WARNING:
Please read the License Agreement on the back cover before removing the Wrapping Material

Validation of DER Interconnection Hardware – Feeder Management Relay

1008858

Validation of DER Interconnection Hardware – Feeder Management Relay

1008858

Technical Update, August 2004

EPRI Project Manager

W. Steeley

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI PEAC Corporation

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520. Toll-free number: 800.313.3774, press 2, or internally x5379; voice: 925.609.9169; fax: 925.609.1310.

CITATIONS

This document was prepared by

EPRI PEAC Corporation
942 Corridor Park Blvd.
Knoxville, TN 37932

Principal Investigator or Author
R. Langley
E. Hubbard

This document describes research sponsored by EPRI.

The publication is a corporate document that should be cited in the literature in the following manner:

Validation of DER Interconnection Hardware – Feeder Management Relay, EPRI, Palo Alto, CA: 2004.1008858.

PRODUCT DESCRIPTION

An EPRI-sponsored survey examined the state of interconnection hardware and practices used in the connection of distributed generation and storage to the electric power system. The assessment reviewed the adequacy of these products and practices to meet expected future and widespread distributed energy resources (DER) applications. From this technology assessment, gaps were identified. This project goes on to test the performance of several available interconnection products used for protective relaying and paralleling functions. The results of laboratory testing are detailed in this reported.

Results and Findings

The multifunction protective relay that was evaluated during this phase of the project performed as expected. In most test cases, the performance accuracies were within the manufacturer's specifications. Analysis of the test results revealed no apparent or potential compatibility issues with existing and developing DER interconnection safety and application standards, such as IEEE 1547 or UL 1741.

Challenges and Objectives

This report was composed for people involved in the interconnection of DER to the electric power grid. By understanding the way interconnection devices perform during electrical disturbances, these users will be able to better select and install particular interconnection devices. The objectives of the project were:

- To provide input and feedback for the further development and enhancement of the DER test protocol developed during the 2002 project (SC-830) and to provide similar input and feedback to the developing IEEE 1547.1, *Draft Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources With Electric Power Systems*
- To conduct laboratory testing on inverters, multifunction relays, and paralleling switchgear currently available for DER applications

Applications, Values and Use

Relaying, disconnection, and fault-protection devices are used in nearly all installations to realize a safe and effective interconnect of DER. Some of the DER system designs also include paralleling and transfer switches, load control, and communication, which add cost for increased functionality. For all of these types of interconnection equipment, performance and cost are critical, which is one reason why many manufacturers of inverter-based DER are designing their interconnection and protection systems with "digitally emulated" protection relay functions. New DER technologies have led to new types and designs of interconnection equipment with limited field experience. Field experience, along with testing, is needed to ensure that interconnection equipment is compatible with pertinent interconnection standards such as IEEE 1547, UL 1741, and IEEE 929. Also, laboratory testing can lead to standard methods and application-specific test protocols. Results from consistent test procedures will eventually help to define appropriate requirements for certification of interconnection hardware.

EPRI Perspective

Compatible and economical connection of DER with the electrical power grid is a key to realizing the full value of DER. Relaying, disconnection, and fault-protection devices are used in nearly all installations to realize a safe and effective interconnect. Some of the DER system interconnection equipment also includes paralleling and transfer switches, load control, and communication, which add cost for increased functionality. For all of this interconnection equipment, performance and cost are critical. Field experience, along with testing, is needed to ensure that interconnection equipment is compatible with pertinent interconnection standards.

Approach

Specifications and performance claims were gathered on some of the latest interconnection technologies, including connection type, electrical ratings, and applications. To obtain this information, individual interconnection equipment companies were contacted based on a contacts database developed in 2001. From those contacts, information about new DER interconnection products that are available for testing was gathered. Samples were obtained from the manufacturers, and test plans were developed based on functional specifications and existing and emerging interconnection standards. Bench-top testing was performed on selected units at the EPRI PEAC Distributed Resources and Power Quality Test Laboratory. Individual hardware performance was reported to the manufacturer, and a summary of all test results was incorporated in separate EPRI reports for sponsors. This report summarizes the results of one of the interconnection hardware products tested during 2004.

Keywords

Distributed resource
Distributed generation
Interconnection hardware
Protection relay
Intertie relay
Paralleling switchgear

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

1.1 Background

Compatible and economical connection with the electrical power grid is a key to realizing the full value of distributed energy resources (DER). An EPRI-sponsored survey examined the state of interconnection hardware and practices used in the connection of distributed generation and storage to the electric power system. The assessment reviewed the adequacy of these products and practices to meet expected future and widespread DER applications and identify technology gaps. Results of the assessment are compiled in a published report, *Technology Assessment of Interconnection Products for Distributed Resources: Survey Results* (1001242). The results are intended to assist system engineers in understanding the availability, application, and relative cost of interconnection products.

Relaying, disconnection, and fault-protection devices are used in nearly all installations to realize a safe and effective interconnect. Some of the DER system designs also include paralleling and transfer switches, load control, and communication, which add cost for increased functionality. For all of these types of interconnection equipment, performance and cost are critical. New DER technologies, such as inverter-based DER systems used for fuel cells, photovoltaics, and microturbines, bring new types and designs of interconnection equipment with limited field experience. Field experience, along with testing, is needed to ensure that interconnection equipment is compatible with pertinent interconnection safety and application standards, such as IEEE 1547, UL 1741, and IEEE 929. Also, laboratory testing can provide valuable feedback and input during the development of standardized methods and application-specific test protocols, such as the developing IEEE 1547.1. Results from consistent test procedures can eventually be used to define appropriate requirements for certification of interconnection hardware.

1.2 Approach

Specifications and performance claims were gathered on some of the latest interconnection technologies, including connection type, electrical ratings, and applications. To obtain this information, manufacturers of interconnection equipment were contacted based on a contacts database originally developed in 2001 and expanded in 2002, 2003, and 2004. From this information and sponsor feedback, DER interconnection products that are available for testing were identified. Samples were obtained from the manufacturers, and test plans were developed based on functional specifications and existing and emerging interconnection standards. Bench-top testing was performed on selected units at the EPRI PEAC Distributed Resources and Power Quality Test Laboratory. Individual hardware performance was reported to the manufacturer, and a summary of all test results was incorporated into a series of EPRI reports for each product.

EPRI PEAC has developed test protocols and conducted laboratory testing on many critical utility devices and systems. Such tests have included performing full-scale system and bench-top testing, as were performed here on some of the latest multifunction relays currently available for DER applications. EPRI PEAC constructed a test fixture to facilitate bench-top and application-specific testing at the EPRI PEAC laboratory using an Omicron relay test set and injecting low-voltage signals into the current-transformer (CT) and potential-transformer (PT) connection points of the systems under test to evaluate compliance with IEEE 1547. Utilities do not always have such laboratory capability. Even if they do, budget constraints may prevent performing such thorough tests. In any event, a fair and unbiased evaluation of such critical interconnection equipment using the latest industry standards and guidelines as provided in this report is invaluable.

1.3 Objectives

The key objectives of this research and testing project are:

- To provide test experiences and feedback for the continued development and enhancement of DER test protocols for multifunction relays, paralleling switchgear, and controls used specifically for DER interconnection applications
- To conduct laboratory testing on some of the latest multifunction relays currently available for DER applications

1.4 Scope of Work

EPRI PEAC obtained test specimens of the multifunction relays from participating manufacturers. EPRI PEAC used a specially designed test fixture to facilitate bench-top testing at the EPRI PEAC laboratory in Knoxville, Tennessee. The test voltage and current waveforms were created using an Omicron relay test set. The small-signal tests were performed by injecting low-voltage signals into the CT and PT connection points of the systems under test to evaluate compatibility with the IEEE 1547 requirements.

1.5 Report Organization

Chapter 2 describes the test setup and approach used for evaluating the specific product under test. Chapter 3 details the test results, discussions, and observations. Appendix A provides the test protocol for distributed energy resources, SC-830, *Part 1 - Small-Signal Test Port Protocol,* prepared as part of this project. It covers protective relays used in grid connection of DER applications.

1.6 The Role of Interconnection Hardware Manufacturers

Manufacturers of DER interconnection products were invited to participate by submitting test specimens recommended for use in DER interconnection applications. Because the investigation was primarily focused on the new generation of interconnection products, new-generation products were requested. Recognized leading manufacturers indicated that they would participate and provided appropriate test specimens. These manufacturers also provided full documentation on their products to be tested and recommendations on the test setup. This collaboration has been key to the success of the project.

2

SMALL-SIGNAL TEST SETUP FOR EVALUATING DER INTERCONNECTION HARDWARE

2.1 Small-Signal Test Setup

The following sections describe the test setup designed for evaluating the performance of DER interconnection hardware using a small-signal (or secondary-injection) test methodology. The test stand, the test-signal generator, the data-acquisition system, and the small-signal tests are described in detail.

2.1.1 Test Stand

The relay was mounted in a 19-inch (48-cm) rack (test stand), as shown in Figure 2-1. The test stand includes relays, fault-indication lamps, relay outputs, and peripheral equipment (DC power supply, terminal strips, wiring, and so on). The relay was mounted and wired according to the manufacturer specifications and the requirements for the small-signal test setup. No PTs or CTs were required because the small-signal test methods are designed to permit testing at low voltage and current test levels (that is, 120 V and 5 A).

Figure 2-1
Small-Signal Test Setup

2.1.2 The Test-Signal Generator and Data-Acquisition System

The Omicron CMC 256-6 EP is a high-precision secondary-injection relay test set that is specifically designed to be used for the evaluation of protection relays, energy meters, and transducers (see Appendix B for specifications). The Omicron CMC 256 and the Omicron Test Universe software were used to create voltage and current signals to evaluate the relay. The test signals were created according to tests and signal properties described in Section 2.2 (also see SC-830 in Appendix A).

The CMC 256 has data-acquisition channels that were used to monitor the fault contacts of the relay during each test. Figure 2-1 shows the Omicron CMC 256 (in the foreground) with the test stand.

A three-phase set of source voltage signals was used to simulate the electric power system (EPS). Generally, the voltage test signals were generated with the following attributes:

- A positive phase sequence
- A secondary base voltage of 120 V (referenced phase-to-neutral)
- A 120° phase shift between the signals

A fourth voltage test signal was used to simulate the voltage at the distributed resource. With the exception of the synchronization tests, this test signal had exactly the same attributes (magnitude, frequency, and phase angle) as Phase A of the simulated EPS voltage test signals.

In addition to the EPS and DER-voltage test signals, a three-phase set of current test signals was used to simulate the EPS currents. Generally, the current test signals were generated with the following attributes:

- A positive phase sequence
- A secondary base current of 5 A
- A 120° phase shift between the signals
- All phase currents in-phase with their corresponding phase-to-neutral voltages (unity power factor) unless intentionally altered during testing

2.2 Selection of the Small-Signal Interconnection Tests and Test Points

The primary objectives of the small-signal testing were to develop and demonstrate a small-signal test methodology for evaluating DER interconnection hardware for compatibility with existing and developing interconnection standards—such as IEEE 929, IEEE 1547, and UL 1741—and to demonstrate the capabilities of several DER interconnection products.

To accomplish the objectives, a small-signal (secondary-injection) test protocol was developed for evaluating DER interconnection hardware (Appendix A contains the protocol in its entirety). The protocol was developed using the interconnection requirements and specifications found in the existing and developing DER interconnection standards, specifically IEEE 1547 and 1547.1.

After the test protocol was developed, the test points for evaluating the interconnection hardware were reviewed. The small-signal test points were chosen to coincide with specific points defined in the specifications and requirements in the 1547 standard. However, utility requirements vary. One reason for testing to the IEEE 1547 standard is that it will likely be used and referenced by electric utilities, end users, system integrators, state commissions, and other interested parties for interconnection applications of DER. Multiple test points were also chosen for each test, and preference was given to the magnitudes and clearing times defined by the 1547 standard. The specific test points are defined in the following sections, which describe and detail each small-signal test used to evaluate the multi-function protection relay.

2.2.1 Selection of the Ramp Rates (Magnitude Tests)

Each magnitude test requires a specific ramp rate (or slope) defined for the parameter under test. For example, an undervoltage magnitude test requires a voltage test signal that decreases in magnitude at a specified rate. The ramp rates were chosen to permit accurate, repeatable test results for the relay, as suggested in the test protocol (Appendix A). The ramp rates were selected based on the expected accuracy and time-delay setting of the protection parameter being tested. The ramp rates are listed in the following sections, which describe the test signals for each test.

2.2.2 Magnitude Tests – General Test Procedures

At the beginning of each magnitude test, the nominal voltage (120 V) and current (5 A) were applied to the relay for 5 seconds to allow it to reset and achieve steady-state operation. Next, the relevant test-signal characteristics (rms magnitude, frequency, and/or phase angle) were increased/decreased to levels that were within 10% of the trip settings. These levels were sustained for a time equal to two times the trip function's time-delay setting. Finally, the test signals were increased/decreased at the specified ramp rates for each test point until the relay had successfully tripped or the magnitude had exceeded the trip level by more than 10% of the trip setting.

During each test, the relay's fault contacts were monitored. At the point when the relay tripped (fault contacts changed states), the magnitude of the test parameter being evaluated (rms voltage, frequency, phase angle, power, and so on) was recorded. Five tests were completed for each test point. The average trip magnitude was computed, recorded, and compared to the manufacturer's stated accuracy. The test results were also analyzed to reveal potential compatibility issues with the application of DER interconnection hardware and DER interconnection standards in general.

2.2.3 Time Test – General Test Procedures

At the beginning of each time test, the nominal voltage (120 V) and current (5 A) were applied to the relay for 5 seconds to allow it to reset and achieve steady-state operation. Next, the relevant test-signal characteristics (rms magnitude, frequency, and/or phase angle) were increased/decreased to levels that were within 10% of the trip settings. These levels were sustained for a time equal to two times the trip function's time-delay setting. Finally, the test signals were instantaneously[1] increased/decreased to a magnitude that exceeded the trip level by 10% of the setting.

During each test, the relay's fault contacts were monitored. At the point when the equipment under test (EUT) tripped (fault contacts changed states), the clearing time was recorded.[2] Five tests were completed for each test point. The average operation time was computed, recorded, and compared to the manufacturer's stated accuracy. The test results were also analyzed to reveal potential compatibility issues with the application of DER interconnection hardware and DER interconnection standards in general.

1 The rise time, t_r, of the step function was less than 1% of the time-delay setting. See Appendix A for additional details.

2 For the time tests, the clearing time is defined as the length of time between the initiation of the step function and the point when the fault contacts had successfully changed states. The clearing time includes the time required for the relay to sense the fault condition and change the state of the fault contacts.

2.3 Small-Signal Tests

Thirteen different types of small-signal tests were performed on the multifunction protection relay. Each type of test consisted of three distinct test points (trip level and time-delay settings of the EUT). The tests included the following magnitude tests:

- Undervoltage
- Overvoltage
- Under-frequency
- Over-frequency
- Synchronization voltage difference
- Synchronization frequency difference
- Synchronization phase-angle difference

The tests also included the following time tests:

- Undervoltage
- Overvoltage
- Under-frequency
- Over-frequency

The characteristics of the test signals can be found in the following tables. Specifically, the ramp rates, trip levels, and time-delay settings are listed for each type of test and each test point. The magnitude and time-delay settings with a † denote values based on the IEEE 1547.

Table 2-1
Undervoltage Magnitude Test – Test Signal Characteristics

Undervoltage Trip Level	Undervoltage Trip Time Delay	Undervoltage Ramp Rate
88% (105.6 V) †	2.0 sec	0.038 V/sec
75% (90 V)	2.0 sec	0.038 V/sec
50% (60 V) †	2.0 sec	0.038 V/sec

Table 2-2
Undervoltage Time Test – Test Signal Characteristics

Undervoltage Trip Level	Undervoltage Trip Time Delay
50% (60 V)	0.2 sec†
50% (60 V)	1.0 sec
50% (60 V)	2.0 sec†

Table 2-3
Overvoltage Magnitude Test – Test Signal Characteristics

Overvoltage Trip Level	Overvoltage Trip Time Delay	Overvoltage Ramp Rate
110%† (132 V)	1.0 sec	0.075 V/sec
115% (138 V)	1.0 sec	0.075V/sec
120%† (144 V)	1.0 sec	0.075 V/sec

Table 2-4
Overvoltage Time Test – Test Signal Characteristics

Overvoltage Trip Level	Overvoltage Trip Time Delay
110% (132 V)	0.2 sec†
110% (132 V)	1.0 sec†
110% (132 V)	2.0 sec

Table 2-5
Under-Frequency Magnitude Test – Test Signal Characteristics

Under-Frequency Trip Level	Under-Frequency Trip Delay Time	Under-Frequency Magnitude Test Ramp Rate
0.2 Hz (59.8 Hz)	1.0 sec	0.005 Hz/sec
0.3 Hz (59.7 Hz)	1.0 sec	0.005 Hz/sec
0.7 Hz (59.3 Hz)†	1.0 sec	0.005 Hz/sec

Table 2-6
Under-Frequency Time Test – Test Signal Characteristics

Under-Frequency Trip Level	Under-Frequency Trip Delay Time
0.7 Hz (59.3 Hz)	0.2 sec†
0.7 Hz (59.3 Hz)	1.0 sec
0.7 Hz (59.3 Hz)	5.0 sec

Table 2-7
Over-Frequency Magnitude Test – Test Signal Characteristics

Over-Frequency Trip Level	Over-Frequency Trip Time Delay	Over-Frequency Ramp Rate
0.2 Hz (60.2 Hz)	1.0 sec	0.005 Hz/sec
0.5 Hz (60.5 Hz) †	1.0 sec	0.005 Hz/sec
1.0 Hz (61.0 Hz)	1.0 sec	0.005 Hz/sec

Table 2-8
Over-Frequency Time Test – Test Signal Characteristics

Over-Frequency Trip Level	Over-Frequency Trip Time Delay
0.5 Hz (60.5 Hz)	0.2 sec†
0.5 Hz (60.5 Hz)	1.0 sec
0.5 Hz (60.5 Hz)	5.0 sec

Table 2-9
Synchronization Voltage Difference Test – Test Signal Characteristics

Distributed Resource Voltage	Synchronization Voltage Difference Setting	Synchronization Voltage Ramp Rate
Low (Low to Nominal)	10.0 V†	0.075 V/sec
	5.0 V†	0.075 V/sec
	3.0 V†	0.075 V/sec
High (High to Nominal)	10.0 V†	-0.075 V/sec
	5.0 V†	-0.075 V/sec
	3.0 V†	-0.075 V/sec

Table 2-10
Synchronization Frequency Difference Test – Test Signal Characteristics

Distributed Resource Frequency	Synchronization Frequency Difference Setting	Synchronization Frequency Ramp Rate
Low (Low to Nominal)	0.3 Hz†	0.0025 Hz/sec
	0.2 Hz†	0.0025 Hz/sec
	0.1 Hz†	0.0025 Hz/sec
High (High to Nominal)	0.3 Hz†	-0.0025 Hz/sec
	0.2 Hz†	-0.0025 Hz/sec
	0.1 Hz†	-0.0025 Hz/sec

Table 2-11
Synchronization Phase-Angle Difference Test – Test Signal Characteristics

Distributed Resource Phase Angle	Synchronization Phase-Angle Difference Setting	Synchronization Phase-Angle Ramp Rate
Lagging (Lagging to Unity)	20.0°†	0.5°/sec
	15.0°†	0.5°/sec
	10.0°†	0.5°/sec
Leading (Leading to Unity)	20.0°†	-0.5°/sec
	15.0°†	-0.5°/sec
	10.0°†	-0.5°/sec

3
TEST REPORT: GE MULTILIN SR760 FEEDER MANAGEMENT RELAY SYSTEM

3.1 Device Description

3.1.1 General Description[3]

The GE SR760 Feeder Management Relay is a microprocessor-based unit designed for the management and protection of distribution feeders, buses, transformers, and transmission lines. It provides protection, monitoring, and control with local and remotes capabilities. The front panel displays warning lights and urgent messages that can be viewed with the push of a button. Figure 3-1 is a photo of the GE SR760.

Figure 3-1
The General Electric SR760 Feeder Management Feeder Relay

3.1.2 Key Features[3]

3.1.2.1 Features and Benefits

- Virtual and expandable I/Os to reduce hardware costs
- Flash memory for field upgrades
- Diagnostic features: event recording and oscillography
- IRIG-B time synchronization

[3] Courtesy of the General Electric Company.

- Test mode for forcing contact I/O states
- Multiple settings groups
- Innovative current differential scheme with adaptive restraint
- Charging current compensation for applications on long lines or cables
- Channel asymmetry compensation (GPS)
- Programmable pushbuttons for critical operations such as breaker switching or lockout
- Programmable either through front panel or menu based software

3.1.2.2 User Interface

- Intuitive Windows® -based enerVista software for setting and monitoring
- RS232 port, faceplate accessible
- 2 RS485/Rs422 Rear Port (DNP®)
- 2x40 character display and keypad
- Target LED indicators (trip, alarm, pickup, breaker open/closed)
- IRIG-B time code format

3.1.3 Options[3]

3.1.3.1 Protection and Control

- Bus/line undervoltage
- Negative-sequence voltage
- Phase/neutral/gnd/neg seq/sens gnd inst O/C
- Phase/neutral/gnd/neg seq/sens gnd time O/C
- Bus overvoltage/neutral displacement
- Phase/neutral/neg seq/sens gnd/gnd directional control
- Bus under-frequency/rate of change
- Undervoltage automatic restoration
- Under-frequency automatic restoration
- Breaker failure with current supervision
- Bus transfer
- Programmable logic inputs
- Multiple setpoint groups

3.1.3.2 Monitoring and Metering

- Synchrocheck
- Phase/neutral current level
- Power factor
- Autoreclose
- Over-frequency
- Breaker open/close
- Manual close blocking
- Cold load pickup blocking
- Breaker operation failure
- Trip/close circuit failure
- Total breaker arcing current
- VT failure
- Demand
- Analog input
- Event recording
- Analog output
- Fault locator
- Trip counter

3.1.4 Applications[3]

- Transmission lines of any voltage level, including series-compensated lines
- Standalone or component in automated substation control system
- Single- or three-pole tripping

3.2 Device Setup and Test Results

The GE SR760 was installed according to the documentation supplied by the manufacturer. Table 3-1 shows the general settings for all setup and protection functions. The setup and protection functions that were changed to evaluate specific test points, along with the test results, are shown in Tables 3-2 through 3-12. In the tables, bolded text indicates test results that were not within the manufacturer's documented accuracy specifications.

Table 3-1
GE SR760 Functions and Settings: General

Function	Setting	Function	Setting
Phase TOC1 input	RMS	Bus OV1 pickup	1.1 VT
Phase TOC1 pickup	1.5 p.u.	Bus OV1 delay	1 s
Phase TOC1 curve	IEEE mod inverse	Under-frequency1	59.3
Phase IOC1 pickup	2 p.u.	Delay	1s
Phase IOC1 pickup delay	0 s	Over-frequency1	60.5
Neutral TOC1 input	RMS	Delay	1s
Neutral TOC1 pickup	1.5 p.u.	Max volt difference	1.2 kV
Neutral TOC1 curve	IEEE mod inverse	Max freq diff	0.3 Hz
Neutral IOC1 pickup	2 p.u.	Max angle diff	20°
Neutral IOC1 pickup delay	0 s	Dead source	DB or DL
Ground TOC1 input	RMS	Dead bus max V	0.2 VT
Ground TOC1 pickup	1.5 p.u.	Dead line max V	0.2 VT
Ground TOC1 curve	IEEE mod inverse	Live bus min V	0.8 VT
Ground IOC1 pickup	2 p.u.	Live line min V	0.8 VT
Ground IOC1 pickup Delay	0 s	Bus VT connection type	Wye
Bus UV1 pickup	0.88 VT	Line VT comparison	Va
Bus UV1 delay	2 s	VT	120

3.2.1 Undervoltage Magnitude Tests

The undervoltage magnitude tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 undervoltage protection was reconfigured to be compatible with each test point. The undervoltage magnitude test results are shown in Table 3-2. According to the documentation supplied by the manufacturer, the GE SR760 undervoltage accuracy was stated as ±0.25% of VT.

Table 3-2
Undervoltage Magnitude Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Phase UV1 pickup	0.88 (p.u.)	Phase UV1 delay	0.883	0.003
	Phase UV1 delay	2 (s)			
2	Phase UV1 pickup	0.75 (p.u.)	Phase UV1 delay	0.753	0.003
	Phase UV1 delay	2 (s)			
3	Phase UV1 pickup	0.5 (p.u.)	Phase UV1 delay	0.502	0.002
	Phase UV1 delay	2 (s)			

3.2.2 Undervoltage Time Tests

The undervoltage time tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 undervoltage protection was reconfigured to be compatible with each test point. The undervoltage time test results are shown in Table 3-3. According to the documentation supplied by the manufacturer, the undervoltage time-delay accuracy was stated as ±100ms. According to GE, the operational time of the output relay is 0.020 ms.

Table 3-3
Undervoltage Time Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Phase UV1 pickup	0.5 (p.u.)	Phase UV1 delay	0.223	0.0223
	Phase UV1 delay	0.2 (s)			
2	Phase UV1 pickup	0.5 (p.u.)	Phase UV1 delay	1.029	0.029
	Phase UV1 delay	1 (s)			
3	Phase UV1 pickup	0.5 (p.u.)	Phase UV1 delay	2.032	0.032
	Phase UV1 delay	2 (s)			

3.2.3 Overvoltage Magnitude Test

The overvoltage magnitude tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 overvoltage protection was reconfigured to be compatible with each test point. The overvoltage magnitude test results are shown in Table 3-4. According to the documentation supplied by the manufacturer, the GE SR760 overvoltage accuracy was stated as ±0.25% of VT.

Table 3-4
Overvoltage Magnitude Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Phase OV1 pickup	1.1 (p.u.)	Phase OV1 delay	1.101	0.001
	Phase OV1 delay	1 (s)			
2	Phase OV1 pickup	1.15 (p.u.)	Phase OV1 delay	1.152	0.002
	Phase OV1 delay	1 (s)			
3	Phase OV1 pickup	1.2 (p.u.)	Phase OV1 delay	1.202	0.002
	Phase OV1 delay	1 (s)			

3.2.4 Overvoltage Time Test

The overvoltage time tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 overvoltage protection was reconfigured to be compatible with each test point. The overvoltage magnitude test results are shown in Table 3-5. According to the documentation supplied by the manufacturer, the overvoltage time-delay accuracy was stated as ±100 ms. According to GE, the operational time of the output relay is 0.020ms.

Table 3-5
Overvoltage Time Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Phase OV1 pickup	1.1 (p.u.)	Phase OV1 delay	0.253	0.053
	Phase OV1 delay	0.2 (s)			
2	Phase OV1 pickup	1.1 (p.u.)	Phase OV1 delay	1.053	0.053
	Phase OV1 delay	1 (s)			
3	Phase OV1 pickup	1.1 (p.u.)	Phase OV1 delay	2.042	0.042
	Phase OV1 delay	2 (s)			

3.2.5 Under-Frequency Magnitude Test

The under-frequency magnitude tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 under-frequency protection was reconfigured to be compatible with each test point. The under-frequency magnitude test results are shown in Table 3-6. According to the documentation supplied by the manufacturer, the GE SR760 under-frequency accuracy was stated as ±0.02 Hz.

Table 3-6
Under-Frequency Magnitude Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Under-frequency1 pickup	59.8 (Hz)	Under-frequency1 pickup	59.799	0.001
	Under-frequency1 delay	1 (s)			
2	Under-frequency1 pickup	59.7 (Hz)	Under-frequency1 pickup	59.695	0.005
	Under-frequency1 delay	1 (s)			
3	Under-frequency1 pickup	59.3 (Hz)	Under-frequency1 pickup	59.295	0.005
	Under-frequency1 delay	1 (s)			

3.2.6 Under-Frequency Time Test

The under-frequency time tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 under-frequency protection was reconfigured to be compatible with each test point. The under-frequency time test results are shown in Table 3-7. According to the documentation supplied by the manufacturer, the GE SR760 time-delay accuracy was stated as ±25ms. According to GE, the operational time of the output relay is 0.020 ms. As can be seen in the graph below, the relay did not activate during that time.

Table 3-7
Under-Frequency Time Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average)	Deviation From Set Point (Average)
1	Under-frequency1 pickup	59.3 (Hz)	Under-frequency1 delay	0.258	0.058
	Under-frequency1 delay	0.2 (s)			
2	Under-frequency1 pickup	59.3 (Hz)	Under-frequency1 delay	1.069	0.069
	Under-frequency1 delay	1 (s)			
3	Under-frequency1 pickup	59.3 (Hz)	Under-frequency1 delay	5.056	0.056
	Under-frequency1 delay	5 (s)			

3.2.7 Over-Frequency Magnitude Test

The over-frequency magnitude tests were performed on the GE SR760 at three different test points. The GE SR760 over-frequency protection was reconfigured to be compatible with each test point. The over-frequency magnitude test results are shown in Table 3-8. According to the documentation supplied by the manufacturer, the GE SR760 over-frequency accuracy was stated as ±0.02 Hz.

Table 3-8
Over-Frequency Magnitude Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average, Hz)	Deviation From Set Point (Average, Hz)
1	Over-frequency1 pickup	60.2 (Hz)	Over-frequency1 pickup	60.2	0.0
	Over-frequency1 delay	1 (s)			
2	Over-frequency1 pickup	60.5 (Hz)	Over-frequency1 pickup	60.5	0.0
	Over-frequency1 delay	1 (s)			
3	Over-frequency1 pickup	61 (Hz)	Over-frequency1 pickup	61.0	0.0
	Over-frequency1 delay	1 (s)			

3.2.8 Over-Frequency Time Test

The over-frequency time tests were performed on the SR760 at three different test points. The SR760 over-frequency protection was set for 60.5 Hz, and the time delay was reconfigured to be compatible with each test point. The over-frequency time test results are shown in Table 3-9. According to the documentation supplied by the manufacturer, the GE SR760 time-delay accuracy was stated as ±25 ms. According to GE, the operational time of the output relay is 0.020 ms. As can be seen from the table, none of the test appeared to be within the manufactures stated accuracies.

Table 3-9
Over-Frequency Time Test Results

Test Point	Device Function	Setting	Triggered Trip Element	Measured Trip Point (Average, sec)	Deviation From Set Point (Average, sec)
1	Over-frequency1 pickup	60.5 (Hz)	Over-frequency1 delay	0.289	0.089
	Over-frequency1 delay	0.2 (s)			
2	Over-frequency1 pickup	60.5 (Hz)	Over-frequency1 delay	1.081	0.081
	Over-frequency1 delay	1 (s)			
3	Over-frequency1 pickup	60.5 (Hz)	Over-frequency1 delay	5.091	0.091
	Over-frequency1 delay	5 (s)			

3.2.9 Synchronization Voltage-Difference Test

The synchronization voltage-difference tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 synchronization protection was reconfigured to be compatible with each test point. The synchronization low-voltage difference test results are shown in Table 3-10, and the high-voltage difference test results are shown in Table 3-11. According to the documentation supplied by the manufacturer, the GE SR760 voltage synchronization accuracy was stated as ±0.25% of full scale. The voltage synchronization max voltage difference setting is the only setting that actually refers to primary voltage when setting the protection. The max voltage difference must be set in terms of primary p.u. For all other settings, it is measured against the VT settings, which in this case is 120 V.

Table 3-10
Synchronization Low-Voltage Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max volt diff	10.1	0.1
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max volt diff	4.96	-0.40
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max volt diff	3.014	0.014
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

Table 3-11
Synchronization High-Voltage Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max volt diff	10.123	0.123
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max volt diff	5.083	0.083
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max volt diff	3.118	0.118
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

3.2.10 Synchronization Frequency-Difference Test

The synchronization frequency-difference tests were performed on the GE R760 at three different test points, as described in Chapter 2. The GE SR760 synchronization protection was reconfigured to be compatible with each test point. The device functions and settings for each test are shown in Table 3-1. The synchronization low-frequency-difference test results are shown in Table 3-12, and the high-frequency-difference test results are shown in Table 3-13. According to the documentation supplied by the manufacturer, the GE SR760 synchronization accuracy was stated as ±0.02 Hz.

Table 3-12
Synchronization Low-Frequency-Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max freq diff	0.24	0.06
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max freq diff	0.201	0.01
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max freq diff	0.1	0.0
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

Table 3-13
Synchronization High-Frequency-Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max freq diff	0.3	0.0
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max freq diff	0.2	0.0
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max freq diff	0.1	0.0
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

3.2.11 Synchronization Phase-Angle-Difference Test

The synchronization phase-angle-difference tests were performed on the GE SR760 at three different test points, as described in Chapter 2. The GE SR760 synchronization protection was reconfigured to be compatible with each test point. The synchronization leading-phase-angle-difference test results are shown in Table 3-14, and the lagging-phase-angle-difference test results are shown in Table 3-15. According to the documentation supplied by the manufacturer, the GE SR760 synchronization accuracy was stated as ±2 deg.

Table 3-14
Synchronization Leading-Phase-Angle-Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max angle diff	20.4	0.4
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max angle diff	15.84	0.84
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max angle diff	10.82	0.82
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

Table 3-15
Synchronization Lagging-Phase-Angle-Difference Test Results

Test Point	Device Function	Setting	Triggered Element	Measured Sync. Point (Average)	Deviation From Set Point (Average)
1	Max volt diff	10 (V)	Max angle diff	-20.38	-0.38
	Max freq diff	0.3 (Hz)			
	Max angle diff	20 (deg)			
2	Max volt diff	5 (V)	Max angle diff	-15.68	-0.68
	Max freq diff	0.2 (Hz)			
	Max angle diff	15 (deg)			
3	Max volt diff	3 (V)	Max angle diff	-10.22	-0.22
	Max freq diff	0.1 (Hz)			
	Max angle diff	10 (deg)			

3.3 Testing Summary – Magnitude Tests

A review of the results for the magnitude tests shows that the GE SR760 was accurate and produced highly repeatable results for all magnitude tests. All test results were within the manufacturer's accuracy specifications. The test results reveal no apparent or potential compatibility issues with DR interconnection standards.

3.4 Testing Summary – Time Tests

A review of the results for the time tests shows that the GE SR760's time test results were highly repeatable. The voltage time tests were all within the manufacturer's stated accuracies. However, the frequency time tests were all considerably outside of the manufacturer's stated timing accuracy.

Looking at the results as a whole, the time tests for the GE SR760 (along with the time test results from other DR interconnection protection products that have been tested by EPRI) revealed a potential compatibility issue with DR interconnection standards relative to required clearing times.[4] It should be noted that the GE SR760 is usually one component part in a complete interconnection system (ICS). Thus, timer/time-delay settings may require adjustment to accommodate the operating time of a pilot relay and/or the interconnection device (breaker, contactor, relay, and so on) or accuracy tolerances. The time setting will likely need to be set lower than the limits found in the interconnection standards. In the end, it is the ICS's capability to meet the requirements of the interconnection standards that ultimately determines whether or not an ICS is considered to be in compliance with the standards.

3.5 Testing Summary – Synchronization Tests

A review of the results for the synchronization tests shows that the GE SR760 produced highly repeatable results for all synchronization tests. With only one exception, all of the eighteen test cases were within the manufacturer's stated accuracies.

3.6 Commentary – Setup, Use, and Programmability

During these tests, communicated with the GE SR760 was achieved through an RS-232 serial connection using GE's software. The software was simple to use and navigate. All functions are in a simple-to-use tree menu, and the trip contact is a pre-defined contact that can be assigned with a drop down menu. Although some functions were designated as "control" functions instead of "protection" functions, such as over-frequency and synchronization, they can be programmed to act as protection. With these two functions, the output was programmed as an alarm function, and was designated to Relay 3 for an output signal, which allows them to be used as part of a protection strategy.

[4] Clearing time is a term defined in the IEEE standard 1547. The standard defines clearing time as the time between the start of the abnormal condition and the DR ceasing to energize the area EPS.

Wiring of the relay was extremely simple. There was an easy-to-use schematic included in the manual and the terminals themselves were labeled as well. This would prove to be very handy for cases when the user's manual is not available.

The relay's front panel is easy to navigate and read. Numerous LED's show the relay's status with a text message display that updates regularly showing any faults that occur. All in all the setup, use, and programmability proved to be very user-friendly and intuitive.

A
DISTRIBUTED ENERGY RESOURCES INTERCONNECTION HARDWARE TEST PROTOCOL (DRAFT)

TEST PROTOCOL FOR DISTRIBUTED ENERGY RESOURCES

SC-830

Version 2.0, December 2003

Protective Relays Used in Grid Connection of Distributed Energy Resources
Part 1 - Small-Signal Test Port Protocol

Prepared by:

EPRI PEAC Corporation
942 Corridor Park Boulevard
Knoxville, Tennessee 37932

NOTICE

PROPRIETARY NOTICE:

This document, in whole or any part thereof, contains proprietary information, and is intended for the sole use, of EPRI PEAC Corporation. Copying this document, or any part thereof, is expressly forbidden without prior written approval of EPRI PEAC Corporation.

NON-ENDORSEMENT NOTICE:

The use of data or specifications in this document is not an endorsement of any product. There may be other products from different manufacturers that may be equally acceptable in any given application. The data and specifications are presented for completeness to aid the reader in assessing the presented results.

LEGAL NOTICE:

This document was prepared by the EPRI PEAC Corporation. Neither the EPRI PEAC Corporation, EPRI, members of EPRI, nor any person acting on behalf of any of them: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this document; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this document; or (c) grants any right, title, license, or permission to use any information, apparatus, method, or process described in this document. Use of information, apparatus, method, or process disclosed in this document may infringe privately owned rights.

FOREWORD

This test protocol for distributed energy resources (DER) is based on the concepts and format of other application-specific test protocols developed and successfully implemented by EPRI PEAC to determine the system compatibility (SC) for a variety of electrical equipment. The present document describes a test protocol providing meaningful and consistent compatibility tests on interconnection relay packages. Thus the numbering as SC-830 places this document in a category of protocols related to utility connection. The objective is to provide a consistent approach to evaluating DER in carrying out intended functions in the expected application environment. In many ways, the compatibility of these resources with other nearby electrical equipment and with the electric grid is critical to acceptance. In developing this protocol, we have taken advantage of the many parallels that can be drawn between distributed generation, energy storage, and end-use load equipment when considering test and compatibility requirements.

Sophisticated equipment and processes in the residential, commercial, and industrial environments demand compatibility between end-use systems and the utility grid. Power electronics create an opportunity for better production, conditioning, and utilization of electric energy but can become a source of problems if the electromagnetic characteristics (immunity and emissions limits) of the equipment are not compatible with the characteristics (avoidable and unavoidable disturbances) of the power system. This need has created a growing demand for conditioning equipment that can provide an interface between sensitive end-use equipment, distributed generation, and disturbances generated in the power system or end-user facilities. However, compatibility is a two-way proposition: the equipment not only must be protected against disturbances (immunity), but also should not introduce excessive disturbances (emissions).

Sometimes efforts to increase immunity or to control emissions lead to side effects that also impact compatibility. Ascertaining that compatibility exists is best demonstrated by appropriate tests addressing the issues of immunity, emissions, and potential side effects. In the fast-paced development of distributed energy resources and related power electronics equipment, the normal voluntary consensus standards might not yet provide for these appropriate tests. Protocols such as this one are intended to lead the standards-development process and provide experience in evaluating the performance of new types of equipment. Whenever possible or applicable, related industry standards are used as a basis for these tests. Other tests, which might not be included in current industry standards, are proposed in an attempt to identify latent compatibility problems, such as malfunctions caused by electromagnetic disturbances in the power system or product failure modes. Unlike product standards or specifications, this test protocol is not intended to impose specific performance requirements on manufacturers or other organizations but rather to identify the operating characteristics.

Each test protocol contains as a first part an introduction to the subject and presentation of general rationales. All parties involved in the test program must have developed a complete understanding of this part to make informed decisions on the selection and performance of a specific test program. A second part provides a detailed description of the test procedures, with one chapter on electrical tests and another chapter on environment-oriented tests. Appendices provide background information and explanatory notes necessary to support the specific tests.

A.1 Introduction

A.1.1 Scope

The SC-830 protocol examines the performance of distributed generation protection equipment relative to the application environment and expectations of utility distribution engineers. This interconnection equipment may be specific-purpose modules, such as a relay or a controlled switch, or the equipment may be integrated into the DER system such as an inverter or power conditioner. The protocol applies to both; however, different test procedures may be required. The main distinction in practical tests is a small signal for relay or other control devices compared to the full-scale testing that may be required for protection that is integrated into an inverter-connected DER system. This protocol includes definitions, reference standards, and performance criteria with test rationale, purpose, guidelines, and instrumentation. It is intended to provide a standard test plan for evaluating currently available equipment for interconnecting distributed resources to the electric power system.

The tests set forth in this protocol are intended to evaluate the protective performance of multifunction relays, which are also referred to as intelligent electronic devices (IEDs), and paralleling switchgear. However, the test methods presented in this protocol may also be used to evaluate equipment other than that mentioned above for compliance to IEEE 1547. The title of this standard is “Standard for Interconnecting Distributed Resources with Electric Power Systems,” which is referenced in this protocol.

All interconnections between distributed resources and electric power systems must provide adequate protection for both the electric power system (EPS) and the DER. However, IEEE 1547 is only concerned with the protection of the electric power system from the distributed resource. That distinction is reflected in this test protocol as it evaluates the level of protection provided to the EPS by various types of interconnection apparatus

This protocol is intended to be compatible with industry standards, in particular the safety requirements set forth by Underwriters Laboratories (UL), the Institute of Electrical and Electronics Engineers (IEEE), and the American National Standards Institute (ANSI). Applicable standards, test procedures, and other requirements specified by the respective electric utilities or by local authorities having jurisdiction might be more stringent than the criteria defined in the present protocol. Therefore, meeting the criteria defined herein should not be construed as a waiver of any other relevant performance or safety requirements.

A.1.2 Objective and Purpose

This protocol intends to evaluate performance, accuracy, and compatibility of DER grid interconnection hardware. The objective is to provide a consistent approach to evaluating DER interconnection hardware for carrying out its intended functions in the expected application environment. It provides a test methodology for assessing the protection capabilities of currently available interconnection equipment and its ability to meet the level of protection requirements applicable to different distribution systems and as set forth in standards such as IEEE 1547.

A.1.3 Limitation

This test protocol does not cover testing for safety.

A.1.4 Definitions and Word Usage

The technical terms used in this document have been systematically harmonized with relevant IEEE standards and style. Specifically, the interconnection and other technical terms used in this document are intended to have the same meaning as defined in IEEE 1547 and IEEE standard 100. Words of common usage but broad meaning in the English language are used in this document with the specific meaning recommended by the IEEE Style Manual and the International Electrotechnical Commission (IEC) directives, as listed below. It is important to recognize the difference between the common usage and the dedicated meaning because the test planning and implementation involve concepts of permission, interdiction, recommendation, probability of occurrence, and similar concepts that must be clearly understood as such by the reader.

can, cannot. A verbal form conveying (im)possibility or (in)capability, whether material, physical, or causal.

may. A verbal form conveying that a course of action by the equipment user or test operator is permissible within the limits of the present protocol. Compare with ***might.***

might. A verbal form conveying the possibility of a situation or phenomenon to occur, without intervention from the user or test operator.

must. A verbal form conveying the necessity of performing an action in order to attain a desired goal.

Note: *In this protocol, this term is typically used when describing test procedures that have to be applied consistently to obtain repeatable and reliable results. This term is not used to convey a mandate. Compare with* ***shall.***

reader. The person using this document for any purpose.

shall. A verbal form conveying requirements strictly to be followed, from which no deviation is permitted.

Note: *Because the present protocol is offered in terms of recommendations for equipment performance, the expectations aspects of the protocol are not to be expressed in terms of "shall"—except when test safety issues are involved.*

should, should not. A verbal form conveying a preference among several possibilities, but not a requirement. In the negative form, conveys deprecation, but not prohibition of a course of action.

sponsor. The entity for which the system-compatibility tests are being performed in accordance with the present protocol.

user. The occupant, owner, or operator of the power system or premises.

A.1.5 Standards and Reference Documents

This protocol is concerned with the testing of hardware and equipment used for the interconnection of distributed energy resources (DER) to the electric power system. DER can have a wide-reaching impact on the performance and safety of an EPS. Therefore, it is necessary to carefully define and monitor electrical parameters at the interconnection and the performance of both the DER and the EPS.

The present test protocol, seen as a "living document," can serve both as an input to the standardization effort and as a recipient of developing concepts and criteria in evaluating the performance of DER integration equipment.

A.1.5.1 Reference Standards

IEEE Std. 1547, *Standard for Interconnecting Distributed Resources With Electric Power Systems.*

ANSI/IEEE Std. C37.90-1989, *IEEE Standard for Relays and Relay Systems Associated With Electric Power Apparatus.*

ANSI/IEEE Std. C37.90.1-1989, *IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.*

ANSI/IEEE Std. C37.90.2-1995, *IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference From Transceivers.*

ANSI/IEEE Std. C37.98-1987, *IEEE Standard Seismic Testing of Relays.*

ANSI/IEEE Std. C37.62.41-2000, *Guide for Surge Voltages in Low-Voltage AC Power Circuits.*

IEEE Std. 100, *IEEE Standard Dictionary of Electrical and Electronic Terms.*

IEEE Std. 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.*

IEEE Std. 929-2000, *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems.*

IEEE Std. 1001-1988, *Guide for Interfacing Dispersed Storage and Generation Facilities With Electric Utility Systems.*

IEC 255-5-1977, *Isolation Testing for Electrical Relays.*

UL 1741, Inverters, *Converters, and Controllers for Use in Independent Power Systems.*

"New York State Standardized Interconnection Requirements and Application Process for New Distributed Generators 300 kVA or Less Connected in Parallel With Radial Distribution Lines," NY State Dept. of Public Service, Albany, NY, Feb. 8, 2002.

"Distributed Generation Interconnection Manual," Public Utility Commission of Texas, Austin, TX, May 1, 2002.

A.1.5.2 Reference Documents

Technology Assessment of Interconnection Products for Distributed Energy Resources: Update 2001, EPRI, Palo Alto, CA: 2001. 1003969.

Distributed Generation Relaying Impacts on Power Quality, EPRI, Palo Alto, CA: 2000. 1005917.

Engineering Guide for Integration of Distributed Generation and Storage Into Power Distribution Systems, EPRI, Palo Alto, CA: 2000: 1000419.

A.2 Existing Standards

Standards normally lag new technology development by 10 years or more. It usually takes a few years to determine which technologies and configurations will survive competition. Then another few years of field experience are needed to determine which technical issues need to be addressed by standards. And finally, the process of reaching consensus among the stakeholders participating in the standards development will take several more years. Distributed generation and storage with photovoltaic, wind, and battery systems have been around for 20+ years and are now supported by both performance standards and installation codes. The newer generator technologies that may be used in DER applications, such as fuel cells and microturbines, are causing some new standards activity. Useful standards for the application of these technologies are expected to follow the slower track of standards development.

Three organizations are major players in providing interconnection codes and standards for distributed generation that can be applied to DER systems:

- Institute of Electrical and Electronics Engineers (IEEE)
- National Fire Protection Association (NFPA)
- Underwriters Laboratories (UL)

A.2.1 History of Interconnection Standards in IEEE

The Public Utilities Regulatory Policy Act (PURPA) of 1978 enabled independent generators to sell electricity to regulated utilities. In the mid 1980s, with significant support from an industry fueled by U.S Department of Energy (DOE) renewable energy programs and the PURPA Act, IEEE sponsored and developed the first DER interconnection standards. Several excellent documents were published including IEEE Standards 929, 1001, and 1035. As often happens in long-term research programs, some results are lost or postponed because they are ahead of their time. This has been the case with the *Guide for Interfacing Dispersed Storage and Generation Facilities With Electric Utility Systems,* ANSI/IEEE 1001-1988, which expired in December of 1995 because it had not been updated. A complimentary standard, *IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters,* ANSI/IEEE Std. 1035-1989, suffered the same fate when it was not reaffirmed within the IEEE five-year review cycle.

These documents came from the IEEE Standards Coordinating Committee (SCC) 23 on Dispersed Storage and Generation. This committee was primarily made up of power engineers with utility system relaying and protection experience, including several recognized experts and fellows of IEEE. Consequently, Standard 1001-1998 is an excellent rundown of utility engineering issues and recommended relaying protection schemes for interconnection. The terminology was familiar to protection engineers. The distributed storage and generation resources were referred to as “non-utility generation” (NUG) and “qualifying facilities,” which came from PURPA.

In contrast, the IEEE 1035 standard covered the less well-known inverter interface and encouraged more “on-board” control and protection functions. The concept of the built-in interface was to avoid relatively high-cost utility-grade relay packages for small, dispersed generators involving DC technologies that needed an inverter for connection to the pubic power supply. One standard that addresses this application scenario, *IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,* Std. 929, did survive since its origin in the late 1980s. A new edition was approved in 2000 and is available from IEEE. It contains some practical requirements for inverter-connected dispersed PV generators, primarily single-phase and less than 10 kW. Recommendations for larger systems and other technologies are currently not covered by standards.

A.2.2 Update on Recent IEEE Standards for Interconnection

In several areas, voluntary standards for distributed generation and storage are emerging. One of the objectives of this guide is to identify the state of consensus DER evaluation criteria and standards. The critical elements for achieving widespread acceptance of these standards and related test methods will be:

- An appropriate forum and balanced stakeholder participation in development
- Technical understanding combined with hands-on experience with actual systems
- Carefully developed rationale and formal test procedures to evaluate performance

Fortunately, today these early documents and the people involved in their origination are providing a catalyst for a new IEEE initiatives for interconnection standards. Consequently, the pressure to pursue some form of onboard or other low-cost grid-interface package has increased. Also, in this era of deregulation of the electric power industry and increased difficulty to site central power plants, interest in this standards-making activity is extraordinary.

IEEE started work on IEEE 1547 in 1999, and it is now an officially accepted IEEE standard. The 1547 standard was developed as a single basic interconnection standard for distributed generation technologies. The scope of the proposed standard includes “criteria and requirements for interconnection of distributed generation with electric power systems (EPS).” The purpose states that it “provides a uniform standard for interconnection of distributed resources with electric power systems.”

Distributed resources are defined in the standard as sources of electric power that are not directly connected to a bulk power transmission system. These resources include both generators and energy-storage technologies. And the term *distributed generation* is defined as electric generation facilities connected to an area EPS through a point of common coupling (PCC), a subset of DER (see Figure 2-1).

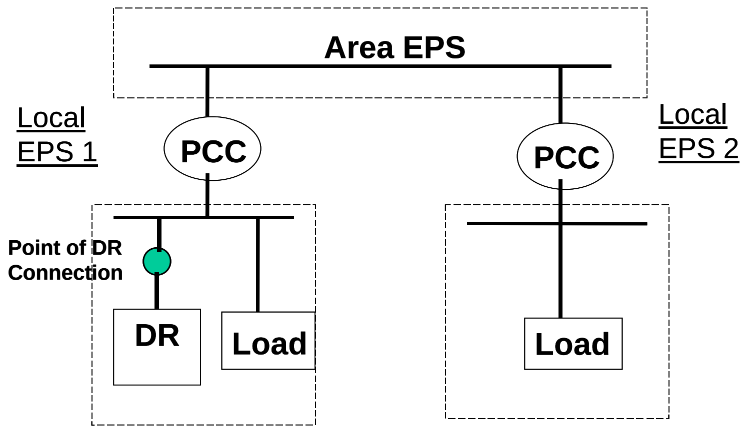

Figure A-1
An Area EPS Is Capable of Serving Two or More Local EPSs

The standard provides requirements relevant to performance, operation, testing, safety, and maintenance of the interconnection. The standard applies to interconnection of either a single distributed generation based on that unit's rating or multiple distributed generation units within a single local EPS based on the aggregate rating of all the units that are within the local EPS. The standard is limited to units of less than a rating of 10 MW. Power quality requirements are also given in IEEE 1547, using IEEE standards as the reference. Limitation of harmonics, flicker, and DC injection are all addressed. Unintentional operation as an isolated "island" of generation and load is not allowed.

Voltage regulation, grounding, synchronization, inadvertent starting, reconnection after an outage (a five-minute delay is proposed), monitoring, isolation devices (required by the NEC), and response to abnormal conditions are all addressed in the document. One difficult issue has been the use of distributed generation on networks. Although this has been done many times in the field, interconnections have been custom designed, and the idea of a universal standard for networks is troubling to many. The result so far has been a lot of debate and discussion that has all but removed coverage of this topic from the initial standard.

Many of these technical requirements were developed to interconnect large (>50 MW) qualifying facilities. Few of these existing requirements were established to account for small generation technologies, such as use in DER, and the specific needs related to control, metering, and power quality. Protection equipment is sometimes specified to prohibit relaying equipment from being contained within a single device. This reduces the probability of total system failure as a result of the failure of a single component. This redundancy is a feature that many DER owner/operators object to because it can increase project cost and design complexity.

As small, distributed generation technologies have evolved, many suppliers have developed alternative solutions to traditional interconnection designs. Suppliers are moving toward integrating these solutions into their distributed generator packages to lower the overall cost of the system. In order to ensure safety and reliability, utilities must test each alternative solution before it can be integrated with a utility distribution system. Consequently, some of the newer integrated solutions are not readily embraced by utilities.

The central issue in the technical area is whether standards can be developed that will allow for a cost-effective interconnection solution without jeopardizing the safety and reliability of the electric power system. These standards will come from IEEE as well as the other traditional sources such as NEMA, NFPA, and UL. Two such standards are listed below that may impact installation and safety of a DER project. NFPA covers the safe installation of any type of generator “on a premises” such as a commercial or industrial facility. The UL standard for safety is related to inverter-connected distributed generators.

A.2.3 Standard for Installation - NFPA 70-1999, National Electrical Code

Use this standard to determine appropriate DER wiring with the building-wiring interface. Also spelled out are requirements for a visible disconnect, service entrance wiring, grounding separately derived voltage sources, and transfer switching and protection of the DER with respect to the building interface.

A.2.4 Standard for Safety – UL 1741 – “Standard for Inverters, Converters and Controllers for Use in Independent Power Systems,” Underwriters Laboratories, Inc., January 2001

Use this standard for safety to establish the performance criteria for inverters, converters, and controllers for use in independent power systems. Tests include the harmonic distortion, DC injection, utility voltage and frequency variations, anti-islanding, loss of control circuit, overloads, load transfer, and voltage surge.

A.2.5 IEEE 1547 – Standard for Interconnecting Distributed Resources With Electric Power Systems

Although the available U.S. state interconnection standards share many similarities with IEEE 1547, it is currently the only standard available in the United States to govern all types of DER interconnection on a nationwide level. Several states have adopted their own requirements for the interconnection of distributed resources to the EPS. IEEE 1547, “Standard for Interconnecting Distributed Resources With Electric Power Systems,” is intended to provide a single technical document that can be universally adopted to govern the interconnection of distributed resources with electric power systems. For this reason, 1547 sets forth the minimum technical requirements for the interconnection itself and is not specific to a single DER technology. 1547 is applicable to all DER technologies with aggregate capacity of 10 MVA or less at the point of common coupling and is mainly concerned with the connection of DER to radial primary and secondary distribution systems.

The bulk of IEEE 1547 is comprised of Chapters 4 and 5, “Interconnection Technical Specifications and Requirements” and “Test Specifications and Requirements.” The interconnection requirements presented in Chapter 4 cover basic operational and protective requirements of the DG installation that must be met at the PCC. Chapter 5 follows with the test specifications needed to meet the requirements of Chapter 4. It is worth noting that the existing state-level interconnection standards from New York, Texas, and California all require similar levels of protection, but they are not in full agreement with each other or IEEE 1547.

The National Rural Electric Cooperative Association (NRECA) has developed an application guide for distributed generation interconnection that specifically addresses the emerging IEEE standard 1547. This guide is available from NRECA, and as of preparation of this report, it could be obtained from http://www.nreca.org/leg_reg/DRToolKit/DRApplicationGuide-Final.pdf. It provides rules of thumb that engineers at each cooperative can apply to develop detailed technical interconnection requirements that work for their systems.

A.3 General Guidelines

A.3.1 Equipment Under Test

A.3.1.1 Multifunction Protective Relays

The current multifunction protective relay is a microprocessor-based computer capable of monitoring many power system parameters at one time. These devices are now commonly referred to as integrated electronic devices (IEDs) to better reflect their capabilities. Due to the multifunction capability of these devices, it is possible to replace large cabinets of relays, each performing specific tasks, with a single IED. In addition to providing the traditional protection needed to operate the power system, the modern IED also provides a variety of communication and data-acquisition options, as well as increased flexibility through user-defined setpoints. In some cases, a single IED can satisfy all of the protection requirements needed to connect a distributed generator to the existing electric power system.

A.3.1.2 Paralleling Switchgear (Protection and Dispatch Control)

Switchgear units provide connection and branching points in electrical distribution circuits. Modern paralleling switchgear often incorporate microprocessor-based control centers that provide many of the same protection functions as modern IEDs. The control centers allow for highly intelligent paralleling of distributed generators with the EPS. This technology also makes it more economical to operate standby generators for peak shaving because it simplifies the interconnection and protection hardware needed to parallel with the EPS.

A.3.1.3 Information About the Test Specimen(s)

To ensure correct application of the equipment under test (EUT), the following information should be recorded on data sheets labeled "Manufacturer Nameplate Information." A complete interconnection package may consist of several separate elements from different manufacturers. This possible diversity makes it imperative to maintain detailed documentation of the equipment sources, ratings, and specifications as appropriate, such as:

- Manufacturer's name or trademark
- Product name, model number, and serial number
- Reference to listing or certification as applicable (UL, FCC, and so on)
- Other auxiliary equipment data

A.3.2 Procedures for Specimen Procurement

Test specimens should be obtained with the cooperation of the manufacturer to ensure that the system being tested corresponds to the current (and well-identified) design of the system. Therefore, in addition to the information listed above, the manufacturer of the system will be requested to provide the testing laboratory with all relevant device information. This information should include the exact date of manufacture, recent design changes (if any), and other information that will keep the tested system in the correct context. Instances have occurred when performing blind testing of products without cooperation from the manufacturer, the manufacturer, faced with unfavorable results, offers the rationale that improvements have been made in the design over that which was submitted to the blind test program. To ensure integrity of the data and promote a relationship of trust, it is imperative that this detailed product information be considered confidential and be recorded only in laboratory notebooks.

A.3.3 Test Plan and Number of Specimens

The plan must consider the test sequence and assignment of test specimens in the form of a matrix rather than by arbitrary specimen number. Where appropriate, enough specimens should be obtained to avoid cumulative stresses on specimens intended for durability demonstrations, making provisions for initial or preliminary setting of the test parameters, and unexpected failure of specimens. The test specimens obtained from the manufacturer should be identified according to the test plan matrix.

To obtain consistent and reproducible test results from a limited number of available test specimens, it is important to observe a crescendo of stresses when a specimen is to be subjected to more than one test. Failure-mode tests may be performed at the end of the test series on any specimen, regardless of its test sequence history. On the other hand, those tests aimed at some degree of demonstration of durability should only be performed on specimens that have received no significant stress in the test program. A desirable flexibility in the test schedule aimed at performing meaningful tests must be reconciled with the objective of consistent and uniform testing. This approach should be documented in a decision tree that is part of the test record, thereby validating comparable test results performed on different equipment or at different laboratories.

A.3.4 Standard Test Conditions

The comparison of the test results between two or more systems will be valid only if the tests have been performed under identical test conditions. Significant parameters include the following, with possible addition of other parameters revealed by the manufacturer's specifications or other test standards incorporated into this protocol:

- Ambient temperature: 25°C (77°F)
- Relative humidity: less than 85%
- Altitude: less than 1000 meters (3281 feet)

A.3.5 Incoming Inspection

Information germane to the success of the testing project can be obtained from a preliminary inspection of the specimen to be tested. Upon receipt of the test specimens, the test laboratory should take the necessary steps to obtain the product specifications identified in 3.1.3, if not already provided. A thorough review of all available manufacturer's data, including nameplate data and other labels, will reveal important information concerning the setup and operation of the equipment. An external inspection of the specimen will provide information about the required connections, controls, interfaces, and so on and reveal evidence of possible shipping and mishandling damage. Before applying power to the specimen, an internal inspection may be performed to identify loose or damaged components, if damage is suspected.

A.3.6 Test Setup

A.3.6.1 Test Sample Mounting

Test samples should be mounted in accordance with the manufacturer's specifications. IEDs will most likely be rack-mountable, whereas paralleling switchgear will have its own metal enclosure. In the case of testing transfer switches without a metal enclosure, a suitable mounting configuration can be determined from the manufacturer's specifications.

Electrical connections should be made in accordance with the manufacturer's specifications. These connections include external unit power, connections to test ports, and CT/PT connections, depending on the type of test being performed and the available connection points.

A.3.6.2 PT Connections

Efficient testing may require testing on more than one sample at a time. Testing multiple samples at once also eliminates discrepancies between sample tests because all samples are subjected to the exact same test at the same time. Most tests can be carried out in this manner by wiring the devices in parallel with each other. This configuration is realized by connecting the Phase A inputs for all devices in parallel with each other and then connecting them to a common source, as shown in Figure 3-1. The source in this case is the output of the programmable power supply (relay test set or controllable test source). Similarly, procedures are followed for the other phases. Whenever possible, install all inputs for testing to reveal any effects due the presence of the other input signals (the input signals not being varied during a test).

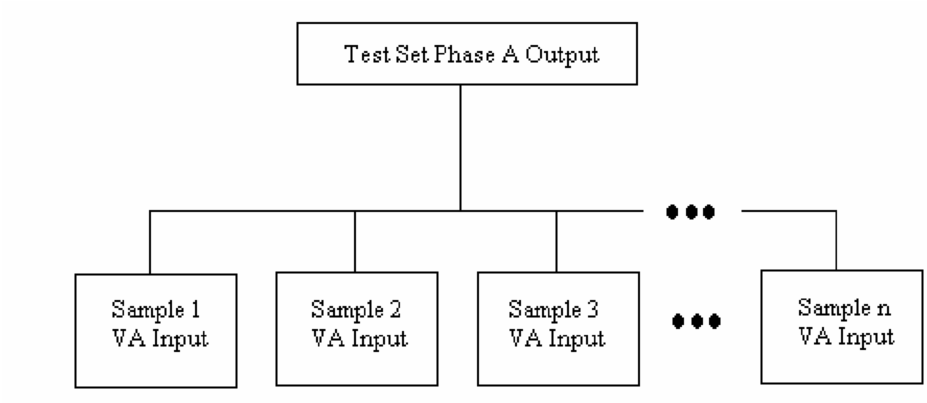

Figure A-2
Electrical Connections for PT Inputs

A.3.6.3 CT Connections

CT connections should be made according to the manufacturer's specifications. Most devices tested will only need CT connections in place for test plans that include reverse-power and/or overcurrent tests. Whenever possible, install all inputs for testing to reveal any effects due the presence of the other input signals (the input signals not being varied during a test).

A.3.6.4 Grounding

During tests, as well as in actual use, proper grounding conditions on the test premises should be specified and strictly enforced in accordance with the provisions of the NEC® [5] and other applicable codes in the jurisdiction of the test laboratory.

[5] NEC® is a registered Trade Mark of the National Fire Protection Association.

A.3.7 Device Settings

The new IEDs bare little resemblance to their older electromechanical counterparts. Traditionally, a relay performed one function such as overvoltage protection (function 59) or synchronism check (function 25). A modern IED or paralleling switchgear system now performs many protective functions plus a variety of communication and data-acquisition duties. In application, all protection functions should be set to comply with relevant DER interconnection standards (such as the local utility requirements, IEEE 1547, UL 1741, IEEE 929, and others as appropriate). Similarly, during testing, all relevant protection functions should be programmed and/or set according to the test objectives, regardless of which protection functions are actually under test. Enabling all protection functions during testing will help reveal incompatibilities between protective functions, which affect the performance of the device under test.

A.3.8 Test Instrumentation

To implement the small signal testing of DER interconnection hardware, the following test equipment and instrumentation are suggested.

A.3.8.1 Test-Signal Generator

For most testing situations, the test-signal generator will require at least four (4) independent voltage channels and three (3) independent current channels. An all-inclusive, high-precision secondary-injection relay test set designed specifically for evaluating protection relays is a useful tool for small-signal testing of DER interconnection hardware systems. If configured properly, other test-signal-generating systems consisting of arbitrary waveforms generators and power amplifiers may be used as effectively.

A.3.8.2 Data-Acquisition System

The input waveforms (test signals) and the output states of the test specimens should be recorded during each test to facilitate an evaluation the test specimen’s performance. To make proper evaluations, all input voltages and currents should be recorded. Test data may be recorded using multi-channel oscilloscopes or other suitable data-acquisition devices. The bandwidth of the data-acquisition and acceptable input signal levels should be adequate to accurately and reliably record the required test data according to the test objectives.

A.3.8.3 Device Under Test – Built-in/Internal Data Acquisition

Many IEDs, paralleling switchgear, and other protective devices have built-in data acquisition, event and fault logs, and fault-analysis capabilities. When possible, use the internal data-acquisition and -analysis systems to support the external data-acquisition system(s) during testing. The internal systems can be used to help identify which protection functions were triggered during testing.

A.3.9 Test Signals

A.3.9.1 Magnitude Test (Ramp Function) – General

The test signal described below is used to characterize the accuracy of the magnitude setting for relevant protection parameters, including undervoltage, overvoltage, under-frequency, over-frequency, synchronization magnitude difference, synchronization frequency difference, and synchronization phase difference.

Vary the parameter under test (PUT) according to the magnitude ramp function defined herein. Only the PUT shall be varied. Therefore, all other parameters shall be held at nominal values. The ramp shall take the form of Equation A-1.

$$p(t) = m \cdot (t - t_0) + P_b \qquad \textbf{Eq. A-1}$$

where p is the PUT, m is the slope of the ramp function, t is time (measured in seconds), and P_b is the starting point of the ramp function (in units of the PUT).[6] The slope, m, is defined by Equation A-2.

$$m = \frac{(0.5 \cdot a)}{(2 \cdot z)} \qquad \textbf{Eq. A-2}$$

where z is the time-delay setting (in seconds) for the PUT plus the manufacturer's stated operating time[7] (in seconds), and a is the manufacturer's stated accuracy of the PUT.

Figure A-3 is a graphical representation of a ramp function used for a low-magnitude parameter test of the PUT (for example, undervoltage, under-frequency, and so on). In the figure, p represents the magnitude of the PUT, t represents time, P_N is the nominal condition of the PUT, P_T is the trip magnitude of the PUT, t_i is the start time of the ramp, and t_h is the hold time[8] for the test signal at starting point, P_b.

---

[6] The starting point, P_b, shall be within 10% of but not exceed the trip point magnitude.

[7] The operating time is defined as the length of time for the EUT's output to change states (trigger a fault condition) based on an out-of-tolerance condition for the PUT.

[8] The hold time, t_h, shall be greater than the time-delay setting of the PUT.

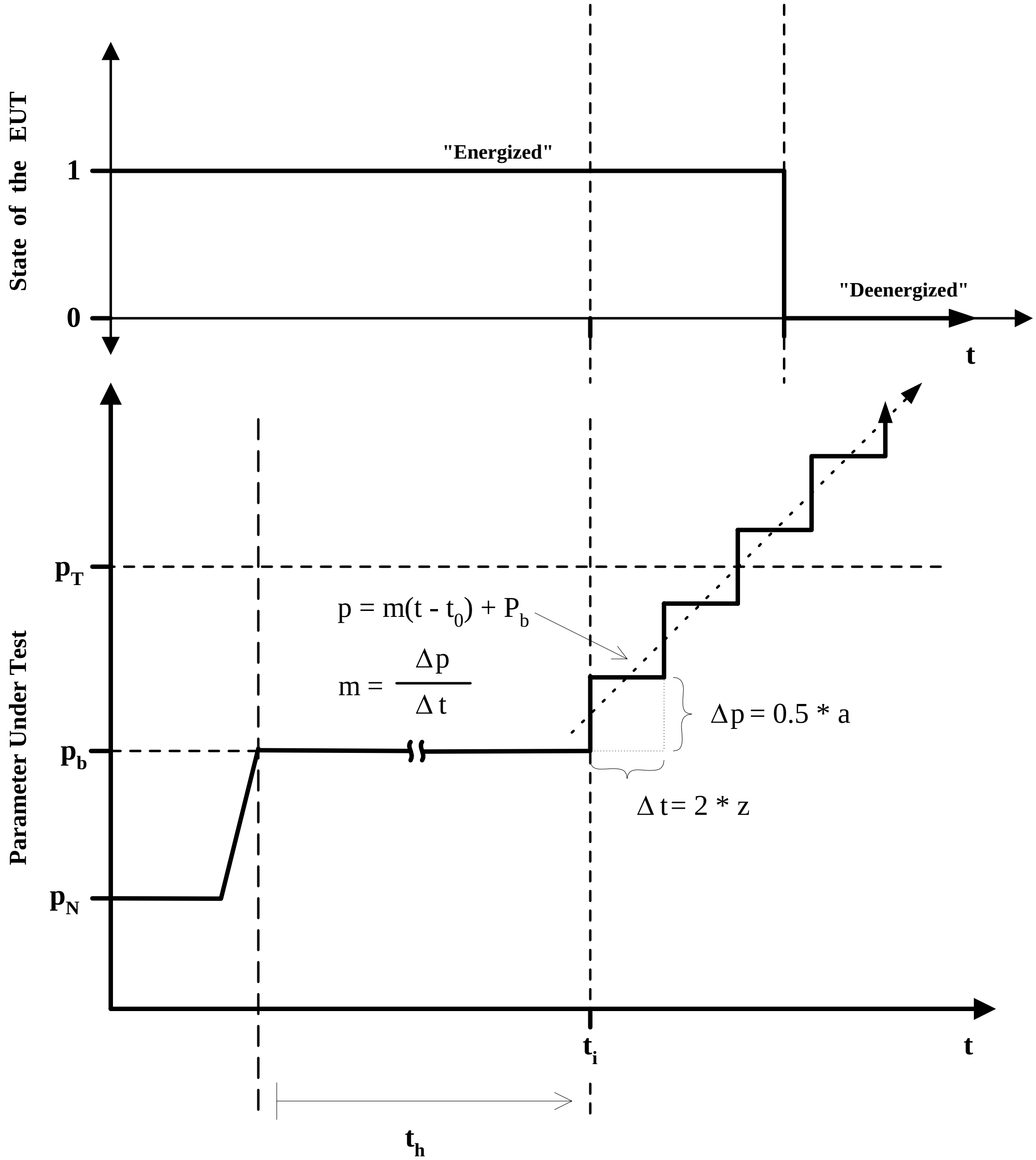

Figure A-3
Graphical Representation of a Magnitude Test Using a Ramp Function for the PUT

For cases when the ramp function conflicts with a design characteristic or settings of the EUT, an alternative method that is agreeable to the manufacturer and the testing agency may be used.

A.3.9.2 Time Test (Step Function) – General

The test signal described below is used to characterize the accuracy of the time-delay setting for relevant protection parameters, including undervoltage, overvoltage, under-frequency, and over-frequency.

Vary the parameter under test (PUT) according to the magnitude step function defined herein. Only the PUT shall be varied. Therefore, all other parameters shall be held at nominal values. The time test signal shall take the form described in Equation A-3.

$$p(t) = A \cdot u(t - t_i) + P_b \qquad \textbf{Eq. A-3}$$

where p is the magnitude of the PUT, t is time (measured in seconds), A is a scaling factor,[9] and P_b is the starting point of the step function (in units of the PUT).[10]

Figure A-4 is a graphical representation of the function used for a time test of the PUT. In the figure, p represents the magnitude of the PUT, t represents time, P_N is the nominal condition for the PUT, P_T is the trip magnitude of the PUT, P_b is the starting point of the step function, P_U is the final value of the step function, t_0 is the start time used for calculating the trip time, t_i is the start of the step function, t_r is the rise time of the test signal from ($|t_0 - t_i|$),[11] t_h is the hold time[12] for the test signal at the starting point, P_b, and t_t is the time delay of the PUT.

---

[9] The scaling factor, A, shall be chosen such that P_U is at least 110% of P_T.

[10] The starting point, P_b, shall be within 10% of but not exceed the trip point magnitude.

[11] The rise time, t_r, shall be less than 1% of the time-delay setting of the PUT.

[12] The hold time, t_h, shall be greater than the time-delay setting of the PUT.

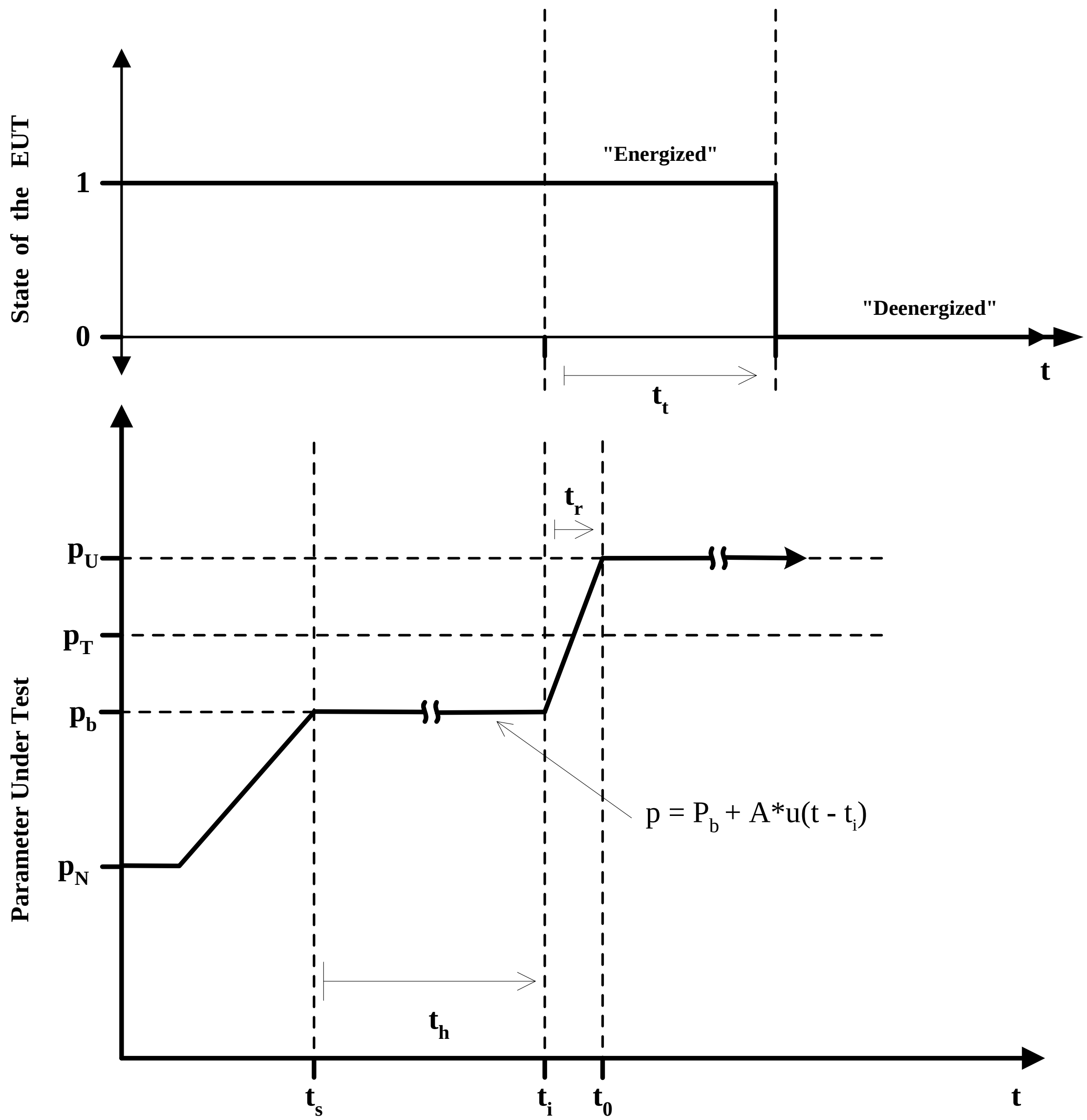

Figure A-4
Graphical Representation of a Time Test Using a Step Function for the PUT

For cases when the step function conflicts with a design characteristic or settings of the EUT, an alternative method that is agreeable to the manufacturer and the testing agency may be used.

A.3.9.3 Reverse-Power Magnitude Test (Ramp Function)

The test signal described below is used to characterize the accuracy of the reverse-power magnitude protection setting.

Vary the current test signals (magnitude and phase angle) according to the ramp function defined herein. Only the current test signals shall be varied. Therefore, the voltage test signal shall be held at nominal values. The current test-signal magnitude (i) and phase angle (θ) shall take the form described in Equations A-4 and A-6.

$$i(t) = m \cdot (t - t_0) + I_b \qquad \textbf{Eq. A-4}$$

where i is the current magnitude, m is the slope of the ramp function, t is time (measured in seconds), and I_b is the starting point of the ramp function.[13] The slope, m, is defined by Equation A-5.

$$m = \frac{(0.5 \cdot a)}{(2 \cdot z)} \qquad \textbf{Eq. A-5}$$

where z is the time-delay setting (in seconds) for the reverse-power protection parameter plus the manufacturer's stated operating time[14] (in seconds), and a is the manufacturer's stated accuracy of the reverse-power protection parameter.

The current phase angle, θ, defined as the phase difference between the voltage and current test signals shall be varied according to Equation A-6.

$$\theta(t) = -180 \cdot u(t - t_s) \qquad \textbf{Eq. A-6}$$

where θ is the current phase angle, t_s is the time when the phase-angle change occurs, and t is time (measured in seconds).

Figure A-5 is a graphical representation of a reverse-power magnitude test using the current magnitude ramp function coupled with a current phase-angle step function. In the figure, i represents the current magnitude, θ represents the phase angle of the current test signal, t represents time, I_N is the nominal current condition, I_T is the trip magnitude[15], t_i is the start time of the ramp, t_s is the instance when the phase transition occurs, and t_h is the hold time[16] for the test signal at starting point, I_b.

---

[13] The starting point, I_b, shall be within 10% of but not exceed the trip point magnitude.

[14] The operating time is defined as the length of time for the EUT's output to change states (trigger a fault condition) based on an out-of-tolerance condition for the reverse-power protection function.

[15] For the reverse-power magnitude test, the reverse-power trip magnitude ($P = 3 \cdot |V| \cdot |I| \cdot \cos\theta$) will be a function of the magnitude of the current test signal, because the voltage magnitude is at nominal and the phase difference between the voltage and current test signals, θ, is 180°.

[16] The hold time, t_h, shall be greater than the time-delay setting of the reverse-power protection function.

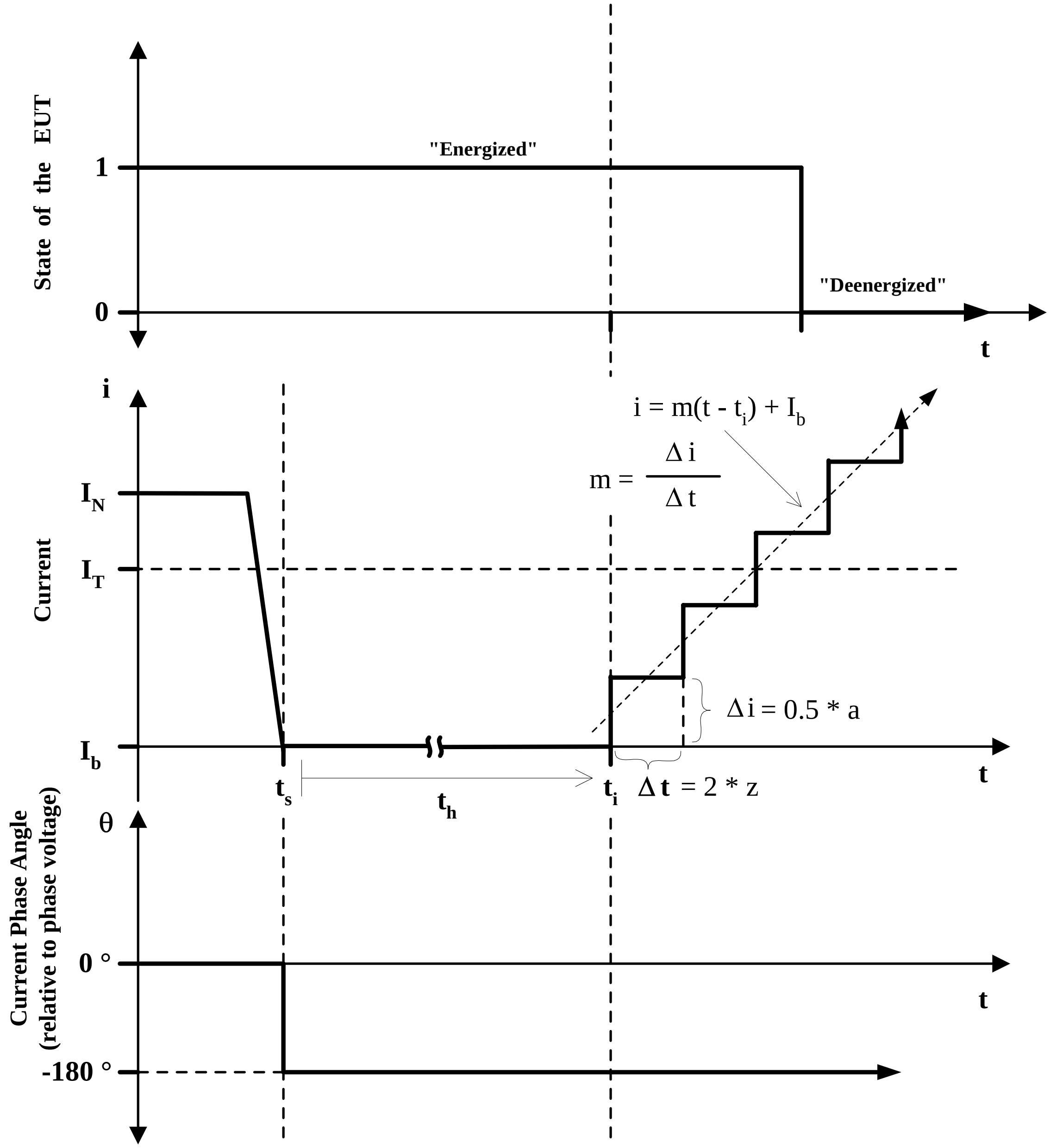

Figure A-5
Graphical Representation of the Reverse-Power Magnitude Test Using a Current Magnitude Ramp Function Coupled With a Current Phase-Angle Step Function

For cases when the ramp function conflicts with a design characteristic or settings of the EUT, an alternative method that is agreeable to the manufacturer and the testing agency may be used.

A.3.9.4 Reverse-Power Time Test (Step Function)

The test signal described below is used to characterize the accuracy of the time-delay setting for reverse-power protection parameter.

Vary the current test signals (magnitude and phase angle) according to the ramp function defined herein. Therefore, the voltage test signal shall be held at nominal values. The current test-signal magnitude (i) and phase-angle (θ) shall take the form described in Equations A-7 and A-8.

$$i = I_b + A \cdot u(t - t_i) \qquad \textbf{Eq. A-7}$$

where i is the current test-signal magnitude, t is time (measured in seconds), A is a scaling factor,[17] and I_b is the starting point of the step function.[18]

$$\theta(t) = -180 \cdot u(t - t_s) \qquad \textbf{Eq. A-8}$$

where θ is the current phase angle, t_s is the instance when the phase-angle change occurs, and t is time (measured in seconds).

Figure A-6 is a graphical representation of the functions used for a reverse-power time test. In the figure, i represents the current test signal, θ represents the phase angle of the current test signal, t represents time, i_N is the nominal current magnitude, i_T is the trip magnitude[19], i_b is the starting point of the current-magnitude step function, i_U is the final value of the current-magnitude step function, t_0 is the start time used for calculating the trip time, t_i is the start of the current-magnitude step function, t_r is the rise time of the test signal ($|t_0 - t_i|$),[20] t_h is the hold time[21] for the test signal at the starting point, i_b, and t_s is the instance when the phase transition occurs.

---

[17] The scaling factor, A, shall be chosen such that i is at least 110% of I_T for $t > t_i$.

[18] The starting point, I_b, shall be within 10% of but not exceed the trip point magnitude.

[19] For the reverse-power time test, the reverse-power trip magnitude ($P = 3 \cdot |V| \cdot |I| \cdot \cos\theta$) will be a function of the magnitude of the current test signal, because the voltage magnitude is at nominal and the phase difference between the voltage and current test signals, θ, is 180°.

[20] The rise time, t_r, shall be less than 1% of the time-delay setting of the PUT.

[21] The hold time, t_h, shall be greater than the time-delay setting of the PUT.

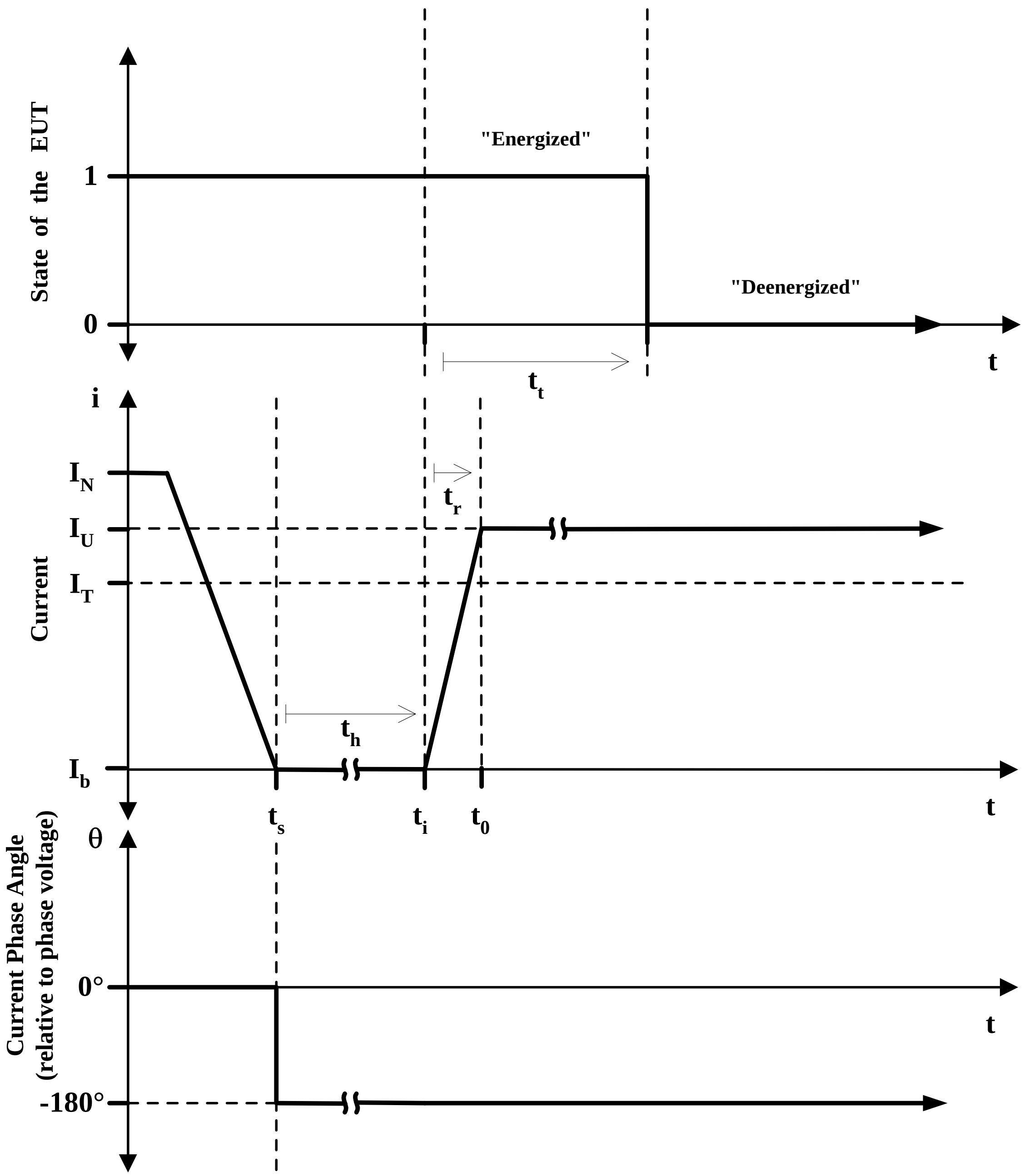

Figure A-6
Graphical Representation of a Reverse-Power Time Test Using a Current Magnitude Step Function Coupled With a Current Phase-Angle Step Function

For cases when the step functions conflict with a design characteristic or settings of the EUT, an alternative method that is agreeable to the manufacturer and the testing agency may be used.

A.4 Characterization of Response to Abnormal Voltage and Frequency

A.4.1 Rationale – Undervoltage and Overvoltage

Interconnection standards require DER units to "cease to energize" the local electric power system (local EPS) when the power system voltage decreases to specified lower limits. For example, IEEE 1547 states the following:

> "When any voltage is in a range given below (see Table A-1), the DER shall cease to energize the Area EPS within the clearing time as indicated. Clearing time is the time between the start of the abnormal condition and the DER ceasing to energize the Area EPS."

Table A-1
Interconnection System Response to Abnormal Voltages[22]

Voltage Range (% of base voltage)	Clearing Time b (s)
V < 50	0.16
50 • V • 88	2
110 • V • 120	1
V • 120	0.16
Notes: (a) Base voltages are the nominal system voltages as stated in ANSI C84.1 Table 1. (b) DER • 30 kW, Maximum Clearing Times; DER > 30 kW, Default Clearing Times	

The values specified in the IEEE 1547 standard are similar to those presented in UL 1741, "Inverters, Converters, and Controllers for Use in Independent Power Systems." However, it should be noted that UL 1741 specifies a faster clearing time of 0.1 sec. for V < 50% of nominal. Additionally, UL 1741 expands the upper range to 110% • V • 137% while also allowing a slower clearing time of two seconds in that range. IEEE 929, *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,* and the New York, California, and Texas state DER interconnection standards also outline similar protection requirements.

[22] From Section 4.2 of the IEEE 1547, "The Standard for Connecting Distributed Resources With Electric Power Systems."

A.4.2 Undervoltage Magnitude Test

A.4.2.1 Objective

This test is performed to characterize the accuracy of the undervoltage protection magnitude setting(s) of the EUT. The undervoltage protection accuracy of the EUT shall be specified prior to beginning the tests.

A.4.2.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Magnitude Test described in Section A.3.9.1, adjust the source and DER voltages to starting point V_b. The voltages shall be held at this level for a period t_h. At the end of this period, initiate undervoltage ramp functions for the source and DER voltages.[23]

6. Record the voltage magnitude when the EUT trips.

7. Return the voltage to nominal V_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.2.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

---

[23] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.3 Undervoltage Time Test

A.4.3.1 Objective

This test is performed to characterize the accuracy of the undervoltage protection time-delay setting(s) of the EUT. The undervoltage protection time-delay accuracy of the EUT shall be specified prior to beginning the tests.

A.4.3.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Time Test described in Section A.3.9.1, adjust the source and DER voltages to starting point V_b. The voltages shall be held at this level for a period t_h. At the end of this period, initiate undervoltage step functions for the source and DER voltages.[24]

6. Record the time between the initiation of the step function and the point when the EUT trips.

7. Return the voltage to nominal V_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.3.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

[24] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.4 Overvoltage Magnitude Test

A.4.4.1 Objective

This test is performed to characterize the accuracy of the overvoltage protection magnitude setting(s) of the EUT. The overvoltage protection accuracy of the EUT shall be specified prior to beginning the tests.

A.4.4.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Magnitude Test described in Section A.3.9.1, adjust the source and DER voltages to starting point V_b. The voltages shall be held at this level for a period t_h. At the end of this period, initiate overvoltage ramp functions for the source and DER voltages.[25]

6. Record the voltage magnitude when the EUT trips.

7. Return the voltages to nominal V_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.4.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

[25] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.5 Overvoltage Time Test

A.4.5.1 Objective

This test is performed to characterize the accuracy of the overvoltage protection time-delay setting(s) of the EUT. The overvoltage protection time-delay accuracy of the EUT shall be specified prior to beginning the tests.

A.4.5.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Time Test described in Section A.3.9.1, adjust the source and DER voltages to starting point V_b. The voltages shall be held at this level for a period t_h. At the end of this period, initiate overvoltage step functions for the source and DER voltages.[26]

6. Record the time between the initiation of the step functions and the point when EUT trips.

7. Return the voltages to nominal V_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.5.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

[26] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.6 Rationale – Under-Frequency and Over-Frequency

Interconnection standards require DER units to "cease to energize" the local electric power system (local EPS) when the power system frequency decreases to specified lower limits. For example, the IEEE 1547 states the following:

> "When the system frequency is in a range given below (Table A-2), the DER shall cease to energize the Area EPS within the clearing time as indicated. Clearing time is the time between the start of the abnormal condition and the DER ceasing to energize the Area EPS."

Table A-2
Interconnection System Response to Abnormal Frequencies[27]

DER Size	Frequency Range (Hz)	Clearing Time [a] (s)
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 - 57.0} (Adjustable setpoint)	Adjustable 0.16 to 300
	< 57.0	0.16
Note. (a) DER ≤ 30 kW, Maximum Clearing Times; DER > 30 kW, Default Clearing Times		

The values specified in the IEEE 1547 standard are similar to those presented in UL 1741, "Inverters, Converters, and Controllers for Use in Independent Power Systems." However, it should be noted that UL 1741 specifies a faster clearing time of 0.1 sec. for $f < 59.7$ Hz or $f >$ 60.5 Hz of nominal. IEEE 929, *Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,* and the New York, California, and Texas state DER interconnection standards also outline similar protection requirements.

A.4.7 Under-Frequency Magnitude Test

A.4.7.1 Objective

This test is performed to characterize the accuracy of the under-frequency protection magnitude setting(s) of the EUT. The under-frequency protection accuracy of the EUT shall be specified prior to beginning the tests.

[27] From Section 4.2 of the IEEE 1547, "The Standard for Connecting Distributed Resources With Electric Power Systems."

A.4.7.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Magnitude Test described in Section A.3.9.1, adjust the frequencies of the source and DER voltages and the DER current to their starting points f_b. The frequencies shall be held at this level for a period t_h. At the end of this period, initiate under-frequency ramp functions for the source and DER voltages and the DER current.[28]

6. Record the frequency magnitude when the EUT trips.

7. Return the frequency to nominal f_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.7.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.4.8 Under-Frequency Time Test

A.4.8.1 Objective

This test is performed to characterize the accuracy of the under-frequency protection time-delay setting(s) of the EUT. The under-frequency protection time-delay accuracy of the EUT shall be specified prior to beginning the tests.

---

[28] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests all three phases simultaneously.

A.4.8.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Time Test described in Section A.3.9.1, adjust the frequencies of the source and DER voltages and the DER current to their starting points f_b. The frequencies shall be held at this level for a period t_h. At the end of this period, initiate under-frequency step functions for the source and DER voltages and the DER current.[29]

6. Record the time between the initiation of the step function and the point when EUT trips.

7. Return the frequency to nominal f_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.8.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.4.9 Over-Frequency Magnitude Test

A.4.9.1 Objective

This test is performed to characterize the accuracy of the over-frequency protection magnitude setting(s) of the EUT. The over-frequency protection accuracy of the EUT shall be specified prior to beginning the tests.

[29] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.9.2 Test Guidelines and Procedures

1. Connect the equipment under test (EUT) according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Magnitude Test described in Section A.3.9.1, adjust the frequencies of the source and DER voltages and the DER current to their starting points f_b. The frequencies shall be held at this level for a period t_h. At the end of this period, initiate over-frequency ramp functions for the source and DER voltages and the DER current.[30]

6. Record the frequency magnitude when the EUT trips.

7. Return the frequencies to nominal f_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.9.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.4.10 Over-Frequency Time Test

A.4.10.1 Objective

This test is performed to characterize the accuracy of the over-frequency protection time-delay setting(s) of the EUT. The over-frequency protection time-delay accuracy of the EUT shall be specified prior to beginning the tests.

---

[30] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

A.4.10.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Referring to the Time Test described in Section A.3.9.1, adjust the frequencies of the source and DER voltages and the DER current to their starting points f_b. The frequencies shall be held at this level for a period t_h. At the end of this period, initiate over-frequency step functions for the source and DER voltages and the DER current.[31]

6. Record the time between the initiation of the step functions and the point when the EUT trips.

7. Return the frequencies to nominal f_N (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.4.10.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

[31] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests all three phases simultaneously.

A.5 Characterization of Response to Reverse-Power

A.5.1 Rationale

Interconnection standards require DER units to "cease to energize" the local electric power system (local EPS) during unintentional islanding conditions. For example, IEEE 1547 states the following:

> "For an unintentional island in which the DER energizes a portion of the Area EPS through the PCC, the DER interconnection system shall detect the island and cease to energize the Area EPS within two seconds of the formation of an island."

The IEEE 1547 standard goes on to say that one of the ways in which the above stated requirement may be met is with reverse-power protection.

> "The DER installation contains reverse or minimum power flow protection, sensed between the Point of DER Connection and the PCC, which will disconnect or isolate the DER if power flow from the Area EPS to the Local EPS reverses or falls below a set threshold."

In addition to the unintentional island protection functionality described by the IEEE 1547, local and regional DER interconnection standards may not allow end users to net-export power back to the area EPS. Thus, reverse-power protection is a requirement for interconnection.

A.5.2 Reverse-Power Magnitude Test

A.5.2.1 Objective

This test is performed to characterize the accuracy of the reverse-power protection magnitude setting(s) of the EUT. The reverse-power protection accuracy of the EUT shall be specified prior to beginning the tests.

A.5.2.2 Test Guidelines and Procedures[32]

1. Connect EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

[32] This test will require voltage and current test signals to be applied to the EUT.

4. Record all settings.

5. Referring to the Reverse-Power Magnitude Test described in Section A.3.9.3, adjust the current to starting point I_b. Initiate a phase step function from 0° to -180°. The current shall be held at this magnitude and phase for a period t_h. At the end of this period, initiate the current ramp function.[33]

6. Record the current magnitude when the EUT trips.[34]

7. Return the current to nominal magnitude I_N and phase $\theta = 0°$ (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.5.2.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.5.3 Reverse-Power Time Test

A.5.3.1 Objective

This test is performed to characterize the accuracy of the reverse-power time-delay setting(s) of the EUT. The reverse-power protection time-delay accuracy of the EUT shall be specified prior to beginning the tests.

A.5.3.2 Test Guidelines and Procedures

1. Connect the equipment under test (EUT) according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source and DER voltages and the DER current(s) to the nominal operating conditions for the EUT.

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

---

[33] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

[34] Because the source voltage is 1.0 per unit and the phase relationship between the source voltage and current is -180°, the reverse-power trip magnitude will be directly proportional to the current magnitude at the trip point.

4. Record all settings.

5. Referring to the Reverse-Power Time Test described in Section A.3.9.4, adjust the current to starting point I_b. Initiate a phase step function from 0° to -180°. The current shall be held at this magnitude and phase for a period t_h. At the end of this period, initiate a current step function.[35]

6. Record the time between the initiation of the step function and the point when the EUT trips.

7. Return the current to nominal magnitude I_N and phase $\theta = 0°$ (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

A.5.3.3 Expected Results

The EUT is expected to trip within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.6 Characterization of Synchronization Compatibility

A.6.1 Rationale

Interconnection standards require DER units to synchronize with the area EPS prior to interconnection. For example, the IEEE 1547 states the following:

> "The DER unit shall parallel with the Area EPS without causing a voltage fluctuation at the PCC greater than ±5% of the prevailing voltage level of the Area EPS at the PCC, and meet the flicker requirements of clause 4.3.2."

In clause 4.3.2 of the IEEE 1547 standard, the document states that flicker limits are such that "the DER shall not create objectionable flicker for other customers on the Area EPS."

Clause 5.1.2 (of IEEE 1547) contains the acceptable limits for synchronization, which are based on the aggregate kVA rating of the DER system. Table A-3 was taken from Table 5 of the IEEE 1547. The table contains the acceptable limits for synchronization. It specifically addresses the limits for voltage, frequency, and phase differences at the moment the interconnection device connects the area EPS and the DER system.

Table A-3
The IEEE 1547 Synchronization Parameter Limits for Synchronous Interconnection to an EPS (or an Energized Local EPS to an Energized Area EPS)

[35] This procedure assumes a single-phase EUT. For three-phase EUT, begin with tests on Phase A only. After completing five tests on Phase A, execute five tests for Phase B only followed by five tests for Phase C only. Complete the undervoltage magnitude testing with tests on all three phases simultaneously.

Aggregate Rating of DER (kVA)	Frequency Difference (f, Hz)	Voltage Difference (V, %)	Phase-Angle Difference (,º)
0–500	0.3	10	20
> 500–1500	0.2	5	15
> 1500–10,000	0.1	3	10

A.6.2 Synchronization VoltaGEDifference Test

A.6.2.1 Objective

This test is performed to characterize the accuracy of the synchronization voltaGEdifference magnitude setting(s) of the EUT. The synchronization voltaGEdifference protection accuracy of the EUT shall be specified prior to beginning the tests.

A.6.2.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.
2. Set the source voltage(s) to the nominal operating conditions for the EUT.[36]
3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).
4. Record all settings.
5. Set the DER voltage magnitude to starting point V_b.[37, 38] The DER voltage magnitude shall be held at this level for a period t_h. At the end of this period, initiate a DER-voltage magnitude ramp function with positive slope.
6. Record the difference between the source and DER voltage magnitudes when the EUT closes the interconnection.

[36] This test does not require current test signals to be applied to the EUT.

[37] The source and DER voltages should be at nominal frequency and in-phase.

[38] The starting point voltage, V_b, is less than or equal to V_N minus 1.1 times the EUT's synchronization voltaGEdifference setting and a ramp function with negative slope.

7. Return the DER voltage magnitude to the starting point V_b (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

9. Repeat Steps 5 through 8 using a starting point voltage V_b that is greater than or equal to V_N plus 1.1 times the EUT's synchronization voltaGEdifference setting and a ramp function with negative slope.

A.6.2.3 Expected Results

The EUT is expected to close the interconnection within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.6.3 Synchronization Frequency-Difference Test

A.6.3.1 Objective

This test is performed to characterize the accuracy of the synchronization frequency-difference setting(s) of the EUT. The reverse-power protection accuracy of the EUT shall be specified prior to beginning the tests.

A.6.3.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source voltage(s) to the nominal operating conditions for the EUT.[39]

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Set the DER voltage frequency to starting point f_b.[40, 41] The DER voltage frequency shall be held at this level for a period t_h. At the end of this period, initiate a DER voltage frequency ramp function with positive slope.

---

[39] This test does not require current test signals to be applied to the EUT.

[40] The source and DER voltages should be at nominal voltage magnitudes.

[41] The starting point frequency, f_b, is less than or equal to f_N minus 1.1 times the EUT's synchronization frequency-difference setting and a ramp function with negative slope.

6. Record the difference between the source and DER voltage frequencies when the EUT closes the interconnection.

7. Return the DER voltage frequency to the starting point f_b (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

9. Repeat Steps 5 through 8 using a starting point voltage f_b that is greater than or equal to f_N plus 1.1 times the EUT's synchronization frequency-difference setting and a ramp function with negative slope.

A.6.3.3 Expected Results

The EUT is expected to close the interconnection within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

A.6.4 Synchronization Phase-Difference Test

A.6.4.1 Objective

This test is performed to characterize the accuracy of the synchronization phase-angle-difference setting(s) of the EUT. The synchronization phase-angle-difference accuracy of the EUT shall be specified prior to beginning the tests.

A.6.4.2 Test Guidelines and Procedures

1. Connect the EUT according to the instructions and specifications provided by the manufacturer and as described in Section A.3.6.

2. Set the source voltage(s) to the nominal operating conditions for the EUT.[42]

3. Set (or verify) all EUT parameters to the nominal operating settings (refer to Section A.3.7 for additional detail).

4. Record all settings.

5. Set the DER-voltage phase angle to starting point ϕ_b.[43, 44] The phase angle of the DER voltage shall be held at this level for a period t_h. At the end of this period, initiate a DER voltage phase-angle ramp function with positive slope.

---

[42] This test does not require current test signals to be applied to the EUT.

[43] The source and DER voltages should be at nominal voltage magnitudes and frequencies.

6. Record the difference between the source and DER voltage phase angles when the EUT closes the interconnection.

7. Return the DER-voltage phase angle to the starting point ϕ_b (and reset the EUT as necessary).

8. Repeat Steps 5 through 7 four more times for a total of five tests.

9. Repeat Steps 5 through 8 using a starting point voltage ϕ_b that is greater than or equal to ϕ_N plus 1.1 times the EUT's synchronization frequency-difference setting and a ramp function with negative slope.

A.6.4.3 Expected Results

The EUT is expected to close the interconnection within the specified accuracy for all tests. The test results may be used to characterize or verify the protection level accuracy relative to manufacturer specifications, interconnection standards, periodic verification of calibration, and so on.

---

[44] The starting point frequency, ϕ_b, is less than or equal to ϕ_N minus 1.1 times the EUT's synchronization frequency-difference setting and a ramp function with negative slope.

B
TEST SIGNAL GENERATOR: OMICRON CMC 256-6 EP

The Omicron CMC 256-6 is a high-precision secondary-injection relay test set designed to evaluate protection relays, energy meters, and transducers. The CMC 256 and the Omicron Test Universe software were used to create voltage and current signals to evaluate the relays and the automatic transfer switch. The CMC 256 has 10 data-acquisition channels that were used to monitor the states of relay fault contacts. Additional specifications and a photo of the Omicron test set are shown in Figure B-1.

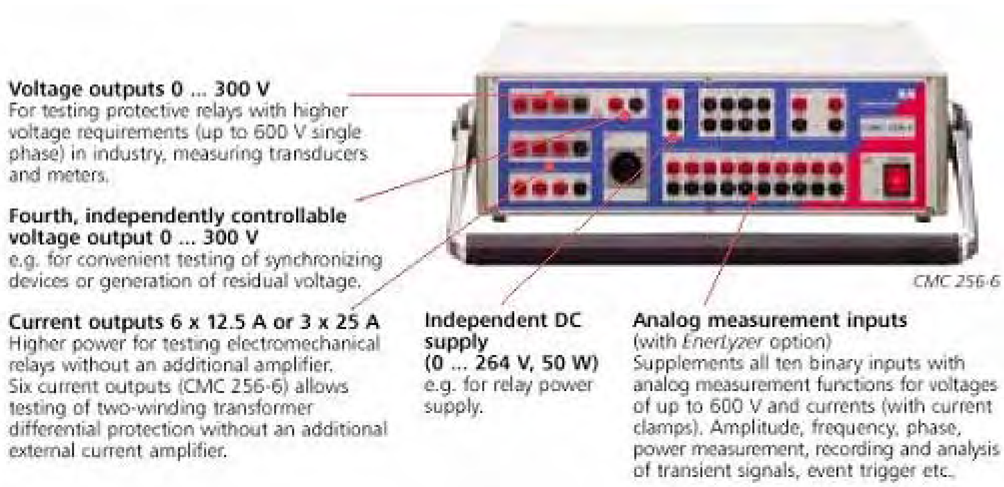

Table B-1
The Omicron CMC 256-6

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

Printed on recycled paper in the United States of America

1008858

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com