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EMP-Resilient Electric Grid Transformer Analysis

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ABSTRACT

The response of a high-voltage (HV) transformer to fast rise time voltages, such as that from a electromagnetic pulse (EMP) can result in interruption of power distribution and possibly system failure. To help identify these potential occurrences, it is necessary to develop a transformer model that not only captures the input / output response of the transformer but also the internal behavior. The model constructed should cover the frequency band of interest while capturing the internal physical and electrical characteristics. This broad-band, high-fidelity model would enable the prediction of unwanted effects through simulation. A proposed modeling scheme for a HV transformer is described in Part 1 of this report. Part 2 of this report details assessments of internal voltage and electrical field holdoff testing of transformer insulation dielectric breakdown, including comparison of low frequency (DC/60 Hz) holdoff to rise times characteristic of lightning (1 μs) and EMP E1 transients (10-30 ns). This initial project is a path toward establishing electrical grid transformer failure criteria for EMP voltage transients. We developed modeling methods and measured breakdown electrical field statistical distributions for direct current, 60 Hz, lightning and EMP characteristic voltage rise times. Methods of nanosecond-scale capacitive discharge unit high voltage source development, suggestions for de-rating of 60 Hz insulation maximum electrical fields for EMP nanosecond pulse voltage withstand rating, and potential methods for increasing transformer resilience to such fast rise time pulses are described.

ACKNOWLEDGEMENTS

Ray Martinez, James Taylor and Jordy Machado-Lopez were instrumental in building the high voltage test sources, conducting experiments and acquiring the breakdown data contained herein. We wish to acknowledge Drew Padgett for providing a technical review of the manuscript.

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EXECUTIVE SUMMARY

It is critical for the security of the national electric grid to have an up-to-date assessment of probability, severity, and susceptibility of critical assets to geomagnetic disturbance (GMD) and credible modern electromagnetic pulse (EMP) events (both natural and man-made), as well as quantify the risks of economic and infrastructure losses based on current and future scenarios for Grid Resiliency infrastructure. Moreover, hardening of assets, resilience, and restoration have not been studied as a means of developing Resilient Grid framework. Among current needs identified for an EMP are:

- Understanding and estimation of EMP coupling to electrical infrastructure,
- Understanding and estimation of EMP damage (or temporary upsets) to electrical infrastructure, electronics, and other critical electrical utility assets,
- Development of analytical models for component-level susceptibility to EMP events at different fidelity levels and validation of these models during experimental trials, and
- Reduced complexity experiments sufficiently representative to produce valid results.

Analysis of coupling to electrical infrastructure and systems-level analysis are being conducted in separate efforts. The present report summarizes limited-scope, initial efforts toward developing effective transformer models and establishing transformer insulation EMP-specific breakdown distribution functions as criteria for transformer damage or failure prediction.

Toward establishing damage criteria for high voltage transformers, 20 kV and 100 kV pulse discharge units were developed with 10-30 ns rise times. These were used to measure breakdown voltages and dielectric strengths of commercial transformer dielectric insulation materials. This work observed that insulation resistance breakdown electrical fields, which are typically measured for electrical standards at low frequency (DC/60 Hz), may overestimate breakdown electrical fields under simulated EMP rise time waveforms (10–30 ns) by 13-36%.

For future work, three avenues are suggested toward ultimate identification of specific analysis of transformer resilience and vulnerability determination:

(1) obtaining constitutive property parameters including frequency-dependent electromagnetic properties of the transformer insulator and core materials

(2) developing a means of obtaining proprietary or proxy HV transformer-specific design details for modeling of general or specific transformer vulnerabilities

(3) identification of specific peak electrical field regions in transformers, where electrical fields may exceed EMP dielectric breakdown criteria of traditional dielectrics (e.g. E > 130 kV/mm)

(4) inclusion of these failure modes in systems models, or evaluation of potential methods for increasing local dielectric holdoff, including minimization of local electrical field enhancement or use of low microwave loss, solid polymer insulation, or encapsulation, in which EMP breakdown fields may exceed 200-1000 kV/mm.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ABB	ABB Corporation, formerly Allmänna Svenska Elektriska Aktiebolaget (ASEA) and Brown, Boveri, & Cie (BBC)
AC	Alternating current
C	Capacitance
DC	Direct current
E	Electrical field
EMP	Electromagnetic pulse
FRA	Frequency response analysis
HV	High voltage
Hz	Hertz
kV	Kilovolt
L	Inductance
M	Mutual inductance
mm	Millimeter
MTL	Multiconductor transmission line
μs	Microsecond
ns	Nanosecond
Q	Charge
R	Resistor
RLC	Resistor, inductor, capacitor
V	Voltage

1. INTRODUCTION

It is critical for the security of the national electric grid to have an up-to-date assessment of probability, severity, and susceptibility of critical assets to geomagnetic disturbance (GMD) and credible modern electromagnetic pulse (EMP) events (both natural and man-made), as well as quantify the risks of economic and infrastructure losses based on current and future scenarios for Grid Resiliency infrastructure. Moreover, hardening of assets, resilience, and restoration have not been studied as a means of developing Resilient Grid framework. Among current needs identified for an EMP are:

- Understanding and estimation of EMP coupling to electrical infrastructure,
- Understanding and estimation of EMP damage (or temporary upsets) to electrical infrastructure, electronics, and other critical electrical utility assets,
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- Reduced complexity experiments sufficiently representative to produce valid results.

Analysis of coupling to electrical infrastructure and systems-level analysis are being conducted in separate efforts. The present report summarizes limited-scope, initial efforts toward developing effective transformer models and establishing transformer insulation EMP-specific breakdown distribution functions as criteria for transformer damage or failure prediction.

This modeling procedure produces a complicated resistance, inductance, and capacitance (RLC) network describing internal interactions due to an external insult. Although the analysis path appears straightforward, several complications for implementation were identified. These complications include that: (1) geometry information details and designs for HV transformers are normally viewed as proprietary, (2) the broadband electromagnetic parameters of materials needed to perform an accurate simulation, may not be readily available, and (3) under the proper conditions this RLC network can be combined with other techniques [e.g. the multiconductor transmission line (MTL) method or other evolving analysis procedures to determine the response of these high-voltage transformer systems to fast rise time excitations].

2. TRANSFORMER MODELING

The response of a high-voltage transformer to fast rise time voltages can result in interruption of power distribution and possibly failure. To help identify these potential occurrences it is necessary to develop a transformer model that not only captures the input / output response of the transformer but the internal behavior as well. The model constructed should cover the frequency band of interest while capturing the internal physical and electrical characteristics. This broad-band, high-fidelity model would enable the prediction of unwanted effects through simulation. A proposed modeling scheme for a HV transformer is described in the first section of this report.

2.1. Transformer modeling geometry

The electrical modeling and analysis of any power transformer begins with the geometry of the transformer. To put the following analysis in the proper context, a basic geometry is first described. A simplified view of the transformer is shown in Figure 2-1 and consists of a core, low-voltage, and high-voltage windings.

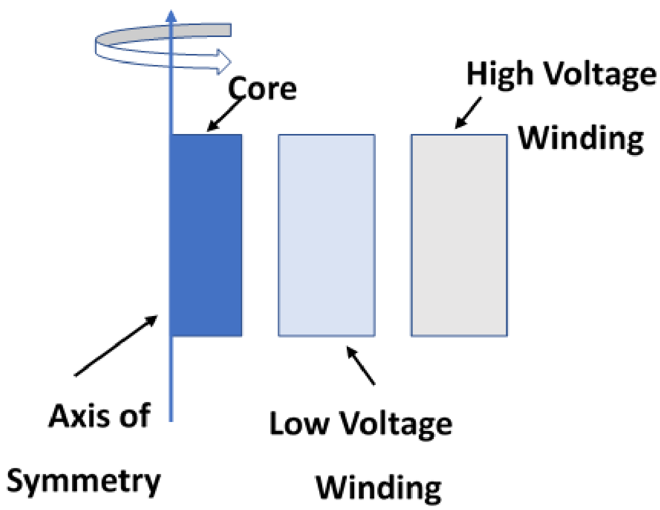

Figure 2-1 Basic transformer geometry.

This reveals the overall geometrical configuration without information concerning the specific details of the windings. From the ABB Transformer Handbook [1], a practical design of the low-voltage and the high-voltage windings are helical and disc windings, respectively.

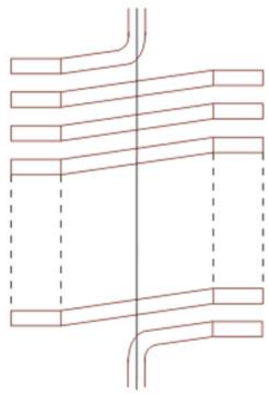

Figure 2-2a. Helical winding.

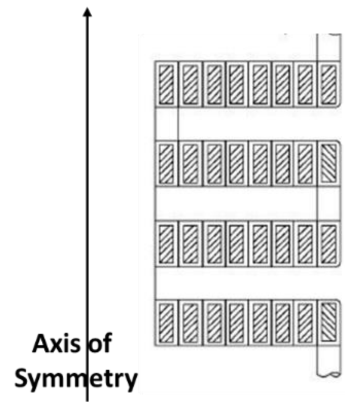

Figure 2-2b. Disc winding.

Helical Windings, shown in Figure 2-2a, consist of winding wire in an axial direction along the axis of symmetry and are used for the low-voltage wire, and carry high current. **Disc windings**, shown in Figure 2-2b, consist of several flat coils or discs in series or parallel. The coils are formed with rectangular strips wound spirally from the center outwards in the radial direction. In comparing the two windings, the helical winding is geometrically similar to the disc winding – with only one turn per disc.

The challenges facing the successful generation of this high-fidelity broadband model of the transformer include obtaining sufficiently accurate specifications the following details:

- Identification of the geometrical configuration of interest.
  - Coil winding geometry
  - Core placement

- Broadband electrical properties including those of the:
  - Coil insulation (e.g. Kraft paper, oil, dielectric electrical characteristics)
  - Core magnetic properties

- Physical model size may lead to challenging computational complexity when numerical techniques are used.
  - Finite Element Method
  - Boundary Element Method

2.2. Electrical modeling results and discussion

An appropriate transformer model is dictated by the electrical environment and response that is desired from the model. A typical model would focus on input to output response of the transformer and consist of combining several lumped parameters (circuit elements). The complexity of this model (number of circuit elements) will depend on the highest frequency of interest. The external electromagnetic excitation for this program is well above the operating frequency of the transformer. As a starting point, a simplified model is where only the input-output characteristics are of interest, as shown in Figure 2-3.

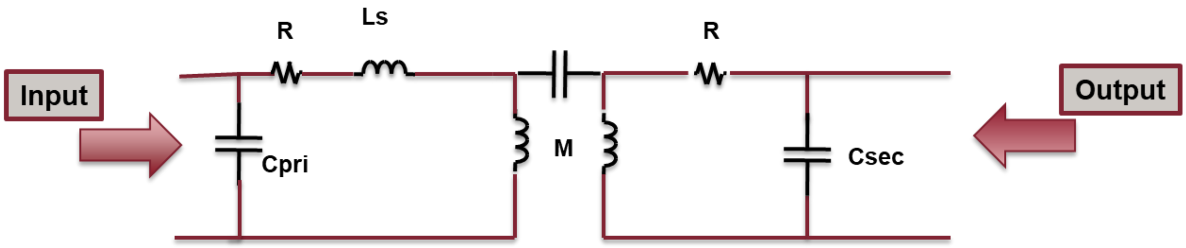

Figure 2-3 Simplified transformer model.

The internal model consists of lumped elements – at low frequencies it is described as a series of inductors, coupled inductors, and resistors. As the frequency increases the capacitance between the input and output ports as well as the capacitance between the turns of the transformer must be considered to accurately model the frequency response of the transformer. This would be considered a broad-band model which is linear and still focuses on the input to output behavior but with a more complicated lumped element structure. These values of these elements can be generated from measurements referred to in the literature as frequency response analysis (FRA) [2]. This useful technique has limitations since the circuit elements are identified to match overall response and may not reveal the internal physical characteristics of the device. For example, the interwinding capacitance is replaced by a single capacitor, and the inductance between windings is replaced by a single inductor which may be suitable for describing the input-output behavior. Note that this is sometimes referred to as a black-box model since only the input-output response is obtained.

A more precise model focuses not just on the overall response of the transformer but the internal behavior as well. In order to extend this frequency range and examine the internal response, it is necessary to use a turn-to-turn modeling procedure instead of disk-to-disk, or primary to secondary modeling. For this to be accomplished the basic geometry described in the preceding section must be supplemented by the precise geometry and electrical properties of the materials. For the capacitance, this includes the wire size (conductor and insulation), the electrical (dielectric) property of the insulation, and the winding placement. In addition, if oil is used for cooling the dielectric property of the oil must be known. For the inductance, this includes the wire size (conductor and insulation), winding placement, and any material that has magnetic properties. For clarity of the internal behavior, the circuit shown in Figure 2-3 is expanded to include the interwinding capacitances, mutual inductances and self-inductances of the windings in Figure 2-4.

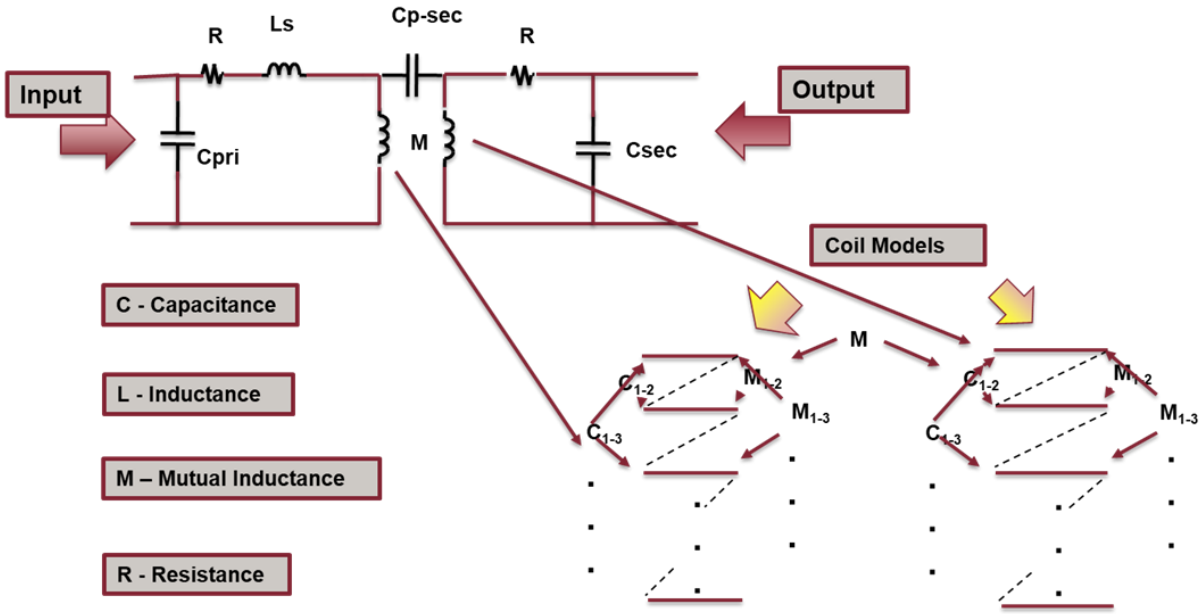

Figure 2-4 Proposed schematic for the internal transformer circuit.

The next step is to describe how these additional circuit elements can be calculated.

Capacitance Calculation

There are several methods that can be used to calculate the capacitance. Two methods use formulas that are exact for either a parallel plate capacitor or two round wires. Other analytic approximations are shown in [3]. These are exact but are approximate for the geometry of interest. Other methods are numerical in nature and have the distinct advantage of representing the conductor as well as the wire insulation and insulators between the windings. These numerical methods are the finite element and boundary element methods.

Boundary element approach

The boundary elements solution uses the following procedure - apply a voltage on a conductor (winding) while the other windings are grounded. This is repeated for all the windings.

The procedure is:

1) Apply 1 V to the conductor and 0 V to the other conductive structures.
2) Calculate the total charge on each conductor Q_j.
3) Solve for the capacitance terms via $C_{ij} = Q_j/V_i$.

Finite element approach

The finite element method (FEM) is similar except the entire region is meshed instead of just the boundaries.

The procedure is:

1) Apply 1 V to the conductor and 0 V to the other conductive structures.
2) Calculate the scalar electric potential by using the FEM.
3) Compute the electric field strength and the electric flux density.
4) Obtain the capacitance values by computing the energy stored in the field and equating that to ½ CV^2 for the self-term. For the non-self-terms the procedure described in the boundary element method is used.

These numerical techniques can be employed on a 2-dimensional geometry yielding capacitances per unit length or to the more accurate 3-dimensional geometry. The numerical techniques will also reveal where approximations to the expanded circuit can be made. For example, the capacitance between two widely separated windings can be neglected.

Inductance Calculation

There are two types of inductances that need to be considered – self and mutual. For this calculation each winding is approximated by a single filament or multiple filaments. The mutual inductance is then calculated using the analytical results in Smythe, in conjunction with the Elliptic integrals of the first and second kind [4]. The self-inductance is found by assuming a finite radius for the filament and thus avoiding the singularity encountered with the Elliptic integrals.

Resistance Calculation

The resistance can be calculated using the DC resistance, which depends on the conductivity and cross-sectional area combined with a term that accounts for the skin effect at high frequencies. The frequency-dependent conductances of the insulating materials are estimated using the effective loss tangents of the constitutive materials when available.

3. TRANSFORMER INSULATION ELECTRICAL TESTING

EMP and switch disconnect operations are known to produce high voltage transients with rise times of 2.5-20 nanoseconds. While these transients are known to have caused failure in oil-insulated transformers and bushing failures [6], the underlying breakdown strength of high voltage transformer insulation as a function of rise time is not well-understood. In particular, dielectric holdoff measurements of dielectric strength and breakdown voltages are typically conducted at 60 Hz, as per ASTM D149 – 20 [7], "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies," and IEC 243-1. As noted in ASTM D149 – 20, "At frequencies above 800 Hz, dielectric heating is a potential problem" which can contribute to decreased dielectric strength. In this work, we measured the breakdown strength of oil-paper insulation and a polymer insulator as a function of pulse rise times at slow ramps approximating AC, 1 μs (lightning impulse standard specified in IEC 60060-1 [8], 1.2 μs rise time, 50 μs decay time), and a simulated EMP E1 rise time (30 ns) to develop statistics of the breakdown process and determine the effect of rise time on breakdown distribution. The goal was to enable a conditional probability distribution of dielectric failure as a function of electrical field and rise time for system level analysis.

3.1. Transformer insulation testing methodology

In this work, discussions with ABB identified candidate transformer geometries, conductors, and insulator systems relevant to grid transformer reliability testing. The geometry under test was selected to simulate helical transformer windings of the type described above in Figure 1-2a and shown in Figures 3-1 and 3-2, typically used in three phase grid applications.

Figure 3-1. Image of ABB commercial grid scale transformers and a representative helical transformer winding, utilizing copper conductors and Kraft paper insulation.

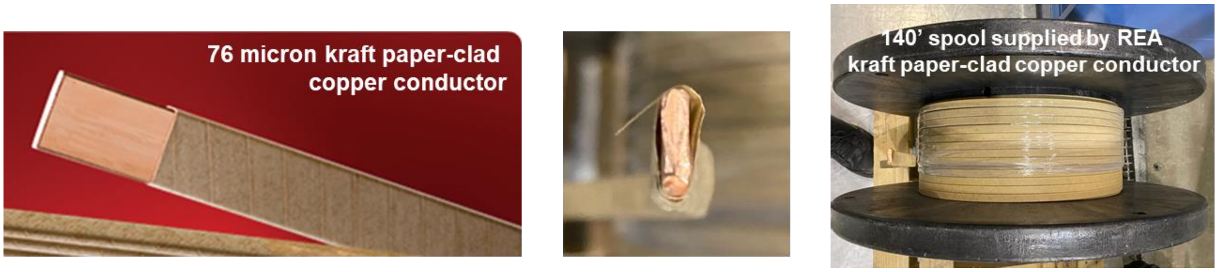

Figure 3-2. Images of Kraft paper spiral-wound, rectangular cross section, copper transformer conductors, of the type typically used for transformer windings shown in Figure 3-1.

The rectangular cross section conductors tested, specified by ABB and supplied by ABB vendor REA Wire, were wound with 76 μm thick Kraft paper, to be used in oil-impregnated Kraft paper-oil insulation. A vacuum oil impregnation chamber was used to infiltrate transformer oil (SHELL DIALA S2) into the Kraft paper, with vacuum pulled three times to 100 milliTorr, after which no air bubbles were seen escaping. Samples were tested by applying voltage with a spherical top electrode, with the flat copper conductor connected to ground, shown in Figure 3-3.

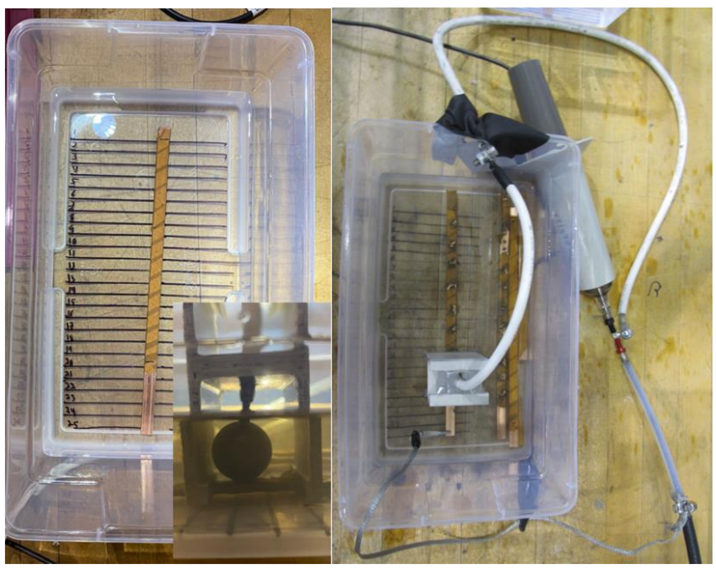

Figure 3-3. Breakdown testing setup. Left, top view of Kraft paper spiral wrapped at a single 76 μm thickness on copper conductors. Right, image of testing, including voltage monitor, spherical electrode holder and damage to insulation from lightning impulse testing. Center inset, side view of spherical electrode under oil, in contact with Kraft paper wrapped conductor at bottom.

Different voltage supplies were used to apply DC (Glassman 125 kV HV Power Supply), 60 Hz (TREK model 50/12 High Voltage 50 kV Power Amplifier), lightning impulse (HILO PG 25-2500 Surge Test Generator, 24 kV, 1.2/50 μs waveform) and simulated EMP waveforms. For the simulated EMP waveform, a custom capacitive discharge unit was developed and built as shown in Figure 3-4. Voltage versus time was monitored by a Tektronix P6015A high voltage monitor and recorded to Tektronix MD06 oscilloscopes.

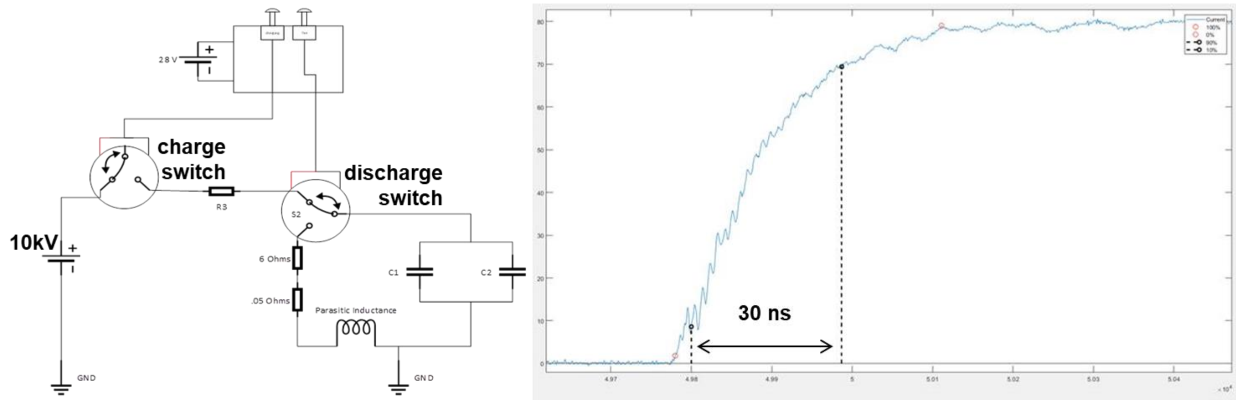

Figure 3-4 Circuit design of 20 kV, 30 ns 10/90 rise time capacitive discharge unit pulser.

3.2. Transformer insulation testing results and discussion

Prior analysis by Vandermaar et al. observed a decrease in breakdown strength during testing under fast rise times, which partially motivated the present study. Our data also shows decreasing breakdown strength with decreasing rise time from 60 Hz to 1 μs to 30 ns. Data from Vandermaar et al. is shown in Figure 3-5, from their prior studies of Kraft paper breakdown field tested with rise times of 30 ns, 1 μs and 120 ms, which indicated breakdown strengths of 150, 155 and 180 kV/mm thickness, respectively. Our measurement results, shown in Figure 3-5, at right, indicated breakdown strengths of 137, 160 and 167 kV/mm, also showing holdoff voltage increases with rise time. These initial results suggested that DC/60 Hz breakdown values may require derating of 18-20% for estimation of EMP dielectric strength for systems analysis.

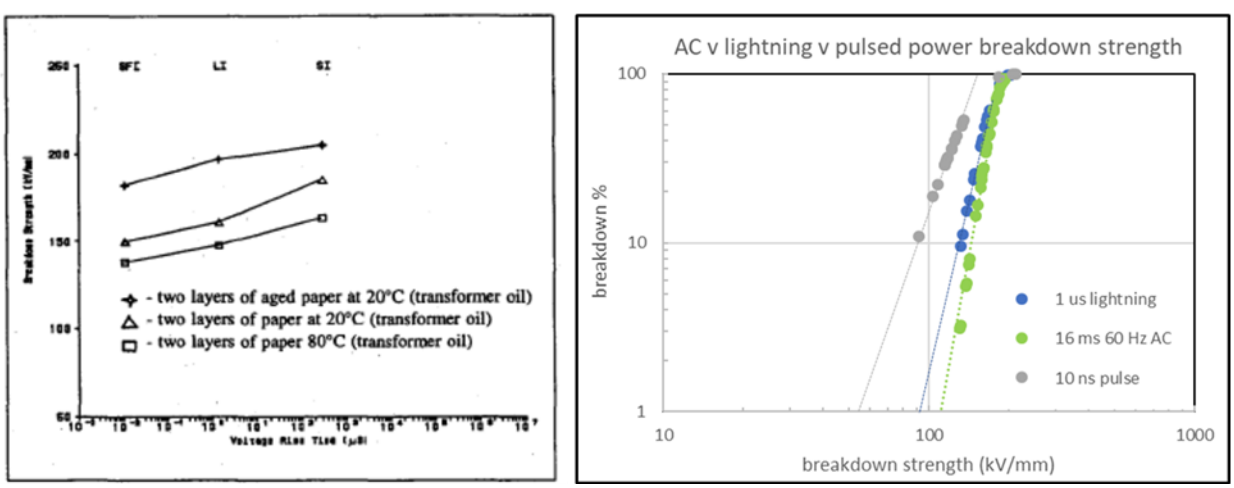

Figure 3-5 Observed breakdown strength of Kraft paper in oil. Left, data for 10 ns, 1 μs and 120 ms waveforms from Vandermaar et al. [6]. Right, Sandia-observed Weibull distributions of breakdown for designed 30 ns, 1 μs and AC rise time waveforms.

The data above was obtained for bare copper conductors with Kraft paper/oil insulation. Discussions with REA Magnet Wire, which supplied the conductor, suggested methods of mitigating high voltage breakdown could include either increasing the Kraft paper thickness or using copper coated with a polymer dielectric varnish (Formvar^{TM}) in addition to the Kraft paper insulation. Polymer-coated conductors (Formvar^{TM}) were tested individually and in combination with Kraft paper/oil insulation to investigate if additional transformer and component protection was feasible through use of this hybrid insulation. Results, including increases in breakdown strength, are shown in Figure 3-6 and Tables 3-1 and 3-2.

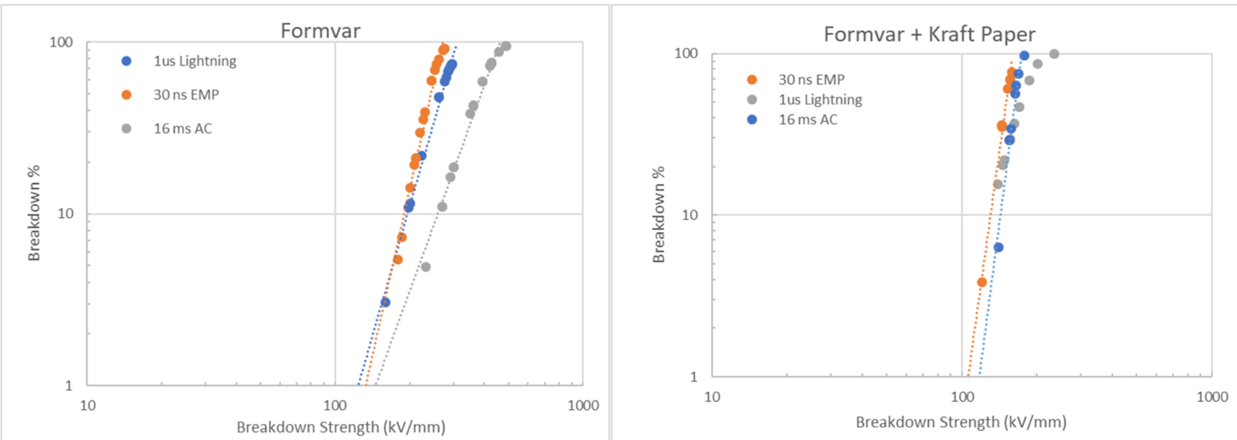

Figure 3-6. Breakdown strengths of Formvar (left) vs. Formvar/Kraft paper (right).

Table 3-1. Dielectric Strength (kV/mm) vs. Waveform

Waveform	Kraft paper (kV/mm)	Formvar (kV/mm)	Kraft paper+Formvar (kV/mm)
AC	167.2	369.4	169.7
Lightning	161.8	260.8	160.2
EMP	131.1	235.1	148.0

Table 3-2. Holdoff Voltage (kV) vs. Waveform

Waveform	Kraft paper (kV/mm)	Formvar (kV/mm)	Kraft paper+Formvar (kV/mm)
AC	12.7	18.5	21.4
Lightning	12.3	13.0	20.2
EMP	10.0	11.8	18.6

Significant increases in both dielectric strength and Weibull distribution minimum breakdown electrical field appeared to be enabled by use of 50 μm Formvar in combination with 76 μm Kraft paper/oil insulation. The most notable increase in EMP holdoff voltage, from 10 kV to 18.6 kV for Kraft paper plus Formvar, appears to be due to both increased total dielectric thickness and increased breakdown strength.

3.3. Transformer insulation breakdown distribution functions

An end goal for this work was to develop distribution functions for breakdown strengths and per-layer holdoff voltages of the dielectric insulators under EMP waveforms, to enable prediction of reliability for subsequent systems analysis. The data was fit to Weibull statistics, to enable either cumulative distribution functions or probability distribution functions.

The Weibull cumulative distribution function for breakdown as a function of voltage (where x = voltage or breakdown strength kV/mm thickness) is given as:

$$F(x, \alpha, \beta) = 1 - e^{-(x/\beta)^{\alpha}}$$

Table 3-3 provides Weibull parameters α and β to enable cumulative probability function development, combined with Tables 3-1 and 3-2.

Table 3-3. EMP waveform Weibull parameters for dielectric strength

Waveform	Kraft paper (kV/mm)	Formvar (kV/mm)	Kraft paper+Formvar (kV/mm)
α	4.847934	8.859655	13.344728
β	143.8123	248.3369	153.78077
RSQ	0.697033	0.954422	0.8468875

The RSQ value is the square of the Pearson product-moment correlation coefficient, comparing the raw data breakdown distribution and Weibull-determined cumulative probability distribution. For the sizes of data sets used, the statistical levels of significance for all sample sets displayed values of $p \leq 0.01$, indicating more than a 99% chance of a sample occurring within the Weibull distribution function parameters for each dielectric type.

The Weibull fitted cumulative distribution functions are plotted compared to the raw data for Kraft paper/oil for EMP waveform testing in Figure 3-8, in both logarithmic and linear breakdown strength scales.

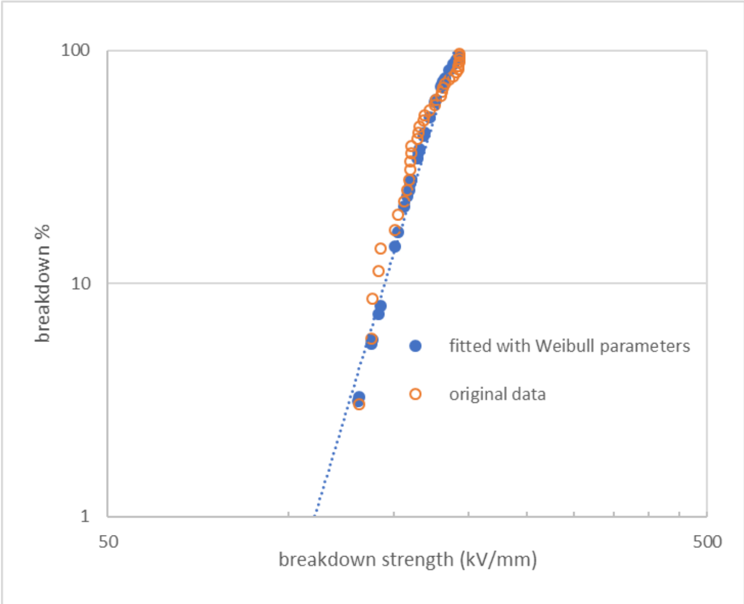

Figure 3-7. Breakdown probabilities of Kraft paper/oil at 30 ns rise time. Raw data and Weibull statistical fits are shown vs. dielectric strength on logarithmic scale.

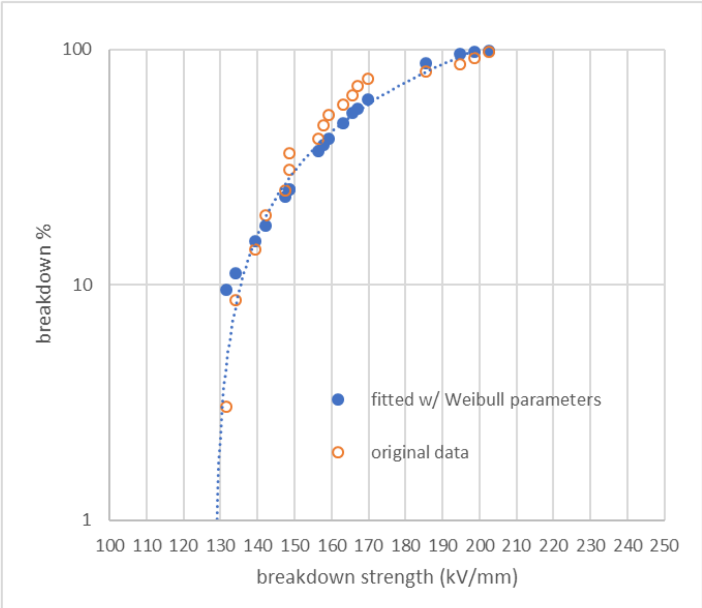

Figure 3-8. Breakdown probabilities of Kraft paper/oil at 30 ns rise time. Raw data and Weibull statistical fits are shown vs. dielectric strength on linear scale.

Work is continuing to extend insulation breakdown testing to 100 kV maximum voltages, to enable multilayer Kraft paper/oil insulation breakdown distribution analysis and evaluation of thicker and hybrid insulator materials for medium voltage and high voltage applications.

4. CONCLUSIONS, EXPECTED OUTCOMES AND IMPACTS

This report summarizes both initial model development and experimental measurements of insulator dielectric strength and holdoff voltage. For the modeling, with the above analyses and computations complete, the results can be assembled to produce a broadband frequency model that gives not only the input to output behavior but the internal response as well. This modeling procedure produces a complicated resistance, inductance, and capacitance (RLC) network describing the internal interactions due to an external insult.

Under the proper conditions this RLC network can be combined with other techniques such as the multiconductor transmission line (MTL) method [5], or other evolving analysis procedures to determine the response of these high-voltage transformer systems to fast rise time excitations.

Although the analysis path appears straightforward it is quite complicated. The complications include that geometry information for HV transformers are normally viewed as proprietary. In addition, the electromagnetic parameters of materials needed to perform an accurate, broadband simulation, may not be readily available. Future work should ideally comprise (1) obtaining constitutive property parameters including frequency-dependent electromagnetic properties of the transformer insulator and core materials and (2) developing a means of obtaining HV transformer design specifics for modeling of general or specific transformer vulnerabilities.

For the insulator standoff measurements, dielectric strength, holdoff voltage, and statistical distribution function parameters were obtained for EMP waveforms as well as lightning and low frequency waveforms. Conclusions include the recommendation to de-rate standard DC/60 Hz holdoff voltages by 13-36% to estimate EMP waveform holdoff voltages and dielectric strength and to consider increasing Kraft paper/oil and/or conductor polymeric insulator (e.g. Formvar) thickness for greater margin against voltage transients, if feasible.

Low frequency, lightning waveform (1 μs rise) and EMP (30 ns rise) breakdown electrical fields of three different types of transformer dielectrics were measured on insulated copper conductors of the type typically used in ABB electrical grid transformers: (1) vacuum oil-impregnated Kraft paper, (2) dielectric varnish (Formvar^{TM}), and (3) vacuum oil-impregnated Kraft paper atop Formvar^{TM}-coated conductors. Median measured breakdown electrical fields for dielectrics (at 60 Hz ; EMP) were: 76 μm Kraft paper (167 kV/mm; 131 kV/mm), 50 μm Formvar (369 kV/mm ; 235 kV/mm) and 76 μm Kraft paper + 50 μm Formvar (169 kV/mm ; 148 kV/mm). Median measured (60 Hz ; EMP) breakdown voltages were 76 μm Kraft paper (12.7 kV; 10 kV), 50 μm Formvar (18.5 kV; 11.8 kV) and 76 μm Kraft paper + 50 μm Formvar (21.2 kV ; 18.5kV). Use of an insulating varnish, such as Formvar, appeared to provide additive protection in addition to additional layers of Kraft paper insulation. Using Formvar in combination with Kraft paper and/or increasing the number of Kraft paper layers are potential approaches to increasing transformer resiliency to transient electrical field threats.

Through obtaining constitutive parameters of transformer components, modeling of realistic transformer designs, prediction of peak electrical fields and development of dielectric strength distribution functions, a candidate approach to assess transformer resilience in EMP and other high pulsed electrical field environments has been developed in this project.

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