diagnostic scheme would be beneficial in one location (68 $/customer/event) whilst not being beneficial in another at (44 $/customer/event).

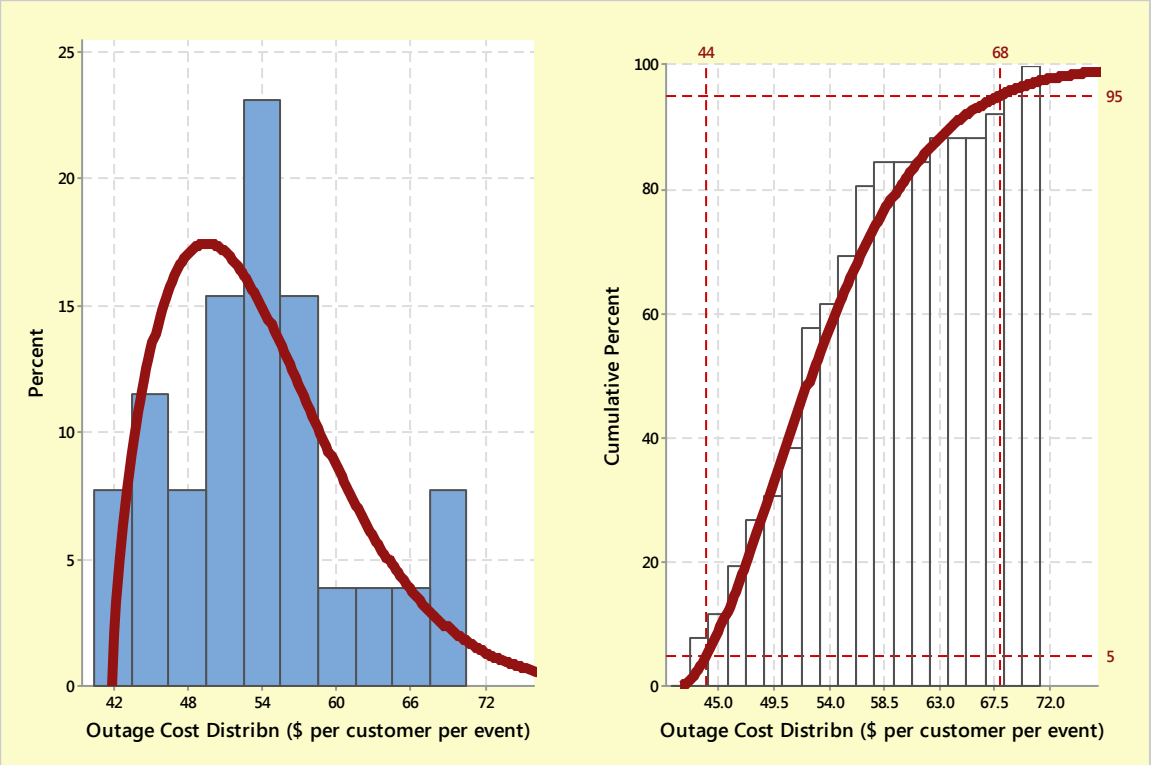

Figure 21: Distribution of Cost/Customer/Event Used to Calculate Outage Cost

Cost of Undertaking Diagnostics

In addition to the Outage Cost, the costs of undertaking diagnostics and the Run to Failure case depend upon other costs for which it is only possible to develop a range of estimates (Table 3). The next analyses have undertaken Monte Carlo Simulations, based upon 20,000 iterations, which have sought to understand the impact of the different uncertainties on the cost estimates for diagnostic testing undertaken by a service provider. These simulations have been carried out using the Outage Cost distribution in Figure 21 and cost distributions based on the ranges in Table 3 (a nomal distribution with suitable means and standard deviations has been used to model each range). 20,000 simulations of the five costs have been used. The Scenario uses the repair / outage data

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detailed in Table 7 for only replacement of Action Required segments. The diagnostic case has 23 Proactive Replacements and 13 Outages. The Run to Failure case has 0 Proactive Replacements and 19 Outages.

The results for the individual cost elements are shown in Figure 22 as histograms.

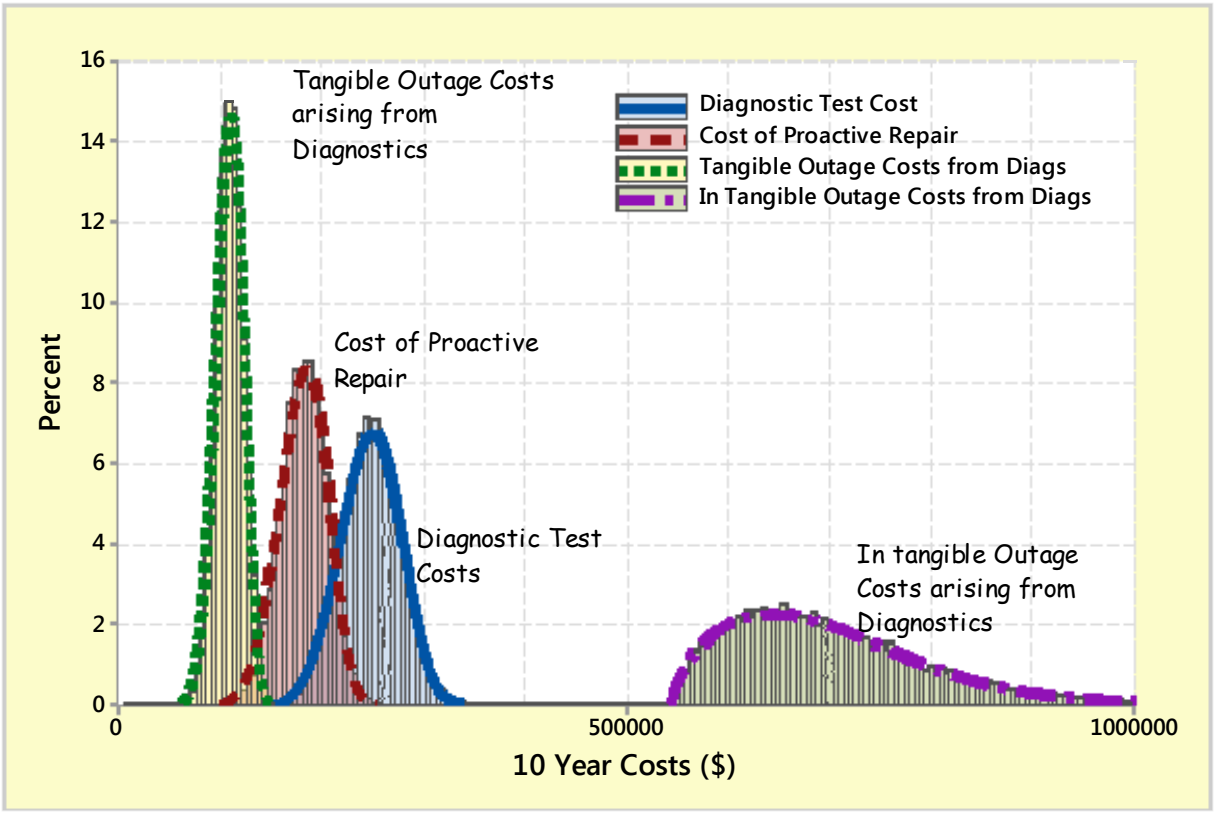

Figure 22: Results of Monte Carlo estimates of Component Costs for Diagnostic Testing conducted by a Service Provider (Table 7)

The four distribution elements in Figure 22 are the component costs that must be summed to derive the total cost (Figure 23).

The large spread in the total cost is essentially derived from the uncertainty in the outage cost per customer per event (rightmost curve of Figure 22). It is also important to understand the uncertainty in any cost and thence as this drives the estimate of the benefit. In this case the best single estimate of cost of the program using diagnostics is $1.24 M over 10 years, yet a reasonable (say 90%) uncertainty in this is +15% and -13% ($1.08 M to $1.42 M from Figure 23). Consequently it is clear that these probabilistic effects need to be considered when undertaking any robust modelling of diagnostic financial benefits. Furthermore this goes a long way to explain the differing cost / value opinions that may be drawn from seemingly the same scenario.

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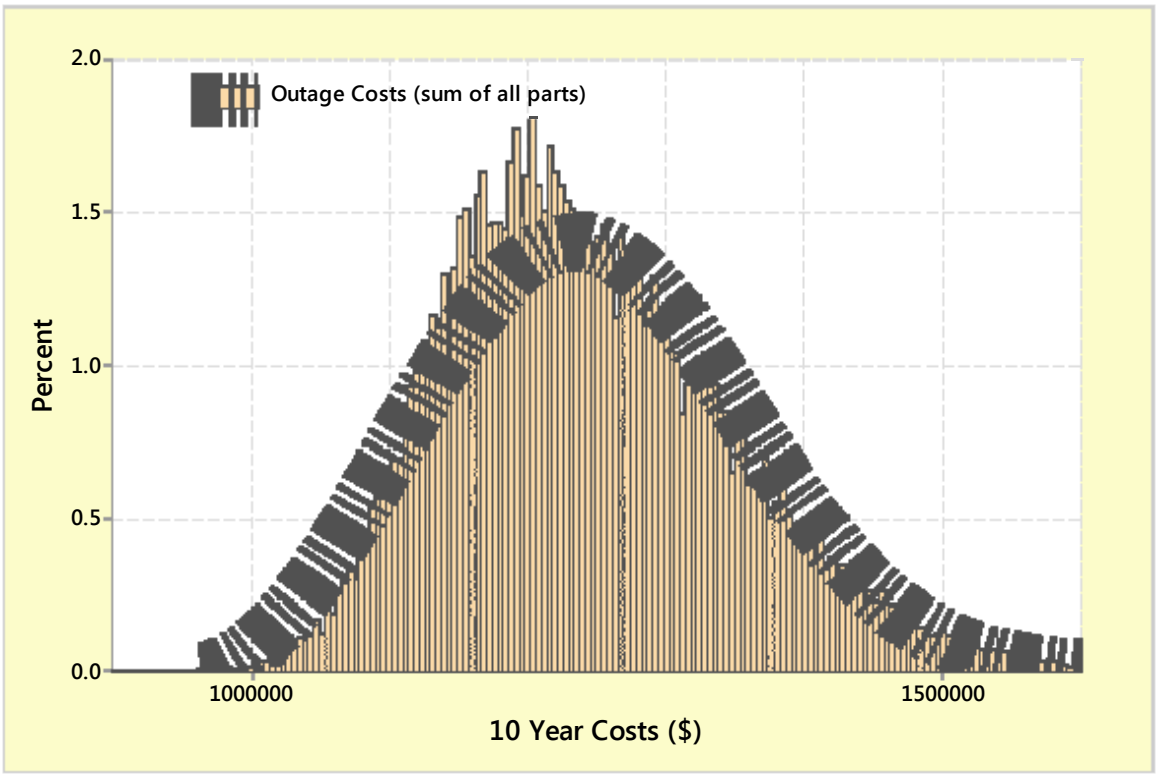

Figure 23: Summation of separate Monte Carlo estimates (Figure 22) to giveTotal Cost of Diagnostic Testing by a Service Provider (Table 7)

Cost of Undertaking Different Diagnostic and Remediation Scenarios

The analysis represented in Figure 23 represents that costs over 10 years of reliability when a diagnostic test is carried out by a service provider and the utility undertakes proactive replacement of the components identified as Action Required (AR). Clearly there are other scenarios that may be calculated in the same manner (estimate the component costs (Figure 22) and then sum them (Figure 23)).

Many alternate scenarios can be concieved; however the ones considered here are identified in Table 8

Table 8: Diagnostic and Rehabilitation Scenarios Considered for Monte Carlo Simulations

Description	Diagnostic Implemented by	Rehabilitation by
Diagnostics Provider AR	Service Provider	Proactive Replacement of AR
Diagnostics Utility AR	Utility	
Diagnostics Provider AR&FS	Service Provider	Proactive Replacement of AR & FS
Diagnostics Utility AR&FS	Utility	
Replace All	None	Complete Replacement
Run To Failure		Replacement upon Failure in Service

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Two approaches to proactive replacement are considered a) only replace Action Required (23 Proactive Replacements) and b) replace both Action Required and Further Study (65 Proactive Replacements).

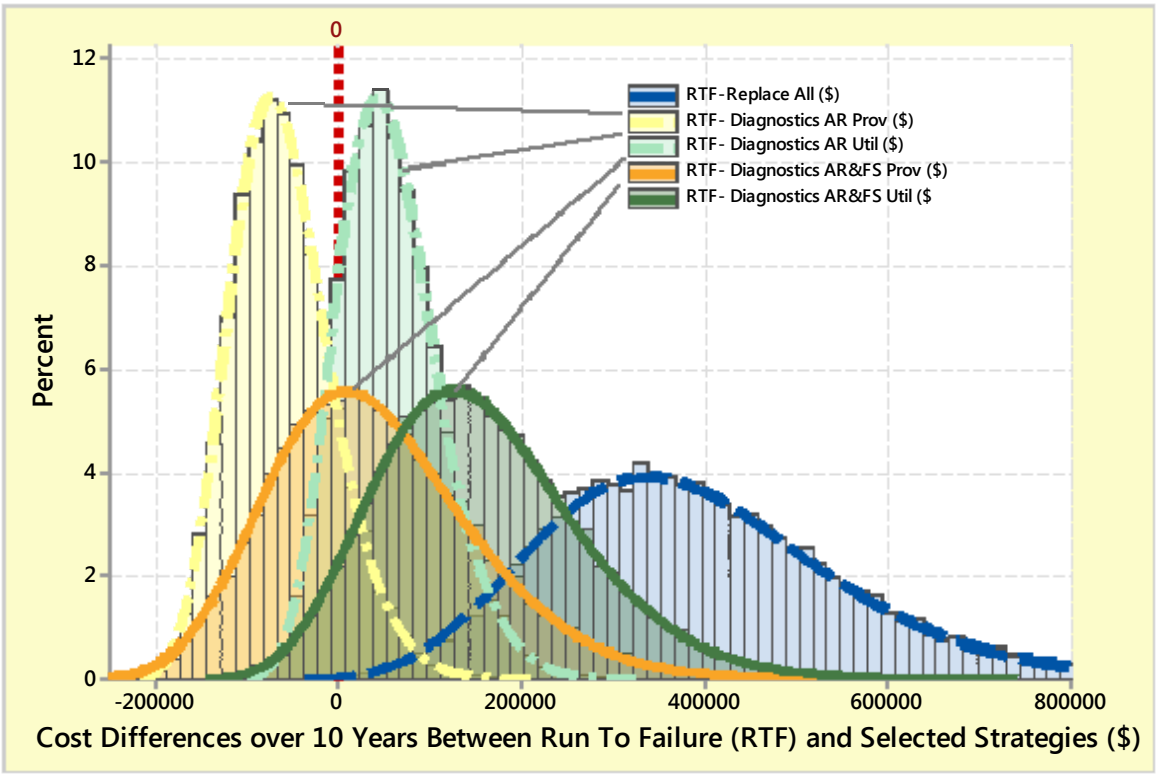

Figure 24: Cost Differences over 10 Years Between Run To Failure (RTF) and Selected Strategies (Table 8)

Figure 24 shows the cost differences over 10 years between Run to Failure (RTF) and Selected Strategies. These differences have ben estimated by taking the Monte Carlo distributions for each scenario and subtracting the distribution for the Run to Failure (RTF) case. The resulting positive numbers show that there is a cost benefit for the scenario, whilst the negative numbers show that there is no cost benefit.

Figure 24 shows:

- There are a range of cost benefits for each scenario – it is difficult to consider a single number
- How the diagnostic is deployed impacts the cost benefit – in most, but not all, cases utility deployment of a diagnostic delivers larger benefits than those from a provider
- The actions taken following the diagnostic impacts the cost benefit – addressing Action Required and Further Study brings larger benefits than addressing Action Required only

Clearly the simulations above are not exhaustive and for expediency some interesting ones have been omitted, such as:

- Rejuvenation of all segments as a remediation strategy – this would need reasonable cost ranges and an estimate for the outage rate post rejuvenation

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- Simple Withatsnd as a diagnostic
- Monitored Withstand as a diagnostic
- Mixed replacement and rejuvenation as a remediation strategy (for example Replace AR and Rejuvenate FS)

13.4 Conclusions

Estimating diagnostic program costs is a complicated but survivable ordeal that requires significant knowledge of costs that are difficult to precisely quantify. The most diffciult element is obtaining a good estimate for the true of an outage. The true cost of an outage involves elements beyond the labor and materials needed for restoring service. Customers are impacted by outages and these do affect the utility's bottom line.

Using established tools for estimating the cost of outages, it is possible to show that diagnostic programs can provide financial benefit to a utility when reasonable costs of outages are used. Were these outage costs not to be included then there would be no way to place a financial value on high reliability and so run to failure would always be the default mode of operation. On the other hand, utilities have increased their use of diagnostics since the *CDFI* began in 2004 and so there must be benefit present for them to have adopted and continued these programs.

It is clear that challenges still remain to be studied in this area, and they include:

- It is obviously beneficial not to subject a cable system to a system fault and any subsequent location trauma (thumping). It is intuitively reasonable that these will accelerate ageing in the cable system. Diagnostic testing clearly reduces outages and thus reduces tehse stresses. However it is not clear how to either represent these benefits of place a value on them so that they may be included in the financial estimations.
- Run to Failure and Complete Replacement clearly represent the extremes of the remediation spectrum. However there are a plethora of alternate schemes: Diagnostic Guided Rolling replacement, Rejuvenation, Mixed Replacement & Rejuvenation, Diagnostic Guided Accessory Replacement etc

What is also clear is that diagnostics do not make sense in all situations and so a utility must carefully weigh these issues before embarking on diagnostic programs.

13.5 References

1. D. Johnson, “Risk-based Approach to Justifying Cable Intervention”, Presented at the Fall 2014 ICC Meeting in Colorado Springs, CO, in Subcommittee C: Cable Systems, Oct 7, 2014.

CHAPTER 14

Glossary

Nigel Hampton and Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

14.0 GLOSSARY

The definitions below pertain to their use within this document. These definitions may differ slightly from those used by other sources.

ac: Alternating Current, usually with a constant amplitude
Acceptance Test: A field test made after cable system installation, including terminations and joints, but before the cable system is placed in normal service. The test is intended to detect installation damage and to show any gross defects or errors in installation of other system components.
Age Line: A probabilistic description of how a diagnostic classification changes with age of the cable system from all No Action Required when new to increasingly Action Required as the system ages.
Aging: Irreversible degradation of the capabilities of a cable system that is correlated with age
Amplitude or Range Resolution (TDR): The ability of a particular pulse setting (width and amplitude) to traverse the full cable system length and provide clear location information of accessories and other discontinuities.
Assessment Class: A classification of a diagnostic feature or features (bounded by limits based on population probability) that provides a convenient means to describe and rehabilitate a number of cable sections, segments, or circuits. The most common ones used in this project are: Action Required (AR) – poorest performing 5% for a diagnostic, No Action Required (NA) – best performing 80% for a diagnostic, Further Study (FS) – the 15% performance range for a diagnostic residing between 80th & 95^{th} percentiles.
Attenuation: The reduction in peak amplitude of a signal as it travels along a cable. Important concept in PD & TDR tests
Back to Service: A non-diagnostic test that is conducted after work but before placing the cable system back into service to ensure no very gross workmanship errors have occurred during the repair.
Bounce Diagram: A graphical method to interpret the traces resulting from PD and TDR tests
Box or Whisker Plot: A convenient way of graphically depicting the variation between groups of numerical data. The plots display variation in samples without making any assumptions of the underlying statistical distribution. These plots typically focus on the median and middle 50% of available data (interquartile range).
Breakdown: Permanent failure through insulation.
Cable Diagnostic Focused Initiative (CDFI): Large scale independent investigation conducted by NEETRAC to establish the best practice and use of cable system diagnostic technologies with

the support of utilities, manufacturers, diagnostic providers, and US DOE.
Cable Injection or Rejuvenation: A means by which medium voltage cable systems can be remediated by the replacement of accessories, removal of water, and injection of a water reactive silicone fluid.
Cable System: Cable with installed accessories (terminations, elbows, and joints).
Calibration: In the context of Partial Discharge testing Calibration is the means by which the voltage response of the measurement system (data acquisition unit, sensors, and cable system) is related to the output of a pulse generator with known charge.
Capacitive Current: The portion of the current flowing in the cable system that is required to charge and discharge the capacitance of the cable system**.**
Characteristic Impedance (Z_0): The relationship between the series and shunt equivalent elements in a cable system that is modeled using signal transmission theory. Used to determine the tendency of a signal to reflect at different cable system components.
Cold Shrink: An elastomeric sleeve that has been factory expanded onto a supporting removable plastic core. The sleeve shrinks upon removal of the supporting core during the installation.
Combined Diagnostic Test: A test where two or more diagnostic tests are carried out simultaneously. Each diagnostic provides distinct information on a cable system.
Commissioning Test: A test conducted after the construction of a new cable system but before ownership transfers to a utility. The goal of the test is to minimize the likelihood of infant mortality failures and hopefully to reduce the long term failure rates by reducing the chance for defects to remain present in the cable system.
Confidence Intervals: Confidence intervals consist of a range of values (the interval) that act as good estimates of the uncertainty in the parameter of interest. When presented graphically, confidence intervals can be shown at several confidence levels, for example 90%, 95% and 99%. The percentage indicates the probability that the true answer is present within the band.
Conseil International des Grands Réseaux Électriques (CIGRE): A global electro-technical organization. It was founded in Paris, France in 1921. Its scope includes the technical and economic aspects of the electric grid, as well as the environmental and regulatory aspects.
Crosslinked Polyethylene (XLPE): A thermoset unfilled polymer used as electrical insulation in cables.
Cumulative Distribution: The distribution that describes the probability that a real-valued property will be found to have a value less than or equal to a chosen level *x*.
Damped AC (DAC) Test: A Partial Discharge detection test where the voltage source is formed by a dc supply, the cable capacitance, and and an external inductance. The alternating frequency

portion of the applied voltage waveform is in the range 30 Hz to 300 Hz.
Damped ac (DAC): Decaying oscillation of a resonant circuit. Used and likely effective for PD testing. No evidence of effectiveness found for commissioning or dielectric loss testing. Virtually no use in North America
DC Hipot: A withstand or Proof test that is conducted using a direct current voltage. The test is defined in terms of voltage magnitude and time.
dc: Direct Current
Diagnostic Program Stages – Selection, Action, Generation, and Evaluation (SAGE): Suggested stages/steps of a planned diagnostic program.
Diagnostic Rank: The relative position of a cable system based on the outcome of a diagnostic test. The outcome may be defined in terms of the directly measured property (partial discharge magnitude) or a derived property such as a Health Index (Tan Delta, etc.).
Diagnostic Test*:* A field test made during the operating life of a cable system. It is intended to determine the presence, likelihood of future failure and, for some tests, locate degraded regions that may cause future cable and accessory failure.
Diagnostic Time Horizon: The period of time that the result of a diagnostic test may be projected forward in time and still be considered accurate. This will vary for each diagnostic and interpretation method and is not well defined. It may be thought of as the point at which a diagnostic result would change from one classification to a more severe one.
Dielectric Loss: An assessment of the electric energy lost per voltage cycle. A poorly performing cable system tends to lose more energy per ac cycle. Measurements can be made for selected voltages or over a period of time at a fixed voltage. The stability of the loss, the variation with voltage and absolute loss are used to estimate the condition. Data can be derived from time based (if sufficient time is taken) or frequency-based test methods.
Dielectric Puncture: see Dielectric Breakdown
Dielectric Spectroscopy: Measures of the dielectric property at different frequencies. The absolute loss and the variation with frequency are used to estimate the condition. Data can be derived from time-based (if sufficient time is taken) or frequency-based test methods.
Differential Tan δ or Tip Up (TU): Difference between the Tan δ (TD1) at voltage 1 and Tan δ (TD2) at voltage 2, a higher voltage. Very commonly used in VLF Tan δ testing with measurements at $0.5U_0$ and $1.5U_0$
Dispersion: The spreading (spatially) of a signal as different frequency components of the signal travel at different velocities along a cable. Important concept in PD and TDR tests.
Electrical Trees: Permanent dendritic growths, consisting of non-solid or carbonized micro-

channels, that can occur at stress enhancements such as protrusions, contaminants, voids or water trees subjected to electrical stress. The insulation is damaged irreversibly at the site of an electrical tree.
Ethylene Propylene Rubber (EPR): A type of thermoset-filled polymer used as electrical insulation in cables and accessories. There are several different formulations of EPR and they have different characteristics. The term also encompasses ethylene propylene diene monomer rubber (EPDM).
Extra High Voltage (EHV): Cable systems within the voltage range 161 kV to 500 kV, though more often between 220 kV and 345 kV. Also referred to as Transmission Class, though usually having a higher design stress levels than HV.
Extruded Dielectrics: Insulation such as EPR, HMWPE, PE, WTRXLPE, XLPE, etc. applied using an extrusion process.
Failure in Service (FIS): A failure that occurs under the voltage and thermal stresses of normal operation.
Failure Mechanisms: The different mechanisms by which the ultimate failure of a cable system occurs, different from the degradation mechanism.
Failure on Test (FOT): A failure that occurs under the voltage and thermal stresses of a diagnostic test.
Failure Rate: The number of failures of a defined type (on test or outage) as a fraction or percentage of a selected population, usually either initial population or remaining population.
Filled Insulation: Extruded insulations where a filler (Carbon Black or Clay) has been incorporated to modify the inherent properties of the base polymer. This class includes all types of EPR, Vulkene etc.
"Ghost" Reflection: A reflected signal in a PD or TDR test that continues to travel and reflect multiple times within the cable system length; thereby appearing as extra components.
"Health" Index: A method to combine different diagnostic features into a single meaningful number using a clear methodology – analogous to Consumer Price Index, Air Quality Index etc.
Heat Shrink: An open ended crosslinked elastomeric sleeve that has been factory expanded under the action of heat and then quenched below its crystalline melting point. The sleeve shrinks to the original unexpanded size upon the application of heat during the installation.
High Frequency Current Transformer (HFCT): A sensor commonly used in field tests using PD methods. Generates a voltage signal that is proportional to the current signal that passes through the sensor.
High Voltage (HV): Cable systems within the voltage range 46 kV to 161 kV, though more often

between 66 kV and 138 kV. Also referred to as Transmission Class though usually has lower design stress levels than EHV.

"Hold" Phase: The constant voltage amplitude phase of a withstand test. The voltage exposure recipe of a withstand test is defined by the voltage/stress amplitude and the length of the hold phase. The outcome of a withstand test (the percentage of cable systems failing on test) is non-linearly dependent upon the length of the hold phase and the voltage magnitude.

Installation Test: A field test conducted after cable installation but before jointing (splicing), terminating, or energizing. The test is intended to detect shipping, storage, or installation damage. It should be noted that temporary terminations may need to be added to the cable to successfully complete this test.

Inter Quartile Range (IQR): The middle 50% of a data set that provides a measure of statistical dispersion. It is equal to the difference between the upper and lower quartiles, IQR = $Q_3 - Q_1$. The IQR is used to build box and whisker plots.

Isothermal Relaxation Current (IRC): A diagnostic test thought to be useful at the start of *Phase I* of *CDFI*, but its use and efficacy has not been verified; presumed not to be used in North America.

Jacket: An extruded outer polymeric covering for cables designed to protect the cable core and the metallic shielding (wires, tapes or foils).

Joint: A device to join two or more sections of power cable together. A joint includes a connector to secure the cable conductor and a stress controlling / insulating body to manage the electrical stress.

Laminated Dielectrics: Insulation formed in layers typically from tapes of either cellulose paper or polypropylene or a combination of the two. Examples are the PILC (paper insulated lead covered) and MIND (mass-impregnated non-draining) cable designs.

Leakage Current: The current component that flows in the resistive element of the insulation of a cable system. This current component corresponds to current that is in phase with the applied ac voltage and continues flowing once the cable capacitance has been charged under dc voltage conditions. Leakage currents are believed to increase as the system degrades.

Length Adjusted: The outcome of a withstand test depends upon the length of cable system tested (i.e. the number of likely weak links in a chain). Longer lengths have more weak links and experience more failures on test and thus apparently poorer reliability. The outcome of the withstand test is adjusted using the censoring concepts within Weibull Analysis or Dauser Shifts.

Level of Tan δ (TD): The magnitude of the dielectric loss – non dimensional. Commonly referred to as a number with is multiplier of 10^{-3} (i.e. $3*10^{-3}$ is often referred to as a loss of 3).

Lower Quartile: The 25th percentile (splits off the lowest 25% of data from the highest 75%).

Maintenance Test: A field test made during the operating life of a cable system. It is intended to detect deterioration and to check the serviceability of the system.
Mass Impregnated Non Draining Cable (MIND): A cable design using paper insulation impregnated with a thick compound such that the compound does not leak out should the lead sheath be breached.
Mean: Usually refers to the arithmetic mean which is the most common measure of the central tendency of a normal distribution.
Median: The number separating the higher half of a data set from the lower half. Otherwise known as the data point corresponding to the 50^{th} percentile.
Medium Voltage (MV): Cable systems within the voltage range 6 kV to 46 kV, though more frequently between 15 kV and 35 kV. Also referred to as Distribution Class.
Monitored Withstand Test: A test in which a voltage of a predetermined magnitude is applied for a predetermined time. During the test, other properties of the test object are monitored and these are used, together with the breakdown (pass or fail) results, to determine the condition of the cable system.
Offline Test: A diagnostic where energizing and measurement equipment are temporarily coupled to the cable system, while the system is removed from operating voltage and not carrying load. The measurement equipment is removed after test and the system returned to normal voltage and load. Measurements are made at any voltage selected by the test equipment operator with all the load components removed from the cable system under test.
Online Monitoring Test: A diagnostic where measurement equipment may be permanently coupled to the cable system while the system is under voltage and carrying normal load, and monitored remotely at any desired occasion to determine the cable system health.
Online Test: A diagnostic test where measurement equipment is temporarily coupled to the cable system, while the system is under voltage and carrying load, and monitored remotely for a selected period of time to determine the cable system health. The measurement equipment is removed after test while the system is under voltage and carrying load.
Outage: A failure in service that results in at least one customer being without power for a period of time.
Outcome Line: A probabilistic description of what is likely to happen in service for each diagnostic class (i.e. No Action Required, Further Study, etc.) as the cable system continues to age.
Outlier: an observation that is distant from other observations. An outlier may be indicative of variability in the measurement or it may indicate experimental error; the latter are sometimes excluded.

Paper Insulated Lead Covered (PILC): A cable design using paper insulation impregnated with a fluid and encased in lead to prevent the fluid from leaking out of the insulation.
Paper Insulation: Paper tapes wrapped around a conductor (almost always copper), the interstices between the tape edges (butt gaps) are filled with either oil (PILC) or waxy compound (MIND).
Pareto Principle: A common heuristic (rule of thumb) in business; e.g., "80% of your sales come from 20% of your clients." Named after the Italian economist Vilfredo Pareto, who showed that approximately 80% of the land in Italy was owned by 20% of the population.
Partial Discharge (PD): A low voltage (mV or μV) signal resulting from the breakdown of gas enclosed in a dielectric cavity. The signal generated during the partial breakdown travels down the cable system and may be detected at the end by special sensors.
PCA Distance: Principal Component Analysis is the primary analytic tool used for Health Index estimation. The three to four Principal Components are combined into a single vector which is then compared to another reference vector. The difference between these two vectors is the PCA Distance. This is analogous to the Mahalanobis distance.
PD Sensors: Capacitive, inductive, or resistive devices through which currents correlated with Partial Discharges flow. The voltages that result are conditioned and displayed by suitable recording devices
PE-Based: Extruded insulations that do not have an incorporated filler (Carbon Black or Clay). This class includes all types of HMWPE, PE, WTRXLPE, XLPE, etc.
Percentile: A measure indicating the value below which a given percentage of observations in a group of observations fall (e.g. the 20^{th} percentile is the value (or score) below which 20 percent of the observations may be found).
Performance Rank: Partial Discharge Magnitudes (mV), Tan Delta Tip Ups, PCA Distances all represent performance of the cable system. Furthermore the magnitudes have meaning – large numbers indicate poor performance, small numbers indicate good performance. Ordering the relevant metrics from smallest to largest results in a rank ordering that is correlated with the cable system performance. Thus understanding the rank position provides, with suitable random sampling, a definitive perspective of the true cable system performance in the field
Pico Coulomb (pC): Historical metric for the assessment of partial discharge when undertaking tests using the methods detailed in IEC 60270 for tests in high voltage laboratories. IEC 60270 assumptions are not fulfilled in field tests, thus the value and comparability of pC values are lower in field tests than in small laboratory loops.
Polyethylene (PE): A polymer used as electrical insulation in cables.
Power Frequency: A substantially sinusoidal waveform of constant amplitude with an

alternating frequency in the range 49 Hz to 61 Hz.
Principal Component Analysis (PCA): A statistical procedure that converts a set of observations of possibly correlated variables into a set of variables called **principal components**. The number of principal components is less than or equal to the number of original variables. It is useful to reduce the complexity of analysis when there are many types of observations.
Principal Component: The outcome of PCA Analysis. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component in turn accounts for the next largest amount of variability.
Probability Plot: A graphical technique for comparing two data sets
"Ramp-up" Phase: The voltage ramp that precedes the constant voltage amplitude phase of a withstand test. The voltage exposure recipe of a withstand test is defined by the voltage/stress amplitude and the length of the hold phase. The Ramp Up phase does not contribute to the voltage exposure recipe.
Reflection Coefficient (ρ): Ratio of the difference in characteristic impedances of difference cables and accessories. This relationship determines the portion of a signal that is reflected back to its source and the portion that is transmitted to the next component.
Resonant ac: The voltage waveform commonly used in a commissioning test. The voltage exposure recipe is defined by a voltage/stress amplitude and the length/duration of the hold phase. DAC tests do not meet this definition as the amplitude is not constant and a recipe cannot be defined.
Scaled Charge (pC): When the IEC 60270 assumptions are not fulfilled the value and comparability of charge values are much lower than in small laboratory loops. When it is appropriate to consider charge (usually the integration of the measured current over time), the term Scaled Charge is used so as not to increase confusion with the "pC" used to refer to charge in small laboratory loops (IEC 60270).
Shielded Cable: A cable in which an insulated conductor is encapsulated in a conducting 'cylinder' that is connected to ground. The voltage at the exterior of such a cable is by definition at ground potential.
Simple Withstand Test (SW): A test in which a voltage of a predetermined magnitude is applied for a predetermined time. If the test object survives the test it is deemed to have passed the test.
Space Charge: Quasi-permanent injected charge that is trapped within the insulation of a cable system. This charge is sufficient to modify the applied ac and Impulse voltage stresses.
Splice: A joint.
Survivor Curve: A survivor curve plots the number of survivors within a system as a percentage of the initial population against time or cycles or any suitable variable that describes "exposure".

The curve starts in the top left at 100 and decays towards zero in the bottom left. The shape of the curve relates to the failure rate and ultimately the hazard plot.
Tan δ (TD): The tangent of the phase angle between the voltage waveform and the resulting current waveform. Can alternatively be described as the ratio of the loss current to the charging current.
Tan δ Non-linear Voltage Dependence or Tip Up of the Tip Up (TuTu): The differential Tan δ is the difference between the Tan δ (TD1) at voltage 1 and Tan δ (TD2) at voltage 2, a higher voltage. This is the first feature for Tan δ analysis and assumes that the voltage dependence is linear. However experience has shown that there are cases where this is not linear and these cases are quite concerning. Thus the difference of the differential Tan δ is a useful feature. This is calculated from the TD 1.5 (i.e. a voltage midway between 1 and 2).
Tan δ Speed: In the monitored withstand mode of testing one of the features is how the Tan δ changes with time. The magnitude is conveniently labeled as Tan δ Speed. Obviously high speeds are concerning as they tend to be well correlated with problems in service.
Tan δ Stability (STD): In standard Tan δ and monitored withstand tests, a series (6 and 180, respectively) of measurements are made sequentially at different times. The amount of variation in Tan δ over the constant voltage period is conveniently described by the standard deviation of the 6 – 180 data points. High standard deviations are concerning as they tend to be well correlated with problems in service.
Tan δ Trend: In the monitored withstand mode of testing one of the features is how the Tan δ changes with time. The direction of the change (increasing or decreasing) is conveniently labeled as Tan δ Trend. Obviously high positive speed trends are concerning as they tend to be well correlated with problems in service, whereas high negative speed trends are merely confusing.
Termination: A device that manages the electric stress at the end of a cable circuit, while sealing the cable from the external environment and providing a means to access the cable conductor. Devices referred to as Elbows or Potheads are types of terminations.
Time Domain Reflectometry (TDR): A technique to determine cable system lengths and positions of joints using reflections from a rapid rise time low voltage pulse.
Time Domain Spectroscopy (TDS): A diagnostic technique that examines a response as a function of measurement frequency. Dielectric loss measurements can be made at different frequencies and thereby plotted. Another way of doing this is to measure the dielectric function as a function of time and then perform a mathematical transform to derive the spectra. Spectra derived in this manner are termed Time Domain Spectroscopy**.**
Time Frequency Map (TF-Map): The major problem with PD tests in the field is that the signal and noise are convoluted and that it is not possible to be certain that when filtering that only the noise is belong filtered away. One way to reduce these concerns is to map the equivalent pulse length deviation (a time) and pulse frequency deviation (a frequency) for each received pulse; thence a Time-Frequency Map. Clusters of PD like and Noise like pulses can be separated and

any filtering more precisely performed.
Time Resolution (TDR): A pulse used in TDR testing that has a finite width in terms of time, and hence distance when coupled with the appropriate Velocity of Propagation. Thus the finite distance width leads to the uncertainty in distance measurement and thence resolution (i.e. the ability to clearly distinguish between two closely located features). This is analogous to Spatial Resolution and Rayleigh Criteria in optics. For reference, a 1 GHz frequency pulse has a pulse width of 20 cm in PE-based cable insulations.
Ultra Wide Band (UWB): The outcome of a PD diagnosis is influenced to a very high degree by the frequency range over which the measurements are made (i.e. the bandwidth of measurement). Ultra Wide Band (UWB) measurements are used to maximize the chances of capturing PD signals (known to be very high frequencies). However the simple PD metrics of Apparent IEC 60270 charge no longer hold as the signals essentially travel – hence field data / criteria cannot relate to the data collected in the field
Upper Quartile: The 75th percentile (splits off the lowest 75% of data from the highest 25%)
Velocity of Propagation (VOP): The velocity by which an electromagnetic pulse (TDR signal, PD signal) propagates down a concentric dielectric. This is some fraction of the speed of light. However it is not constant and depends upon the impedance of the cable system in this case. A good selection of the VOP is required to undertake accurate distance estimation.
Very Low Frequency (VLF): AC waveform of constant magnitude with an alternating frequency in the range 0.01 Hz to 1.0 Hz.
VLF Cosine Rectangular: A VLF waveform that can be approximated by a rectangular waveform of 0.1 Hz, where the transitions have the shape of a cosine and a frequency determined by the capacitance of the device under test. The frequency of transition is not fixed (or known) and it is likely in the range 30 to 300 Hz**.**
VLF Sinusoidal: A VLF waveform that can be closely approximated to a sine wave. The most common embodiment has a frequency of 0.1 Hz, however the frequency may be lowered (manually or automatically) to accommodate longer or more lossy test lengths that require more power to energize.
Voltage Exposure: Withstand Tests are essentially Proof Tests (in the same way that all firearm barrels are subjected to overstressing). Clarity and reproducibility are important in Proof Tests. In cable system Withstand Tests clarity and reproducibility are ensured through a defined Voltage Exposure; which is a prescribed Voltage Level for a prescribed Time. This is often referred to as a Test Recipe. The voltage levels and times are non-linearly related and are chosen with great thought and care. Common examples of Proof Tests conducted on cable systems are $1.7U_0$ applied for 60 min, 20 impulse shots (10 positive, 10 negative) at 1,050 kV, etc.
Water Tree Retardant Crosslinked Polyethylene (WTRXLPE): A thermoset polymer used as electrical insulation in cables that is designed to retard water tree growth.

Water Trees: Dendritic pattern of electro-oxidation that can occur at stress enhancements such as protrusions, contaminants, or voids in polymeric materials subjected to electrical stress and moisture. Within the water tree the insulation is degraded due to chemical modification in the presence of moisture.

CHAPTER 15

CDFI Brochures

Jean Carlos Hernandez-Mejia and Nigel Hampton

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

15.0 *CDFI* BROCHURES

The brochures that follow are arranged such that they may be directly printed (front and back) to make a trifold pamphlet. They are designed to be taken out to the field and used as quick references for those techniques that the *CDFI* has developed criteria for.

The following brochures are included:

1. Tan δ Diagnostics of Distribution and Network Cable Using *CDFI* MV Test Protocl
2. Monitored Withstand Tan δ Using the CDFI MV Test Protocol PE-Based
3. Monitored Withstand Tan δ Using the CDFI MV Test Protocol Filled (i.e. EPR, Kerite, & Vulkene®
4. Monitored Withstand Tan δ Using the CDFI MV Test Protocol Paper – PILC

INTERPRETATION

Actions following a Further Study diagnosis might include

- review data for a rogue measurement in the sequence – most common in the first acquisition
- check insulation type so that correct assessment table is used
- re clean terminations & repeat measurements
- compare with previous tests or other results from other phases of this cable
- if Filled insulations are tested check specific variety of material; if identified as discharge resistant or mineral filled XLPE consult CDFI / NEETRAC for guidance
- conduct IEEE400.2 Standard (30 mins) VLF Withstand whilst monitoring Tan δ – see Monitored Withstand Brochure for guidance
- place on "watch list"

Actions following an Action Required diagnosis might include

- review data for a rogue measurement in the sequence – most common in the first acquisition
- check insulation type so that correct assessment table is used
- re clean terminations & repeat measurements
- compare with previous tests or other results from other phases of this cable
- if Filled insulations are tested check specific variety of material; if identified as mineral filled XLPE consult CDFI / NEETRAC for guidance
- conduct IEEE400.2 Standard (60 mins) VLF Withstand whilst monitoring Tan δ – see Monitored Withstand Brochure for guidance
- Retest in near future
- place on "watch list" & consider remedial actions for the circuit

FURTHER HELP

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NEETRAC

www.neetrac.gatech.edu

Diagnostic Tool
http://www.neetrac.gatech.edu/cdfi-publications.html

Final Report available for download at:
http://www.neetrac.gatech.edu/cdfi-publications.html

Other Useful Documents:

1. Perkel, J.; Del Valle, Y.; Hampton, R.N.; Hernandez-mejia, J.C.; Densley, J., "Interpretation of dielectric loss data on service aged polyethylene based power cable systems using VLF test methods," IEEE Transactions on Dielectrics and Electrical Insulation, Year: 2013, Volume: 20, Issue: 5, pp.1699 - 1711
2. Hernandez-Mejia, J.; Perkel, J.; Harley, R.; Hampton, N.; Hartlein, R., "Correlation between tan δ diagnostic measurements and breakdown performance at VLF for MV XLPE cables," IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 16, Issue: 1, Year: 2009, Pp. 162 – 170.
3. Olearczyk, M.; Hampton, R.N.; Perkel, J.; Weisenfeld, N., "Notes from Underground," IEEE Power and Energy Magazine, Year: 2010, Volume: 8, Issue: 6, Pages: 75 – 84.
4. IEEE Std. 400™ – 2012: IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above.
5. IEEE Std. 400.2™ – 2013: IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz).

The CDFI data have been incorporated in the most recent update of IEEE Std. 400.2 - 2013

CDFI

(CABLE DIAGNOSTICS FOCUSED INITIATIVE)

TAN δ DIAGNOSTICS OF DISTRIBUTION & NETWORK CABLE SYSTEMS USING THE CDFI MV TEST PROTOCOL

DOE AWARD NO. DE-FC02-04CH11237

FOR FURTHER DETAILED INFORMATION CONSULT
http://www.neetrac.gatech.edu/cdfi-publications.html

Georgia Tech NEETRAC National Electric Energy Testing, Research and Applications Center

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Historical figures of merit within CDFI for US utility cable systems over a period of 11 yr. Figures of Merit are based on more than 4,000 separate field measurements at VLF.

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Assessment of PE-based Insulations (i.e. PE, XLPE, WTRXLPE)			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.0	>1.0
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<6.7	6.7 to 94.0	>94.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}-TD_{U_0}) - (TD_{U_0}-TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
	&	or	
Mean TD at U_0	<6.0	6.0 to 70.0	>70.0

A minimum of 6 measurements should be made at each voltage level; to determine the parameters detailed above.

In these tests (all materials) the "operational U_0" is used to determine test voltages.

The user *may* elect to add a measurement at $2U_0$ of engineering information if this does not exceed the IEEE Std. 400.2 - 2013 test voltage withstand voltages.

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Assessment of Unidentified Filled Insulations			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.2	>1.2
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<3.0	3.0 to 30.0	>30.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}-TD_{U_0}) - (TD_{U_0}-TD_{0.5U_0})\}$	<1.0	1.0 to 18.0	>18.0
	&	or	
Mean TD at U_0	<25.0	25.0 to 150.0	>150.0
Condition Assessment of Mineral Filled Insulations (i.e. EPR) *			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 0.8	>0.8
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<2.0	2.0 to 40.0	>40.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}-TD_{U_0}) - (TD_{U_0}-TD_{0.5U_0})\}$	<1.0	1.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<16.0	16.0 to 75.0	>75.0

* Experience has shown that it is difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect /missing records, obliterated or obscured markings on the cable jacket, indistinct coloring etc. In these cases it is recommended to use the criteria for **Unidentified Filled** data.

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Assessment of Paper Insulations (i.e. PILC)			
Stability for TD_{U_0} (standard deviation)	<0.2	0.2 to 1.5	>1.5
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-30.0 to 22.0	-30 to -60 or 22 to 220	<-60.0 or >220.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}-TD_{U_0}) - (TD_{U_0}-TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<100.0	100.0 to 250.0	>250.0

Consult CDFI website for most recent version.
Version 1
http://www.neetrac.gatech.edu/cdfi-publications.html

An excel tool, which simultaneously assesses all features has been developed to enhance the analyses, especially in the region of Further Study (cable circuits ranked 5 to 15%) & "Action Required" (the lowest ranked 5% of cable circuits). The tool may be downloaded from the CDFI website
http://www.neetrac.gatech.edu/cdfi-publications.html

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INTERPRETATION

Cable systems with an evaluation in the "Ramp-up" Phase resulting in a "Red No" require remedial actions in the near future and thus it is assumed that they have not passed the monitored withstand test; then the remedial actions following a "Red No" evaluation should be sequentially undertaken as follows:

- Review data for a rogue measurement in the sequence – most common in the first voltage cycle,
- Confirm insulation type to ensure that criteria apply,
- Verify the integrity of the terminations and if compromised replace them and repeat the test,
- Retest in the near future and observe trends (6 months to a year), or,
- Place on "watch list" and consider system replacement in the near future.

Cable systems with an evaluation of the "Hold" Phase resulting in a "Further Study" may require remedial actions in the near future that should be sequentially undertaken as follows:

- Review data for a rogue measurement in the sequence – most common during the first voltage cycles,
- Confirm insulation type to ensure that criteria apply,
- Verify the integrity of the terminations and if compromised replace them and repeat the test,
- Retest in the near future and observe trends (6 months to a year), or,
- Place on "watch list" and consider system replacement in the near future.

FURTHER HELP

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NEETRAC

www.neetrac.gatech.edu

Final Report available for download at:
http://www.neetrac.gatech.edu/cdfi-publications.html

Other Useful Documents:

1. Perkel, J.; Del Valle, Y.; Hampton, R.N.; Hernandez-mejia, J.C.; Densley, J., *"Interpretation of dielectric loss data on service aged polyethylene based power cable systems using VLF test methods,"* IEEE Transactions on Dielectrics and Electrical Insulation, Year: 2013, Volume: 20, Issue: 5, pp.1699 - 1711
2. First practical utility implementation of monitored withstand diagnostics in the USA; CL Fletcher, J Perkel, RN Hampton, JC Hernandez, J Hesse, MG Pearman, CT Wall, W Zenger*; International Conference on Insulated Power Cables JICABLE11*, Versailles France, June 2011; Paper A.10.2
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5. IEEE Std. 400.2 – 2013: IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz).

CDFI

(CABLE DIAGNOSTICS FOCUSED INITIATIVE)

MONITORED WITHSTAND TAN δ USING THE CDFI MV TEST PROTOCOL PE-BASED

DOE AWARD NO. DE-FC02-04CH11237

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Georgia Tech NEETRAC
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Prepared by NEETRAC under GTRC Project # E-21-RJT

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Historical figures of merit researched (Monitored Withstand) within CDFI for USA utility cable systems over a period of 7 years for more than 1380 separate measurements.

Tan δ Monitored Withstand Tests are **conducted for 30 min** as recommended by IEEE Std. 400.2 – 2013.

This time ***may*** be amended ***if*** the conditions listed in the Framework and Tables below are fulfilled:

A minimum of 6 measurements should be made at each voltage level; to determine the parameters detailed above.

A TDR Measurement is always "Good Practice" in advance of a Tan δ measurement as it serves to confirm Capacitance measurements and obtain a qualitative estimate of neutral condition.

In these tests (all materials) the "Operational U_0" is used to determine test voltages.

The maintenance test voltages for the "Hold" Phase as specified in the IEEE Std. 400.2 – 2013 are as follows:

"Hold" Phase Recommended Test Voltage Levels				
CABLE SYSTEM VOLTAGE (kV)	**15**	**20**	**25**	**35**
Maintenance Testing RMS (kV)	16	20	24	33
Maintenance Testing Peak (kV)	22	28	34	47

Anticipated Failure rates On Test (FOT) for the "Hold" Phase are approximately as follows:

- 15 Minutes 2.0% per 1000ft
- 30 Minutes 2.7% per 1000ft
- 60 Minutes 3.7% per 1000ft

Georgia Tech NEETRAC National Electric Energy Testing, Research and Applications Center

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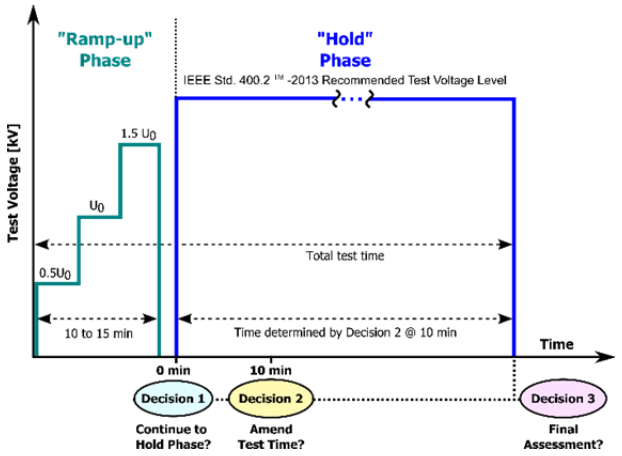
Tan δ Monitored Withstand Framework



Decision 1 – Continue to "Hold" Phase?
After "Ramp-up" – Made online during test

Feature [E-3]	"No"*	"Yes"**	"No"***
Ramp-Up Phase Evaluation			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.0	>1.0
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<6.7	6.7 to 94.0	>94.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}–TD_{U_0}) – (TD_{U_0}–TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
	&	or	
Mean TD at U_0	<6.0	6.0 to 70.0	>70.0

* "**Green No**" – Cable system condition is assessed as best performing 80% and thus it is not necessary to continue to "Hold" phase so that time and resources might be saved.

** "**Amber Yes**" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems pass to the "Hold" phase for consideration in Decision 2 and Decision 3.

*** "**Red No**" – Cable system condition is assessed as being on the poorest performing 5% and thus it is not necessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair cost. Systems in this category can be acted on in a planned manner by managing optimal time and cost.

Decision 2 – Amend Test Time?
Made online during test

Feature [E-3]	"Reduce to 15 min"	"Extend to 60 min"
Initial "Hold" Phase Evaluation		
Absolute Change in Tan Delta $\lvert TD_{10}-TD_0\rvert$	<0.6	>8.0
	&	or
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5.0
	&	or
Tan δ Level (Mean Tan δ – TD_{10})	<14.0	>70.0

Decision 3 – Final Assessment?
Made offline after test

"No Action Required"	"Further Study Advised"	"Action Required"
Final "Hold" Phase Evaluation		
An excel tool, which simultaneously assesses all final features (**Speed 10-15, Speed 0-5, Speed 0-t_{final}, Standard Deviation, and Mean Tan δ**) is under development to enhance the analyses, especially in the region of Further Study (cable circuits ranked 5 to 15%) & "Action Required" (the lowest ranked 5% of cable circuits).		
http://www.neetrac.gatech.edu/cdfi-publications.html		

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INTERPRETATION

Cable systems with an evaluation in the "Ramp-up" Phase resulting in a "Red No" require remedial actions in the near future and thus it is assumed that they have not passed the monitored withstand test; then the remedial actions following a "Red No" evaluation should be sequentially undertaken as follows:

- Review data for a rogue measurement in the sequence – most common in the first voltage cycle,
- Confirm insulation type to ensure that criteria apply,
- Verify the integrity of the terminations and if compromised replace them and repeat the test,
- Retest in the near future and observe trends (6 months to a year), or,
- Place on "watch list" and consider system replacement in the near future.

Cable systems with an evaluation of the "Hold" Phase resulting in a "Further Study" may require remedial actions in the near future that should be sequentially undertaken as follows:

- Review data for a rogue measurement in the sequence – most common during the first voltage cycles,
- Confirm insulation type to ensure that criteria apply,
- Verify the integrity of the terminations and if compromised replace them and repeat the test,
- Retest in the near future and observe trends (6 months to a year), or,
- Place on "watch list" and consider system replacement in the near future.

FURTHER HELP

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CDFI

(CABLE DIAGNOSTICS FOCUSED INITIATIVE)

MONITORED WITHSTAND TAN δ USING THE CDFI MV TEST PROTOCOL FILLED (i.e. EPR, KERITE, & VULKENE®)

DOE AWARD NO. DE-FC02-04CH11237

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This time ***may*** be amended ***if*** the conditions listed in the Framework and Tables below are fulfilled:

A minimum of 6 measurements should be made at each voltage level; to determine the parameters detailed above.

A TDR Measurement is always "Good Practice" in advance of a Tan δ measurement as it serves to confirm Capacitance measurements and obtain a qualitative estimate of neutral condition.

In these tests (all materials) the "Operational U_0" is used to determine test voltages.

The maintenance test voltages for the "Hold" Phase as specified in the IEEE Std. 400.2 – 2013 are as follows:

"Hold" Phase Recommended Test Voltage Levels				
CABLE SYSTEM VOLTAGE (kV)	**15**	**20**	**25**	**35**
Maintenance Testing RMS (kV)	16	20	24	33
Maintenance Testing Peak (kV)	22	28	34	47

Anticipated Failure rates On Test (FOT) for the "Hold" Phase are approximately as follows:

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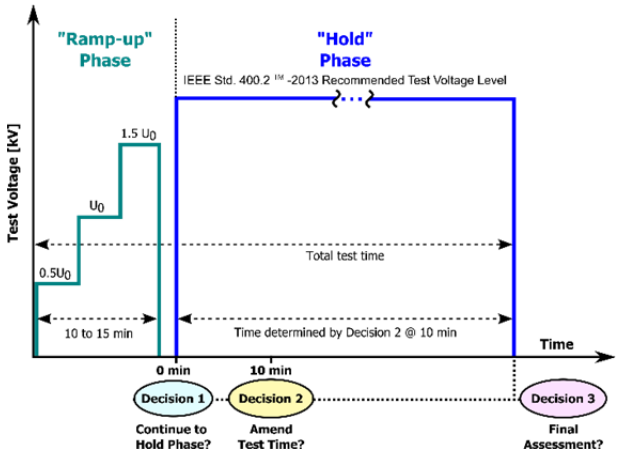
Tan δ Monitored Withstand Framework



Decision 1 – Continue to "Hold" Phase?
After "Ramp-up" – Made online during test

Feature [E-3]	"No"*	"Yes"**	"No"***
Ramp-Up Phase Evaluation			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.2	>1.2
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<3.0	3.0 to 30.0	>30.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}–TD_{U_0}) – (TD_{U_0}–TD_{0.5U_0})\}$	<1.0	1.0 To 18.0	>18.0
	&	or	
Mean TD at U_0	<25.0	25.0 to 150.0	>150.0

* "**Green No**" – Cable system condition is assessed as best performing 80% and thus it is not necessary to continue to "Hold" phase so that time and resources might be saved.

** "**Amber Yes**" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems pass to the "Hold" phase for consideration in Decision 2 and Decision 3.

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Decision 2 – Amend Test Time?
Made online during test

Feature [E-3]	"Reduce to 15 min"	"Extend to 60 min"
Initial "Hold" Phase Evaluation		
Absolute Change in Tan Delta $\lvert TD_{10}-TD_0\rvert$	<0.6	>6.0
	&	or
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5.0
	&	or
Tan δ Level (Mean Tan δ – TD_{10})	<13.0	>105.0

Decision 3 – Final Assessment?
Made offline after test

"No Action Required"	"Further Study Advised"	"Action Required"
Final "Hold" Phase Evaluation		

An excel tool, which simultaneously assesses all final features (**Speed 10-15, Speed 0-5, Speed 0-t_{final}, Standard Deviation, and Mean Tan δ**) is under development to enhance the analyses, especially in the region of Further Study (cable circuits ranked 5 to 15%) & "Action Required" (the lowest ranked 5% of cable circuits).

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CDFI

(CABLE DIAGNOSTICS FOCUSED INITIATIVE)

MONITORED WITHSTAND TAN δ USING THE CDFI MV TEST PROTOCOL PAPER - PILC

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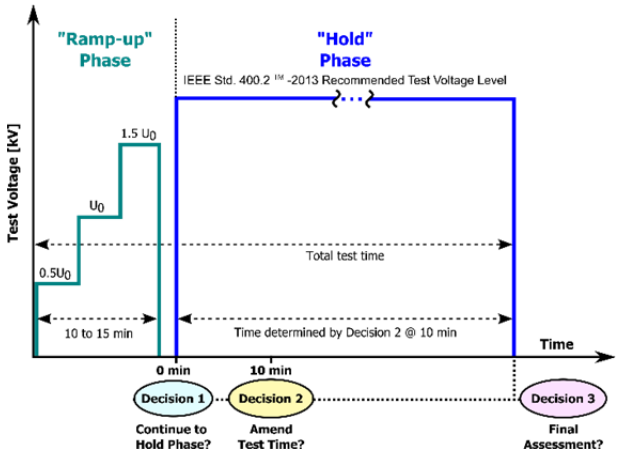
Tan δ Monitored Withstand Framework



Decision 1 – Continue to "Hold" Phase?
After "Ramp-up" – Made online during test

Feature [E-3]	"No"*	"Yes"**	"No"***
Ramp-Up Phase Evaluation			
Stability for TD_{U_0} (standard deviation)	<0.2	0.2 to 1.5	>1.5
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-30.0 to 22.0	-30 to -60 or 22 to 220	<-60.0 or >220.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}–TD_{U_0}) – (TD_{U_0}–TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<100.0	100.0 to 250.0	>250.0

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** "**Amber Yes**" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems pass to the "Hold" phase for consideration in Decision 2 and Decision 3.

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Decision 2 – Amend Test Time?
Made online during test

Feature [E-3]	"Reduce to 15 min"	"Extend to 60 min"
Initial "Hold" Phase Evaluation		
Absolute Change in Tan Delta $\lvert TD_{10}-TD_0\rvert$	<1.4	>5.0
	&	or
Tan δ Stability (Standard Deviation – STD_{10})	<0.6	>5.4
	&	or
Tan δ Level (Mean Tan δ – TD_{10})	<80.0	>180.0

Decision 3 – Final Assessment?
Made offline after test

"No Action Required"	"Further Study Advised"	"Action Required"
Final "Hold" Phase Evaluation		

An excel tool, which simultaneously assesses all final features (**Speed 10-15, Speed 0-5, Speed 0-t_{final}, Standard Deviation, and Mean Tan δ**) is under development to enhance the analyses, especially in the region of Further Study (cable circuits ranked 5 to 15%) & "Action Required" (the lowest ranked 5% of cable circuits).

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