Final Technical Report (FTR)

Cover Page

a. *Federal Agency*	Department of Energy	
b. *Award Number*	DE-EE0009019	
c. *Project Title*	Adaptive Protection and Validated Models to Enable Deployment of High Penetrations of Solar PV (PV-MOD)	
d. *Recipient Organization*	Electric Power Research Institute	
e. *Project Period*	*Start: 4/1/2020*	*End: 6/30/2024*
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Signature of Certifying Official — *Date*

By signing this report, I certify to the best of my knowledge and belief that the report is true, complete, and accurate. I am aware that any false, fictitious, or fraudulent information, misrepresentations, half-truths, or the omission of any material fact, may subject me to criminal, civil or administrative penalties for fraud, false statements, false claims or otherwise. (U.S. Code Title 18, Section 1001, Section 287 and Title 31, Sections 3729-3730). I further understand and agree that the information contained in this report are material to Federal agency's funding decisions and I have any ongoing responsibility to promptly update the report within the time frames stated in the terms and conditions of the above referenced Award, to ensure that my responses remain accurate and complete.

Acknowledgement: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO), under DE-FOA-0002064 under the Award Number DE-EE009019.

Executive Summary:

The availability and validation of various PV models in commercial tools differ, with some models not yet thoroughly validated for advanced inverter functionalities and reliable performance under weak system conditions. Many existing models do not fully incorporate new inverter control functions, which can affect system stability. The increasing deployment of solar PV and other inverter-based resources (IBRs), including distributed energy resources (DERs), is influencing the reliable operation of protection schemes in distribution systems and microgrids. Emerging adaptive protection schemes (APS) offer new opportunities for protecting these systems during varying configurations and DER operating conditions, though their demonstration and validation remain limited. Adaptive protection schemes face similar challenges, as they are typically designed for specific configurations. There is a growing need for tools and methodologies to streamline the deployment of adaptive protection for safe and reliable DER integration.

The project main objective was to develop and validate high-fidelity generic models of solar PV facilities for stability, protection, EMT, and QSTS analyses. This objective was achieved, and these models can now be integrated into commercial software tools, enabling utilities, vendors, and developers to study high-penetration PV systems more confidently. The project also demonstrated advanced applications of these models, including the design and deployment of adaptive protection schemes in high-penetration field applications and microgrids, supporting grid safety and reliability.

Several milestones were reached by the end of the project. A sophisticated inverter test plan was developed, and inverters representative of the North American marketplace were selected. EPRI and NREL tested various inverters, conforming to IEEE standards. Improvements were made to existing generic models of IBR units, IBR plants, and aggregated feeders for various analyses. The first generic electromagnetic transient (EMT) model for a solar PV plant was developed, conforming to IEEE Std 2800™-2022 and validated against laboratory measurements of a 2.2 MVA large-scale battery energy storage system (BESS) inverter. That model was then used to produce reference responses illustrating examples of validated and verified IBR plant models that pass or fail tests for technical minimum capability and performance as specified in the IEEE standard.

The developed, tested, and validated generic models can be used for transmission planning, stability assessments, expansion planning, and evaluating potential future IBR interconnection requirements. They can also support interconnection screens and conformity assessments of IBR plants, including solar PV. The project significantly contributed to the ongoing standardization and model-based representation and verification of IBR responses.

The project further addressed challenges of common distribution protection schemes with increasing deployment of DER by developing, validating, and demonstrating adaptive protection schemes (APS) that can improve the reliable and safe integration of DER into distribution systems. New APS were designed using improved DER models for three common distribution systems: a radial feeder, a meshed network, and a microgrid. Modeling and hardware-in-the-loop (HIL) testing of the APS were conducted, successfully showing their effectiveness and selectivity. Proof-of-concept field demonstration was

achieved for two APS, i.e., one on a radial feeder and another one in a microgrid. Field demonstration could not be achieved for the APS on a meshed network, primarily due apprehension of one utility partner and also due to limited access to the protective algorithms in the network protectors. Guidelines developed from the lessons learned in the project lay out the general process followed in the design, installation, and commissioning of APS for various distribution systems. Distribution utility partners' apprehension about field demonstration of the new APS were addressed—with varying success—by taking a stepped risk-management approach of modeling of a wide range of sensitivities first, performing in-depth proof-of-concept testing in the laboratory including HIL next, and finally deliberately implementing and commissioning the actual protection equipment and algorithms into parts of—or in parallel operation to—the three real distribution systems. Future work should include pilot projects that further show the acceptable performance of the developed APS before these schemes be rolled out more widely. Inclusion of both utility and original equipment manufacturers (OEMs) in future projects could increase chances of successful field demonstration. Despite challenges in achieving the field demonstration goal of the project for all three APS, the research significantly contributed to the innovation of adaptive protection solutions for scalable and reliable DER integration into distribution systems.

This project significantly enhances the understanding of the impact of using appropriate inverter models on distribution and transmission (T&D) systems. By addressing the limitations of existing generic models, the project introduces high-fidelity models for stability, protection, electromagnetic transient (EMT), and quasi-static time series (QSTS) analyses. These models, integrated into commercial software tools, enable utilities, vendors, and developers to confidently study high-penetration PV systems. The project also demonstrates advanced applications, including adaptive protection schemes (APS) for distribution systems and microgrids, ensuring grid safety and reliability.

The technical effectiveness and economic feasibility of the methods are evident through the development and validation of sophisticated inverter test plans and the selection of representative inverters. Testing by EPRI and NREL on retail, commercial, and utility-scale inverters, conforming to IEEE standards, underscores the robustness of the models. Improvements to existing generic models for various analyses further enhance their validity and applicability. The project also identifies gaps in common distribution protection schemes and designed new APS using improved DER models, demonstrating their effectiveness through modeling and hardware-in-the-loop (HIL) testing.

The project's benefits to the public are manifold. By advancing the standardization and model-based representation of IBR response, it supports transmission planning, stability assessments, and future IBR interconnection requirements. The generic models can facilitate better communication between transmission planners and developers, supporting expected IBR plant capability and performance. Additionally, the development of APS for radial feeders, meshed networks, and microgrids supports the integration of distributed energy resources (DERs) into distribution systems, enhancing grid reliability and safety. The project's emphasis on thorough testing and simplicity in design ensures practical and scalable solutions for DER integration.

Table of Contents:

1. Background:

The availability and validation of various PV models in commercial tools vary, with many lacking thorough validation for advanced inverter functionalities and reliable behavior under weak system conditions. Additionally, existing models often do not represent new inverter control functions, which can impact system stability.

Adaptive protection schemes face similar challenges, as they are typically designed for specific configurations. There is a growing need for tools and methodologies to streamline the deployment of adaptive protection for safe and reliable DER integration.

The project's main goal is to develop and validate high-fidelity models of solar PV facilities for stability, protection, EMT, and QSTS analyses. These models will be integrated into commercial software tools, enabling utilities, vendors, and developers to study high-penetration PV systems confidently. The project will also demonstrate advanced applications of these models, including the design and deployment of adaptive protection schemes in high-penetration field applications and microgrids, ensuring grid safety and reliability

This project was categorized under two areas, namely:

- Thrust 1: which focuses on model development, validation and commercialization.
- Thrust 2: which involves the development, testing and commissioning adaptive protection schemes to support high penetration and resiliency applications.

The key drivers for this project includes:

- Solar photovoltaic (PV) and other inverter-based resources (IBRs) are increasingly impacting response of distribution and transmission (T&D) systems
- Existing models have reportedly failed to predict solar PV and IBR plants' mis-operations
- Recent standardization of IBR technical requirements for capabilities and performance provides new opportunities for generic models
- Deployment of solar photovoltaic (PV) and other distributed energy resources (DERs) are increasingly impacting the reliable operation of protection schemes in distribution systems and microgrids
- Emerging adaptive protection schemes (APS) provide new opportunities for reliably protecting distribution and microgrids during varying system configuration and DER operating conditions
- Demonstration and validation of adaptive protection schemes with DERs remain limited

Project Objectives:

The objectives of this research project were:

- Characterize IBR unit response by lab testing for residential-, commercial-, and utility-scale inverters
- Characterize IBR plant response with field data
- Compare generic model and original equipment manufacturer (OEM)-model responses
- Develop, improve, and validate generic models for interconnection of solar PV plants and for planning, operating, and protecting (T&D) systems with IBRs
- Disseminate learnings and model specifications to, and collaborate with industry stakeholders like OEMs, software vendors, and utility engineers
- Design and automate assessment of new adaptive protection scheme (APS) by use of DER models that have been improved and validated in Thrust 1 of the PV-MOD project
- Deploy, test, and validate new APS prior to high DER penetration field applications
- Field demonstrations of APS on real distribution and microgrids with high DER penetration
- Development of adaptive protection guides for broad industry adoption and generic modeling

This report describes work on inverter characterization, collecting field data for gap assessment, and testing various inverter sizes and functionalities in laboratories. It continues with refining and validating the developed inverter models and focuses on implementing these models into vendor commercial tools. Throughout the process, vendor and industry engagements were done in parallel. Additionally, it includes designing an adaptive protection prototype, performing studies and analyses to demonstrate adaptive protection implementation, and testing adaptive protection using Hardware in the Loop (HIL). The project concludes with field demonstrations of adaptive protection schemes on real systems and developing adaptive protection guides for broad industry adoption. The rest of the report is organized as follows: Sections 2 to 2.4 describes a summary of the project results and discussions, section 3 highlights the significant accomplishments and conclusion, while section 4 summarizes the future research.

2. Project Results and Discussion:

This section highlights the work done, including results to create and validate high-fidelity models of solar PV facilities for various power system analyses, including stability, protection, EMT, and QSTS. These models were integrated into commercial software tools, aiding power system engineers in planning, operating, and protecting transmission and distribution systems. The validated models allowed utilities, vendors, and developers to study high-penetration PV systems, make informed reliability investment decisions, and design systems utilizing smart inverter capabilities. Additionally, the project showcased the advanced use of these models in automating the assessment and design of adaptive distribution protection schemes. These schemes were deployed, tested, and validated in high-penetration field applications and microgrids, ensuring the resilience of critical infrastructure and maintaining grid safety and reliability amid dynamically changing system configurations and operating conditions.

—Thrust 1—
Model development, validation and commercialization

2.1. Methodology/Approach for Thrust 1: Model development, validation and commercialization

The approach taken in thrust 1 follows three steps (Figure 1): first, the inverter resources are characterized in lab and field testing; second, the existing models are assessed for validly representing the performance of the inverter resources and gaps are filled, where necessary, by specification of new controls; and third, the improved models are disseminated through vendor and industry engagement.

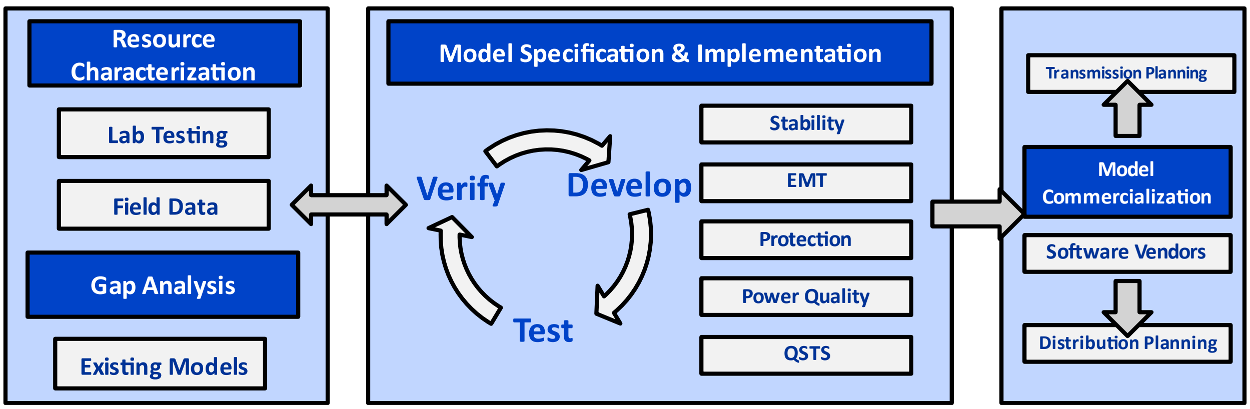


Figure 1: Summary of the approach

The following section highlights the methods and results for the thrust 1:

2.1.1. Resource Characterization:

The behavior of various solar PV and energy storage inverters across residential, commercial/industrial, and utility scales were characterized during and after disturbances. This involved extensive lab testing and field measurements, including fault simulations, using EPRI and NREL facilities. New insights from these tests guided subsequent steps. Below is a summary of the characterization tasks that were performed:

i. Lab testing: retail, commercial scale, utility scale inverters.
   - Developed and refined draft test plan; tested and analyzed results for a 2.2 MVA large-scale BESS inverter with most of the latest IEEE capabilities in two configurations: one for distribution performance (per IEEE 1547-2018) and one for transmission configuration (per IEEE 2800-2022). Details of the summary of the test results are under the project results section.
   - Tested and analyzed results for a three-phase 36.6 kVA legacy solar PV inverter (UL 1741 SA certified) and two IEEE 1547-2018 compatible (UL 1741 SB certified) inverters, i.e., a single-phase 8 kVA battery storage inverter, and a three-phase 53 kVA solar PV inverter

ii. Field data collection and analysis:
   - Developed field measurement guidelines
   - Collected and analyzed field data for five events provided by three utility project partners

2.1.2. Modeling & Model Validation

Existing generic models of solar PV and other IBRs were assessed for gaps, and new or revised control structures were developed or enhanced. All new models have configurable functions and control parameters for various studies, addressing some of the gaps identified in the respective model type. Validation was primarily done at the unit level by comparison with laboratory testing at EPRI and NREL test sites. Despite of several utilities and a major developer having provided field data to the research, validation at the plant and at feeder levels met significant challenges.

The scope of the modeling tasks included:

i. Model development and improvement of QSTS, short circuit, harmonic, stability, and EMT models
ii. Model validation of:
    - Steady-state short-circuit model improvements
    - Hybrid power quality model specification
    - Phasor-domain (RMS) IBR plant and IBR unit model improvements, validated against EMT models
    - Generic time-domain (EMT) large-scale IBR unit and plant controller model compatible with IEEE 2800-2022, validated with measurements from one 2.2 MVA BESS inverter tested in the NREL lab
    - OpenDER, IEEE 1547-2018 compatible individual DER phasor-domain model specification with ability to extent into an EMT model, validated against multiple residential-scale inverters tested in the EPRI lab

2.1.3. Vendor and Industry Engagement

Availability of validated generic models across commercial vendor platforms was an important success factor for the broad dissemination of the results from this research. EPRI engaged with leading vendors of dynamic stability and short-circuit analysis tools, industry standards associations, and technical societies to distribute the develop models and model improvements. EPRI informed and trained stakeholders through project workshops, industry working groups, and its utility/ISO research collaborative, including the EPRI Modeling and Model Validation Working Group and Distribution Protection Task Force, which includes over 50 U.S. utilities. The various tasks conducted included:

i. Software Vendor liaison:
    a. Shared specification of models with vendors
    b. Implementation of models into vendor tools, e.g. EMTP and PSCAD
ii. Forums, Working groups, task forces:
    - WECC MVS/REMWG
    - NERC IRPS & SPIDER
    - IEEE Task Forces, 2800 and P2800.2 Working Groups
    - IREC Phasor-domain (RMS) Aggregate DER model improvements (FIGII)
    - EPRI Distribution Advanced Modeling WG (DAWG)
    - EPRI OpenDER User Group (DERMUG)
iii. Webinars, workshops and tech transfer sessions
    - EPRI Tutorial at 2023 ESIG Fall Technical Workshop

2.2. Summary of project results for Thrust 1: Model development, validation and commercialization

2.2.1. Inverter Testing

2.2.1.1. Inverter Test Plan

A laboratory test plan to characterize the transient, dynamic, and steady-state performance of inverters under a wide range of normal and abnormal voltage and frequency test conditions was developed [1]. The purpose of these tests was to collect measurement data for inverter unit model validation. While some of the tests could provide information to assess the capability of an inverter unit to support conformity of an IBR plant or DER system with interconnection standards like IEEE 2800 or IEEE 1547, this was not the purpose of the testing and care should be taken before drawing any conclusions on conformity from the measured response.

The test plan characterizes the dynamic and steady-state response of the inverter units under test (EUTs). Table 1 provides a list of the tests performed in two inverter configurations, one for distribution and another for transmission application. The total number of tests performed are specified within each cell. Tests for which the inverter could be expected to perform similarly, like the harmonic tests, were only performed for one of the two configurations. Solar PV inverters were only tested in discharge mode while battery energy storage (BESS) inverters were additionally tested in idle mode and in charging mode.

Table 1: List of tests performed in the distribution and transmission configurations

Chapter in Inverter Test Plan	Transmission Application Configuration			Distribution Application Configuration		
Inverter Types	All	BESS only		All	BESS only	
Operating Mode	P>0	P=0	P<0	P>0	P=0	P<0
2. Inverter Hardware Design and Control Configuration						
3. Abnormal Low Voltage Response	18-60	0	0	126-216	108-126	126-216
4. Response to External Reference Change	3-18	0	0			
5. Harmonics	3,4	0	0			
6. Transient Overvoltage (TROV)	4	0	0			
7. Impedance	0-3	0	0			
8. Abnormal Frequency Response	4-8	0	0	4-8	4-8	4-8
9. Voltage Phase Angle Change	6	0	0	6	0-6	0-6
10. Island Operation				100-225	0-72	0
11. Open Phase Operation				30	0	0
12. Control Stability				6	0	0

Legend:

P>0: discharging (P>0) P=0: idle P<0: charging | Tested | Not tested

2.2.1.2. Lab-tested Inverters

To sufficiently represent inverters commonly deployed in the field, a total of [five] inverters were tested. Table Table 1 lists the inverters and the configuration in which they were tested. Two commercial-scale inverters, one residential-scale, and [two] utility-scale inverter were tested. This includes both solar PV and battery energy storage inverters.

Table 2: List of inverters tested

Inverter Label	Inverter rating and type	Category	Compliant Standards	Test Configuration	
				Distribution	Transmission
Tested at the EPRI Power Quality Lab, Knoxville, TN					
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	Commercial-scale, legacy DER	UL 1741 SA, IEEE 1547-[2012]	Yes	No
EPRI-2	**53 kVA, three-phase solar PV inverter**	Commercial-scale, modern DER	UL 1741 SB, IEEE 1547-2018	Yes	No
EPRI-3	**8 kVA, single-phase BESS inverter**	Residential-scale, modern DER	UL 1741 SB, IEEE 1547-2018	Yes	No
Tested at the National Wind Technology Center, NREL Flatirons Campus Laboratories, CO					
NREL-1	**2.2 MVA, three-phase BESS inverter**	Utility-scale, modern DER	UL 1741 SA, VDE AR-N 4110/4120	Yes	Yes
NREL-2	**2 MVA, three-phase solar PV inverter**	Utility-scale, modern DER	UL 1741 SA, VDE AR-N 4110/4120	No	Yes

2.2.1.3. *Test Results*

Table 3 provides a summary of the lab testing results. The objectives of each test and the key observations for each inverter's response are listed. For further details, refer to [2] for example test results and findings for the 2.2 MVA large-scale BESS inverter.

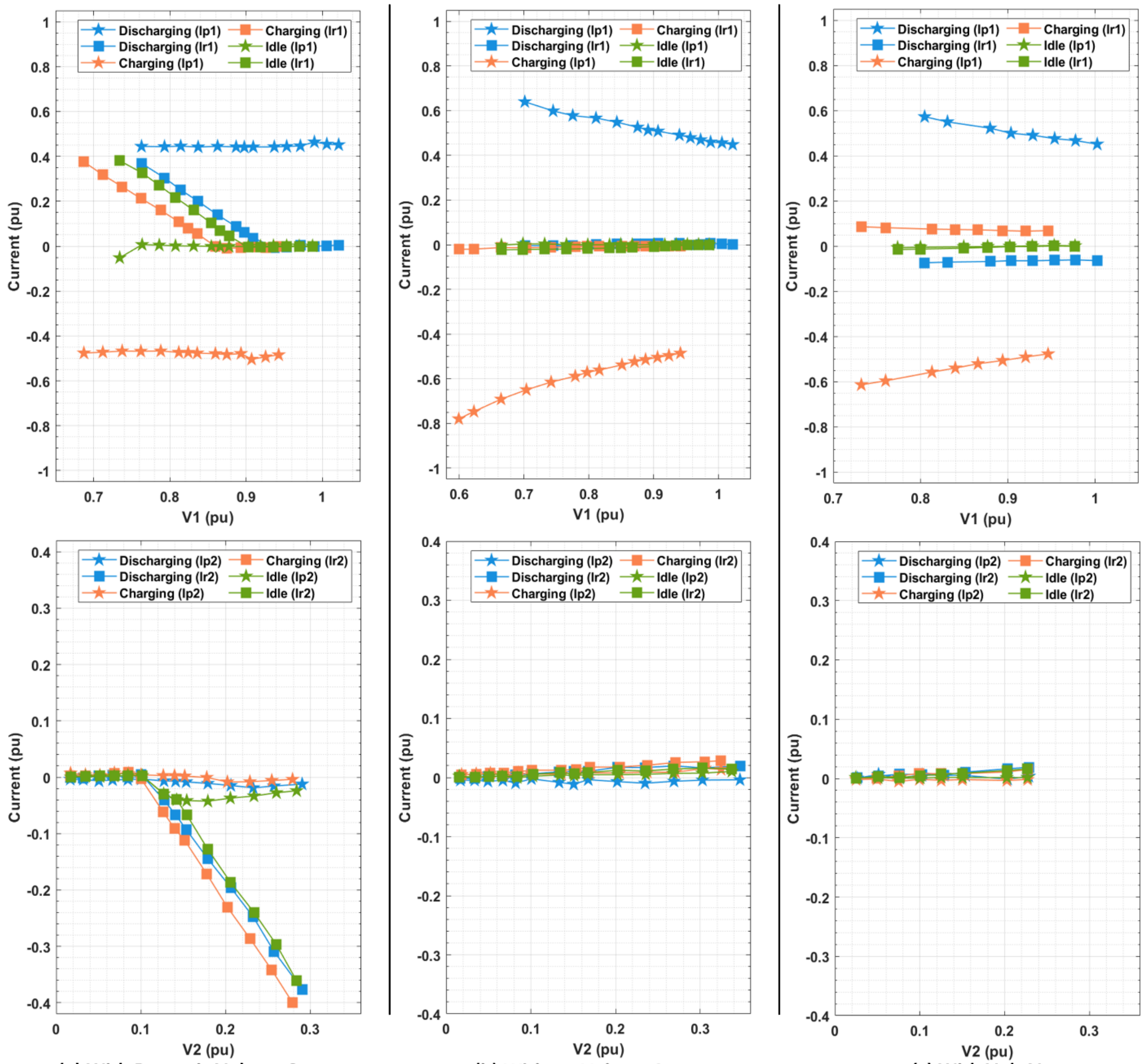
Table 3: Summary of lab testing results for Abnormal Low Voltage Response

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Enters LVRT and injects reactive current if voltage drops below 0.88pu (configurable) • Provides reactive current in proportion to the voltage deviation.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• The inverter meets the Category III ride-through requirements within the mandatory operation region in IEEE 1547-2018 • With volt-var inverter contributes mainly positive seq current with minimum negative seq current • With Dynamic Voltage Support inverter contributes both positive and negative seq current, for three-phase faults minimum negative seq current.
EPRI-3	**8 kVA, single-phase BESS inverter**	• Without voltage support Charging, and discharging modes: Inverter contributes fault current. Idle modes: Inverter contributes minimal fault current • With Volt-Var enabled (OLRT=5s): The fault currents take much longer to settle Charging, discharging, and idle modes: Inverter contributes fault current

NREL-1	**2.2 MVA, three-phase BESS inverter**	• With dynamic voltage support enabled, the inverter contributes only positive-sequence fault current for balanced faults and positive- and negative-sequence fault currents for unbalanced faults • With Volt-Var and without voltage support, the inverter only contributes positive-sequence fault current
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested, because inverter is typically not used for distribution-connected resources
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• With dynamic voltage support enabled, the inverter contributes only positive-sequence fault current for balanced faults and positive- and negative-sequence fault currents for unbalanced faults
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested, because of delays related to NREL test site equipment limitations

2.2.1.4. Example Inverter Test Results:

Abnormal Low Voltage Response: Figure 1 provides a snapshot of the steady-state fault current contribution of the inverter to single line-to-ground faults in the distribution configuration when tested under three different settings: 1) Without voltage support, 2) With Volt-Var enabled, and 3) With Dynamic Voltage Support (DVS) enabled. In tests without voltage support and with Volt-Var enabled, the inverter only injects positive-sequence current with very minimum negative-sequence current. Furthermore, when operating in the idle mode with DVS enabled, the inverter contributes reactive currents during the single line-to-ground faults.



(a) With Dynamic Voltage Support (b) Without Voltage Support (c) With Volt-Var

Figure 2: Snapshot of 2.2 MVA BESS inverter symmetrical current components during single line-to-ground faults

These test results are intended to provide an improved understanding of the transient and dynamic response of an inverter to grid disturbances. Data from these tests can be used to parameterize inverter models in power system simulation software and be used to validate the electromagnetic transient model of the inverter.

Table 4: Summary of lab testing results for Chapter 4. Response to External Reference Change

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Active power response inconsistent in all cases
EPRI-2	**53 kVA, three-phase solar PV inverter**	N/A
EPRI-3	**8 kVA, single-phase BESS inverter**	• Approximately 0.66 s to 1 s reaction time (or delay/dead-time) before the DER responds to the step change in reference setpoint.
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Not tested because of delays related to NREL test site equipment limitations
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Tracks the external P_{ref}, Q_{ref} setpoints with a response time of approximately 16 ms (1-cycle)
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 5: Summary of lab testing results for Chapter 5. Harmonics

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
Not tested		
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Meets IEEE 1547-2018 voltage phase angle ride-through requirements. • 120Hz (double fundamental frequency component) visible during unbalance.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Individual current harmonics components and the total rated-current distortion (TRD) across all tests are within requirements specified in IEEE 1547-2018.
EPRI-3	**8 kVA, single-phase BESS inverter**	• Individual current harmonics components and the total rated-current distortion (TRD) across all tests are within requirements specified in IEEE 1547-2018.
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Total rated-current distortion (TRD) across all tests is within the IEEE 1547-2018 requirements
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 6: Summary of lab testing results for Chapter 6. Transient Overvoltage (TROV)

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
Not tested		
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Total rated-current distortion (TRD) across all tests is within IEEE 2800-2022 requirements
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 7: Summary of lab testing results for Chapter 7. Impedance

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
Not tested		
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Not tested because of delays related to NREL test site equipment limitations
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 8: Summary of lab testing results for Chapter 8. Abnormal Frequency Response

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Q changed periodically (10s interval) as frequency deviated. • Such changes was found to be caused by inverter anti-islanding(AI) function. • Inverter AI function may lead to power quality or system transient stability issues, if designed too aggressive or in cases with high renewable penetration.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Frequency-droop response is as expected for both low-frequency and high-frequency events
EPRI-3	**8 kVA, single-phase BESS inverter**	• Discharge and Idle Modes Frequency-droop response is as expected for both low-frequency and high-frequency events. • Charging Mode with Pmin =0, the DER abruptly stops charging at the start of the frequency ramp
NREL-1	**2.2 MVA, three-phase BESS inverter**	• With short-circuit ratio (SCR)=5, in the charging mode, the inverter inadvertently detects an island and trips when recovering from the low-frequency event for the scenarios without voltage support and with DVS enabled • In all other tested scenarios, the frequency-droop response is as expected
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested

Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• The frequency-droop response is compliant with IEEE 2800-2022 requirements in all tested scenarios
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 9: Summary of lab testing results for Chapter 9. Voltage Phase Angle Change

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Meets IEEE 1547-2018 voltage phase angle ride-through requirements. • 120 Hz (double fundamental frequency component) visible during unbalance.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Inverter complied with IEEE 1547-2018 voltage phase angle ride-through requirements
EPRI-3	**8 kVA, single-phase BESS inverter**	• 20° step change: DER ceased charging during the voltage phase angle change and resumed charging approximately 5 s after the last voltage phase angle change. • 60° step change: DER tripped in charging and idle modes. The cause for DER tripping is likely overvoltage during the phase jump.
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Meets IEEE 1547-2018 voltage phase angle ride-through requirements • Extended voltage trip settings used to avoid tripping on voltage violations
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested
Transmission Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-2	**53 kVA, three-phase solar PV inverter**	• Not tested, because inverter is not used for transmission-connected resources
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources

NREL-1	**2.2 MVA, three-phase BESS inverter**	• Meets IEEE 2800-2022 voltage phase angle ride-through requirements • Extended voltage trip settings used to avoid tripping on voltage violations
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations

Table 10: Summary of lab testing results for Chapter 10. Island Operation

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	**Unintentional Island Operation** • Compliance with the 2s unintentional islanding rule in IEEE 1547-2018 was verified in all cases. • In most cases, with aggressive grid-support functions, lower run-on times were observed when compared with default settings **Ground-Fault and Load Rejection Overvoltage** • Comply with the default Cat III trip settings in IEEE 1547-2018. • Overvoltages as high as 2.14 pu were recorded. • The inverter tripped within 160 ms for OV2 (V>1.2 pu) overvoltages complying with the default Cat III trip settings in IEEE 1547-2018
EPRI-2	**53 kVA, three-phase solar PV inverter**	**Unintentional Island Operation** • When islanded with high quality factor loads, higher inverter run-on times were observed in most cases • When operating in the unity power factor mode with quality factor=2, the inverter run-on times exceeded 2 s **Ground-Fault and Load Rejection Overvoltage** • Peak overvoltage as high as 1.83 pu was recorded but for very short duration (cumulative duration of overvoltage>1.7 pu is less than 0.3 ms) • Overvoltages during single line-to-ground (SLG) faults are within the IEEE 1547-2018 specifications
EPRI-3	**8 kVA, single-phase BESS inverter**	**Unintentional Island Operation** • Discharge mode: Compliant with the IEEE-1547-2018 2s rule in all cases • Idle mode: Violates the IEEE-1547-2018 2s rule for the case with default grid support function settings and load quality factor=2. **Ground-Fault and Load Rejection Overvoltage** • The overvoltage depends on the generation-to-load ratio and point-on-wave at which the island is formed • Peak overvoltage as high as 2 pu was recorded but for very short duration (cumulative duration < 0.1 ms)
NREL-1	**2.2 MVA, three-phase BESS inverter**	**Unintentional Island Operation** • In the discharge mode, compliant with the 2s IEEE 1547-2018 trip requirement • In the idle mode, run-on time exceeds 2s for cases with minimum reactive power mismatch **Ground-Fault and Load Rejection Overvoltage** • Complies with the IEEE 1547-2018 voltage trip requirements • Instantaneous overvoltages as high as 1.46 pu were recorded but for very short duration (cumulative duration <1.6 ms)

NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations
Transmission Configuration		
Not tested, because unintentional island operation and ground-fault and load rejection overvoltage are less of issues for transmission-connected resources.		

Table 11: Summary of lab testing results for Chapter 11. Open Phase Operation

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Three-phase voltage became unbalanced and distorted. With voltage at open phase elevated. • Inverter tends to regulate negative sequence current causing further voltage imbalance.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• With low pre-event active power output the inverter tripped slightly over the 2s IEEE 1547-2018 trip requirement for open-phase conditions • With higher pre-event active power output the inverter tripped well within the 2s IEEE 1547-2018 trip requirement for open-phase conditions with default settings
EPRI-3	**8 kVA, single-phase BESS inverter**	• Not tested, because inverter is not used for transmission-connected resources
NREL-1	**2.2 MVA, three-phase BESS inverter**	• Meets IEEE 1547-2018 open-phase detection requirements • DER transformer saturation and ferro resonance occurred resulting in overvoltages (System dependent)
NREL-2	**1.5 MVA, three-phase solar inverter**	•• Not tested because of delays related to NREL test site equipment limitations
Transmission Configuration		
Not tested, because open-phase operation are less of an issue for transmission-connected resources.		

Table 12: Summary of lab testing results for Chapter 12. Control Stability

Inverter Label	Inverter rating and type	Key observations in inverter response
Distribution Configuration		
EPRI-1	**36.6 kVA, three-phase solar PV inverter**	• Volt-var and volt-watt functions may become unstable and cause sustained voltage and power oscillations when aggressive settings are used. • Stability of these functions is also affected by system parameters. In general, risk of instability is higher in weak grids • For the test cases, frequency – watt function did not cause oscillation.
EPRI-2	**53 kVA, three-phase solar PV inverter**	• No oscillations or instability observed with aggressively configured Volt-Var or Frequency-Watt functions
EPRI-3	**8 kVA, single-phase BESS inverter**	• No oscillations or instability observed with aggressively configured Volt-Var or Frequency-Watt functions

NREL-1	**2.2 MVA, three-phase BESS inverter**	• No oscillations or instability observed with aggressively configured Volt-Var or Frequency-Watt functions
NREL-2	**1.5 MVA, three-phase solar inverter**	• Not tested because of delays related to NREL test site equipment limitations
Transmission Configuration		
Not tested, because control stability issues expected to first arise at distribution level.		

2.2.2. Field data collection and analysis

With the support of two utility partners and NERC, several disturbances were identified from which field data was collected for model validation. Guidelines for event selection were developed early in the research that, among others, specified the preferred location of monitoring equipment, desired time and measurement resolution, required data types, and suitable triggers for IBR plant performance monitoring. A total of eight field events were collected, five from one utility, two from NERC, and one from the second utility. However, not all of the received measurements of voltages and currents waveforms had the appropriate time resolution. For more details on the Field data collection guidelines see [19] and for the NERC events analysis (the partner did not have sufficient measurements that met the specified criteria) see [20]. Due to insufficient IBR plant data, model validation based on the field data received from the two utility partners could not be completed by the end of this research.

2.2.3. Model Development and Improvements

Several existing models were improved and a few new models were developed. Following sections highlight the model development and improvement results.

2.2.3.1. Novel IEEE 2800-2022 conforming IBR plant generic EMT model

2.2.3.1.1. Overview of the model

EPRI developed the specification for a novel generic model of a photovoltaic (PV) inverter in transmission connected plants for implementation in an electromagnetic transients (EMT) simulation package that has the necessary controllers to meet the range of performance requirements in IEEE 2800-2022. The model specification was documented in [16]. It does not represent any specific equipment manufacturer and uses basic building blocks available in commercial EMT simulators. The implemented model prototype was published and documented in [17], is open, and configurable by the end-user.

Figure 3 shows the control architecture of the inverter. The control structure cascades an outer loop that develops current references to an inner loop that regulates the inverter output current. Details on the hardware modeling and control blocks are documented in [16].

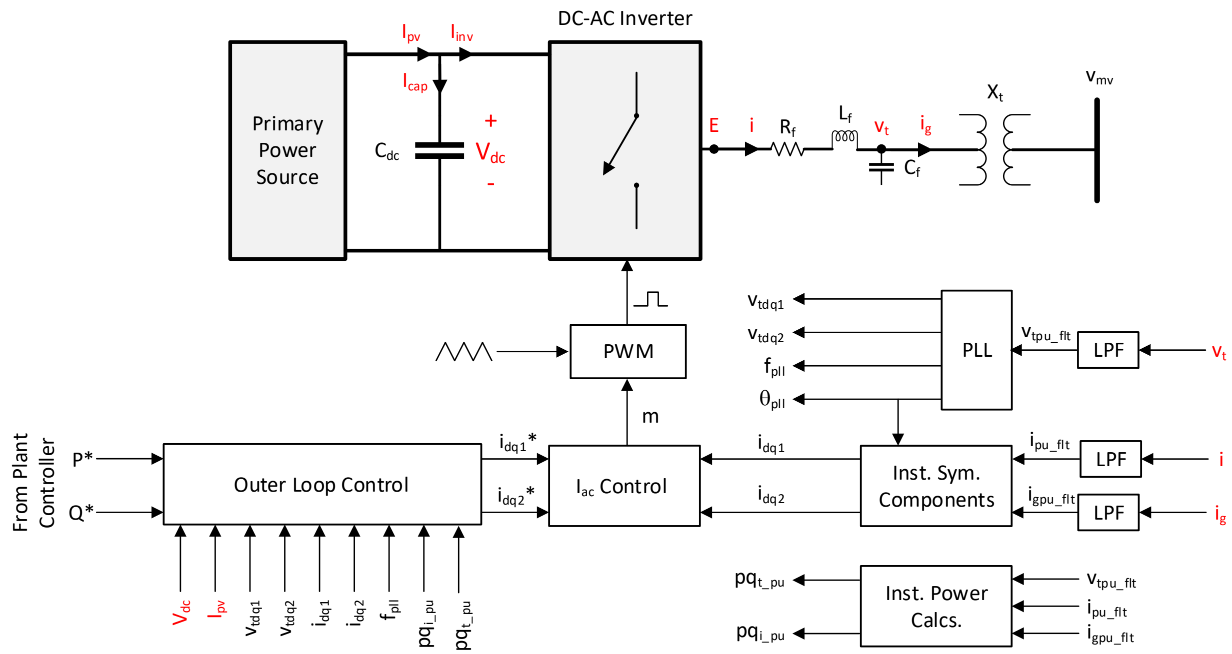


Figure 3: Control architecture of the generic PV inverter model

The model includes a plant controller model that provide the active and reactive power references to the inverter model. The bandwidth of the plant voltage controller and active power controller are typically much smaller than the bandwidth of the inverter level control. For example, IEEE 2800-2022 states the closed loop step response time of the plant level voltage control is typically in a range from 1 to 30 seconds. Therefore, the generic plant controller REPC_C model specification [18] for positive sequence stability simulators was considered a sufficient representation even in EMT domain. The REPC_* models are continuously being improved based on recent disturbances [12].

Figure 4: shows the integration of the REPC_C model in the EMT simulator. Details on the power plant controller modeling and implementation in the model prototype are documented in [16].

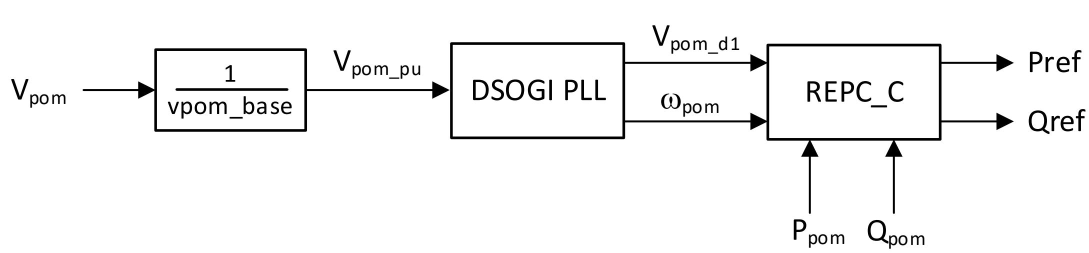


Figure 4: Plant controller

2.2.3.1.2. Use cases and selected simulation examples

The anticipated use cases of this model include:

- Research into the potential limitations of simplified simulators (e.g., positive sequence stability and phasor domain short circuit models). This includes identifying improvements to models used in these simplified simulators.
- Research into the drivers of observed failed ride-through of inverter-based resources (IBRs).
- Development of tools to aid engineers study the wide frequency range of dynamics that may be introduced to the system by IBRs.
- Analysis of the desired response of IBRs for grid-specific applications. For example, creation of reference performance for IBR plant conformity assessment with IEEE 2800-2022, or analyzing the range of capabilities specified in IEEE 2800-2022 and other capabilities not currently specified.
- Futuristic studies where the specific equipment manufacturer is unknown or plant-specific user-defined models (UDMs) are not available.

Chapter 4 of [16] presents example simulations of the generic inverter model prototype in PSCAD™ for various fault ride-through (FRT) operation and step changes in the test system frequency. One example simulation shows the response of the generic model with the FRT positive sequence voltage control and FRT negative sequence voltage control enabled. Figure 5: shows the response of the model in terms of the fundamental frequency positive and negative sequence components of the inverter terminal voltage and current. These plots show an example configuration of the model that produces a response consistent with the requirements in Clause 7.2.2.3 of the IEEE 2800-2022 standard.

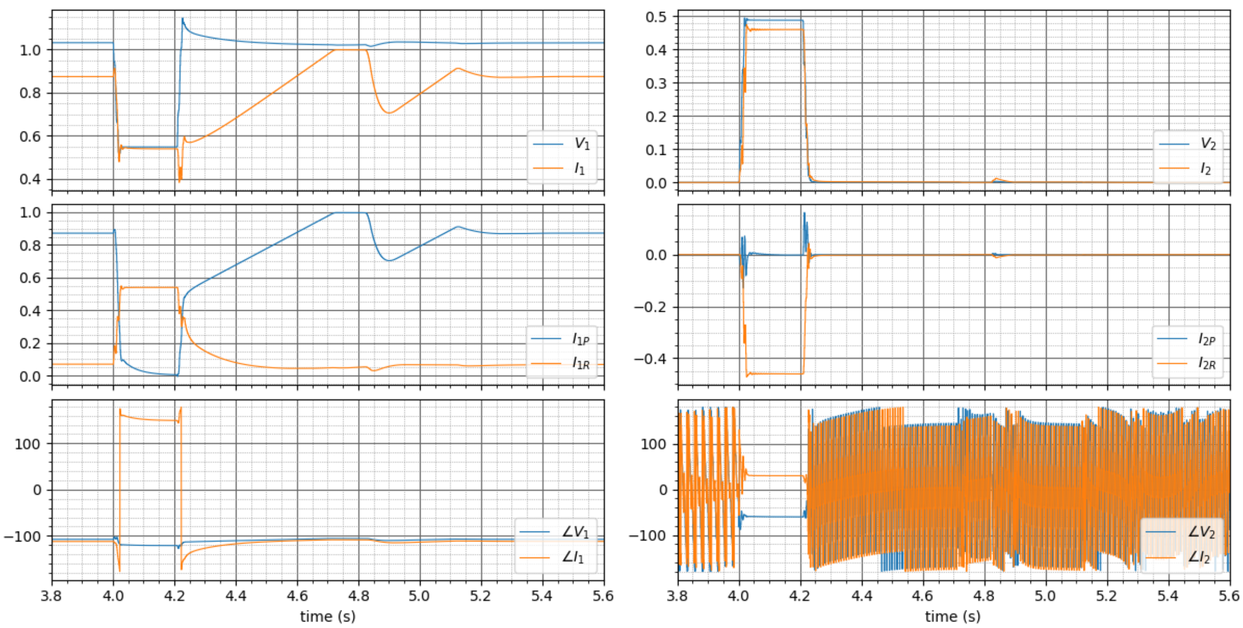


Figure 5:Fundamental frequency components of the inverter terminal voltage and current.

2.2.3.1.3. Known limitations and future improvements

The end-user of the generic model of a photovoltaic (PV) inverter in transmission connected plants for implementation in an electromagnetic transients (EMT) simulation package should note the known limitations of the model structure as documented in of [16]. Although highly configurable and validated based on at least one commercially-available large-scale inverter (see section 2.2.4.1), this generic EMT model is not expected to provide an exact match to the response of all commercial inverters, specifically during the transient period. The model is also not expected to predict controller instability resulting from a specific design or control implementation.

The model specification and model prototype published in [16] and [17] focused on the representation of the inverter as well as a plant controller based on the REPC_C. However, representation of a generic IBR plant's equivalent collector system, main plant transformer, and tie line to the transmission grid was not in the focus of this model specification. Without sufficient representation of these parts of an IBR plant, the validity of the developed model remains limited.

The following model specification could be added in future improvements of the model:

- Protection functions in the PV inverter: phase jump
- Curtailed mode operation of the PV inverter
- Battery model
- (Equivalent) collector system, main plant transformer, and tie line

2.2.3.2. Novel IEEE 1547-2018 compatible individual DER phasor-domain model

2.2.3.2.1. Overview of the model

EPRI developed an Open-Source Distributed Energy Resource (OpenDER) Model [3].The OpenDER model that aims to accurately represent steady-state and dynamic behaviors of inverter-based distributed energy resources (DERs). The model follows interconnection standards or grid-codes and is informed by the observed behaviors of commercial products. The current version release of the model includes photovoltaic (PV) and battery energy storage system (BESS) DER behaviors according to the capabilities and functionalities required by the IEEE standard 1547-2018. This first-of-its-kind model can be used to run snapshot, Quasi-Static Time Series (QSTS), and a variety of dynamic analyses to study the impacts of DERs on distribution operations and planning.

2.2.3.2.2. Objectives

The objectives of the OpenDER model include:

- Harmonize accurate interpretations of the IEEE Std 1547™-2018 DER interconnection standard among all the stakeholders, including utilities, distribution analysis tool developers, and original equipment manufacturers (OEMs).
- Build consensus through an open-to-all DER Model User's Group (DERMUG), which will utilize EPRI developed model specifications and codes and provide feedback for continuous improvement of the OpenDER model.
- Help the industry properly model the DERs that are (or to be) grid interconnected and evaluate the associated impacts on distribution circuits accurately.

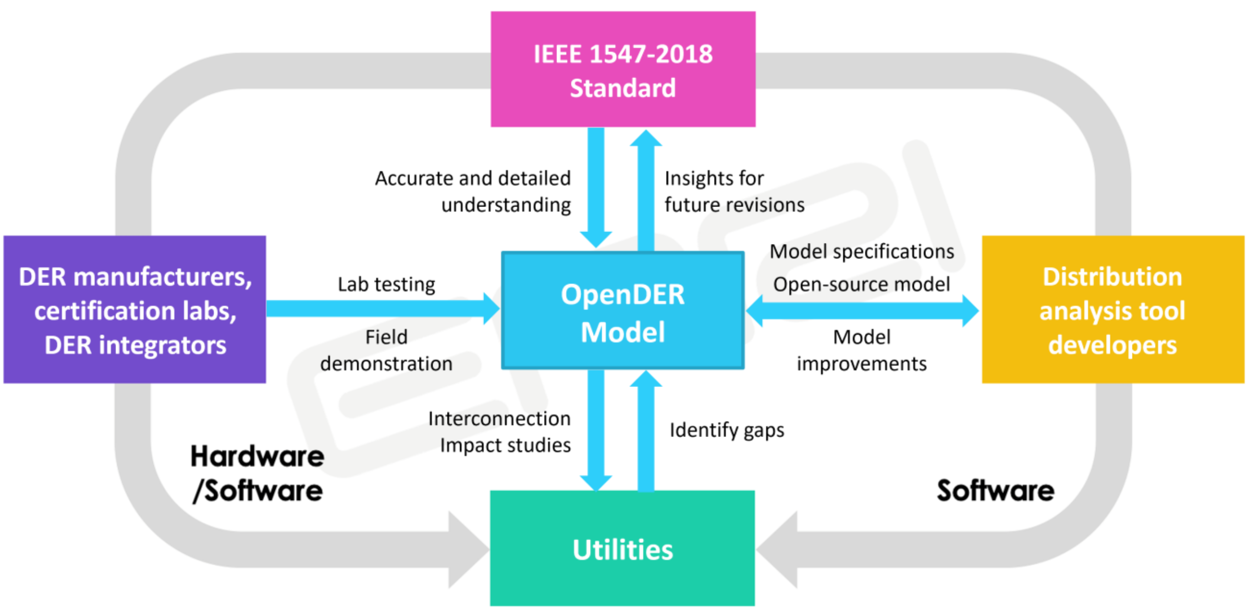


Figure 6: Harmonizing understanding of the DER behavior among all stakeholders

2.2.3.2.3. OpenDER Model Formats

EPRI has developed and continues to maintain the OpenDER model in two formats:

1. *A model specification document presenting the DER model in terms of equations and block/flow diagrams* [4]. This free, publicly available document can be used as a reference by any stakeholders who want to develop their own DER model, such as power system analysis tool developers, utilities, R&D organizations, consultants, and academia. Because the model is being developed and documented in a modular fashion, it can be used in whole or in part depending on needs. The model specification can also be used as a reference to understand the detailed requirements of IEEE Std 1547-2018, and associated interpretations.

2. *An open source DER model in software format* [3]. EPRI has released model code in Python which can be used by various stakeholders for their own DER model development or can be interfaced with commercial tools. It can also be used to benchmark and validate existing DER models.

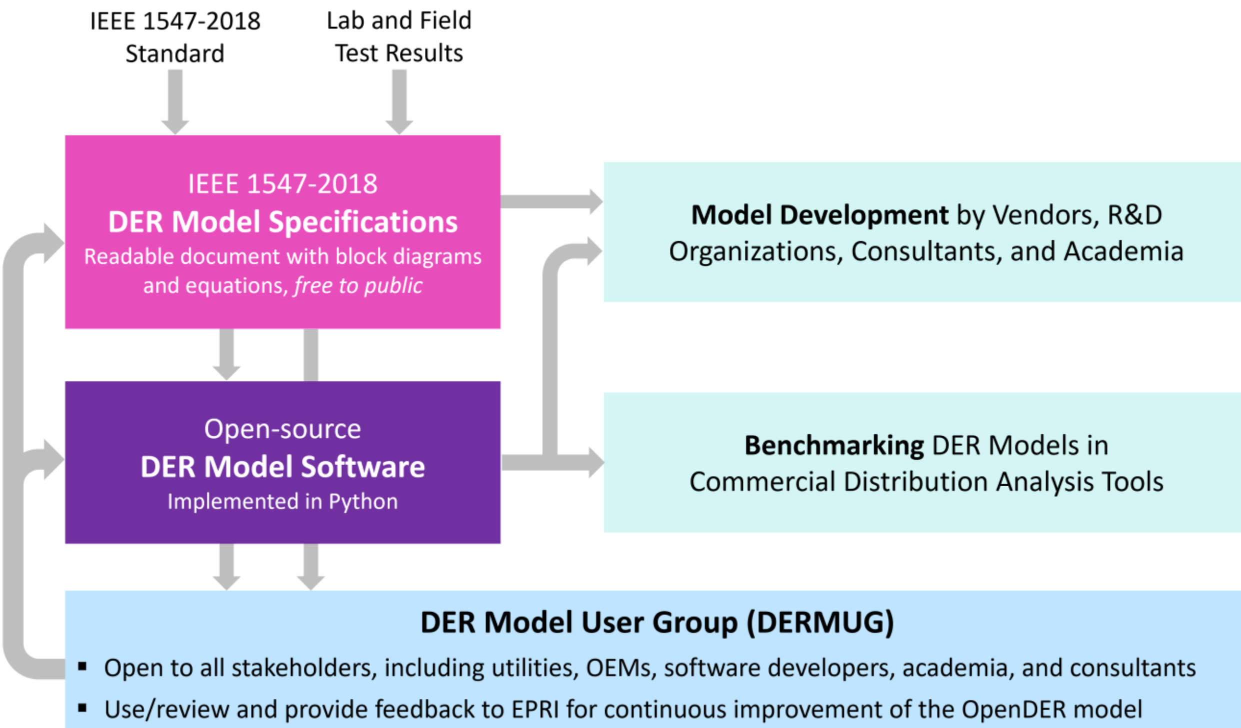


Figure 7: OpenDER Model Formats and Potential Usage

2.2.3.2.4. OpenDER model and DER Model User Group (DERMUG)

In addition to having developed the OpenDER model under this project, EPRI has been hosting a series of meetings of a DER model user's group (DERMUG). The purpose of the DERMUG is to utilize, critique, and build consensus on the OpenDER model. EPRI facilitated discussions to explain modeled DER behaviors, collect feedback, and enhance the OpenDER model based on errors, gaps, and improvement needs identified by the user's group.

The DERMUG is open to all interested parties, including utilities, inverter manufacturers, power system analysis tool developers, consultants, and anyone who is interested to get involved in DER model development. Refer to EPRI's website for further information on potential future meetings.[1]

2.2.3.3. Improvements to existing model types

Within this project, the project team also refined existing and developed new PV models to ensure system reliability. Lab test data were used to develop and benchmark various model aspects. Finally, prototype models and detailed specifications were shared with vendors through EPRI's vendor engagement process.

2.2.3.3.1. Steady-state short-circuit model improvements

Improvements to steady-state short-circuit models were documented in [5], with validation results presented in [6] based on [7].

Steady-state fault analysis programs have traditionally used a classical Thevenin equivalent (voltage source behind impedance) to represent the short circuit behavior of a synchronous generator (SG). This model does not apply to a PV inverter given its different fault current characteristics.

With support from this project, EPRI co-led the IEEE Power System Relaying and Control Committee (PSRC) working group C24 and recommended a voltage controlled current source model to represent a PV inverter in short circuit studies, as shown in Figure 8.

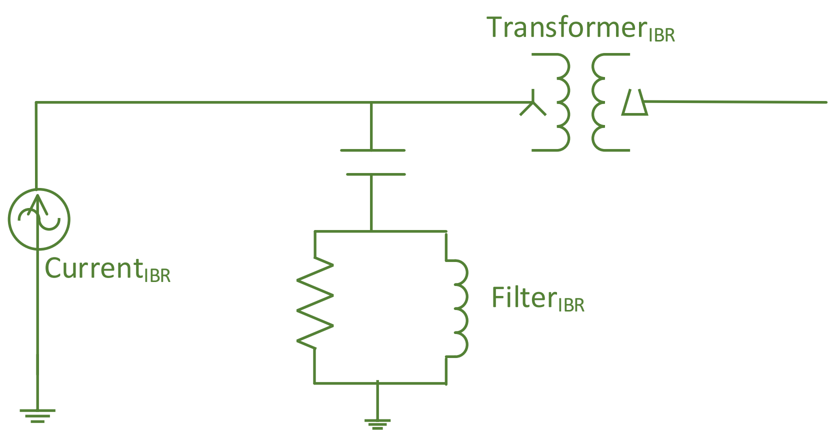


Figure 8: showing voltage controlled current source short-circuit model.

The recommended model has two key differences with respect to the classical SG model:

1) The generator is represented by a current source instead of a voltage source and
2) In contrast to the classical synchronous generator (SG) model which is linear, the recommended PV model is nonlinear and hence requires iteration with network solver.

[1] https://www.epri.com/opender

Two implementations of the model have been developed by commercial fault analysis programs including ASPEN OneLiner and PSS®CAPE, as shown in Figure 9.

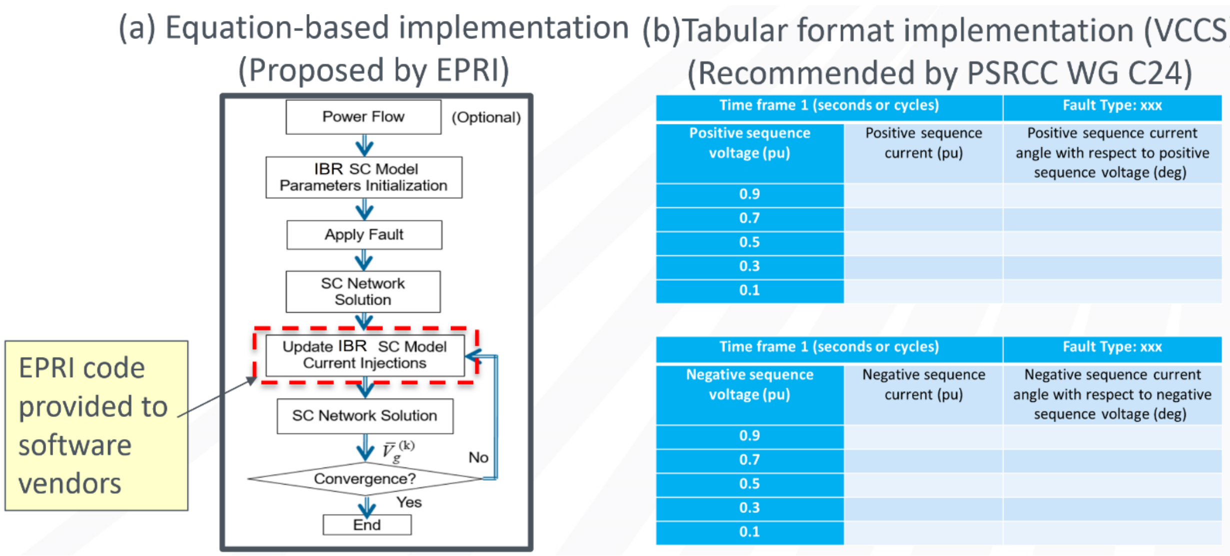


Figure 9: showing the two implementations of the voltage controlled current source short-circuit model.

a) **Equation-based implementation**: Proposed by EPRI, this implementation uses a set of generic equations to represent converter control and fault ride through functionality, current limiter scheme, and active/reactive power control priority. The input of the model is the voltage at converter terminal, and the output is the calculated short circuit current of the converter. At each iteration of the solver, the network solver calculates and supplies the value of terminal voltage, and the model calculates the corresponding short circuit current and injects it into the grid. Subsequently, the network solver updates the terminal voltage. The iteration continues until converge is achieved. ASPEN OneLiner and PSS®CAPE have implemented the model.
b) **Voltage-Controlled Current Source (VCCS)**: Recommended by IEEE PSRC WG C24, this implementation uses a table providing short circuit current as a function of voltage. Each row of the table corresponds to a voltage amplitude and provides the amplitude and phase angle of fault current at that voltage. The table can be provided at different time frames following the inception of the fault (i.e., 1 cycle, 3 cycles, 5 cycles) and provide the voltage and current quantities in phase domain (phase a, b, c) or in sequence domain (positive and negative sequence components). The existing implementations in ASPEN OneLiner and PSS®CAPE provide only a single time frame representation of positive sequence quantities.

The EPRI team has engaged protection software vendors to support the implementation of the models and benchmark the implementations to ensure consistency across different platforms. Over the course of this project, the following improvements were made to the proposed models:

- On the equation-based model, the team added current limiter scheme options to the model to capture various fault responses under unbalanced faults. The user can select option based on expected fault current behavior. The two implemented options include:
    - Current limiter option 1: limit d- and q-axis components of positive and negative sequence currents;
    - Current limiter option 2: limit the active and reactive components of positive and negative sequence currents.

  The need for these options originated from analyzing the short circuit behavior of a manufacturer PV inverter model. Conducted simulations suggest that, for a PV inverter with dynamic negative sequence reactive current support, the current limiter scheme has an impact on fault response under an unbalanced fault. Given the lack of standardization for the implementation of current limiter scheme, various implementations are possible, leading to different fault responses. The EPRI team added a current limiter option which produced more consistent results to the tested manufacturer model.
- On the VCCS model implementation, the EPRI team in collaboration with IEEE PSRC suggested a table format shown in the figure below which more accurately represents the negative sequence fault current characteristics. Originally, the IEEE PSRC WG C24 had suggested a different format which used separate tables for positive and negative sequence quantities; the EPRI team found that this original format was not accurate due to the coupling between positive and negative sequence currents. The study further revealed that that the format of the table depends on the current limiter scheme.

2.2.3.3.2. Harmonic models for PV inverters

Improvements to harmonic models for PV inverters have been documented in [8] along with a brief summary published in [9]. Validation examples were presented in [10], including the discussion of potential advantages and limitations of a new hybrid model that is a quasi-Norton equivalent, meaning that its impedance does not change as a function of frequency.

The validated generic harmonic models, modeling methods, and learnings presented in this report could potentially be used to implement IBR plant conformity procedures that are being developed in IEEE P2800.2, *Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems* [11].

2.2.3.3.3. Phasor-domain (RMS) IBR unit models

As part of this project, several existing second-generation IBR unit models in positive-sequence phasor domain models were enhanced. An overview on the most recent model versions is available in [12]. One notable improvement of IBR unit models achieved by this research includes the REGC_C model that was implemented in PSS/E [13] and has the following benefits:

- Allows adequate representations of equipment in low short circuit scenarios
- Allows users to model the dynamic behavior of this type of equipment under the low short circuit scenario
- Allows users to better represent actual field equipment in their systems

2.2.3.3.4. Phasor-domain (RMS) IBR plant models

In addition to the improvement of positive-sequence phasor-domain models for IBR units, this research supported significant improvements of the corresponding IBR plant-level models. One notable example is the development and refinement of the REPC_D model specifically for hybrid-plants or plants with multiple aggregated inverter-based generation models [14].

2.2.3.3.5. Phasor-domain (RMS) Aggregate DER model improvements

Gaps in the Aggregate DER Model (DER_A) were identified as it pertains to the post-disturbance response of the model when dynamic voltage support (DVS) is enabled. The DVS is an optional capability per IEEE 1547-2018 that provides fault current during voltage ride-through to support voltage. The proposed model improvements allow the user to specify the duration for which the model continues to use the DVS control loops after the voltage has returned to the continuous operating region. Details are presented in chapter 2 of [12].

2.2.4. Model Validation and Application Examples:

The developed models were validated—to the extent possible—using lab test data and field data from participating utilities. Some of the models were presented to the WECC and NERC modeling task forces for acceptance and future implementation in commercial simulation software.

2.2.4.1. Validation of novel generic EMT model

2.2.4.1.1. Example of the inverter level model based on lab measurements

Examples of the validation of the IBR unit representation with the novel generic EMT model conforming with IEEE 2800-2022 are available in chapter 5 of [16]. Balanced and unbalanced faults with varying retained voltage levels in the faulted phases were considered in the comparison. The measured voltage at the 13.2 kV bus from NREL's laboratory tests with the inverter offline was played into the voltage source of the PSCAD model test system. The plot step of the simulation matches the sampling rate of the laboratory measurements.

Figure 10: compares the response of the generic model to the laboratory measurements for a B-C fault that causes a negative-sequence voltage of 0.25 pu. The signals compared are:

- fundamental frequency positive voltage magnitude (V_1)

- fundamental frequency negative voltage magnitude (V_2)
- fundamental frequency positive sequence active current (I_{1p})
- fundamental frequency positive sequence reactive current (I_{1r})
- fundamental frequency negative sequence active current (I_{2p})
- fundamental frequency negative sequence reactive current (I_{2r})
- Instantaneous active power (P)
- Instantaneous reactive power (Q)

The fundamental frequency components of the voltages and currents were calculated by a DFT of a one-cycle moving window of data based on Clause 7.2.2.3 of IEEE 2800-2022. The instantaneous active and reactive power are calculated and filtered as detailed in Chapter 5 of [16]. The filter removes the 120 Hz component present due to the unbalance in the signals while minimizing the phase distortion.

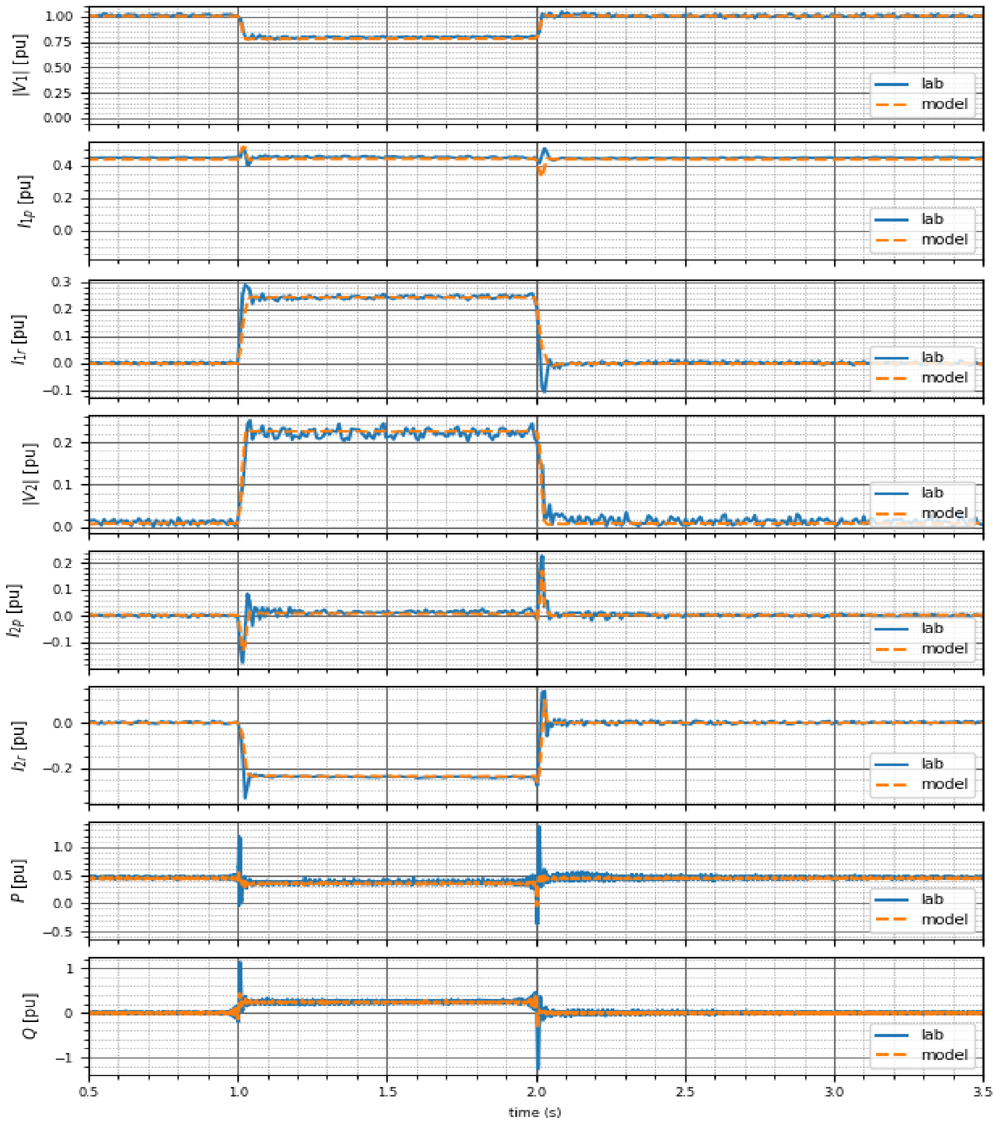


Figure 10: BC fault: V_2 = 0.25 pu.

The comparisons show that the new generic EMT model's response reasonably matches the laboratory measurements for the balanced and unbalanced faults considered. The differences noted in the transient period at fault inception and fault clearing are hypothesized to be due to the unknowns of the inverter output filter design and current controller bandwidth.

2.2.4.1.2. Plant level model validation based on field measurements

Plant-level validation of the generic EMT model was not successfully completed due to challenges in the measurement resolution of field data provided by NERC and difficulty with obtaining IBR plant design data from the utility partner. The latter did not allow a sufficiently accurate representation of the IBR plant, including its collector system, main IBR transformer, and tie line to the transmission grid.

While IBR model performance trends aligned with some of the plant performance recorded in the field, other parts of the IBR plant performance could not be reproduced with the generic EMT model without additional information about the IBR plant.

2.2.4.2. Validation of phasor-domain inverter and plant model based on EMT model response

Results for the validation of the improved generic positive-sequence phasor-domain IBR inverter and plant models were documented in [21] based on the following method:

- The positive sequence models were validated against the adequately configured generic EMT model and suitable parameter configurations were determined for the positive sequence models to match the generic EMT model performance.
- The traces of the positive sequence models were plotted with the EMT model performance results to show the accuracy of the validation exercise.

Future work may include:

- The positive sequence models could be further validated against an OEM provided, user-defined EMT model and suitable parameter configurations could be determined for the positive sequence models to match the OEM EMT model performance.
- The traces of the positive sequence models could be plotted and compared with additional lab test results and field measurement to further assess the versatility of the models to represent a variety of IBR plants and configurations.

2.2.4.3. Production of reference responses for IBR plant conformity assessment

The novel generic model of a photovoltaic (PV) inverter in transmission connected plants for implementation in an electromagnetic transients (EMT) simulation package that has the necessary controllers to meet the range of performance requirements in IEEE 2800-2022 was used to produce example reference responses from which some were conforming and others non-conforming with performance requirements specified in IEEE 2800-2022. Figure 11 shows one example of such response with shaded areas illustrating performance spaces that include conforming (green and yellow) versus non-conforming (red) IBR plant response.

This concept of shaded areas could potentially be used to document IBR plant conformity assessment under a future IEEE P2800.2, *Recommended Practice for Test and Verification Procedures for Inverter-based Resources (IBRs) Interconnecting with Bulk Power Systems* [11].

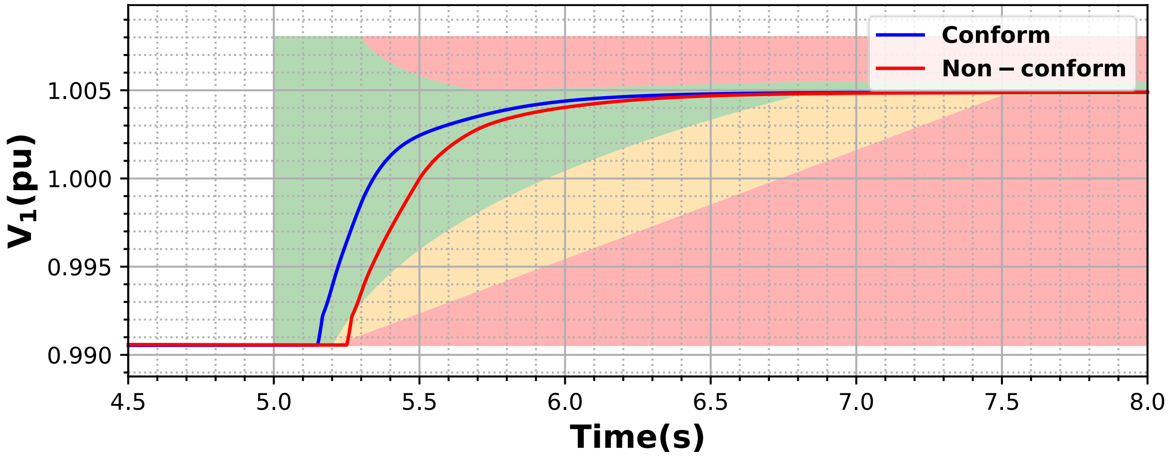


Figure 11: Response of EMT model to step change in voltage at the POI.

—Thrust 2—

Design, testing, and commissioning of adaptive protection schemes for high penetration of DER

2.3. Methodology/Approach for Thrust 2: Design, testing, and commissioning of adaptive protection schemes for high penetration of DER

The project aims to identify and characterize adaptive protection schemes for Distributed Energy Resources (DER) reliability and resiliency applications. This involves assessing the needs, benefits, and barriers of such schemes, and demonstrating advanced analytical methods to automate complex design assessments. Prototypes of adaptive protection schemes were developed for field demonstration sites. Broad industry inputs were leveraged from EPRI's T&D Protection Task Force, IEEE Power System Relaying & Control Committee members, and others to identify barriers, challenges, and opportunities for adaptive protection. The project also documented state-of-the-art technology and industry application assessments (See [24][25]).

Necessary grid, protection, and DER data were collected from each demonstration site to develop representative models. EPRI's Automated Protection Toolkit was applied to evaluate adaptive protection needs and configurations, considering various fault conditions, grid configurations, and DER in-feed cases. Initial autonomous and centralized controller-driven adaptive protection scheme logic were developed and tested using commercially available analysis tools, along with available DER models. EMT modeling of the proposed schemes were performed using refined inverter models, and pseudo-HIL testing were conducted at EPRI lab facilities using commercial protection relays.

Models of the three host sites were developed in an EMT environment, including representations of adaptive protection schemes. Simulations were performed to consider a wide range of faults, grid conditions, and DER in-feeds, with schemes refined as needed. Select grid and DER condition cases were tested, and the adaptive protection scheme designs were validated using actual field hardware and refined models (where applicable). Field deployment procedures and testing plans were developed. A real-time demonstration of protection setting assessments and relay configuration adjustments was conducted, considering DER in-feed, feeder switching, and grid automation changes on a utility partner's pseudo-DMS system. The designed adaptive protection scheme was also deployed and field-tested at a utility partners microgrid site. Field tests were performed for on-grid and off-grid verification, and results were documented [31][32]. Some of the results are described in the subsequent sections.

2.4. Summary of project results for Thrust 2: Design, testing, and commissioning of adaptive protection schemes for high penetration of DER

Adaptive protection is a broad term that covers schemes that involve the modification of settings, logic, or behavior of one or more relays that are part of protection schemes, in response to external commands or changes in system conditions. These conditions could be part of the electrical system, i.e., voltage, current, frequency, or external factors like weather, time of day, season, etc. The use of microprocessor based numerical protection relays and widespread availability of SCADA communication channels has allowed utilities to use adaptive protection schemes to increase resiliency and add flexibility in the operation and control of the power system.

As part of this project, three specific use cases for adaptive protection were identified. With increasing DER penetration, the impacts on distribution protection were investigated for these three use cases and adaptive protection mitigation schemes proposed. The three scenarios were [22][23][24][25][26] :

- Radial distribution feeders
- Microgrids
- Low voltage meshed secondary networks

The guide through the pre-design planning, design, settings development, pre-deployment testing, and commissioning process for these adaptive protection schemes. are explained in the subsequent sections.

2.4.1. Pre-Design Planning

Taking an outcome-led approach is essential to getting the best results. This approach defines what the protection scheme should deliver using a clear set of success merits. These success merits define what successful operating experience looks like. Once these success merits are in place, the schemes could be set and tested to verify they meet them. Simulation scenarios and tests can then be developed to ensure the adaptive protection solution can clearly and unambiguously meet each success merit.

The success merits identify clear performance requirements, outcomes for grid scenarios and disturbances, and outcomes from internal and external component failures. These success merits can then be used to develop simulation scenarios and tests which could be used to evaluate the adaptive protection scheme performance. Figure 12 presents a high-level overview of the general approach taken to this process.

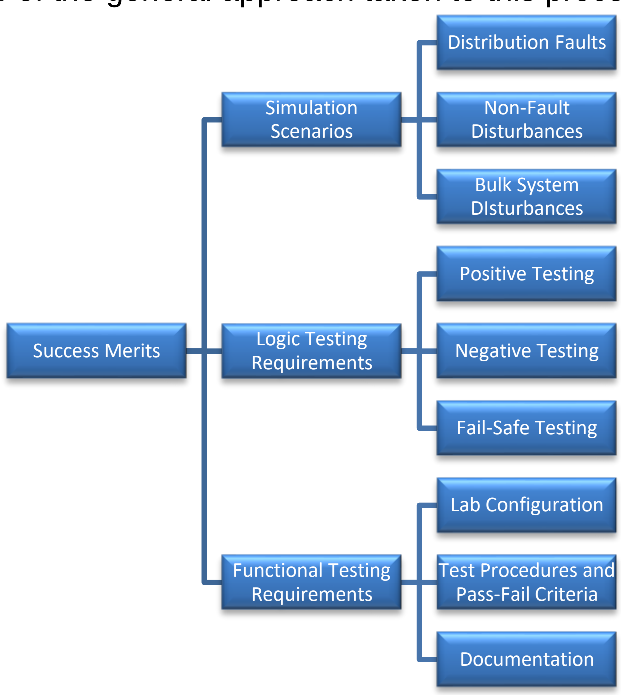


Figure 12: Conversion of Success Merits into Testing Requirements

Depending on the application, the success merits may be different. Let's take a look at the success merits that were identified for the three specific scenarios this section is focused on.

The success of the adaptive protection logic design for use on radial distribution feeders can be measured by [22][23][24][25]:

- A centralized adaptive protection design which can dynamically respond to system operating conditions and enable the target feeder to be operated in multiple configurations without compromising protection sensitivity.
- A scheme with clear criteria or automated system to inform the grid operator of the optimal adaptive protection state for the current system conditions.
- A design that detects and isolates all credible low impedance balanced and unbalanced faults during normal and abnormal grid configurations.
- Protection that trips in a timely and coordinated manner for faults during nominal (normal and alternate) grid configurations.
- Protection that trips in a timely and coordinated manner for faults during abnormal grid configurations, respecting that available fault current and the number of series protective devices may mean coordination is not achievable for all devices in certain edge cases.
- Protection that trips in a timely and coordinated manner when cumulative DER installed capacity on the feeder results in the reverse flow of power up to conductor continuous rated current or the short circuit ratio falls below a value of 10.

The success of the adaptive protection logic design for use on microgrids can be measured by [22][23][24][25]:

- A centralized or de-centralized adaptive protection design which can dynamically respond to microgrid operating state and transitions without compromising protection sensitivity.
    - A centralized adaptive protection scheme would change protection configuration in response to commands from a microgrid controller or protective device at the point of interconnection between microgrid and distribution grid.
    - A de-centralized adaptive protection scheme which uses measured current to enable or disable a sensitive voltage-controlled overcurrent function
- A design that detects and isolates all credible low impedance balanced and unbalanced faults during normal and abnormal grid configurations.
- A design that detects and isolates all credible low impedance balanced and unbalanced faults in both grid-connected and islanded modes.
- Protection that does not incorrectly trip during soft or hard black starts.
- Protection that does not trip during block loading, motor-starting, or cold-load pickup.
- Protection that correctly responds to adaptive protection commands from the microgrid controller.

The success of the adaptive protection logic design for use on secondary networks can be measured by [22][23][24][25]:

- A de-centralized adaptive protection design that permits reverse power flows through the Network Protector and network transformer and thus enables increased penetration of DER on secondary networks without compromising sensitivity to credible faults.
- Protection that trips in a timely and coordinated manner for credible faults on the secondary network in line with existing utility protection practices and requirements.
- Protection that trips in a timely and coordinated manner for faults on the primary feeders in line with existing utility protection practices and requirements.
- Protection that does not trip when cumulative DER installed capacity on the secondary network results in the reverse flow of power through the Network Protector under nominal conditions where there is no fault, or the primary breaker is not open.
- A design that permits closing of Network Protectors for low and high-DER cases.
- Protection that does not permit back-feeding of currents onto the primary feeder with the feeder breaker open.

In addition to the application specific success criteria, all three scheme designs would have the following common success merits:

- A scheme with a clear design, clear implementation plan, clear and comprehensive testing procedures, and clear operating documentation to enable application to most distribution grids.
- A scheme which can be readily deployed to common protection and controller equipment already in use by distribution grid utilities.
- Protection that does not trip during transformer inrush in the absence of a fault.
- Protection that does not trip during bulk-system disturbances including auto-reclosing, abnormal voltage, and abnormal frequency events.
- A scheme design that takes that does not misoperate during internal and external device failures.

2.4.2. Scheme Design and Settings Development

Once success merits are identified, the next step is to develop the scheme. If custom schemes using relay logic are to be used it is essential that internal relay logic be designed to provide consistent, reliable performance for expected conditions.

Protection engineers aim to develop and deploy simple and straightforward protection schemes. Such schemes have numerous advantages such as not requiring expensive hardware investments, being relatively effortless to replicate when needed at other sites, and being easy to troubleshoot when the system does not operate as expected following any failures. Also, simple systems are easy to test. Protection systems are typically tested on a wide variety of system operating conditions and scenarios that even relatively simple schemes take a large amount of effort to test thoroughly. As the schemes become more complicated the challenges associated with testing such schemes become exponentially higher. The designer of the scheme needs to take these into account when coming up with the adaptive protection scheme.

In this section, the design of the three adaptive protection schemes and the associated process for calculating appropriate settings for each scheme is explained. The schemes have been designed to be as simple and straightforward as possible. Despite keeping the schemes simple, testing each scheme involved performing hundreds of tests to ensure that the design would work as expected for a wide variety of system operating conditions.

2.4.3. Radial Distribution Feeder Adaptive Protection Scheme

The radial feeder adaptive protection scheme involved coming up with a system to dynamically respond to changing operating conditions and different feeding arrangements. It was determined that settings groups could be used to enable the reclosers to adapt to these changing conditions and still provide fast, sensitive and reliable protection performance.

Most existing reclosers on the feeders enable multiple settings groups to be used in their relays. Some of these could be used as part of our protection scheme. Assuming four settings groups are available for reconfiguration under this scheme, alternate settings could be calculated would be used based on the operating configuration [27] [29].

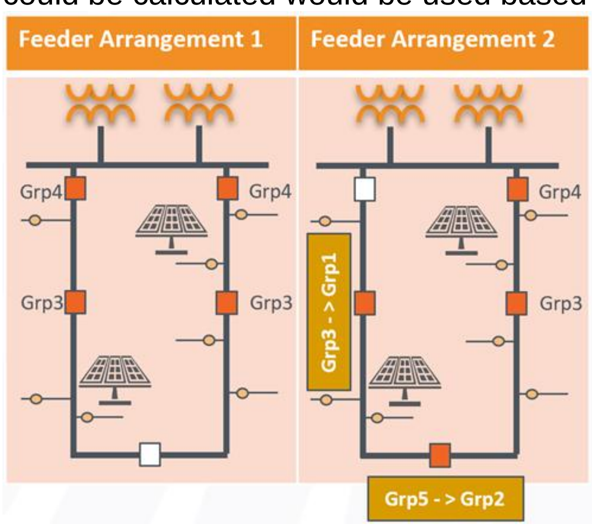


Figure 13: Simplified example of how reclosers adapt settings group in response to feeder configuration [22]

To configure each of the four available settings groups for all reclosers under all conditions presents an optimization challenge. It would be possible to use various optimization algorithms to determine the best settings for each group in each recloser across various feeding arrangements and the various DER and short circuit levels permutations.

As a counterpoint to this optimization approach, it was considered whether a standard set of settings groups could be deployed to all electronic reclosers across feeders. Such an approach would significantly reduce engineering effort and deployment strategy as each recloser has identical settings groups; the analysis is then reduced to determining which settings group each recloser should select for a given feeding arrangement.

Choosing the appropriate settings for each group typically requires an understanding of minimum credible fault current magnitudes and maximum load flow for normal and abnormal grid conditions. This can be achieved using planning or protection short circuit analysis tools.

Once the settings are determined and the relays and reclosers are programmed with the appropriate settings groups, the centralized DMS/SCADA that can communicate with these devices needs to be updated with the requisite logic to allow the operator to manually send commands to the relays to instruct them to change settings groups as operating conditions change. Depending on the capabilities available within the DMS system, the process of sending the settings group change command to the devices can be automated based on predefined rules. This would mean that there is no operator intervention needed for the operation of this scheme.

2.4.3.1. Key Points

Either an optimization approach or a standardized settings approach may be adopted for the protection devices that are part of this adaptive protection scheme. A thorough analysis of the system on which this scheme is to be implemented is needed to ensure that the right set of standard settings can be used for each group in the recloser. Based on the nature of various parts of the system, different regions within the utility may need different standard settings.

It may not be possible to adequately protect the grid for every feeder configuration. The feeder may be so long that the fault level is comparable to load current, so fault clearance is not guaranteed. For grids with many reclosers or normally open switches, it may not be possible to configure the protection to maintain the same level of selectivity for all possible configurations. A balance between sensitivity and selectivity will be needed to ensure that the feeders remain protected during faults under all possible operating conditions.

This adaptive protection solution cannot be deployed without appropriate system operator training and DMS design. Some DMS products provide the capability to perform protection coordination studies and support adaptive protection with multiple settings groups. With this capability, the operator can examine the feasibility of a given feeding arrangement by choosing between available settings groups. The standardized settings groups approach also makes this more intuitive to the operator. A fully automated system may require the development of logic within the DMS application to issue relay/recloser settings group change commands as switches open and close to transition from one feeding arrangement to another, or DER production levels fluctuate.

Another aspect to look at is to determine the right order in which relays/reclosers are issued the settings group change command when multiple devices need their settings groups changed on account of topology changes. Since it takes a non-insignificant amount of time from when the command is issued and when the relay activates the new settings group, there exists a non-zero-time interval when the relay/recloser in not performing its protection functions. To account for any faults that may occur during that time interval it is essential to ensure that the backup protection device is active and ready to provide the necessary protection during that time window.

2.4.4. Microgrid Adaptive Protection Scheme

It is preferred to design microgrid protection systems such that they can adequately protect the feeder in both grid-connected and islanded mode without changing settings or enabled functions. This simplifies the overall design and avoids the need for adaptive protection. However, depending on the microgrid design it may be necessary to employ different overcurrent settings and functions to keep digital relays coordinated and sensitive to credible faults under all microgrid operating modes [27][28].
For microgrid adaptive protection, a per-phase voltage-controlled overcurrent protection scheme was chosen as the primary feeder protection method during islanded-mode, while conventional inverse overcurrent protection can be used in grid-connected mode. The conventional inverse overcurrent protection element can be left permanently enabled if its minimum pick up exceeds the maximum available short circuit current level in island mode. In such cases the conventional inverse overcurrent protection cannot trip during island mode and there is no need to disable it. Otherwise, it should be disabled during island-mode.

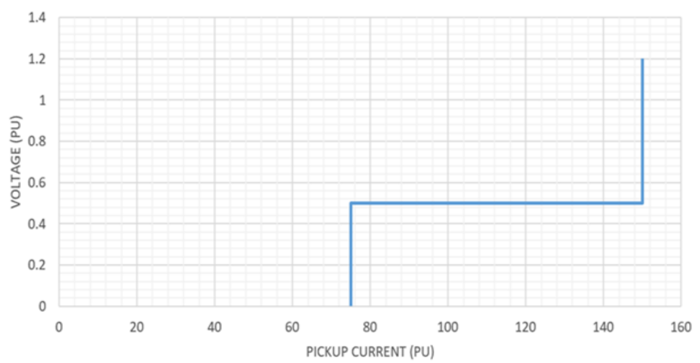


Figure 14: Grid Connected and Islanded Mode Overcurrent Pickups

The scheme can either be controlled centrally, using the microgrid controller, or can be deployed de-centralized, where the relay makes the decision on operating state locally. The centralized version of this scheme requires a microgrid controller to command the relay to transition between grid-connected and island-mode protection. The scheme can be de-centralized by dynamically blocking the voltage-controlled overcurrent element if the measured short circuit current exceeds a set threshold.
If inverse time elements are used, the scheme can be deployed on microgrids with multiple midline reclosers. Selection of the voltage-controlled overcurrent pickup current is based on available setting ranges, microgrid load characteristics (motor starting current etc.), and minimum fault current levels (typically for medium or high impedance fault), while the time dial is chosen based on downstream protection devices with which it must coordinate.

The undervoltage threshold was chosen such that it would allow the largest motor within the microgrid area to start up. Also, simulations were executed to identify the voltage drop that occurred for faults that resulted in the minimum fault current. This was used to determine the maximum and minimum thresholds for the undervoltage element pickup. Since the undervoltage element supervises the associated overcurrent element, the pickup for the overcurrent element can be set below the load current expected on the feeder under maximum loading conditions. E.g., for one of the systems simulated the undervoltage pickup was set to 0.8pu while the associated overcurrent pickup was set to 50% of the maximum steady state load current through the recloser in island mode. A summary of the tests is in Table 13

Table 13: Microgrid APS Test Summary

Project Phase	Grid Model	Number of Tests	Pass	Conditional Pass	Fail	Comments
Preliminary Testing	A	25	24	-	1	Failed test corresponds to starting a very large induction motor.
Pre-Deployment Testing	B	90	66	9	15	Insufficient voltage drop to activate APS during failed tests. Conditional pass for cases where a different protection element operated to clear the fault.
Commissioning Testing	C	9	7	-	2	Adjusting settings fixed issue with failed tests.

2.4.4.1. Key Points

When possible, design microgrids to use the same protection settings for both grid connected and islanded modes of operation. This simplifies the overall protection scheme as there is no need for the protection devices to switch settings groups or activate alternate protection elements if the operating mode changes. Also, if the microgrid area may be operated as an island only infrequently, it may be worthwhile to do an assessment to determine the likelihood of a fault occurring when the microgrid is operating in islanded mode. If it is deemed an acceptable risk, protection at the PCC can be used to protect the entire microgrid in islanded mode and simplify the protection scheme.

Definite time elements can be used in place of inverse time elements to simplify coordination between series devices. Since the fault current contribution from sources within the microgrid is low, the risk of damage to power system equipment is lower and therefore fault clearance times can be chosen to be constant for a fault in a given protection zone irrespective of fault current magnitude.

For the decentralized mode of this scheme, the blocking threshold for the voltage-controlled element is set such that is exceeds the maximum short circuit current magnitude which can occur while operating in island-mode. Thus, if the measured current exceeds the threshold, the microgrid can only be in grid-connected mode.

Since the load and fault currents under islanded mode tend to be very close to each other, having a good idea of the expected load current under islanded operating mode is essential. Though typical short circuit models may ignore load, for situations involving microgrids, having data about loads is essential to setting the protection elements appropriately.

2.4.5. Low Voltage Meshed Secondary Network Adaptive Protection Scheme

The adaptive protection logic for low voltage meshed secondary networks was designed to enable limited reverse flow of power from the secondary network to the primary feeder, while still providing fast and coordinated protection tripping for primary-side feeder faults. This logic design can be used to supplement existing logic and can be customized based on site or grid-specific requirements.

When the calculated rate of change of real power (RoCoP) is higher than a user programmable forward threshold and the measured forward[2] real power is greater than the forward power threshold, a timer is started. This timer serves the function of blocking the reverse rate of change of real power element for through faults (as highlighted in the red box in Figure 15) [27] [30].

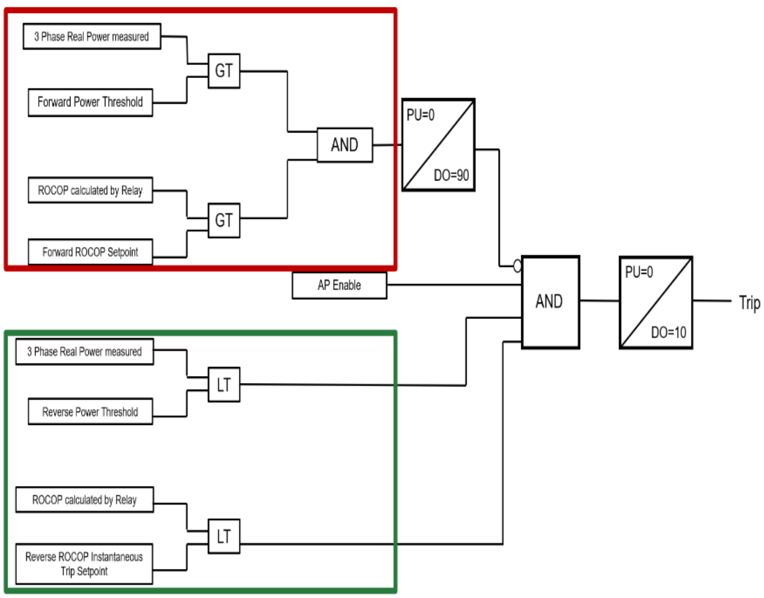


Figure 15: Proposed adaptive protection scheme logic diagram

If the calculated rate of change of real power is less than the reverse RoCoP setting and the reverse real power flow is lower than the reverse power pickup setting (as highlighted in the green box in Figure 15), with the adaptive protection scheme enabled, a trip command is generated as long as the blocking timer is not active. Figure 15 shows the logic diagram of the proposed AP scheme.

The time interval for RoCoP was set at 100ms (6 cycles). For RoCoP calculation, the following calculation is implemented.

[2] Forward direction represents positive flow of power from the primary feeder through the network protector towards the secondary network. Negative power flow represents reverse power flow, i.e., power flowing from the secondary network through the network protector towards the primary feeder.

$$RoC\ of\ Power = \frac{Power\ Flow_i\ -\ Power\ Flow_{i-1}}{Time\ Interval}$$

where,
$Power\ Flow_i$ = Most recent real power flow measurement
$Power\ Flow_{i-1}$ = Power flow measurement at previous calculation interval
$Time\ Interval$ = Defined to be 100ms

The settings for the forward and reverse power and rate of change of power thresholds were calculated based on the simulation performed for the secondary networks under test. The settings were adjusted based on the maximum expected DER penetration level on the secondary network. During pre-deployment testing, the DER output was varied from zero to 200% of the maximum expected load on the circuit and the scheme's performance was evaluated.

2.4.5.1. Key Points

All logic development and testing were performed by EPRI using a protection relay and not a network protector due to ease of availability. Network protectors do not have the capability to support custom logic unlike modern microprocessor-based protection relays; therefore, the adaptive protection logic needs to be included in the firmware of the network protector whereby it can be turned ON or OFF and the corresponding protection settings can be programmed for appropriate operation. To that end, it is necessary to include the network protector manufacturer when planning to adopt this scheme so that the equipment manufacturer can help set this up for success.

Though cookbook settings may become apparent over time, currently it is recommended that studies be performed to determine the appropriate settings for the rate of change of power thresholds based on the level of expected penetration.

EPRI is working with one manufacturer to test the logic for the adaptive protection scheme within their hardware. The vendor is encoding the logic within the firmware for the network protector and testing the scheme. Their testing showed similar results to those obtained by EPRI when using an off the shelf microprocessor-based protection relay.

2.4.6. Pre-Deployment Laboratory Testing

Testing of adaptive protection solutions involved both positive testing and negative testing. Positive testing involves replicating the intended faults, logic conditions, and disturbances and assessing whether the scheme meets key performance metrics such as fault detection, trip time, and so on. Negative testing of the scheme focuses on replicating other grid conditions, disturbances, logic conditions, and system failures to verify correct response – typically that the scheme does not trip or otherwise behave in an undesired manner.

The test procedures should be developed to assess performance for all permutations of internal and external logical states associated with the relays and controllers that are part of the protection scheme. This ensures there is no logic condition which could result in unexpected behavior, inconsistent behavior, or the relay entering an unstable or non-responsive state.

The testing requirements determined in Figure 12 identify the simulations that need to be performed to test the performance of the scheme. These studies use phasor-domain and time-domain simulations to determine expected grid behavior. The output from these simulations is then converted to voltages, currents, and binary signal status which can be replayed through the relay or controller in the lab to evaluate performance. Figure 16 shows how the test would be setup to include the hardware in the loop. This approach is used both for pre-deployment testing and/or in the substation or the field during commissioning. Two types of simulations are usually used – stepped-event simulations and transient simulations, depending on the identified need [29].

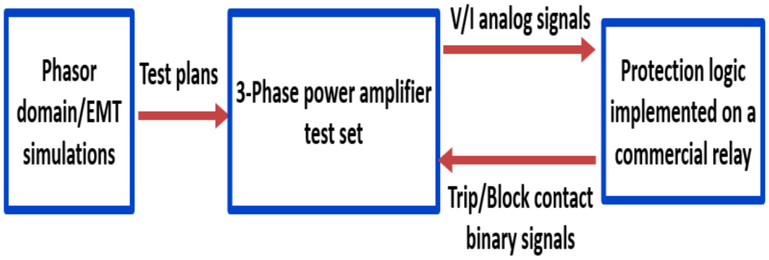


Figure 16: Information flow diagram of the testing setup

At a high level, the pre-deployment lab testing uses the following approach:

- Verify protection element operation - such as voltage and current protection pickup threshold accuracy – for the adaptive protection scenario.
- Verify adaptive protection hardware solution by replaying disturbances.
- Fault and non-fault disturbances and events are selected on a site-specific basis, but are expected to include:
    - Balanced and unbalanced short circuit events – momentary, transient and permanent feeder faults as well as transformers, cable, and DER faults
    - Fault location, isolation, system restoration (FLISR) schemes
    - Unbalanced grid conditions
    - Broken conductor faults and high-impedance faults
    - Transformer energization and cold-load pickup
    - Bulk system frequency events, bulk system auto reclosing (phase jumps), bulk system islanding
    - Inadvertent islanding of DER
    - Distribution grid instantaneous and time-delayed reclosing
    - Loss of communications; loss of potential; temporary interruption of power supply

2.4.7. Commissioning and Installation Testing

Once the scheme is ready to be deployed and settings have been developed for a specific site, the final step before the scheme can be put in service is commissioning and installation testing. Though the process for the testing is similar to pre-deployment laboratory testing, during installation testing, the actual equipment that will be put in service is used to perform the tests.

The relays and controllers are programmed with the settings determined for the particular site and test cases are chosen based on the simulations that were performed to determine the settings. These tests are then performed on the equipment that is to be put in service following successful commissioning. Where feasible, the entire scheme should be tested as a complete system instead of performing tests on individual components of the system, as may have been performed during testing in the laboratory. E.g., the test may involve injecting voltages from the secondary terminals of the voltage transformer, currents from the secondary terminals of current transformers, and the tripping signal actually tripping the breaker in the field. When communication-based schemes are used, those should also be included as part of the test. If SCADA can remotely enable or disable the scheme, these communication signals should also be tested as part of the commissioning process. Once again, both positive and negative testing should be performed to ensure the scheme behaves as expected for all tested cases.

On successful completion of all testing, the primary equipment can be energized, and the scheme can be placed in service. It is good practice to analyze events once they occur after the scheme is put in service. This allows us to validate the performance of the scheme to real world events as they occur on the system and determine if any tweaks or modification need to be made to the scheme to ensure appropriate operation under a wide variety of system conditions.

As stated previously, keeping schemes simple ensures that the likelihood of errors and mistakes is low. The more complex the scheme the more involved, complicated, and tedious the commissioning testing process to ensure that the installation has been done appropriately.

3. Significant Accomplishments and Conclusions

3.1. Thrust 1- Model development, testing and validation and commercialization

3.1.1. Challenges:

- Collecting field and system events data of interest from plant owners and utilities
- Neither IEEE 1547-2018 nor IEEE P2800 certified inverters were currently available in the marketplace; UL 1741SB certified inverters for the former were not available until much later into the project
- Inadequate laboratory facilities to conduct some types of specialized tests
- Getting vendors to adopt validated models into their software tools

3.1.2. Key milestones & achievements

At the end of the project, the following milestones were achieved:

- Developed a sophisticated inverter test plan (see info box) and selected inverters representative of the North American marketplace
- EPRI tested 3x retail- and commercial-scale inverters from which 2x conform with IEEE Std 1547™-2018 and are UL 1741 Supplement B certified.
- NREL tested 2x utility-scale inverter capable of supporting compatibility with IEEE Std 2800™-2022.
- Developed the first generic electromagnetic transient (EMT) model for a solar PV plant conforming with technical minimum capability and performance requirements specified in IEEE Std 2800™-2022.
- Proposed and implemented improvements for existing generic models of IBR units, IBR plants, and aggregated feeders for positive sequence, short-circuit, harmonic, and quasi static time series analysis.
- Produced reference responses for comparison with validated and verified IBR plant models in IEEE Std 2800™-2022 and P2800.2 conformity assessment.

3.1.3. Conclusion

The developed, tested and validated generic models can be useful today and in future. Specifically, it can be used for transmission planning, which entails stability assessments, expansion planning, as well as determination of future IBR interconnection requirements like GFM performance. It can also be used to support interconnection screens, screening for potential insufficiency of IEEE 2800 technical minimum requirements and also to support conformity assessment. This will in turn allow transmission planners adequately communicate to developers the expected IBR plant

capability and performance. Finally, the generic models can help create reference response to compare OEM models with. The project significantly contributed to, and accelerated, the ongoing standardization and model-based representation & verification of IBR response.

3.2. Thrust 2- design, testing, and commissioning of adaptive protection schemes for high penetration of DER

3.2.1. Challenges

- Getting utility partners to allow field demonstration on their site and system due to perceived customer impacts
- Utilities not allowing project team to test new protection schemes on the spot network. Instead, APS implementation on spot network was limited to the network protector manufacturer's OEM' tests.
- Several changes in the site/location and system used for microgrid field demonstration

3.2.2. Key milestones and achievements

- Identified gaps in common distribution protection schemes and analyzed how adaptive protection schemes can improve the integration of DERs into distribution systems
- Designed new APS by use of improved DER models for three common distribution systems: a radial feeder, a meshed network, and a microgrid
- Modeling & hardware-in-the-loop (HIL) testing of the three developed adaptive protection schemes
- Demonstrated the effectiveness and selectivity of the APS to prepare for field deployment
- Field demonstration for radial distribution feeder and microgrid adaptive protection schemes

3.2.3. Conclusions

This methods and approach for the adaptive protection thrust summarized in this document explains the general process that was followed in the design, installation, and commissioning of adaptive protection schemes for radial distribution feeders, microgrids, and low voltage meshed secondary networks to allow them to host higher penetrations of DER. The various sections documented the protection schemes associated with each of these three types of distribution systems. The same design process can be used to develop adaptive protection schemes for other applications as well.

A primary takeaway from the process is that pre-design planning plays an important role in determining what the expected outcome of the scheme should be. Also, it is recommended that thorough testing be performed on initial applications of these schemes so that any underlying issues can be quickly identified and rectified. To keep testing times reasonable and obtain actionable results from testing, engineers should strive to keep these schemes simple. Complexity increases risks associated with settings errors, equipment failures, improper design, and inadequate testing. Once pilot projects provide acceptable performance, these schemes can then be rolled out more widely without the need for extensive laboratory testing. Commissioning and installation testing are always essential since they test the scheme using the actual equipment that will be deployed at a particular site.

The project significantly contributed to the innovation of adaptive protection solutions analysis and applications for scalable and reliable integration of DERs into distribution systems.

4. Path Forward

4.1. Future Research – Thrust 1

The presented research significantly advanced the capabilities and validity of generic models. It also documented new adaptive protection schemes and their field demonstration. However, model development, improvements, and validation are a ongoing processes that is also closely related to continued improvement of technical minimum capability and performance requirements for IBRs as shown in Figure 17. Therefore, future research should strive for further characterizing IBR responses via lab testing and field measurements, validate and improve generic as well as OEM black-box models, and inform ongoing industry working groups with related scopes.

The following sections list some potentially valuable future research activities.

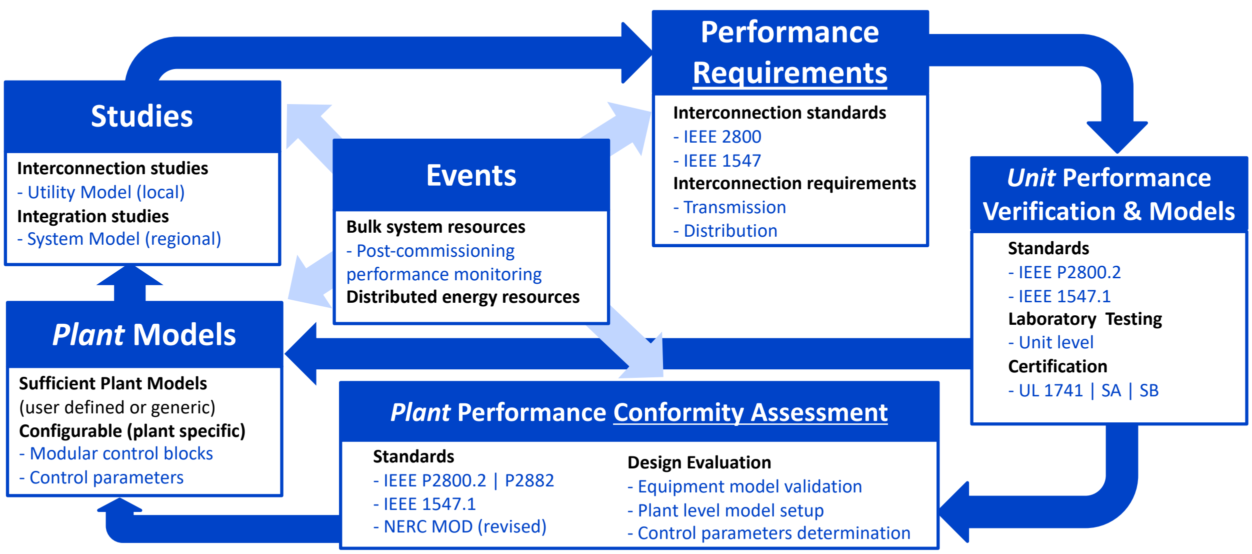


Figure 17: Continuation Model Development, Improvement, and Validation of Inverter-Based Resources

4.1.1. Resource Characterization

Future resource characterization research could include:

- Testing of legacy IBR and DER units to assess and document capability limitations (e.g., for FERC Order 901 directed NERC PRC-029 Implementation Plan)
- Update of the developed inverter test plan to address GFM responses (UNIFI)
- Testing of GFM inverters (UNIFI)
- Continue with field data collection and analysis, including sufficiently detailed IBR plant data (e.g., to inform NERC MOD-026/027 revisions)

4.1.2. Modeling

Future model development, improvement, and validation related research could include:

- Validate OEM black-box models

- Assess conformity of inverters using OEM black-box models
- Investigate what could be recommended as reasonable EMT accuracy requirements to promote informative annex to normative language in future revisions of IEEE P2800.2

4.1.3. Vendor and Industry Engagement

Vendor and industry engagement of future research could strive to:

- Revise IEEE 2800 to remove barriers to, and to possibly include optional capability and recommended performance specifications for GFM response
- Inform future revisions to NERC reliability standards like PRC-028, PRC-029, PRC-030, MOD 026/027, etc.

The following EPRI research activities may continue to investigate the proposed future research for various types of models:

- Quasi State steady state study models
    - PS174A Grid Impact Analysis of DER
    - PS200E Analytics for Operations and Planning
- Steady-state short circuit study models
    - PS173A Modeling and Analytics for Emerging Technologies
    - PS200D Protecting the Modern Distribution Grid
- Fundamental frequency/phasor-domain study models
    - PS173A Modeling and Analytics for Emerging Technologies & DER
    - PS40A Model Development, Validation, and Management
- Electromagnetic transient study models
    - PS173A Modeling and Analytics for Emerging Technologies
    - PS40D Special Assessments Supporting Transmission Planning
    - PS40A Model Development, Validation, and Management
- Power quality/harmonic study model
    - PS40D Special Assessments Supporting Transmission Planning
- Adaptive protection
    - PS200D Protecting the Modern Distribution Grid

4.2. Future Research – Thrust 2

Future work could include the pilot deployment of the various adaptive protection schemes on multiple systems to validate their performance in the real world. For the secondary network based protection scheme to increase DER penetration, additional work would involve identifying additions to the scheme to incorporate three-phase reactive power measurements to supplement the algorithm developed as part of the work so far to determine if implementation can be improved, specifically for meshed networks. Working with DMS vendors to incorporate automating the decision logic proposed for the radial feeder adaptive protection scheme would be the logical next step for the research. This would remove the burden placed on the operator to identify when to manually send the settings group change commands as DER generation levels change, allowing for more granular control of the scheme.

5. Products

5.1. Accepted Manuscripts of Journal Article

OSTI ID	Article Title	Author(s)	DOI (if applicable)	Journal Name	Volume and Page Number	Publication Date
1817776	Analyzing Impact of DER on FIDVR - Comparison of EMT Simulation of a Combined Transmission and Distribution Grid with Aggregated Positive Sequence Models	Deepak_Ramasubramanian; Papiya_Dattaray; Mobolaji_Bello; Jens_C._Boemer; Anish_Gaikwad	https://doi.org/10.1016/j.epsr.2021.107534	Electric Power Systems Research	201	2021
108616	Parameterization of Generic Positive Sequence Models to Represent Behavior of Inverter Based Resources in Low Short Circuit Scenarios	Deepak_Ramasubramanian; Xiaoyu_Wang; Sachin_Goyal; Manjula_Dewadasa;Yin_Li; Robert_J._O'Keefe; Peter_F._Mayer	https://doi.org/10.1016/j.epsr.2022.108616	Electric Power Systems Research	213, 108616	2022,

5.2. Conference Proceedings, Papers, Presentations

OSTI ID	Presentation, Paper Title	Author/ Speaker	DOI (if applicable)	Conference Name	Conference Product Type (paper, proceeding, presentation, other)	Conference Date
	Net load vs distinct DER representation for accurate transmission planning analysis	Deepak Ramasubramanian		IEEE PES General Meeting 2020	presentation	2020
	Use of T&D co-simulation to evaluate impact of load and DER on the bulk power system	Deepak Ramasubramanian, Papiya Dattaray, Parag Mitra		IEEE PES General Meeting 2020	presentation	2020
	EPRI Experience with DER Impact Studies	Deepak Ramasubramanian, Maryclaire Peterson, Jens C. Boemer, Jayanth Ramamurthy, Sharma Kolluri		IEEE PES General Meeting 2020	presentation	2020
	Comparison of aggregated DER representation with co-simulation	Deepak_Ramasubramanian; Parag_Mitra		IEEE PES General Meeting 2021	paper	7/25/2021

	EMT in Transmission Planning Research	Robert Arritt	https://www.emtp.com/support/technical-presentations/view?id=859&title=EMTP%20in%20Transmission%20Planning%20Research&type=During%20this%20presentation,%20a%20few%20examples%20of%20the%20use%20of%20EMTP%20in%20transmission%20level%20planning%20research%20will%20be%20discussed.	IBR (Inverter-Based Resources) - Day 4	paper	9/3/2021
	Bulk System Impact of DER and Loads using T&D Cosimulation and Aggregate models	Papiya_Dattaray; Deepak_Ramasubramanian; Parag_Mitra; Jens_C._Boemer; Mobolaji_Bello; Anish_Gaikwad	10.1109/ISGTEurope52324.2021.9640042	IEEE ISGT Europe 2021	paper	10/18/2021
	Harmonics Modeling in OpenDSS	Roger Dugan	https://sourceforge.net/p/electricdss/code/HEAD/tree/trunk/Version8/Doc/OpenDSSHarmonicsSolution.docx	Open DSS User Page on SourceForge.net	paper	5/12/2022
1889204	Proposal for modifications to DER_A	Deepak Ramasubramanian, Pouyan Pourbeik, Jens Boemer	https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Proposal%20for%20modifications%20to%20DER_A.pdf&action=default&DefaultItemOpen=1	WECC REMWG/MVS Meeting, May 16, 2022	presentation	5/16/2022

1889203	Proposal for New Plant controller and electrical controller	Deepak Ramasubramanian, Pouyan Pourbeik, Jens Boemer	https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Memo_RES_Modeling_Updates_For_New_Plant_and_Electrical_Controls_051322.pdf&action=default&DefaultItemOpen=1	WECC REMWG/MVS Meeting, May 16, 2022	paper	5/13/2022
	Model regc_c preliminary evaluation	Juan J. Sanchez-Gasca Shruti D. Rao Deepak Ramasubramanian	https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/2022-05-18%20MVS%20Mtg%20regc_c%20tests_%20Sanchez-Gasca.pdf&action=default&DefaultItemOpen=1	WECC REMWG/MVS Meeting, May 16, 2022	presentation	5/18/2022
	DER Inverter Testing for Generic Model Development and Improvement	Jens Boemer Aminul Huque	https://epri.box.com/s/w6wbrdftlqfkwdmslvkw5x1qrsb8immk	IREC Forum for Inverter Grid Integration Issues (FIGII) on May 20, 2022	presentation	5/20/2022
	Inverter Current Limit Logic based on the IEEE 2800-2022 Unbalanced Fault Response Requirements	W. Baker, M. Patel, A. Haddadi, E. Farantatos, J. Boemer	https://ieeexplore.ieee.org/abstract/document/10252528	*IEEE Power Engineering Society General Meeting*	paper	2023
	Validation of the Fault Ride-Through Response of a Generic EMT Inverter Model by	W. Baker, D. Ramasubramanian, A. Huque, J. Boemer, V. Gevorgian, P. Koralewicz, E. Mendiola	https://ieeexplore.ieee.org/abstract/document/10252344	*IEEE Power Engineering Society General Meeting*	paper	2023

	Laboratory Testing					
	A Voltage Controlled Overcurrent-based Adaptive Protection Scheme for Microgrids	A. Padmanabhan, T. K. Barik, S. McGuinness, M. Bello, A. Zamani M. Sheikholeslami		2024 77th Annual Conference for Protective Relay Engineers (CPRE)	paper	2024
	Multiple Setting groups based Adaptive Protection for Radial Distribution Feeder	T. K. Barik, A. Padmanabhan, S. McGuinness, M. Bello P. Y. Chan		2024 77th Annual Conference for Protective Relay Engineers (CPRE)	paper	2024
	Adaptive Protection for Meshed Secondary Networks using Network Protectors	T. K. Barik, A. Padmanabhan, S. McGuinness, M. Bello, R. E. Uosef, F. Doherty, D. Khubani, C. Jones J. Foglio		2024 77th Annual Conference for Protective Relay Engineers (CPRE)	paper	2024
	Low-Voltage Network Protection with DER	A Padmanaban		*IEEE Power Engineering Society General Meeting*	paper	2024

5.3. Technical Reports

OSTI ID	Report Title	Author(s)	EPRI weblink
1889183	Guidelines for Field Measurements for Model Validation	W. Baker D. Ramasubramanian B. Arritt A. Gaikwad A. Huque	https://epri.box.com/v/pvmod-milestone-1-2-1
1889185	Data Collection and Analysis	W. Baker D. Ramasubramanian R. Bauer	https://epri.box.com/v/pvmod-milestone-2-2-1
1889186	Identification of Test Needs	A. Huque W. Baker	https://epri.box.com/s/s4guzh4bwfk6ikoksxeig65keaodke4f
1889187	Lab Testing of Inverters -100 kW and below	W. Baker A. Huque J. Shi N. Bilakanti B. Arritt	https://epri.box.com/s/nx59u95bmj5kr1jmuduu88q6k9426bf6
1889202	IBR short circuit model considerations for VCCS tabular model	A. Haddadi	https://wprcarchives.org/wp-content/uploads/2024/03/Haddadi_Aboutaleb_Inverter-Based-Resource-Short-Circuit-Model-%E2%80%92-Considerations-for-VCCS-Tabular-Model_20231012.pdf
1889201	Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants. PV-MOD Milestone 2.7.3.	W. Baker D. Ramasubramanian	https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=82135
1889200	User defined EMT inverter model reference performance, utility scale	W. Baker D. Ramasubramanian B. Arritt	https://epri.box.com/v/pvmod-milestone-2-6-3
1889199	Industry Assessment and Initial Adaptive Protection System Design PVMOD milestones 2.5.1, 2.5.2 and 2.5.3	S. McGuinness A. Padmanabhan T. Barik A. Ovalle	https://epri.box.com/v/pvmod-milestone-2-5-1---3
1889197	Data Collection and Analysis	W. Baker D. Ramasubramanian R. Bauer [NERC]	https://epri.box.com/s/huvfwyillxbykwo7kqtj1fqbru207b78
1889191	Adaptive protection opportunities, gap assessments, and designs	S.McGuinness A. Ovalle A. Kelly	https://epri.box.com/s/g71qc49zwhimaiwvdfx3msxmkg3q99v7
1889190	Development and Refinement of DER Steady State Model for QSTS Analysis	D. van Zandt P. Radatz Y. Ma W. Ren	https://epri.box.com/s/54273s33zp3om4rcodu4cliyw0mgjy8v

		J. Peppanen M. Rylander	
1889189	PV and Dynamic Load Modeling Update	W. Baker B. Arritt D. Ramasubramanian A. Haddadi E. Farantatos A. Gaikwad P. Pourbeik [PEACE]	https://epri.box.com/s/k7i3vvjzgmy9x1nz2bnmibuebmhzpl1r
1889188	State of the Art Gap Analysis of PV Models	W. Baker D. Ramasubramanian A. Haddadi A. Gaikwad E. Farantatos P. Radatz W. Ren D. van Zandt M. Rylander	https://epri.box.com/s/6atp6lrjwjw47xrtz04mndyh9pbd35s1
1894588	Validation of Harmonic Models for PV Inverters -PV-MOD Milestone 2.8.2	B. Arritt R. Dugan	https://epri.box.com/v/pvmod-milestone-2-8-2
	Validation of short circuit Models for PV Inverters PVMOD milestone 2.8.3	J. Boemer A. Haddadi E. Farantatos	https://epri.box.com/v/pvmod-milestone-2-8-3
	Applicability of T&D Co-Simulation for Accurate Capture of Load and DER Dynamic Behavior. EPRI, Palo Alto, CA: 2021. 3002019452.	P. Dattaray D. Ramasubramanian P. Mitra M. Bello J. Boemer A. Gaikwad	https://www.epri.com/research/products/000000003002019452
	Applicability of T&D Co-Simulation for Accurate Capture of Load and DER Dynamic Behavior. EPRI, Palo Alto, CA: 2021. 3002021940.	P. Mitra D. Ramasubramanian M. Bello J. C. Boemer A. Gaikwad	https://www.epri.com/research/products/000000003002021940
	Analyzing the Impact of Aggregated DER Behavior on Bulk Power System Performance: A Summary of Three Case Studies. EPRI. Palo Alto, CA: 2021. 3002019445.	D. Ramasubramanian W. Baker A. Gaikwad J. Boemer	https://www.epri.com/research/products/000000003002019445
	IEEE 1547-2018 DER Model. Version 1.0. EPRI. Palo Alto, CA: December 2021. 3002021694	Y. Ma A. Huque J. Anandan W. Ren W. Wang D. Van Zandt B. Seal P. Radatz	https://www.epri.com/research/products/3002021694
	Differentiating between Applicability of Simulation Domains and Inverter Mathematical Models in these	Deepak Ramasubramanian, Wes Baker, Parag Mitra, Sudipta Dutta, and Anish Gaikwad	https://www.epri.com/research/products/000000003002025063

	Domains. EPRI. Palo Alto, CA: 2022.3002025063.		
	Aggregated Distributed Energy Resource Model Improvements and Validation. PV-MOD Milestone 2.7.7. EPRI. Palo Alto, CA: 2022. 3002021939.	D. Ramasubramanian J. Boemer Pouyan Pourbeik	https://www.epri.com/research/products/000000003002021939
	IEEE 1547-2018 Open Source DER (OpenDER) Model: Version 2.0. EPRI, Palo Alto, CA: 2022. 3002025583	Y. Ma, A. Huque, J. Anandan, W. Ren W. Wang, D. Van Zandt, B. Seal, P. Radatz	https://www.epri.com/research/products/000000003002025583
	Distributed Energy Resource Model Verification Framework: Second Edition. EPRI, Palo Alto, CA: 2022. 3002024404	Y. Ma, P. Radatz, I. Alvarez Fernandez, A. Huque, M. Rylander W. Wang, W. Ren, D. Van Zandt	https://www.epri.com/research/products/000000003002024404
	Verification of DER Models in Commercial Distribution Planning Tools: Synergi 6.16.0 (February 2022). EPRI, Palo Alto, CA: 2022. 3002025699. (only accessible by selected EPRI members)	Y. Ma, P. Radatz, I. Alvarez Fernandez, A. Huque	https://www.epri.com/research/products/000000003002025699
	Verification of DER Models in Commercial Distribution Planning Tools: CYME 9.2.2 (March 2022). EPRI, Palo Alto, CA: 2022. 3002025584. (only accessible by selected EPRI members)	Y. Ma, P. Radatz, I. Alvarez Fernandez, A. Huque, M. Rylander	https://www.epri.com/research/products/000000003002025584
	Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants (PVMOD-EMT-IBR) v1.0 Beta. EPRI, Palo Alto, CA: 2023. 3002025889	D. Ramasubramanian	https://epri.box.com/v/pvmod-milestone-2-7-3
	Model User Guide for Generic Renewable Energy System Models: EPRI, Palo Alto, CA:2023. 3002027129	D. Ramasubramanian	https://www.epri.com/research/products/000000003002027129
	Concepts of Model Quality Testing for Inverter Based Resources	J. Boemer D. Ramasubramanian M. Bello	https://www.epri.com/research/products/000000003002027506
	Adaptive Protection Success Merits, Designs, and Test Procedures. EPRI. Palo Alto, CA: 2023. PV-MOD Milestones 2.9.1 and 2.9.2	S. McGuinness, A. Padmanabhan, T.K. Barik, A. Ovalle	https://epri.box.com/v/pvmod-milestone-2-9-1---2

	Adaptive Protection field demonstration report. EPRI. Palo Alto, CA: 2024. PV-MOD Milestones 3.11.1/2/3	S. McGuinness, A. Padmanabhan, T.K. Barik, M Bello	https://epri.box.com/s/epq32lp8vxv39ww648vwm3eisjyhs9j3
	Adaptive Protection guidebook. EPRI. Palo Alto, CA: 2024. PV-MOD Milestones 3.11.4	S. McGuinness, A. Padmanabhan, T.K. Barik, M Bello	https://epri.box.com/s/tgzg92t3049t875wgsrl3bgn4het5rs6
	Host AP industry workshop, PVMOD milestone 3.11.5. presentation at IEEE PES GM	A Padmanaban	https://epri.box.com/s/jx4yu29h91uw5p9sa3zfbi18697ozhvl

5.4. Websites

URL	Description of Website	Description of Project Information
https://www.epri.com/pvmod	Adaptive Protection and Validated MOdels to Enable Deployment of High Penetrations of Solar PV (PV-MOD)	Public website on epri.com.
https://epri.box.com/s/lsgimk795632lk59oowq49ogl1n5x42x	Inverter Dynamic Characterization	Member-only BOX folder for supplemental project materials.
https://epri.box.com/v/DOE-PV-MOD-DAWG (password: PVMODDAWG)	Distribution Advanced PV Model Working Group (DAWG)	Public BOX folder for DAWG materials
https://epri.box.com/v/PV-MOD-Public (password: PVMODPublic)	Adaptive Protection and Validated Models to Enable Deployment of High Penetrations of Solar PV (PV-MOD)	Public BOX folder for PV-MOD materials

6. Project Team and Roles

Organization	Resources
EPRI (lead).	Jens Boemer, Principal Investigator* Mobolaji Bello, Project Manager Deepak Ramasubramanian, IBR and DER Modeling for TP Lead* Aboutaleb Haddadi, Short-Circuit Modeling SME* Vishal Verma, Transmission Modeling SME Tapas Barik, Adaptive Protection Support Manish Patel, IEEE and NERC Standards Marguerite Holmberg, Transmission Modeling SME Anish Gaikwad, Transmission Vendor Engagement Lead Parag Mitra, Load Modeling for TP SME Aadityaa Padmanabhan, Adaptive Protection Support Evangelos Farantatos, Short-Circuit Modeling SME Sean McGuinness, Adaptive Protection Lead Andres Ovalle, Adaptive Protection SME Aminul Huque, Testing Lead Yiwei Ma, DER Modeling Nishant Bilakanti, DER Testing Devin van Zandt, Vendor Engagement Lead Wei Ren, Distribution Modeling SME Matt Rylander, Distribution Modeling & QSTS SME Lindsey Rogers, Distribution Ops & Planning Manager Erin Jones, Government Contracts Lead
NREL (FFRDC)	Vahan Gevorgian Przemyslaw Koralewicz Emanuel Mendiola
ORNL (FFRDC)	Travis Smith (no longer with ORNL)
Quanta Technology. (Subcontractor)	Amin Zamani
PEACE® (Subcontractor)	Pouyan Pourbeik
Terabase (Subcontractor)	Mahesh Morjaria, Field Measurements Support Rajni Burra, Modeling Support
PPL, ConEd, CoOp in North Carolina, NERC (Utility partners)	Too many to mention

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[5] Short Circuit Models for T&D Analysis: PV-MOD Milestone 2.7.4. EPRI, Palo Alto, CA: 2022.

[6] Validation of Short Circuit Models for PV Inverters: PV-MOD Milestone 2.8.3. EPRI, Palo Alto, CA: 2022

[7] "Impact of Renewables on System Protection" at PSS@CAPE User Group Meeting, June 20-24, 2022, Ypsilanti, Michigan. [Online; refer to Part 3, IBR Short Circuit Model Considerations for VCCS Tabular Table on slides 34ff.]

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[9] Quick Insight Brief: Harmonic Considerations for Inverter-Based Resource Installations. EPRI. Palo Alto, CA: 2022. 3002025217

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[23] Applications of Adaptive Protection on the Current and Future System: Towards the Development of Automated Adaption Protection Schemes for DER. EPRI, Palo Alto, CA: 2019. 3002015452.
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[25] Industry Assessment and Initial Adaptive Protection System Design: PV-MOD Milestones 2.5.1, 2.5.2, and 2.5.3. EPRI, Palo Alto, CA: 2022
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