



IEEE Guide for Power System Protection Testing

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

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STANDARDS

IEEE Guide for Power System Protection Testing

Developed by the

Power System Relaying and Control Committee
of the
IEEE Power and Energy Society

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Abstract: Test approaches and procedures for the components and the overall protection and control system functions are presented in this guide. Test of equipment in the system protection scheme, associated communications equipment, auxiliary power supplies, and the control of power apparatus are addressed. Much of the testing emphasizes a bottom-up approach, in which the basic behavior of scheme components are verified first, followed by testing of interconnected components in a function-oriented assembly.

Keywords: application testing, commissioning testing, design testing, IEEE C37.233™, maintenance testing, performance assessment, type testing

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Introduction

This introduction is not part of IEEE Std C37.233-2023, IEEE Guide for Power System Protection Testing.

This guide focuses on the general approach and specific procedures for testing protective relaying systems that include multiple interacting relay components, auxiliary devices, and power apparatus. In the most critical applications, these system devices may interact over an extended physical or geographic area and use communications systems. The procedures focus separately on type testing (also known as design testing), commissioning testing, periodic maintenance testing, and ongoing performance assessment with a discussion of what each of these test categories aims to accomplish.

Contents

1. Overview	15
1.1 Scope	15
1.2 Purpose	15
1.3 Word usage	15
1.4 General	16
1.5 Types of protection system applications	16
1.6 Types of tests overview	17
1.7 Applicable protection schemes	19
1.8 Considerations for testing and scheme self-monitoring	21
1.9 IEC 61850	25
2. Normative references	25
3. Definitions, acronyms, and abbreviations	26
3.1 Definitions	26
3.2 Acronyms and abbreviations	27
4. Types of tests	28
4.1 Manufacturer certification tests	29
4.2 Manufacturer conformance tests	29
4.3 Manufacturer performance tests	29
4.4 Manufacturer or user's laboratory type application tests	30
4.5 Commissioning tests	31
4.6 Maintenance tests	37
4.7 Maintenance practices	38
4.8 Methods for generating test modules and cases	40
4.9 Retention of test results	54
5. Description of types of relay schemes and testing requirements	56
5.1 Introduction	56
5.2 Line protection	56
5.3 Transformer protection	65
Distribution protection	72
5.4 Shunt capacitor protection	78
5.5 Bus protection	80
5.6 Breaker failure protection and control	82
5.7 Shunt reactor protection	90
5.8 Generator protection	91
5.9 Trip circuit logic schemes	92
6. Protection system communication testing	97
6.1 Power-line carrier testing	97
6.2 Wireless communication	102
7. SIPS test requirements	104
7.1 Proof-of-concept testing	107
7.2 Field commissioning tests	108
7.3 System-wide performance testing during maintenance intervals	108
7.4 Validation through state estimation	109
7.5 Automatic and manual periodic testing of the entire scheme	110
8. Testing protection and control systems with unconventional voltage and current sensing inputs	111
8.1 Protection system testing via primary injection	111

8.2 Special analog and digital input considerations	112
8.3 Testing outputs of unconventional sensors	113
8.4 Verification by condition-based maintenance	115
Annex A (informative) Bibliography	116
Annex B (informative) Suggested line current differential scheme testing procedure	120
Annex C (informative) Impact of high-impedance faults to protective relay performance and system testing	125
Annex D (informative) Transformer oil and winding temperature computational methods	129
Annex E (informative) Measuring and compensating for time delay after trigger for performing end-to-end testing using different relay test sets	131

List of Figures

Figure 1—Example setup for transmission line end-to-end testing using IRIG-B	35
Figure 2—Relationship of maintenance types	39
Figure 3—Simulated stable swing trajectory with three impedance points	43
Figure 4—Calculated simulation states corresponding to Figure 3	44
Figure 5—Waveforms of the simulated states from Figure 3 and Figure 4	44
Figure 6—Testing out-of-step tripping function using state simulation	45
Figure 7—OOS impedance trajectory from dynamic simulation using transient stability program	46
Figure 8—OOS impedance trajectory from dynamic simulation using transient stability program	47
Figure 9—Resulting three-phase voltages and currents translated from stability program	48
Figure 10—Simulation parameters of an unstable out-of-step condition with a testing tool	49
Figure 11—System model for the simulation of an unstable out-of-step condition with a testing tool	50
Figure 12—Traces from simulation of an unstable out-of-step condition with a testing tool	50
Figure 13—Simulation of a stable power swing condition with a testing tool	51
Figure 14—Example traces from an unstable power swing simulation	52
Figure 15—Unstable power swing with single-phase-to-ground (A-phase) fault simulation	53
Figure 16—Example of application test setup using “open-loop” digital simulator	60
Figure 17—Overlapping test methods performed during FAT and Commissioning [B59]	61
Figure 18—Typical setup (at each terminal) for end-to-end testing by secondary injection	63
Figure 19—Test setup for non-invasive thermal protection systems	69
Figure 20—Test load current profile	70
Figure 21—Typical protection for a power transformer included in the transmission line’s zone of protection; e.g., a line with a series transmission transformer with the transformer being considered as part of the line (using redundant communication paths)	71
Figure 22—Line with a series transformer-source bus configured as a double bus and substitute breaker	72
Figure 23—Test system block diagram	74
Figure 24—Testing of distribution protection microprocessor-based device	74
Figure 25—Unsuccessful reclosing simulation	76
Figure 26—Scheme animation for user training (example)	77
Figure 27—Multiple schemes test mode (example)	77
Figure 28—Single scheme test mode	78

Figure 29—Breaker failure relaying scheme 1 logic diagram	83
Figure 30—Breaker failure relaying scheme 1 timing diagram.....	83
Figure 31—Breaker failure relaying scheme 2 logic diagram	83
Figure 32—Breaker failure relaying scheme 2 timing diagram.....	84
Figure 33—CT subsidence current.....	86
Figure 34—Current waveform and protective relay contact bounce	86
Figure 35—Single-line breaker-and-half bus configuration with a fault on Bus I	93
Figure 36—Single-line example of a double bus–single breaker bus configuration with a fault on Bus I	94
Figure 37—Isolator replica with normally closed (NC) and normally open (NO) positions	95
Figure 38—Trip circuit breaker failure scheme.....	96
Figure 39—Power-line carrier wave trap frequency set point verification	98
Figure 40—Setup for power-line carrier testing—equipment setup for transmit test (bridged) reflected power	100
Figure 41—Setup for power-line carrier testing—equipment setup for SWR	100
Figure 42—Simplified overview of SIPS structure	105
Figure 43—Physical architecture of a redundant SIPS.....	105
Figure 44—Simulator setup for testing a redundant SIPS	109
Figure 45—Redundant SIPS systems with central controllers at different physical locations with different communications interface/protocol options.....	110
Figure 46—Typical test setup for overall performance testing and throughput timing measurements	111
Figure 47—Three-turn test primary in window of current sensor	114
Figure B.1—Stub bus and 87L relaying	121
Figure C.1—Impact of the added fault impedance on effective relay reach	127
Figure D.1—Temperature profile assumed in the IEEE loading guide.....	129
Figure E.1—Setup for measuring the delay time after trigger	131
Figure E.2—Data from digital recorder.....	132

List of Tables

Table 1—Samples of functional testing as part of commissioning 55

Table 2—Example test plan for line relaying systems 55

Table 3—Legend for [Figure 29](#) to [Figure 32](#) 82

Table 4—Generator protection functions 91

Table 5—Example of open and closed position definitions 95

Table 6—Typical connection terminals between test and measurement equipment for wave trap
frequency set point verification 99

Table 7—Typical connection for measuring and testing transmit frequency for [Figure 41](#) 101

IEEE Guide for Power System Protection Testing

1. Overview

1.1 Scope

This guide covers suggested test requirements for power system protection scheme testing, system application tests, the scope and level of tests based on the application, and benefits of the overall protective schemes testing. This guide encompasses overall system testing procedures (generators, line, line reactors, transformer, capacitors, special protection schemes, end-to-end testing, distributed application within substation, etc.) and data collection requirements, as well as the test procedure definitions. This guide describes the methods, extent, and types of system tests for protection applications at various voltage levels. Control functions inherent to the protective systems are included. Importance of line testing, indirect trip applications, open/closed-loop tests, and dynamic/nonlinear tests are also covered.

1.2 Purpose

This guide is intended for power system protection professionals. It includes a reference list of type tests for protective devices as well as overall protection scheme performance tests for various types of protection schemes. The guide describes the methods, extent, and types of protection scheme tests. Interlocking and control functions inherent to the protective schemes are included.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

1.4 General

Testing individual relays, or testing within the confines of one traditional protected-zone panel, is not comprehensive enough to demonstrate that the system is ready to respond to a real fault or emergency. This guide focuses on the general approach and procedures for testing protective relaying systems that include multiple interacting relay components, auxiliary devices, and power apparatus.

Many elaborate or wide area protection systems are installed to handle rare and critical events to avoid major system outages. Sustained operation in the field does not give the user benign opportunities to observe and correct performance issues. These systems need accurate and realistic simulation of these rare events for type testing and effective in-service maintenance tests.

This guide presents test approaches and procedures for the components of the system and the overall protection and control system functions. The testing of equipment in the system protection scheme, the associated communications equipment, the auxiliary power supplies, and the control of power apparatus are addressed. The system is tested as a functional unit when possible, but it may be necessary to test components or portions of the system in overlapping test schemes when it is not practical to test the whole system together. Much of the testing emphasizes a bottom-up approach, in which the basic behavior of scheme components is verified first, followed by testing of interconnected components in a function-oriented assembly.

The procedures focus separately on type testing, commissioning testing, periodic maintenance testing, and ongoing performance assessment with a discussion of what each of these test categories aims to accomplish.

Testing procedures in this document are intended not only to assist engineering and maintenance personnel in developing technical testing processes, but also to help in planning testing resource requirements for discussion with utility management.

1.5 Types of protection system applications

The three overlapping categories of system design and applications needing these specialized functional testing approaches are listed below.

1.5.1 Wide area system integrity protection schemes incorporating power system measurements from multiple substations around the network

These types of schemes utilize communications systems to combine results or distribute the control action commands. The testing challenge lies in simulating and observing the performance of the system as installed over its extended physical domain. The user needs robust verification of both security and dependability of the protection.

1.5.2 Wide or local area protection schemes based on exchange of data among relays and microprocessor-based devices on a communications data bus, local area network (LAN), or wide area network

The data communications networks perform the signal exchange previously handled by individually wired dedicated connections that the user can check with simple test instruments. The communications networks may be dedicated, but are increasingly shared with other operating functions, or even with the highly diverse utility information technology (IT) infrastructure. The testing challenge lies in verifying that the protection function performs with robust design margins without imposing the need for impractical levels of expertise in data transmission and protocols or specialized protocol analysis instruments. Testing also needs to demonstrate that no credible interference of unrelated communications traffic leaves the shared communications network unable to serve the critical protective function under test.

1.5.3 Local area protection schemes with complex wired interconnections of components, input signals, and control outputs

The objective of this guide is to verify the output or protection performance of the entire scheme over all the expected combinations or ranges of input conditions. The test can verify behavior by input simulation and observation of the entire ensemble operating as a system. However, this may not show behavior or security margins in signals among the components, so some additional observation of these signals may be required. When a full input-to-output test requires more repetitive cases than is practical, it is sometimes acceptable to test individual components or portions of the scheme separately as long as the boundaries among the tested portions overlap in order to avoid gaps in testing elements. An example is a transformer or generator relaying system with 10 or more electromechanical relays, plus interconnecting wiring and auxiliary tripping devices such as lockout relays. Tripping and lockout operation may occur as a result of inputs to any of a number of measuring elements, each of which are tested. In at least one case, the lockout relay can be operated and its ability to trip and lock out the breakers is confirmed. For many other test cases used to verify the relays that feed the lockout relay, the breaker tripping or the lockout relay operation can be blocked as long as no wire or path is left untested.

1.6 Types of tests overview

This section introduces the three following different situations in the life of relays:

- a. Test performed at the manufacturer's facility.
- b. Tests performed during the installation of relays or relay systems at a power substation's CEE (control equipment enclosure) called commissioning.
- c. Tests performed after a period from the day of installment and maintenance testing in its various forms, including when a device underperforms or fails to perform.

These tests are described in [Clause 4](#).

1.6.1 Application certification type tests in the factory or laboratory

Each manufacturer typically provides its customers with a certificate of performance document for the respective product, that details what tests have been conducted prior to shipment. Products conforming to a recognized standard will typically have been subjected to a number of "design tests," also known as "type tests" as well as "production tests" or "routine manufacturing tests." Design tests are performed on a production sample or prototype to show that the product design is capable to meet specified performance requirements. Once the performance of the design is established, it is not necessary to repeat all of the design tests on every unit produced. Also note that certain design tests may be destructive to the product or may be inordinately expensive to perform; therefore, would be impossible or impractical to perform on every unit produced. The manufacturer's quality control will assure that all the units produced match the design in all essential features. Quality control includes production tests, also known as routine tests, that are performed on every unit produced to confirm that certain essential performance characteristics are achieved. For example, one relay manufacturer provides a "Production Test Report" that details all the routine production tests of various relay elements and features performed on each production unit, such as: System Clock, Temperature, Battery Monitor, and Analog Channels Calibration Tests. The report also shows Relay Self Tests, metering checks, and Inputs/Outputs Test. These checks and tests show a Pass Result within that manufacturer's tolerance parameters. The report is also signed by the company's representative or inspector. All these tests are generally performed based on the manufacturer's own default or generic relay settings. Finally, the customer's specifications are listed.

There are cases where these products are shipped to a panel manufacturer facility where the actual final relay setting is downloaded, and the relay is tested prior to delivery to the end site. The relay panel, itself a manufactured product assembled of manufactured components, may be subjected to certain design tests and routine manufacturing tests as well.

1.6.2 Commissioning tests (at installation site)

These are tests that are conducted during commission of the relay or relay systems. As part of the commissioning stages, and prior to the site relay testing, a complete wire verification should take place. All the internal panel wiring is verified for correctness per design, terminal/lug tightness, and insulation integrity. Similarly, all interconnection wiring between panels and other equipment should also be verified.

A commissioning team is focused on testing the relay or panels of relays as expected and designed by the client. The equipment received is evaluated for shipment damage. There are typically comprehensive tests performed defined by the owner to satisfy the relay's functionality.

The commissioning personnel receive an issued relay settings file from a Relay Setting Engineer. After the issued relay settings are loaded on relay, testing takes place for record keeping purposes. This test is typically an automated test of the elements that are enabled and timers of the setting. Any discovered deficiencies are investigated and corrected, and the test report showing a Pass Result is kept in the records for future reference. One major task of the commissioning team may be to functionally test the relay, proving the logic with all inputs and outputs verified as operational as designed, which can include checking all targets, messages, and any alarm logic. The level of detail required to functionally prove the control logic during commissioning may depend on the thoroughness of design testing performed by the control scheme designer or panel fabricator or other tests previously done on similar installations of the same design by the commissioning team.

1.6.3 Maintenance tests

After the relays have been in-service for some period, maintenance activities are performed. Electromechanical, or in some instances, solid state type relays have traditionally required more maintenance over time due to component aging and wear, and that in most cases, the relays do not have self-performing integrity check alarms. Microprocessor type relays have shown to require less attention mainly due to their self-checking abilities and no mechanical parts.

Clause 4 details maintenance type testing and the various descriptions of these tests, such as period/time based, condition based, performance concerns, and firmware upgrades or operational troubleshooting.

1.6.4 Troubleshooting tests following operations

It is important to emphasize the value of verifying overall system performance following correct as well as incorrect operations. This can be done by retrieving and analyzing sequence-of-events and oscillographic records captured from various devices and recorders for nearby disturbances. It is common practice to check relays that correctly perform for a particular operation, verify security, and quantify various elements within the relay relative to the fault or system operation. Examples of factors that could be analyzed are determining the faulted phase, generation of the correct trip targets, accurate fault location, and whether the tripping occurred by instantaneous or time delay element. Some key steps in reviewing performance of relay systems after operation include the following:

- a) Periodically review the application in light of power system evolution and protection and control system changes.
- b) Analyze relay or digital fault recorder (DFR) data from disturbances for which the protection system did or did not operate. Compare primary protection performance against the alternate protection where applicable.
- c) Consider the correctness of logic, characteristics, set points, relay targets and fault characteristics, hardware integrity, and wiring.
- d) Conduct complete or partial protection commissioning tests that may be necessary in the event of a firmware upgrade or modification. When problems appear, carry out commissioning-like tests to demonstrate continuing suitability or to verify needed changes.

- e) Make and verify needed changes to the periodic test procedures.

It is important to identify relay performance and identify whether a protective device correctly performs. In some instances, the device or the entire protective system may need to be tested. In some instances, it may also be possible to playback records from the devices to determine if the relay would perform similarly (repeatable) and to make adjustments as needed.

1.7 Applicable protection schemes

The document discusses examples of protection schemes and testing approaches for the following applications. In some applications, references are provided to other IEEE guides or standards where specific aspects of testing are covered.

Line protection

- Transmission
- Directional comparison pilot protection
- Multiterminal
- Tapped line configuration
- Line switching equipment integration
- Series compensated
- Shunt compensated
- Current differential or comparison
- Integrated relaying schemes
- Conductor heating/sag (due to load or external factors)
- Distribution circuits, including interaction with reclosers, switches, capacitor banks, monitors, load control systems, and other circuit equipment
- Integrated automatic reclosing and voltage/synch check
- Conditional single-pole tripping and reclosing
- Line reactor (as applicable)
- Surge arresters (as applicable)

Transformer protection

- Multiwinding
- Phase shifting
- Tap changing
- Overload protection with distributed thermal inputs
- Distributed winding measurement or data acquisition systems
- Integrated load, life, and condition monitoring systems
- Predictive, acoustic, or partial discharge detection systems
- Surge arresters (as applicable)

Bus protection

- Percentage restrained current differential
- Medium impedance differential
- High impedance differential
- Distributed measurement and control
- Configuration dependent protection zones and switching
- Postfault closing lockout
- Automatic reclosing
- Overcurrent protection
- Zone interlocked schemes

Shunt capacitor protection

- Capacitor fusing (where applicable)
- Unbalance relaying
- Overcurrent relaying
- Surge arresters (as applicable)
- Phase voltage relays

Breaker failure protection and control

- Breaker failure current supervision (50 BF)
 - Phase current detectors
 - Ground current detectors
- Breaker failure as part of the primary protection
 - Part of feeder, transformer, motor, generator, or transmission line protection, as applicable
 - Part of centralized bus protection
 - Part of distributed line protection
- Breaker failure initiate
- Communications-based breaker failure protection
 - Teleprotection in conventional breaker failure protection
 - High-speed peer-to-peer communications on substation LAN or system WAN, including other protections (as described in IEEE Std C37.119 latest standard)

Reactor protection

- Voltage control
- Current-limiting reactors

Series and Shunt reactors protection (as applicable)

- Overcurrent
- Differential
- Ground/Earth Fault
- Distance protection
- Turn-to-turn
- Breaker failure

RAS/SIPS

- Generator or tie outage reconfiguration or load shedding
- Plant load or tie rejection
- Voltage collapse protection and restoration
- Out of step, synchrophasor-triggered, or phasor measurement unit (PMU)-based protection

Distributed load shedding schemes

- Frequency or voltage-based load shedding that is dependent on centralized system conditions or remote event triggers

There are many other power system apparatus, such as static var compensators, harmonic filters, and automatic transfer schemes, which in most cases are application specific and are not covered in this guide.

1.8 Considerations for testing and scheme self-monitoring

One important aspect of testing any scheme is the documentation. This documentation includes the approved drawings, procedures and results, verifying that tests have been conducted and schemes are performing within design and acceptable parameters. The procedures and test setups also help ensure consistency in testing. Schemes can be simple, and the documentation may also be simple. When schemes are complicated and involve multiple owners and devices at sites, detailed documentation describing the steps necessary to accomplish this testing will make sure that these schemes are tested the same way each time to provide repeatability and comparison of test results. The procedures need to include test setups, equipment required, and procedures to isolate the system to be tested. When testing is conducted in an energized environment, additional steps are needed to help ensure that all elements of the electric system are protected while testing is in progress. Documentation of test procedures are usually retained to track performance history and for future maintenance purposes, and it is available as needed for demonstrating methods used for testing.

Microprocessor-based relays allow the user the ability to download existing event records prior to performing any maintenance and troubleshooting. In some cases, files that are downloaded have proven useful when analyzing future events based on a relay's performance history. It is up to each user to determine the value of retrieving and archiving this information.

1.8.1 Drive for scheme and test simplicity

In designing for robustness, engineers often consider the effectiveness and complexity of the scheme and how it can be tested. During the engineering and design stage, consider the following factors and their impact on testing:

- Supervising elements, their setpoints, and how the elements have been optimized.
- Whether the design includes use of redundant elements, applied in parallel formation, and the impact on security, dependability, reliability, and future expansion of the application. Redundant systems may offer flexibility for testing of elements without removing protection from service during tests. Whether the scheme is voting or vetoing and the impact of security/dependability of the application.
- Impact on scheme complexity: Complex systems have sometimes failed to perform adequately because of difficulty to test and/or identify fundamental design or application flaws.
- Test procedures and verification to return equipment to normal conditions after tests. Test switches and testing equipment present opportunities for test personnel to leave protective devices or systems in a nonfunctioning state.
- Whether the design provides provisions for temporarily disabling or isolating protective elements for testing (test switches, cutoffs, etc.)

1.8.2 Benefits and justification of tests

Traditionally, the protection and control system is designed to identify local fault events, such as a short circuit, based on the voltage, current, and frequency determined at a specific point on the utility system. The protection and control system is designed to help prevent a wide area failure of the utility system by isolating these local events. Changes in the operation of the power system, in terms of location and operation of generation sources, transmission capacity, and load demand, as well as changes in power system equipment such as the growing availability of reliable wide area communications result in changes in some basic philosophies of the protection and control system. For example, wide area protection schemes and system integrity protection schemes are applied more frequently to help prevent failure of the utility system during wide area events or to help prevent local faults from cascading into wide area events. These types of schemes coupled with narrower operating margins make improperly controlled local faults a challenge that is addressed by the testing of the protection and control system as a comprehensive system, not as individual components.

The goal of testing the entire protection and control system is to validate the performance of the entire system, from the individual components to backup, redundant, and auxiliary components, and the interaction between these components work correctly in terms of maintaining the dependability and security of the scheme at a desirable level of performance. The benefit of testing individual components is known from years of experience. If the individual parts work and the scheme is designed and installed correctly, there is a high probability the system will work correctly. However, protection system testing verifies that the scheme is correct in both concept and application settings. An example is end-to-end testing of transmission lines, using test conditions based on fault contingency studies. The different test cases, run simultaneously at each end of the line, confirm that all relays, communications equipment, and auxiliary equipment work for commonly anticipated events and worst-case scenarios. It is even possible to simulate typical modes of failure of the individual components to help ensure the protection and control system will still identify and isolate for fault events. Measuring the actual timing of the protective relay schemes in conjunction with the interrupting devices can also provide more accurate fault clearing time data for power system stability models.

The key benefit of protection system testing includes verification of the protection and control scheme in its entirety. A proper test documents the performance of the protection and control system and limitations of performance. The test documentation also serves as a baseline for evaluating future performance during actual events versus the expected performance. Baseline performance is used to compare differences between expected and actual events. Testing the performance of the protection system, especially wide area protection schemes or system-integrity protection schemes, is dependent on static and dynamic system models. As these schemes and the system behavior during events the schemes are designed to protect are very complex, testing can provide the engineer a better understanding of the protection system, the limits of performance, and the possible modes of failure. One type of testing for system-integrity protection schemes is to install the system, while blocking any control actions, to analyze the performance of this protection system during actual system events. This actual test data can be used to improve the static and dynamic models of the power

system. Another benefit is illustrating or understanding the protection and control system performance during certain types of events and where and why failures may occur. The importance of written test procedures and documentation are described in 4.9.

The design of the protection and control system considers the performance requirements for the specific location, analysis of power system behavior, and an understanding of the actual limits of performance of components available for use in this application. Tests for the protection and control system at a specific location are performed to prove the assumptions made during the design phase, starting with the individual components and working toward testing total system performance.

1.8.3 Built-in checks for internal or system problem identification

A critical aspect of testing is to develop an approach that can detect when the normal evolutionary changes in the power system or protective and communications systems surrounding the scheme under test threaten its ability to perform as designed. As the industry develops such adaptive testing approaches, a focus of the designers of components and systems becomes incorporating the sensing and logic needed to look for impending trouble and make the system robust in the face of such gradual change.

For example, a system integrity protection scheme (SIPS), also known as a special protection system (SPS), or remedial action scheme (RAS), might use an ON-OFF power-line carrier (PLC) channel to transmit a single critical status report between two substations. Many PLC channels are typically multiplexed through symmetric or skewed hybrids, line tuners, and coupling capacitor voltage transformers (CCVTs) and are dependent on tuned line traps and on the modal carrier propagation characteristics of the transmission line itself. For this example, the SIPS is thoroughly tested during commissioning and a simplified maintenance test is periodically or automatically carried out after that. The PLC monitoring may include automatic check-back testing. In subsequent years, several transformer taps may be installed to serve new customers along the line. Additional PLC channels may be multiplexed with those that were operating at commissioning time, both on the line in question and on adjacent lines. At some point, the expanded combination of frequencies and signal levels can mix with the multiplexing schemes and line propagation modes such that the simultaneous operation of two carrier sets not associated with the SIPS may cancel the carrier signal. If this circumstance occurs only during a fault, the SIPS maintenance testing may show satisfactory operation until the need for a SIPS operation arises. For a particular fault situation, the carrier state is not received, and the SIPS fails.

Although there are no convenient checklists to protect against all future changes, the designers and their testing approaches commonly include scheme verification in the face of commonly occurring events and changes that do not call for operation of the scheme under test or for restraint of the scheme. In the example above, using a frequency-shift carrier or continuously observable channel can combine with SIPS carrier dropout monitoring that can point to trouble in the future.

In most cases, checks for nonfault behavior of components can passively monitor critical signals without adding links to the critical protective chain. In hard-coded or programmable logic of microprocessor-based devices, monitored critical signals can be posted as events or alarms to be checked by the user without disrupting the tripping chain. These signals can be supervised by independently programmed logic that filters the alarm cases without having any effect on tripping. The scheme designers generally integrate this monitoring logic so that it is subjected to the full range of type and commissioning tests.

1.8.4 Test from the bottom up

For all of type testing, commissioning testing, and maintenance testing, start with verification of the smallest elements to be verified. Determine what is assumed or known—for example, environmental tests have been performed on a numerical (microprocessor-based) device to be type tested in a SIPS scheme; firmware design is assumed to be solid in a maintenance test. Check the points to be verified on these smallest units and then proceed to check the joint behavior of the next level of interconnected units. Continue until the highest overall system test is completed.

1.8.5 Overlap zones of testing

It is important to design the system and its maintenance test program for segmented testing or self-monitoring of the links in the protective chain. Maintenance verification by testing or observing segments is effective as long as the segments overlap. In other words, the interface between segments or links are verified by observations during the test of the adjacent elements.

For example, a relay input may be isolated and a test signal applied to check for trip output via contact closure. Separately, the breaker may be tested by a manual trip. This pair of tests does not check the ability of the relay trip contact to trip the breaker—an undetected cold solder joint in the relay could pass an ohmmeter test and open up when a real trip is initiated. The overlapping test would be to apply inputs and check relay response as before and then to test breaker tripping by using the front-panel or data communications trip function to operate the breaker.

Also, there may be power system effects that need to be fed into all segments as a result of a specific segment action. Therefore, segmented testing typically considers a scheme's purpose and incorporates sufficient levels of overlapping segments to prove adequacy for overall scheme performance.

1.8.6 Make use of in-service experience

In many cases, faults or system events are used to validate performance of parts or whole protection systems. Events and oscillographic records are used to verify recently exercised elements of the scheme. If a relay in a scheme under test also tripped correctly for a fault, the trip output and trip circuit are probably working and can be left alone.

1.8.7 Use continuous performance checks for schemes using communications messaging

Many new protection schemes make use of control messaging or status and value reporting among multifunction relays, over an Ethernet LAN or other data communications media. The messages may be based on IEC 61850 generic object-oriented substation event (GOOSE) or generic substation state event (GSSE), modbus transmission control protocol (TCP), DNP3/TCP, or any of a number of other standard control protocols or vendor-specific protocols. Serial data links or networks such as RS422 or RS485 are also widely used for critical protection and control.

Implementation of the overall GOOSE/GSSE system normally takes into account the philosophy surrounding maintenance and testing. Provisions for isolating transmission and receiving GOOSE signals for testing can be defined and captured into procedures for engineering prior to commissioning. GOOSE/GSSE system after the initial implementation and commissioning may be difficult to modify [B43].⁸

For Ethernet LANs and IEC 61850 GOOSE/GSSE applications in particular, inactive-withdrawn IEEE Std C37.115™ provided reference background on the analysis of normal and transient levels of message traffic on the LAN. At the time that IEEE Std C37.115 was written, there was a concern over the risk of performance degradation or lost messages due to collisions or LAN capacity during a data storm triggered by a multiple-contingency relaying situation at the substation. While system designers still need to pay attention to these possibilities, the newest LAN implementations are not vulnerable to these shortcomings. Managed Ethernet switches direct the message traffic and eliminate any opportunity for collision and message loss. Network links between microprocessor-based devices and their dedicated Ethernet switch ports operate at speeds between 10 MB/s and 1 GB/s, where a properly designed LAN will not introduce any rational level of message traffic with significant delays that could impact protection performance. Refer to IEEE Std 1615™ for the recommended practice for designing Ethernet networks in substations and to IEEE Std 1613™ for environmental and testing requirements.

⁸The numbers in brackets correspond to those of the bibliography in Annex A.

Additionally, if the protection scheme includes application of cybersecurity communication links (i.e., routable protocols), it is important to verify the performance of the scheme, as well as test data communications channel integrity on a continuous basis. Refer to IEEE Std 1686™ for cybersecurity standards associated with devices used at substations. In such cases, communication link monitoring requires the following:

- For continuously streamed data, such as analog measurements or status reports, establish a predictable maximum time interval between messages in the never-ending transmission stream. The receiving microprocessor-based protection device with integrated communications interface then watches for the critical messages and raises an alarm if valid messages are not received in the expected time frame. This presumes that the integrity of the message is also confirmed via parity, cyclic redundancy check (CRC), or other message bit error detection methods available in the applied communications protocol. In such cases, corrupted messages can be alarmed along with missing messages.
- For transient control messages, such as a control command, it is important to define a companion nontrip monitoring message that is sent as a streaming message and used for monitoring the messaging path as explained above. The monitoring message uses the same data communications hardware, transmission path, and protocol and be as close as practical yet clearly distinguished from the rarely used control command. IEC 61850 GOOSE and GSSE messages used for control inherently offer this capability. The messages are time-tagged and constantly streamed in their quiescent state at a designer-set time interval when the station (including substation, switching station, or generating station) has no protection events in progress. All the relays that subscribe to a GOOSE message from a particular publishing relay watch for the stream of messages, and each can alarm if it is not receiving the stream of no-operate messages at the expected time intervals. Channel problems are thus caught when they occur as opposed to waiting for a mishandled fault to point to a communications failure. The monitoring is complete from relay processor to relay processor, so periodic testing by personnel is neither necessary nor advisable. When a state change, such as a fault, occurs, IEC 61850 GOOSE defines a temporary acceleration of the messaging rate to help ensure that all the subscribing relays have multiple opportunities to receive the critical tripping message without significant time delay.

GPS time tagging or sequential numbering of the messages can improve the quality and precision of the monitoring but is not always necessary. IEC 61850 GOOSE/GSSE includes this message identification feature by which subscribing relays can report the times of missing or corrupted messages.

1.9 IEC 61850

Distributed protection applications are now being implemented based on high-speed peer-to-peer communications defined under IEC 61850 and related standards. It is obviously still necessary to perform the same types of tests whether protection applications are distributed using IEC 61850 or more traditional implementation. Performing these tests in IEC 61850-based systems warrants specific knowledge, some specialized tools, and more detail than can be discussed in this Guide. Good reference documents for specifics around testing IEC 61850-based systems include “Application Testing of IEC 61850 Based Systems” [B20], “Test strategy for Protection, Automation and Control (PAC) functions in a fully digital substation based on IEC 61850 applications” [B5], and “Functional testing of IEC 61850 systems” [B19]. These references cover testing IEC 61850 applications, including GOOSE messaging, devices that use sampled values as the source of current and voltage measurements, time synchronization, and control functionality.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C37.99™, IEEE Guide for the Protection of Shunt Capacitor Banks.^{9,10}

IEEE Std C37.116™, IEEE Guide for Protective Relay Application to Transmission-Line Series Capacitor Banks.

IEEE Std C37.119™, IEEE Guide for Breaker Failure Protection of Power Circuit Breakers.

IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

IEEE Std 643™, IEEE Guide for Power-Line Carrier Applications.

IEEE Std 1613™, IEEE Standard Environmental and Testing Requirements for Communications Networking Devices Installed in Electric Power Substations.

IEEE Std 1615™, IEEE Recommended Practice for Network Communication in Electric Power Substations.

IEEE Std 1686™, IEEE Standard for Substation Intelligent Electronic Devices (IEDs) Cyber Security Capabilities.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

application tests: Specific tests performed to determine the suitability of a product for a specific design application or location.

certification tests: Tests made, when required, to verify selected performance characteristics of a product or representative samples thereof.

commissioning test: A test conducted when the equipment is installed to verify correct operation.

condition-based maintenance (CBM): Periodic equipment servicing performed on an interval derived from continuously or frequently reported results from nondisruptive self-monitoring of components.

performance-based maintenance (PBM): Periodic equipment servicing performed on an interval derived from analysis of historical servicing results and in service performance. Typically used to extend or reduce the interval of time-based maintenance (TBM).

performance test: An evaluation of the performance of an instrument in response to a given influence quantity

primary injection testing: Testing of a protection system by injecting a voltage and/or current at the high voltage interface of the protection system instrument transformers.

secondary injection testing: Testing of a protection system by injecting a voltage and/or current at the output of the instrument transformers of the protection system.

time-based maintenance (TBM): Periodic equipment servicing performed on a fixed maximum interval derived from experience or manufacturer recommendation.

⁹IEEE publications are available from The Institute of Electrical and Electronics Engineers, Inc., (<http://standards.ieee.org/>).

¹⁰The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

¹¹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

3.2 Acronyms and abbreviations

ATP	alternative transient program
BER	bit error rate
BF	breaker failure
BFI	breaker failure initiate
CBM	condition-based maintenance
CCVT	coupling capacitor voltage transformer
CT	current transformer
DCB	directional comparison blocking
DFR	digital fault recorder
DNP	distributed network protocol
DTT	direct transfer trip
DUT	device under test
DUTT	direct underreaching transfer trip
EHV	extra high voltage
EMTP	electromagnetic transients program
FAT	factory acceptance testing
GOOSE	generic object-oriented substation event
GPS	global positioning system
GSSE	generic substation state event
GSU	generator step-up
HV	high voltage
ICT	information and communication technology
IED	intelligent electronic device
IRIG-B	inter-range instrumentation group—time code format B
LAN	local area network
MOV	metal-oxide varistor
MU	merging unit
OST	out of step tripping
PBM	Performance-based maintenance
PLC	power line carrier
PMU	phasor measurement unit
POTT	permissive overreaching transfer trip
PSB	power swing blocking
PSTN	public switched telephone network
PUTT	permissive underreaching transfer trip

RAS	remedial action scheme (synonym of SIPS)
RF	radio frequency
RUT	relay under test
SCADA	supervisory control and data acquisition
SCR	silicon controlled rectifier
SDH	synchronous digital hierarchy
SER	sequence of events recorder
SIPS	system integrity protection scheme
SONET	synchronous optical network
SPS	special protection system (synonym of SIPS)
SWR	standing wave ratio
TBM	time-based maintenance
TCP	transmission control protocol
TOC	time overcurrent
TRV	transient recovery voltage
VLF	very low frequency
VT	voltage transformer

4. Types of tests

In this clause, different types of tests are described. Some of the tests are device specific, and others are application oriented.

As introduced in [Clause 1](#), and to reiterate, there are three situations for testing in the life of relays; tests performed at the manufacturer's facility, tests performed at the installation site (commissioning tests), and tests performed after some time in-service, called maintenance tests.

Tests on relays and relay systems include type tests (also known as design tests) and routine quality assurance tests (routine tests, QA tests, or production tests). Type tests are done on a prototype or sample of a product to confirm that products made to the design will meet the required performance. Routine production tests are performed to confirm that the units being produced match the essential features of the design that was type tested.

Protective relays are usually mass-produced products so there is clear distinction between the type tests performed to prove the design and the routine production tests performed to assure product quality.

Relay systems or relay panels are often custom manufactured or very low-volume production units. In these situations, the actual production unit may serve also as the sample subjected to type testing and conformance testing. As a result, there might not be clear distinction whether a particular test performed on a production unit is a conformance test, type test, or routine production test.

Certification tests, conformance tests, and performance tests may include both type testing and production testing.

4.1 Manufacturer certification tests

Certification tests are performed to verify that a relay system or scheme is performing according to its design. Test results are recorded and retained, and a test report or certificate is issued by the responsible party (testing laboratory or manufacturer) attesting to the results. Relay systems/schemes are usually made up of devices from various manufactures; therefore, certification tests at the factory are important because they provide a modeled, controlled environment similar to that found in “real life.” Models prepared to perform certification tests include circuit breakers simulators and other equipment or functions found in the substation. Certification tests may include type tests or routine quality assurance tests and may include the following:

- Technological conformance tests
- Functional conformance tests
- Functional performance tests

4.2 Manufacturer conformance tests

The goal of conformance testing is to verify the performance of the protective device or protection system against a set of predefined specifications. Technological and functional conformance tests are generally type tests (design tests) made by the manufacturer to validate the design of the microprocessor-based device, and consequently in most cases, there is no need to repeat them for a specific, customized system or scheme. Conformance testing may also refer to routine quality assurance testing that confirms that the units being produced conform to the design as follows:

- *Technological conformance tests:* Technological conformance tests verify the response of the protective function to external disturbances and internal failures. Technological tests cover the verification of the hardware quality, a reliability assessment, and an evaluation of the self-supervision. The verification of the hardware quality includes insulation properties and environmental conditions (electromagnetic compatibility, mechanical, and climatic).
- *Functional conformance tests:* Functional conformance tests verify whether the functionality of a protective function is as expected. Tests are focused on verifying the general characteristics against specification by means of signals without transients and direct current (dc) components. Functional conformance tests are generally steady-state accuracy tests.

4.3 Manufacturer performance tests

A performance test (also referred to as acceptance testing) is a type of test that confirms the performance of protective relays used in a specific application. The testing is a way to rate the performance of a specific relay or system. Performance tests might be type tests (design tests) performed generically to cover all systems of a specific design, or may be application specific for one particular installation, or some combination of type testing and application specific requirements. The test results describe the ability of the relay to perform according to its specifications and the performance of the relay during certain types of common performance requirements and fault conditions. Test conditions are generally derived from testing models based on a simple power system model. These types of tests are typically performed when evaluating a new relay for use on a specific power system, or, in some cases, when evaluating new firmware. See IEEE Std C37.231™ [B45] for additional information regarding firmware revision control. The severity of firmware changes can be used to determine whether a new suite of tests is needed. The general results from certification tests include operating speed, consistency and repeatability of performance, boundary conditions for optimal performance, understanding of settings methodology, and the suitability of this relay for typical applications. As an example, certification tests of a distance relay will illustrate operating speed of the distance element and the reliability of the distance element for zone boundary faults and during CCVT transients. These tests, therefore, determine the general suitability of a distance relay for extra high voltage (EHV) and high voltage (HV) protection applications.

The goal of performance testing is to verify the behavior of the protection under realizable network conditions. It includes aspects like dc offset, source impedance ratio, fault resistance, various types of faults, etc.. In contrast to conformance testing, performance tests do not focus on how a certain function is performed within the protection but on what is to be expected from a function under certain power system conditions. In case of multifunctional protection, the following distinction can be made between function tests and scheme tests:

- *Functional performance tests* are commonly performed on mockup assemblies located in a laboratory under a controlled environment. These mockups, which are made up of relays; other protection system elements; microprocessor-based devices, such as merging units (MUs) or programmable logic controllers; and supplementary apparatus such as circuit breaker simulators, provide the same functionality of the real application. Some components of the real systems need to be simulated like breaker status and operation. The laboratory environment allows all aspects of the system to be monitored, and the final result of the testing is that the user will have a high degree of confidence in the functionality of the systems.

Futhermore, each function is tested and evaluated separately. The performance of an individual protective function is examined in detail.

- *Scheme performance tests*: Scheme performance testing verifies the performance of a protective function under various conditions. Because microprocessor-based protection contains a large number of functionality combinations, it will be impossible to test them all. Scheme performance tests are therefore limited to a number of practical protection applications, with the protection schemes configured as applicable.

Software (firmware) upgrade of a protective function is considered to be a new protection, which would result in similar tests as with a new installation. Due to the interval of software upgrades, full replication of all tests may not be cost effective. Therefore, a limited program can be performed if, in an earlier stage, a complete type test is performed. The limited program includes the following:

- Tests to verify that the new or changed function works correctly.
- Tests to verify that no other functions are declining. This is more complicated because of the number of functions and possible combinations.

NOTE—Some probabilistic analysis may help to determine which elements or hardware components need retesting.¹²

4.4 Manufacturer or user's laboratory type application tests

Application tests are driven by the user's planned objective test criteria. Application tests are specific tests to determine the suitability of a relay for a specific protection system design application or location. Application tests are based on a detailed model of the power system and include performance testing against a wide variety of possible fault conditions. This type of testing typically uses transient simulation to replicate more accurately the behavior of the power system. The goal is to confirm a specific relay will perform for a specific application or location before actual installation. Although certification tests focus on specific relays, which are the basic building blocks, application tests may also be used to verify the entire protection scheme. Application tests are typically performed during the evaluation and design phases. The benefits of application testing are numerous. The application tests document that a specific relay, or algorithm, or a protection scheme is the correct choice for a certain set of power system conditions or criteria. It is typical, for example, to use a transient model of the specific power system, using multiple fault conditions, to determine the suitability of a distance relay. System integrity protection schemes require significant application testing as transient system modeling is inherently used to design the scheme and specify the scheme response to power system events.

¹²Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

A second benefit of application testing can be the determination and documentation of appropriate settings. Application testing verifies the performance of a protection system in total response and will highlight the failure or overlap of specific elements of the scheme. The operating settings of these elements can then be modified based on the results of the application testing.

Several relatively complex examples for which application tests may be performed include system integrity protection schemes (SIPS), series compensation, and single pole tripping.

The following application tests are based on the use of transients for testing protective relays to simulate the behavior of the network during faulted conditions:

- Fault resistance
- Current transformer saturation
- Voltage transformer transients

Commonly practiced methods of creating test files for transient testing include use of transient signals obtained from fault recorders (COMTRADE format), generating test files using simulation programs in combination with playback, or closed-loop test equipment such as real-time simulators. Refer to IEEE Std C37.111™ [B41] for information related to the COMTRADE file formatting and standard.

4.5 Commissioning tests

The primary objectives of commissioning tests are to determine whether equipment was damaged or changed during shipping and field installation to help ensure that equipment is installed and wired properly, to verify that installers entered appropriate settings and option selections, and to observe interaction with the power apparatus. The test focus shifts from verification of design to verification that the system is working at the installation site as the design intended.

Commissioning tests are intended to help ensure the protection system will operate as designed after field installation. These tests verify the individual components, anticipated interactions between components and devices, communications system, and scheme redundancy along with wiring and installation. These basic tests are commonly performed for any new installation or significant modification to an existing installation and are typically combinations of certification and application tests. The certification tests performed during commissioning verify that elements perform in a field installation in a manner consistent with laboratory results. This step is important for equipment with performance that varies due to environmental conditions or age of components, such as electromechanical relays. Application tests performed during commissioning verify that the total installed scheme works as designed and intended, especially regarding installation accuracy and interaction between various protection and control system components.

Commissioning tests are vitally important, as these tests prove that the actual installed system will work as intended. Commissioning tests can become very advanced. End-to-end testing of transmission lines is one advanced method, ensuring that units at both ends operate correctly.

The most important benefit of commissioning tests is verifying that the protection and control system works in the field as intended. An effective method for proving this verification of performance is a commissioner injecting secondary current to simulate a realistic fault condition into the specific relay, forcing the output contacts to work as expected and proving the functional logic. All the relays' inputs and outputs are proven. A second benefit is documentation of field performance as a benchmark for verifying performance for future tests.

For the elements or features that have been set on a device, the tests normally follow the functional hierarchy of the protection system in the following order:

- Check the available system parameter measurements and make sure that they meet the technical specifications.
- Test the enabled and configured protection elements and logic.
- Test the built-in protection schemes.
- Test the multirelay protection schemes.
- After initial testing is complete, but before placing the relays in-service, verify the relay settings are the desired in-service settings and that all temporary changes for testing purposes are restored.
- Perform in-service load checks once energized to verify proper configuration of instrument transformers.

Commissioning tests may require the use of multiple synchronized test devices in order to verify the performance of protection schemes or other distributed applications. Proper simulation of abnormal conditions for each of the devices in a scheme is essential for the testing.

For certain applications using IEC-61850 in intra-substation configurations, testing involves simultaneous monitoring of numerous microprocessor based protective devices, ensuring all GOOSE messages are processed correctly.

The commissioning test responsibilities are as follows:

- a) To integrate the system components with the site current transformers (CTs), voltage transformer (VTs), sensors, communications systems, wiring, and auxiliary power supplies.
- b) To verify that factory-supplied connections are correct and complete.
- c) To help ensure each component performs in accordance with vendor specifications and type testing for that component.
- d) To test interactions, and overall system performance, with a sampling of test cases across the spectrum of possibilities. For commissioning tests, a comprehensive suite as is used for factory type tests is not intended.
- e) To test the overall scheme by simulating power system events that cannot be readily generated on demand through the use of techniques described in this guide. Examples include transient simulation, tests for abnormal conditions, end-to-end testing, and functional testing of applications using IEC 61850.
- f) Operate other power apparatus or secondary control systems in the vicinity to show that the system is secure and/or dependable in the face of spurious environmental influences or communications traffic.
- g) To verify proper mapping and operation of the protective device with other data/control systems to which it is interconnected.
- h) Verify any security measures in place to protect the integrity of protection related information.
- i) To perform in-service readings (load check) of the protective relays upon first energization to assess proper phasing of voltage and current devices in the in-service condition.

In summary, commission testing is used to make sure the protection system is properly installed and working as expected in a substation.

4.5.1 End-to-end testing (Multi-station testing)

End-to-end testing involves time-synchronized testing of a protective system simultaneously at two or more stations. This testing can allow the testers to assess the behavior of communication assisted protection

systems; for example, pilot wire and power-line protection schemes in real-time. It is also useful for verifying the performance of the communication channel. While end-to-end tests are commonly performed during initial installation of the protection system, these tests are sometimes needed to be conducted over life cycle for reasons such as incorrect operation, poor performance, or addition of a new line terminal (in case of line protection).

For end-to-end testing, equipment is required at all terminals of the line under test. This section provides a list of equipment that may be used. This equipment can be used in conjunction with the established testing practices of the owner of the protection equipment. The following description applies to both two and multi-terminal lines.

This list of equipment is based on having qualified personnel and equipment at all ends of the transmission line for which the protection is being tested. There are techniques for having personnel at one terminal only and remotely controlling the activities at the opposing terminal. Refer to Schreiner and Kunter [B60] for more information.

The following equipment may be needed in the end-to-end testing of transmission lines:

a) *Test equipment*

- 1) Interface to a microprocessor-based device: A computer with appropriate manufacturer-specific software is often used in order to communicate with the microprocessor-based device under test to monitor performance, view/retrieve data, and possibly modify settings and application logic.
- 2) Test equipment: To test the devices, test equipment capable of being time-synchronized and to provide three-phase voltages and currents are often used. In some cases, such as line differential, three-phase voltages may not be essential but are useful for testing the performance of ancillary or backup functions. Based on the system under test, microprocessor or electromechanical, review of the Volt-Amp capability of the test equipment is important. For example, there are instances where equipment under test requires paralleling current channels of the test equipment.
- 3) Fault simulation software: Software is needed that can generate fault sequences. The output from this software is used by the secondary injection equipment and provides the sequence information and waveforms necessary for the test. This software may be associated with the specific secondary injection equipment or may be some third-party software that has output data format compatibility with the secondary injection test equipment.
- 4) Fault recorders: To monitor all the requisite test points, the use of a fault recorder at each site may be needed to capture information that is not already recorded by the microprocessor-based device.
- 5) Time synchronization: Time synchronization at all terminals of the transmission line is essential in performing end-to-end tests. Potential sources of time synchronization are: Inter Range Instrumentation Group (IRIG-B), global positioning satellite (GPS), or IEEE Std 1588™ precision time protocol (PTP) equipment to provide the necessary timing accuracy. For traditional communication assisted transfer trip schemes such as permissive overreaching transfer trip (POTT), permissive underreaching transfer trip (PUTT), DCB, etc., a synchronizing accuracy of 1 ms is adequate. For line differential schemes, 10 microsecond accuracy is desired. For end-to-end testing of traveling wave relay schemes, accuracy of ± 100 ns is desired.

NOTE—Time synchronization equipment at the test sites may be loaded to their maximum output capability, and it would be prudent to check that enough signal strength is available prior to commencing the test. An oscilloscope can be used to measure the voltage level of the signal of the time synchronization equipment, and this can be compared with manufacturer specifications. The time synchronization signal may be connected to both the microprocessor-based device under test and the test equipment. This time synchronization is used to coordinate the start of the test cycle at all ends of the transmission line and to time-stamp the data accurately.

- 6) Miscellaneous equipment: In addition to the above equipment, standard miscellaneous devices and components such as multimeters, connector cables from the microprocessor-based device to the laptop, jumpers, tools, and test leads may also be required for testing purposes.
- b) *Communication equipment*
 - 1) Data: Many multi-terminal protection schemes (for example, line differential relays) pass such data as voltage, current, trip signals, and time stamps among each other over existing communication channels in the normal course of operation. Additional data transmission requirements for testing purposes may not be necessary in these cases. For protection schemes where power system data is not normally passed from one terminal to the other (for example, distance protections where only a permissive signal may be sent), some additional methods may be required, such as secured closed network or channel connection. However, this data transmission requirement may not be necessary in most cases, as coordinated testing schemes from test equipment can be used and data can be retrieved from the test equipment and microprocessor-based devices at each site after the tests are completed. In the planning stages of the test, determine what data are required at all ends during the test and how to obtain that data.
 - 2) Voice: A voice channel is necessary for staff to communicate with each other and system control operators. This channel can be anything that is convenient and reliable such as a cell phone or microwave/fiber channel.

The configuration in [Figure 1](#) can be used to perform end-to-end testing of a two-terminal transmission line. The test equipment injects required three-phase voltages and currents into the protection under test. The test equipment also monitors the trip output, breaker failure initiate, transfer trip receive, and transfer trip send signals from the protection. GPS satellite receiver clock synchronization is used in order to allow comparison of data between the two terminals. More detailed description of end-to-end testing is available in the line protection section.

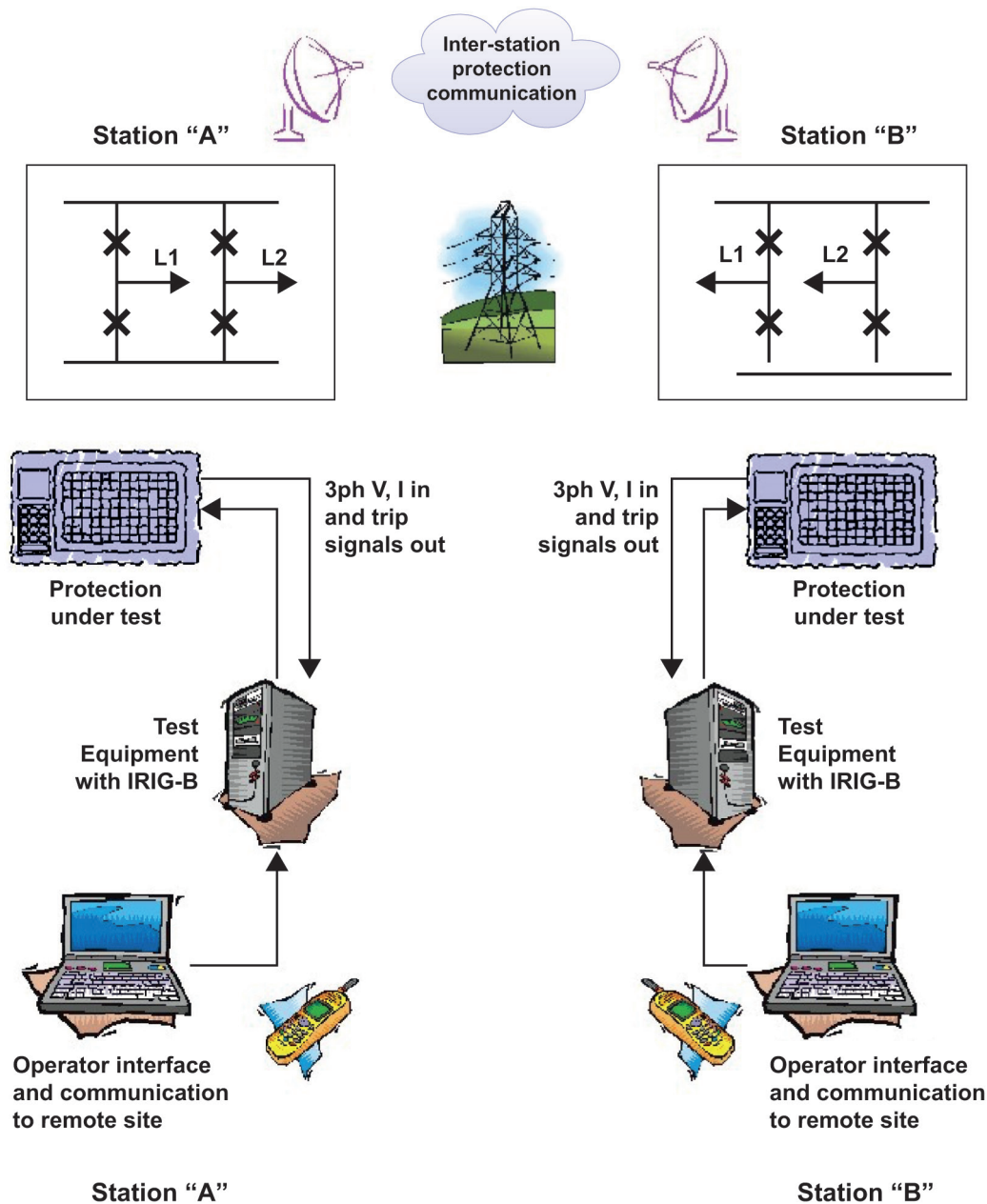


Figure 1—Example setup for transmission line end-to-end testing using IRIG-B

4.5.2 Load check or in-service readings

The final task in commissioning is the activity of taking load checks or in-service readings once the changed relay circuits are energized and placed in-service with sufficient current flowing in the power system. This is a quality assurance check or test to help ensure the currents and voltages are what are expected at the proper phase angle. This verifies the CT Ratio/VT Ratio is properly set from the relay settings and are physically wired correctly at the current and voltage transformer terminal connections through to the device terminals.

There are several methods of obtaining in-service metering data. One method with which this data may be obtained is through the use of metering measurements where an instrument(s) capable of reading voltage magnitudes, current magnitudes, and phase angles is connected directly to the terminals of the device being

checked. A secondary hand-held tong ammeter is used with a polarity reference. The reference voltage for the phase angle meter has the potential leads connected typically to “A” phase potential of the connected bus or line segment being measured or checked. This method may be preferred by certain entities, and it is typical for electromechanical devices or devices without HMI interfaces.

A second method is available when dealing with microprocessor relays that include a meter function. Most microprocessor relays include a meter (or similar) command that provides a direct readout of the voltages, currents, MWs, and MVARs as monitored by the relay. With a testing computer, a simple screen capture can be used to document the results. This may be the preferred documentation method for microprocessor relays because it is simpler than connecting other individual test instruments and hand-writing the results.

Before current checks can be made, make sure the reference voltage VTs primary versus secondary are as expected against a known set of VTs; the primary “A” phase is truly “A” phase, primary phase “B” is “B,” phase “C” is “C,” and secondary voltage magnitudes are proper.

This activity is typically performed by an experienced and competent commissioning agent or relay technician/engineer who knows and follows the procedure correctly. The importance of testing accuracy cannot be overstated; otherwise, false operations/trips may result from an event inside or outside the zone of protection.

An example of a typical load check/in-service procedure is as follows:

- a) A load check form that shows all the necessary data is used for the measurement gathering. This normally includes the following: secondary current, phase angle of measured current against a reference potential, relay circuit information (e.g., relay terminal, relay serial number), and the date of test. Other information may include cross-reference metering for comparison.
- b) Pre-populating the test form with the necessary relay circuit information and knowing where to obtain referenced load readings for comparison purposes may expedite these load-check readings; time is of the essence since load is dynamic and can change quickly while readings are being taken. Obtaining readings that are visible to the Dispatcher allows for metering comparison helping to further avoid scaling inconsistencies.
- c) The phase angle meter is set up with its internal settings to be programmed as proper, with respect to phase reference and depending on the convention of the form used (e.g., ± 180 degrees versus 0–360 degrees I [current] lag V [voltage]).
- d) The potential reference connection may be pre-connected ahead of testing. Note: that in-line fused jumpers within the test, leads may be used in connecting to unfused potential transformers to mitigate the risk of working with live circuitry.
- e) The amount of current in each relay terminal often has a minimum threshold for accurate readings to be obtained. Note that it may be possible that performing load switching is necessary for accurate readings. Such operations are often coordinated with the dispatching authority prior to the test.
- f) Reference load information obtained by other relay systems allows for knowledge of expected readings (e.g., the amps, watts, vars to be measured).
- g) The form can show the phasors of the current or voltage quantities. This allows a check for proper phase sequence.
- h) All information is double-checked for accuracy prior to submission.

4.5.3 Lessons learned—in-service testing

The task of taking in-service readings is a pivotal step in the testing process and has the potential to be overlooked. The following provides some examples:

- A directional comparison blocking (DCB) scheme on a transmission line serving an industrial facility was in service for 10 years with a relay's Zone 2 looking in the reverse direction and Zone 3 looking forward. A misoperation eventually occurred during a major ice storm when an adjacent line at the substation had a static wire fail due to ice build-up, which resulted in a line-to-ground fault. The relay's Zone 2 element tripped for the failed static line and resulted in a significant outage at the industrial facility. During the event analysis, it was determined that the CTs had incorrect phasing, providing current to the relay 180 degrees out of phase. A simple in-service check of the relay's display would have shown an erroneous reading of positive watts being produced by the industrial facility rather than negative watts being consumed.
- End-to-end testing for a current differential scheme was successfully completed but the line was not placed into service until the following day. Several weeks after the line was placed in service, the current differential scheme misoperated for an out-of-section fault that had occurred during severe weather. Oscillography confirmed that currents from both terminals were not summing to zero for the condition. It was determined that CT phase connections at one terminal were incorrectly connected providing current to the relay 180 degrees out of phase. Performing an in-service check by triggering an event report immediately after the line was placed in service would have exposed the problem.
- Testing of a step distance scheme had been completed and the line was placed in service without the CCVT fuses being reinstalled. The following day, a relay technician noticed the relay display was showing no voltage, and the fuses were immediately installed. Fortunately, no negative consequence occurred during the time that the relay had no potential. If the in-service check was performed, the loss of potential (LOP) condition would have been immediately evident after the line was placed in service. As a side note, after this particular incident occurred, the facility added LOP alarming to supervisory control and data acquisition (SCADA) on each of its line protection relays.

4.6 Maintenance tests

Maintenance tests are specific tests to validate that the protection and control system is operating correctly after a period of in-service operational readiness. Calibration tests confirm that individual components are still operating within acceptable performance parameters. This type of test is especially vital for electromechanical and electronic protective device components susceptible to degraded or changing characteristic due to aging and wear. Application or functional tests verify that the total protection system is properly operating. Measurement of power system values, properly identifying fault characteristics, operation of the interrupting devices, and associated interlocking with automatic or manual restoration devices and schemes are verified. Maintenance testing can involve forced outage of protective equipment and testing all or some parts of a protection scheme when performance is identified as questionable and immediate attention is required to correct the operation of the relay or the relay scheme.

Maintenance practices follow different philosophies and regulatory requirements. It is appropriate to perform maintenance tests in an attempt to best balance assurance that the protection system will perform correctly versus the costs involved in maintaining the system. Aside from forced outage and required regulatory testing, there are two basic methodologies in use: time-based maintenance and condition-based maintenance practices.

Periodic maintenance testing is performed to help ensure that the protection and control system is operating correctly after a period of in-service operational readiness. These tests may be used to confirm that individual components are still operating within acceptable performance parameters. This type of test is needed for components susceptible to degraded or changing characteristics due to aging and wear. Full system performance tests may be used to confirm that the total protection system functions from measurement of power system values, to properly identifying fault characteristics, to the operation of the interrupting device and associated interlocking with automatic or manual restoration devices and schemes.

Time-based maintenance is based on scheduled maintenance of a system at regular intervals. Tests are to demonstrate the system and system components perform correctly. Test schedules are generally determined

by operating experience with a system or device, environmental conditions, regulatory requirements, manufacturer's recommendations, and importance of the asset and associated load. Periodic testing can include a review of the recent power system activities on the particular terminal and review that the entire protective system operated correctly since the last scheduled interval. If it is determined that a protection system and scheme has performed correctly, the interval may be adjusted based on most recent operational experience on the respective terminal.

Similar to performance-based maintenance, condition-based maintenance includes examination of the relay system, history of specific systems and devices, and operating experience to perform maintenance only when necessary to help ensure adequate performance of the protection system.

Intelligent electronic devices, such as microprocessor-based protective relays, add an additional form of maintenance testing, which is the ability to perform continuous self-monitoring for correct performance of the device. Self-monitoring capabilities vary between devices and may include the ability to monitor the incoming analog measuring circuits, the device output contacts, GPS time synchronization, communications signals, internal hardware (including battery status and system board voltages), nonvolatile erasable programmable read-only memory, and the internal software algorithms. Failure of a self-test routine typically generates an alarm available through SCADA communications and output contacts. Certain self-test alarms may disable the functioning of the device.

4.7 Maintenance practices

Maintenance and test programs that often incorporate the following types of maintenance practices:

- a) Time-based maintenance (TBM): Externally prescribed maximum maintenance or testing intervals are applied for components or groups of components. The intervals may have been developed from prior experience or manufacturers' recommendations. The TBM verification interval is based on a variety of factors, including experience of the particular asset owner, collective experiences of several asset owners who are members of a country or regional council, or regulatory requirements. The maintenance intervals are fixed and may range in number of months or in years.
- b) TBM can include review of recent power system events near the segment of system considered for maintenance. Operating records may prove that some portion of the protection system has operated correctly since the last test occurred. If specific protection scheme components have demonstrated correct performance within specifications, the maintenance test time clock may be reset for those components.
- c) Performance-based maintenance (PBM): Maintenance intervals are established based on analytical or historical results of TBM failure rates on a statistically significant population of similar components. Some level of TBM is generally followed to justify continued use of PBM-developed extended intervals for low occurrence of test failures or in-service failures.
- d) Condition-based maintenance (CBM): Continuously or frequently reported results from nondisruptive self-monitoring of components demonstrate operational status as those components remain in service. Whatever is verified by CBM does not require manual testing, but taking advantage of this requires precise technical focus on exactly what parts are included in the self-diagnostics. Many microprocessor-based protective relays can perform continuous self-monitoring to verify correct operation of most components within the device. Self-monitoring capabilities may include the alternating current (ac) signal inputs, analog measuring circuits, processors and memory for measurement, protection, data communications, trip circuit monitoring, and protection or data communications signals. For those conditions, failure of a self-monitoring routine generates an alarm and may inhibit operation to avoid false trips. When internal components, such as critical output relay contacts, are not equipped with self-monitoring, they can be manually tested. Method of testing may be local or remote, or through inherent performance of the scheme during a system event.

The TBM is the overarching maintenance process of which the other types are subsets. Unlike TBM, PBM intervals are adjusted based on operational history. The CBM verification intervals can be hours or even milliseconds between non-disruptive self-monitoring checks performed on components as they remain in service.

TBM, PBM, and CBM can be combined for individual components, or within a complete protection system. Figure 2 illustrates the relationship between various types of maintenance practices described in this section. In the Venn diagram, the overlapping regions show the relationship of TBM with PBM historical information, and the inherent continuous monitoring offered through CBM. This figure shows the following:

- *Region 1*: The TBM intervals that are increased based on known reported operational condition of individual components that are monitoring themselves.
- *Region 2*: The TBM intervals that are adjusted up or down based on results of analysis of maintenance history of a statistically significant population of similar products that have been subject to TBM.
- *Region 3*: Optimal TBM intervals based on regions 1 and 2.

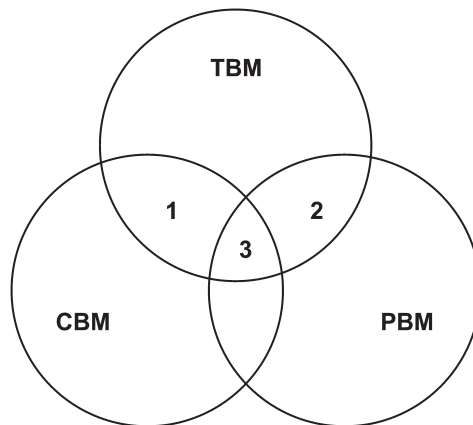


Figure 2—Relationship of maintenance types

4.7.1 Regulatory considerations

It is important to the reliability of the electric system that protection and control systems function properly. Malfunctioning systems can contribute to major power system outages and widespread cascading events. Maintenance programs have demonstrated benefits in uncovering problems and allowing the problems to be addressed under a controlled power system environment. It is important to follow prudent maintenance programs to uncover problems and hidden failures in advance.

The effectiveness of a maintenance program is often tracked and determined by the asset owner. These tracking mechanisms allow the owner to optimize the program based on the application. However, when the performance of a protective device or system has a greater impact to the overall power system, the proper performance of the protective system will benefit the entire electrical grid, which may be composed of several interconnected power systems, or in some cases, possibly part of a regulatory controlled electric system. In some countries or electrical grid systems, the regulatory agency may require evidence that the asset owners each have established a prudent maintenance program that meets a minimum level of standards and practices established by the regulatory body. Furthermore, the regulatory agency may require evidence that the owner is performing maintenance based on the program. Depending on the level of regulatory oversight, the asset owners may be asked periodically to voluntarily, or through a cohesive and collective established audit process, or both, demonstrate that they have met their obligations to maintain the protection and control system.

In a regulatory system, the owner may be required to perform the following tasks (including but not limited to):

- Demonstrate and submit detailed maintenance records and that asset owners are cognizant that regulatory agencies may require verification of the maintenance program.
- Show evidence that protection systems and components are being maintained and tested per the owner's program.
- Show evidence of compliance with the testing intervals mandated by the regulatory authority.
- Submit a program documenting the methodology or philosophy behind the owner's program.
- Show a tracking mechanism and archiving system for the maintenance records related to the protection and control equipment and systems.

4.7.2 Troubleshooting

Troubleshooting operating problems of a protection system may require a combination of commissioning tests and calibration tests, designed to identify specific components or specific parts of the protection system design. Testing may involve positive (expected to operate under testing parameters, in the zone of protection) and negative (not-expected to operate under testing parameters or out-of-zone of protection) test types to provide the desired operation results. Troubleshooting involves good engineering practices, knowledge of the relay scheme, and experience to identify the cause of operating problems.

These tests are often performed after a loss of a significant element of the electric system, or after a suspected incorrect operation of a relay system. During a disturbance in the electric system, relays are expected to operate correctly to isolate the affected equipment. Equipment damage is significantly reduced if the protection system performs properly. When the disturbance compromises a significant corridor, load center, or generation, it may be necessary to analyze the results to determine the proper operation of all protection systems. When the detailed evaluation of the protection records demonstrates satisfactory scheme performance, the operation of the relay system may be considered as a substitute for scheduled periodic maintenance testing under the performance-based testing program.

4.8 Methods for generating test modules and cases

4.8.1 Fault studies

A test module comprises currents and voltages with/without external logic inputs (for example, digital signals for fault inception point or reclosing command) that need to be applied to a protection device or system. In order to generate test modules, specific fault studies need to be conducted and analyzed.

- In general, there are several types of faults. However, there are variations in the way these faults occur.
 - Phase-to-Phase
 - Phase-to-Ground
 - Phase-to-Phase-to-Ground
 - Three-Phase
 - Three-Phase-to-Ground
- Simultaneous faults (uncommon): There can be simultaneous faults of two types mentioned above at the same or different location. For example, a Phase-to-Phase Fault and Phase-to-Ground Fault can occur at the same time, or two separate Phase-to-Ground Faults could demonstrate different fault resistances at the same time. Also, a conductor could break and fault to ground, resulting in an open phase and a Phase-to-Ground fault.