

IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above

IEEE Power & Energy Society

Sponsored by the
Insulated Conductors Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 400™-2012
(Revision of
IEEE Std 400-2001)

5 June 2012

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**Insulated Conductors Committee
of the
IEEE Power & Energy Society**

Approved 29 March 2012

IEEE-SA Standards Board

Abstract: Various field test methods that are currently available or under development are listed in this guide. The guide covers shielded, insulated power cable systems rated 5 kV and above. The guide describes the tests and gives advantages and disadvantages, suggested applications, and typical results. Complete guides covering some of the test methods listed are available in the form of IEEE 400 “point” documents.

Keywords: field testing, IEEE 400, power cable system

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PDF: ISBN 978-0-7381-7266-8 STD97241
Print: ISBN 978-0-7381-7372-6 STDPD97241

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Acknowledgments

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Introduction

This introduction is not part of IEEE Std 400-2012, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above.

This omnibus guide is a revision of the 2001 standard. It provides an overview of available methods for performing electrical tests in the field on shielded power cable systems. It is intended to help the reader select a test that is appropriate for a specific situation of interest. It provides a brief description of all the known sources used to perform field tests with a short discussion of specific tests. The material presented is descriptive and tutorial and does not address the evaluation of test results or the specification of test voltage levels and time of application.

There are several principal changes from the 2001 standard. The document structure is rearranged. Instead of listing and discussing each test method in individual clauses, this edition includes a clause that discusses general considerations for field testing of cable systems followed with another clause in which field testing methods are categorized by their functions and introduced as subclauses. Oscillating wave is renamed damped AC voltage in this edition. Advantages and disadvantages of the test methods are tabulated by category, which makes it easier for comparison between tests with different types of voltage sources. A number of test methods are added in a category named “Dielectric Response” along with dissipation factor and DC leakage current: recovery voltage, polarization/depolarization current, and dielectric spectroscopy. Time Domain Reflectometry and Thermal Infrared Imaging are also added as complementary insulation tests.

Additional details are provided in “point” documents, such as IEEE Std 400.1™, IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above with High Direct Current Voltage; IEEE Std 400.2™, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF); IEEE Std 400.3™, IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment; and IEEE P400.4™^a, Draft Guide for Field-Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current Voltage (DAC). If there is a conflict between this document and the “point” documents, then the “point” documents should be considered as the definitive reference.

^aThis IEEE standards project was not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining a draft, contact the IEEE.

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1. Overview

1.1 Scope

This guide lists the various field test methods that are currently available or under development. The guide covers shielded, insulated power cable systems rated 5 kV and above. The guide describes the tests and gives advantages and disadvantages, suggested applications, and typical results. Complete guides covering some of the test methods listed are available in the form of IEEE 400 “point” documents.

1.2 Purpose

The purpose of this guide is to provide an overview of the various test methods available for evaluating the insulation of shielded cable systems in the field, and to assist cable owners in selecting one or more appropriate tests for a specific application.

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 Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above
Accredited Standards Committee IEEE C2, National Electrical Safety Code® (NESC®).¹

IEC 61230, Live Working—Portable Equipment for Earthing or Earthing and Short-circuiting.

IEEE Std 4™, IEEE Standard Techniques for High Voltage Testing.^{2,3}

IEEE Std 510™, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.

NFPA-70E, Standard for Electrical Safety Requirements for Employee Workplaces.⁴

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms and Definitions*⁵ should be referenced for terms not defined in this clause.

breakdown: Disruptive discharge through or along the insulation.

cable system: One or more lengths of shielded power cable joined together, 5 kV and above, including cable accessories (joints and terminations).

dielectric response: A collection of parameters, such as dissipation factor, DC leakage current, polarization current, etc., which characterize the overall behavior of the insulation of a power cable system under an applied voltage of various types and frequencies at various temperatures.

NOTE—The definition of dielectric response in this document must not be confused with that of the same term used for semiconducting materials.⁶

electrical tree: Tree-like growths, consisting of non-solid or carbonized micro-channels, that can occur at stress enhancements such as protrusions, contaminants, voids or water tree/dry insulation interfaces subjected to electrical stress for extended time periods. At the site of an electrical tree the insulation is damaged irreversibly. If the voltage stress on the electrical tree is above the inception voltage, partial discharge will be present, the tree will grow, and a failure can only be a matter of time.

ethylene propylene rubber (EPR): A type of polymer used as electrical insulation in cables and accessories. There are several different formulations of EPR and they have different characteristics. For purposes of this guide, the term also encompasses ethylene propylene diene monomer rubber (EPDM).

extruded dielectrics: Insulation such as polyethylene (PE), crosslinked polyethylene (XLPE), tree retardant crosslinked polyethylene (TRXLPE), ethylene propylene rubber (EPR), etc. applied using an extrusion process.

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⁴ NFPA publications are available from Publication Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://nfpa.org/codes/index.html>).

⁵ *IEEE Standards Dictionary: Glossary of Terms and Definitions* is available at <http://shop.ieee.org>.

⁶ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

hybrid cable system: A cable system consisting of cables with very different dielectric or construction characteristics; for example extruded dielectric insulation cable and laminated insulation cable or cables with filled and unfilled insulations.

insulation weak spot: A part of the cable insulation system where, due to one or more factors such as mechanical, chemical, or thermal stresses, the insulation medium breaks down before the rest of the system under certain applied voltage. An insulation weak spot that leads to a breakdown at operating voltage is sometimes called a gross defect.

laminated dielectrics: Insulation formed in layers typically from fluid-impregnated tapes of either cellulose paper or polypropylene or a combination of the two. Examples include paper insulated lead covered (PILC) cable designs, Mass Impregnated Non Draining (MIND) cable designs, high pressure pipe type cable designs, and self contained cable systems.

partial discharge (PD): Localized electrical discharge that only partially bridges the insulation between conductors.

partial discharge (PD) pulse: A high-frequency current or voltage pulse that results from a partial discharge. In a shielded power cable, the pulse propagates away from the PD source in both directions along the cable.

polyethylene (PE): A polymer used as electrical insulation in cables.

shielded cable: A cable in which an insulated conductor is enclosed in a conducting envelope.

tests: For the purpose of this guide, several test categories are considered:

a) From the application point of view, there are three categories of tests:

installation test: A field test conducted after cable installation but before the application of joints or terminations.

acceptance test: A field test made after cable system installation, including terminations and joints, but before the cable system is placed into normal service.

maintenance test: A field test made during the operating life of a cable system.

b) From the technical point of view, there are five broad sets of tests:

diagnostic test: A field test made during the operating life of a cable system to assess the condition of the cable system and, in some cases, locate degraded regions that can result in a failure.

non-monitored or simple withstand test: A diagnostic test in which a voltage of a predetermined magnitude is applied for a predetermined time duration. If the test object survives the test it is deemed to have passed the test.

monitored withstand test: A diagnostic test in which a voltage of a predetermined magnitude is applied for a certain time period. During the test, other properties of the test object are monitored to help determine its condition and also evaluate if test duration needs to be extended or may be reduced.

offline testing: The cable system under test is disconnected from the service power source and energized from a separate field test power supply.

online testing: The cable system under test is energized by its normal service power source, usually at 50 Hz or 60 Hz. This type of test enables temporary or permanent monitoring.

c) In this guide, there are also references to tests made after manufacturing the cable components:

factory test: Any series of tests performed on a single cable system component after manufacturing and before shipment.

TRXLPE: A tree retardant crosslinked polyethylene (XLPE) insulation compound containing an additive, a polymer modification or filler that deters the development or growth of water trees in the insulation compound.

NOTE—See Pelissou, et al. [B84].

water tree: A tree-shaped collection of water-filled micro voids that are connected by oxidized tracks. Water trees can occur at electrical field enhancements such as protrusions, contaminants, or voids in polymeric materials subjected to electrical stress in the presence of water.

XLPE: A crosslinked polyethylene insulation.

3.2 Acronyms and abbreviations

AC	alternating current
DAC	damped AC
DC	direct current
DF	dissipation factor also referred to as tan delta
EPR	ethylene propylene rubber.
HMWPE	high-molecular-weight polyethylene
HVDC	high voltage DC
IRC	isothermal relaxation current
PD	partial discharge
PDEV	partial discharge extinction voltage, V_e
PDIV	partial discharge inception voltage, V_i
PE	polyethylene
PILC	paper insulated lead covered
RV	recovery voltage
TDR	time domain reflectometry
TRXLPE	tree retardant crosslinked polyethylene
U_0	nominal rms operating voltage, phase to ground
VLF	very low frequency
XLPE	crosslinked polyethylene

3.3 Word usage (per IEEE Style Manual)

In this document, the word *shall* is used to indicate a mandatory requirement. The word *should* is used to indicate a recommendation. The word *may* is used to indicate a permissible action. The word *can* is used for statements of possibility and capability.

4. Safety awareness

WARNING

For all tests involving hazardous voltage levels, special attention shall be paid to ensure the safety of personnel. Personnel safety is of utmost importance during all testing procedures. All cable and equipment tests shall be performed on de-energized and isolated systems except where otherwise specifically required and properly authorized. Appropriate safety practices shall be followed. Where applicable, the safety practices shall include, but not be limited to, the following requirements:

- 1) Applicable user safety operating procedures.
- 2) IEEE Std 510, IEEE Recommended Practice for Safety in High Voltage and High Power Testing.
- 3) IEEE C2, National Electrical Safety Code (NESC).
- 4) NFPA 70E—Standard for Electrical Safety Requirements for Employee Workplaces.
- 5) Applicable national, state, and local safety operating procedures.
- 6) Protection of utility and customer property.

High-voltage field testing of cable systems involves all of the factors normally associated with working on energized circuits, as well as several unique situations that shall be addressed.

Cable circuits will normally have one or more ends remote from the location of the test equipment and the test operator. These ends must be cleared and guarded to protect the safety of personnel. Reliable voice communication should be established between all such locations and the test operator.

The use of an energized circuit indicator or other suitable device should be used to indicate that the circuit is completely de-energized before application of safety grounds. Portable ground clamps and grounding assemblies built and tested per IEC 61230 are recommended.

Precautions should be taken to allow adequate voltage clearance when testing conductors in close proximity to other energized conductors. Failure to maintain safe clearances can lead to flashover between the test conductor and other live conductors, particularly when test voltages above the rated operating voltage are used. When spacing is marginal, special precautions should be required to prevent flashover.

WARNING

Particular attention shall be directed to the special techniques required for discharging cables after testing to eliminate personnel hazards. Cables have high capacitance and dielectric absorption characteristics. Cables subjected to high-voltage testing that are not grounded for sufficiently long periods of time after such tests can experience dangerous charge buildups as a consequence of the very long time constant associated with dielectric absorption currents. For this reason, the grounding procedures recommended in the appropriate work rules should be followed.

5. General considerations for field testing of cable systems

5.1 Introduction

Cable testing is performed to monitor the condition of a power cable system with the possibility of identifying potential failures and insulation weak spots so that actions can be taken to improve reliability while minimizing the overall cost of ownership. This guide does not cover field tests for fault locating on shielded power cable systems. Refer to IEEE Std 1234TM-2007 [B65]⁷ for fault locating tests.

It is suggested that field testing and evaluation of shielded power cable systems follow a structured program including the following steps:

- a) Identify testing objectives.
- b) Identify cable systems to be tested.
- c) Review specifications and operating conditions of cable and cable system components to be tested.
- d) Select and apply suitable field tests.
- e) Record information and/or documentation for analysis.
- f) Perform recommended corrective actions on cable system.

Different methods can be used to test the insulation of a cable system in the field, ranging from simple (e.g., withstand tests with pass/fail results) to elaborate tests requiring detailed analysis of results (e.g., monitored withstand, partial discharge detection, or dielectric response).

Field testing of cable systems continuously presents many challenges. Cable systems and cable system components have very complex behaviors. The installation environments and each system's history of mechanical, thermal and electrical stresses are also varied and their aging mechanisms are not always completely understood. All these factors make life predictions or estimating the probabilities of failure extremely difficult. At the time of writing this guide, there are no field tests that can predict exactly when a cable will fail. Experience of the user and that of the industry can be considered when selecting and developing a test program and establishing the criteria for test interpretation and acceptance. High-voltage testing carries risks and benefits, each of which should be carefully weighed before they are used (Andrews, et al. [B3]).

5.2 Testing objectives

Setting reasonable expectations is important when establishing objectives for using cable diagnostic testing. Depending on the age, condition, and type of cable system being tested, different objectives would likely be established. The expectations from testing depend on the test procedure as selected for the particular cable system and the type of defects being sought.

New cable systems generally have components that have been tested in the factory and the field testing is intended to detect problems caused by shipping or handling, improper installation, or undetected manufacturing defects.

⁷The numbers in brackets correspond to those of the bibliography in Annex A.

Aged cable systems where failures have occurred are tested to verify that the failed components have been properly replaced or repaired in order to safely return the system to service. Aged in-service cables are also tested to determine the condition of the insulation such as the degree of deterioration.

Field testing of cable systems can also be used as a cable system asset management strategy. It can provide utility planners and other users with condition-based information necessary to minimize capital expenditures and maximize reliability.

In this document, the tests are grouped into the following three different categories:

- Installation tests
- Acceptance tests
- Maintenance tests

Other cable system field tests are performed prior to re-energization with the intention of minimizing the risk of closing on a short-circuited cable system. These tests are not intended to evaluate the cable system insulation but rather, as a general precautionary measure, to verify the absence of low impedance paths from phase to ground prior to re-energizing (e.g., a grounding point connecting the phase conductor to ground). A simple (non-monitored) withstand test can be made with an applied voltage generally in the range of 1 kV or less for a short period of time. These are complementary tests to the tests listed in this document; they should not be used as substitutes for installation, acceptance, or maintenance tests.

5.2.1 Installation tests

Installation tests are used to verify cable sections only after cable laying but before the cable sections are connected to the system. The test, more often performed in industrial and power plants, is intended to detect shipping, storage, or cable installation damage with the advantage of testing cable sections only. Care should be taken to have a proper interface for tests at cable ends to avoid excessive leakage or a possible flashover. Temporary terminations are generally required.

5.2.2 Acceptance tests

Acceptance tests are performed prior to service as part of an on-site commissioning or re-commissioning:

- a) To demonstrate that the transportation, handling and installation have not damaged the cable system components;
- b) To identify poor workmanship as well as to demonstrate that the equipment has been successfully repaired after an on-site repair of new components and significant defects in the insulation have been eliminated.

If a cable or accessory does not pass the test and is repaired or replaced, the acceptance test is usually repeated until the cable system passes the test.

High-voltage testing, with voltage levels and duration below factory tests, of well-installed defect-free new cables and accessories is not likely to cause a significant reduction of their expected service life (Gulski, et al. [B37]).

5.2.3 Maintenance tests

The primary purpose of maintenance tests is to assess the present condition of in-service cable systems. In electrical transmission and distribution, cable systems are a major and very expensive component. Cable

system owners and users can protect this important investment and improve system reliability by periodically monitoring aging of the insulation using maintenance tests and taking appropriate actions based on the test results. A well-maintained record of test data can also serve as reference for future evaluation and be used for trending to enhance diagnostics. The test data on other cables similar in design and service conditions can be used to establish decision criteria. Selection of the systems portion to be tested is discussed in 5.3.

Since maintenance tests are normally conducted on cable systems that have been in service for some time period, the insulation system is likely to have aged to various degrees. There is a possibility that the insulation system cannot withstand the same levels and durations of voltage as those designed for factory tests, which are intended for newly manufactured cables. Testing aged cable systems or cable systems with defects at elevated test voltage levels can accelerate the failure process. Therefore, lower voltage levels or shorter durations or a combination of both are, in general, used for maintenance tests.

To minimize costs and for service continuity, maintenance tests are usually carried out during a non-critical period and under planned conditions.

5.3 Selection of test types

The basic objective for testing is to improve reliability while reducing the overall cost of ownership and operation of the cable system. This can be achieved by testing when the benefits of testing outweigh the costs. The decision to employ field testing should be evaluated by the individual user, taking into account the costs of a service failure, including intangibles, the costs of testing, and the possibility of damage to the system. Since it is generally not possible or desirable to test all cable systems, it is important to identify those cables that are more critical or more likely to fail as part of the test program. Selecting the right segments to test is a key to establishing a cost effective field testing program.

5.3.1 Installation tests

Installation testing is performed on new cable sections only based on user's requirements. The user will decide which test to include in an installation test program based on considerations of past experiences, a need to verify quality of installation, knowledge of cable reliability, and factory tests results.

Once a cable has been terminated or joined to the cable system, installation test should be replaced by acceptance or maintenance tests.

5.3.2 Acceptance tests

Acceptance testing is performed on new cable systems based on user's commissioning requirements. The user will decide which test to include in an acceptance test program based on considerations of past experiences, a need to verify quality of workmanship, knowledge of the reliability of components, and the results of factory tests.

5.3.3 Maintenance tests

Maintenance tests are normally performed on cable systems that have been aged in service for an extended period of time. Cable systems do not age in a uniform manner due to different installation and operating conditions. When designing maintenance test programs, users should not only take the number of years in service into consideration, but also study the performance history of the cable systems in general such as cable failure records, Mean Time Between Failure (MTBF), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), etc. (see IEEE Std 1366-2003 [B66]) and

should correlate information on specific issues of reliability for particular components (information gained from failure expertise or knowledge of defect). When choosing a cable system for maintenance testing, the following should be considered:

- a) Failure history—Cable systems should be considered after a significant increase in failures (cable, joints, or terminations) occur on a per unit basis over a given period of time (generally in years).
- b) Cable system component makeup—The composition of the cable system should be considered. The cable normally has been in service for an extended period of time and its service conditions are of concerns. Components failure records, in service and during field test, is a criterion for selecting cable systems. When known by investigation of failures and knowledge of cable systems, predominant failure mode should be considered to determine what type of tests can be employed.
- c) System considerations—The cable system's relative importance to system reliability should be considered in any decision to apply a field test. Critical cable system can be subjected to Maintenance testing even though they have relatively low failure rates.
- d) Records—Past testing records and historical installation records, when available, should be studied to classify cable systems eligibility.

These criteria can be applied individually or combined to produce a weighted index to assist with cable system selection for Maintenance testing. Following a successful test, the cable system should not be retested within a given period of time or until a selected level of unreliability (service failures) is exceeded. The time period between tests is dependent on the diagnosis used and on time-between-failure data that is typical on a user's system.

5.4 Cable system components and operating conditions

The cable system components and operating conditions should be reviewed to help identify the most appropriate testing method and testing parameters. It is often useful to review factory test data and prior field testing history for a baseline of the cable system components.

5.4.1 Cable system components

After selection of a cable system and prior to selection of a testing technique, it is useful to review cable and accessory purchasing specifications and results of their factory (qualification and production) tests. Refer to relevant industrial standards such as NEMA WC74-2006/ANSI/ICEA S-93-639 [B79], ANSI/ICEA S-108-720-2004 [B4], IEC 60502-2 [B52], IEC 60840 [B53], IEC 62067 [B56], IEEE Std 404TM [B63], IEEE Std 386TM [B58], and IEEE Std 48TM [B57], etc. Electrical characteristics of interest consist of routine factory test requirements such as partial discharge measurements and voltage withstand tests. Qualification tests, such as partial discharge, dissipation factor, insulation resistance, ac breakdown strength, and impulse breakdown strength should also be reviewed. Factory test procedures and data can be used as a reference for tests on in-service cable system components, so long as the user takes into consideration the differences between new components in the factory and in-service components as well as their different environments. It is suggested that the user should refer to the corresponding IEEE 400 "point" documents for interpretation of the test data.

Once the diagnostic test is performed and the results are collected, it is important to note the following when evaluating the test data:

- a) The field test environment (humidity, barometric pressure, temperature, ambient electrical noise, etc.) can influence the test results. For example, the $\tan \delta$ or partial discharge values measured on a cable system that is at the maximum operating temperature can be quite different from the values measured on the same system at ambient temperature.

- b) If the voltage source, in terms of waveform or frequency, etc., for one field test is different from another field test, the results are in general not readily comparable between the two tests.
- c) Cable system components naturally age in service. This can cause the electrical characteristics of these components to change over time. A change in a measured value does not necessarily mean that one or more components in the system will fail in the near future. For this reason, field measurements should be evaluated very carefully. This evaluation should include a comparison with data from similar cable circuits with known performance characteristics.
- d) In all cases, it is suggested that the user refers to field test criteria found in IEEE 400 “point” documents for acceptance or maintenance decisions.

5.4.2 Cable system operating conditions

The cable system operating conditions such as the ones listed below influence cable system aging and should also be reviewed:

- Normal operating voltage, load, and temperature
- Maximum possible overvoltage resulting from switching, surge, or fault conditions
- Cable system configuration: feeders, single phase URD, grounding mode, etc.
- Maximum normal, emergency, and short-circuit current
- Wet or dry location, directly buried or in duct
- Other possible aging factors (hot spots, installation configuration, etc.)

5.4.3 Other system components under test

Prior to any test, users should review other components (transformers, switches, etc.) that are connected to the cable system under consideration, which are subjected to the same testing voltage. These components shall be able to safely withstand the testing voltage for the test duration and their effect on the testing data should be considered.

Users should consider that there can be a high-voltage difference applied on disconnecting apparatus, this voltage being the difference between the cable system under test (with the voltage source used) and the network operating system voltage on another part of the disconnecting apparatus.

5.5 Selection of testing method and application

Clause 6 and Clause 7 will guide the user in selecting and applying one or more field tests to cable systems.

Please note, if a failure occurs during field testing, users should use caution when locating faults with high voltage sources like thumpers (capacitive discharge testing) IEEE Std 1234-2007 [B65]. Thumping at high-voltage levels can affect the dielectric properties of the cable system insulation (Hartlein, et al. [B39]). Care should be taken to minimize the negative effects of fault location. The field tests will usually have to be repeated after fault locating. Users should reduce the duration while thumping to the minimum voltage required to break down the fault to avoid potential damage to the cable system insulation.

5.6 Record information

The following data should be collected with each test for future analysis:

- Cable system name, location, and length
- Cable and accessories (joints and terminations) type, rating, and laying date
- Cable system operating voltage
- Testing method, voltage level (peak and RMS), duration, and other testing parameters: frequency, etc.
- Test equipment used (type and serial number)
- Test results: Pass, fail, or any evaluation measurement based on testing technique
- Test failure voltage level: The instantaneous voltage level at the precise time where failure occurs (not the rms or peak test voltage)
- Time on test before failure occurred
- Cable system component that failed during the test, identification, and location
- Date, location, and name of person performing the test

6. Field testing methods

This clause presents the different testing methods whose use in the field has been reported:

- a) Voltage withstand
- b) Dielectric response
 - Dissipation factor (tan delta)
 - Leakage current
 - Recovery voltage
 - Polarization/Depolarization current
 - Dielectric spectroscopy
- c) Partial discharge
 - Electrical measurement
 - Acoustic measurement
- d) Time-domain reflectometry
- e) Thermal infrared imaging

This clause is originally based on Andrews, et al. [B3]) by permission of NEETRAC. Other documents (Amyot, et al. [B2], Thue [B92], Densley [B24] and [B25]) have reviewed the different existing technologies, standardization, and practices. General information on high-voltage testing can be found in IEC 60060-1 [B48], IEC 60060-2 [B49], IEC 60060-3 [B50], and IEEE Std 4.

For all types of tests, voltage levels and test duration should be consistent with the cable system characteristics. From the point of view of a shielded power cable system quality and reliability, the following three aspects are important for field tests and results evaluation:

- 1) A healthy (defect-free and/or non-aged) insulation can withstand a higher voltage stress level; whereas insulation that has aged and/or that contains defects should have a lower withstand level.
- 2) A test shall be designed in such a way so as to prevent or minimize the shortening of service lifetime due to the field test. In the case of withstand tests, the impact on a defective insulation needs to be high enough to cause a breakdown or to exceed a critical level of a monitored property.
- 3) Voltage level and duration are important and inseparable elements of the on-test and after-test performance of the cable circuit. The recommended test voltages and durations for tests (given in IEEE 400 “point” documents) are based on extensive field-testing and empirical data from experiments. Arbitrarily increasing voltage or extending the test duration from the recommended values can increase the probability of an early failure in service. See also Annex B.

Monitoring insulation properties during a withstand test and the effect of the test voltage during its application can improve the evaluation of the insulation condition.

IEEE 400 “point” documents ([B59], [B60], [B61], [B62]) provide test voltage levels and durations for the different types of tests. Testing at voltage levels and durations other than recommended by the “point documents” should be based on an appropriate performance study (see Annex B for information). If there

is a conflict between this document and the “point” documents, then the “point” document should be considered as the definitive reference.

For each method, a basic description, application information, and a list of advantages and disadvantages are given.

6.1 Voltage withstand

6.1.1 Description

Withstand tests are the application of voltage at nominal level or higher for a prescribed period of time. They can be applied to all cable and accessory types. The tests can be further subdivided into the following two classes:

- a) Simple (non-monitored) withstand—A test voltage is applied and the ability to hold the voltage (i.e., no breakdown occurs) is recorded. The intent of a simple withstand test is to cause weak points in the circuit to fail during voltage application (with minimal fault current) at a time when the impact of the failure is low (no system or customers affected) and repairs can be made more cost effectively. If a failure occurs during the test, then the failure should be located through a fault location process, repaired, and the circuit retested. The results of these tests are described as either Pass or Fail. The following aspects should be considered:
 - High voltage withstand tests are the most elementary of all electrical tests on cable insulation.
 - Gives go/no-go information without indication of the test’s effects on the insulation system.
 - The test voltage is generally higher than the rated voltage. A balance is important between detecting/failing serious defects and avoiding insulation damage at potential defect locations elsewhere in the cable system. The test can weaken regions of the cable system insulation without causing failure during the test and possibly leading to failure in service at a later time.
 - A breakdown of the insulation can occur in an insulation weak spot. It can be sometimes accompanied by pre-breakdown phenomena. (For example, abnormal electrical field distribution at insulation defects can initiate partial discharge activity e.g., treeing, surface discharges, internal discharges.) Depending on the electrical stress level, severity and duration, the erosion process associated with partial discharges can produce a breakdown of the insulation at this spot.
- b) Monitored withstand—A test voltage is applied and one or more additional attributes are measured and used to determine whether the system is a Pass or Fail. These additional attributes are advanced diagnostic properties such as dielectric response or PD. Temporal stability of the measured property can also be used to monitor the effect of the test on the cable system during voltage application.

6.1.2 Application

According to Bartnikas and Srivastava [B10], Thue [B92], and Peschke and von Olhausen [B85], several voltage types have been defined for withstand field testing. The applied voltage can be AC, VLF, DAC, or DC. Typical testing voltages range from one and a half times the operating voltage U_0 , commonly denoted $1.5 U_0$ to $3.0 U_0$. The test voltage can be higher than $3.0 U_0$ for DC.

AC withstand testing (Gockenbach and Hauschild [B33]), (Hauschild, et al. [B40]) has a long history in laboratory testing of all types of cable insulation and has the most direct relation to service stress. Field testing uses frequencies between 20 Hz and 300 Hz. It is applicable to all types of cable systems. For a more advanced diagnostic result, partial discharges and dielectric response can be measured.

Very low frequency (VLF) voltage field testing uses a power source with a frequency ranging from 0.01 Hz to 1.0 Hz to test all types of cable insulation. The most commonly used test frequency is 0.1 Hz. VLF can be used for withstand test (Hampton, et al. [B38]). Higher test voltage levels are required when compared to AC test voltage of power frequency. VLF has mostly been used for distribution class cables. Recently, some users have started using VLF for transmission class cables. For a more advanced diagnostic result, partial discharges and dielectric response can be measured using IEEE Std 400.2-2004™, [B60], which covers in-depth field testing of shielded power cable systems using VLF voltage.

Damped AC (DAC) IEEE 400.4 voltage is also used in some countries for field testing. It can be applied to all types of power cable systems. DAC voltage testing uses damped alternating current at frequencies between 20 Hz and 500 Hz (Wester, et al. [B98]), (Wester [B97]). Damped alternating voltages are generated by charging the test object to a predetermined voltage level and then discharging the test object's capacitance through a suitable inductance. During the charging stage, the test object is subjected to a continuously increasing voltage at a rate dependent on the test object and, during the discharging stage, an under-damped AC voltage at a frequency dependent on the test object and the inductance. The test circuit basically consists of a HV direct voltage source, an inductor, a capacitor, and a suitable switch. When the charging voltage is reached the switch is closed, generating on the test object a damped alternating voltage. DAC can be used as simple withstand test or in combination with PD and dielectric response. Most applications so far are based on the combination of voltage withstand and advanced diagnostic measurements (e.g., partial discharges and dielectric response). For voltage withstand test, a predetermined number of DAC excitation is applied (IEEE P400.4 [B62], Thue [B92], Brettschneider, et al. [B15], Aucourt, et al. [B7], Koevoets [B70]). Due to shorter duration of the excitation and decaying characteristic of the voltage, test results obtained by DAC testing can be different from those obtained by continuous AC withstand voltage testing.

The application of DC voltage has the longest history in testing laminated cable insulation. This method is applicable for failures related to insulation conductivity/thermal problems. The testing equipment is simple, lightweight and requires low input power. The cable system reacts differently under DC voltage from that under normal AC operation. For DC field testing of laminated dielectric shielded power cable systems, refer to IEEE Std 400.1™ [B59].

The use of high-voltage DC (HVDC) withstand test for extruded cables has been the source of much discussion. HVDC is not effective in detecting certain types of insulation defects in a cable system when compared with AC. A majority of cable manufacturers have discontinued the use of HVDC withstand in their production tests. In the past two or three decades, evidence has surfaced indicating the likely adverse effect that HVDC test has on aged XLPE insulations. Subsequently, numerous experiments and discussions have lead to the accepted belief that HVDC voltage does indeed cause space charge build-up in aged XLPE insulation, which, if remaining in the insulation, can result in cable failures when an AC voltage is re-applied. The effect of HVDC tests on aged TRXLPE and EPR insulations is not clear—there is no explicit evidence showing one way or another. ICEA S-94-649-2004 [B47] indicates the voltage levels and durations used for HVDC testing of new cables but states its capability is limited to the detection of gross problems such as improperly installed accessories or mechanical damage. Furthermore it does not recommend HVDC testing on any cables more than 5 years old. There has been a large amount of evidence showing that HVDC is harmful to aged extruded medium voltage cables, especially XLPE cables. Therefore, this guide does not recommend the use of HVDC tests on aged extruded cables.

6.1.3 Advantages and disadvantages

Table 1 and Table 2 respectively list the overall advantages and disadvantages of withstand methods and advantages and disadvantages for different voltage sources.

6.2 Dielectric response

Dissipation factor, DC Leakage Current, Recovery Voltage, Polarization/Depolarization Current and Spectroscopy methods provide an overall condition assessment of the complete cable system by offline testing. A review of these methods, their similarities and differences for dielectric response measurement can be found in Oyegoke, et al. [B81]. A comparison (Hvidsten, et al. [B46]) of four different testing methods (depolarization current, return voltage, tan delta with VLF, and dielectric spectroscopy) for evaluation of water-tree degraded cables show that the condition of old cables with a high density of vented water trees can be correctly assessed by all the test methods.

Dielectric response measurements are intended to perform overall insulation diagnosis. Measurement can be made at different frequencies or, in the time domain with different time parameters. When a given electrical field is applied to a dielectric material, different mechanisms of polarization and conduction are activated. Insulation degradation changes the measured properties: The presence of water trees in extruded insulation or moisture in laminated insulation (Buchholz, et al. [B16]) generally increases polarization and conduction or dielectric losses. Terminations should be carefully cleaned prior to testing as dirty terminations can cause tracking and this will likely affect the measurements.

Dielectric response measurements can be analyzed to identify singular defects effects on the overall measurement but cannot be used to locate the defects. If the water treeing degradation is not uniform, these test methods cannot identify sections affected by the highest degree of degradation.

The measured value is primarily influenced by the condition (age, contamination, and moisture ingress) of the various cable system components (accessories, cable insulation, and shields/neutrals). Most users of dielectric response techniques choose to measure the entire cable system response that would include the responses from all terminations, cable, and joints within the circuit. If a high value of loss is detected, then a user has a number of choices as follows:

- Compare results between different phases of the same segment, comparable adjacent cables, or sequential sections of the same cable to better place the result in context.
- Replace the terminations, especially if they appear to be old or contaminated, and re-measure.
- Perform additional testing in the form of a monitored withstand, non-monitored withstand, or partial discharge test should they wish to identify a localized problem.
- Separate the response of terminations from the collective response of cables and joints, by, if practical, adding guard circuits at the terminations.

Accessory behavior has to be taken into account when performing the interpretation of the measurements, specifically accessories with stress relief materials that have non-linear loss characteristics.

Dielectric response measurements benefit from periodic testing at the same voltage level(s) while observing the general trend in measured values.

Advantages and disadvantages common to all dielectric response methods are listed in Table 3.

Table 1—Advantages and disadvantages of withstand tests

Advantages	<p>Simple (non-monitored) withstand test is easy to employ.</p> <p>Results for the simple withstand test are Pass/Fail. Withstand tests do not require an extensive analysis to interpret results.</p> <p>Can be used in any circuit type: extruded, paper insulated, or hybrid.</p> <p>Can be combined with PD, tan delta, leakage current, and dielectric spectroscopy measurements for monitored withstand. The results can be used as pointers to the cable circuits likely to fail during test or in the future.</p> <p>Field data (Hampton, et al. [B38]) shows that, for properly selected cables, the numbers of additional failures in service on withstand tested cables can be less than the number of failures on similar vintage cables that were not tested.</p>
Disadvantages	<p>Simple withstand tests cannot detect/fail some workmanship defects in acceptance tests.</p> <p>Simple withstand testing does not monitor the effect of the test on the cable system during the voltage application, which can be unknowingly destructive to defects which do not fail during the test. It can degrade some weak locations but not fail them, resulting in a higher risk of failure after the circuit is returned to service.</p> <p>Cable needs to be taken out of service for testing.</p> <p>It is time consuming if multiple failures occur during follow-up tests.</p>

Table 2—Advantages and disadvantages of withstand tests for different voltage sources

Source type	Advantages	Disadvantages
50/60 Hz AC Online	<p>Due to energizing the cable section using the line voltage no external voltage sources are needed.</p> <p>Testing voltage waveform is the same as the operating voltage.</p> <p>Can be combined with PD test.</p>	<p>Elevated voltages not possible.</p> <p>In the case of breakdown during the test, the fault current can be high depending on fault detection and protection equipment.</p> <p>Only defects with the breakdown level at nominal voltage level or below will be found.</p>
AC Offline Sinusoidal Continuous 20 Hz to 300 Hz	<p>Testing voltage waveform is the same (50/60 Hz) or comparable to the operating voltage waveform.</p> <p>Applicable for all types of failures related to insulation.</p> <p>Can be combined with advanced diagnostics e.g., PD, dielectric response measurements.</p>	<p>Long cable lengths are more difficult to test at once.</p> <p>Cable system needs to be taken out of service.</p>
AC Very Low Frequency (VLF 0.01 Hz to 1.0 Hz)	<p>Testing equipment is small and easy to handle.</p> <p>Can grow some defects faster than operating frequency (50/60 Hz) tests.</p> <p>VLF Cosine Rectangular: Large plateau of essentially DC voltage enables measurement of leakage current.</p> <p>VLF Sinusoidal: can be integrated with PD, Tan delta.</p>	<p>Test results with voltage that have frequencies (sinusoidal) or waveform (cosine rectangular) other than 50/60 Hz are different from those with operating voltage.</p> <p>Cable system needs to be taken out of service.</p> <p>Higher test voltage levels are required compared to that of power frequency AC test voltage.</p>
Damped AC (DAC 20 Hz to 500 Hz)	<p>Testing equipment is small and easy to handle.</p> <p>Testing results are generally comparable to 50/60Hz test results.</p> <p>Can be combined with advanced diagnostic techniques such as PD and dissipation factor measurement.</p>	<p>Due to short duration of the excitation and decaying characteristic of the damped AC voltage the breakdown field strengths can be different from those with continuous AC.</p> <p>Use of fixed inductor at different cable capacitances results in variation in natural frequencies.</p> <p>In the case of very short cable length an additional capacitive load is recommended so</p>

Source type	Advantages	Disadvantages
		<p>that voltage frequency remains adequate.</p> <p>The damped AC voltage decay characteristic depends on the actual dielectric loss behavior of a particular cable section.</p> <p>Cable system needs to be taken out of service.</p> <p>It is suggested to combine DAC with other types of tests such as PD or tan delta.</p>
High Voltage Direct Current (HVDC)	<p>More than 40 years testing experience and data for PILC cable.</p> <p>Testing equipment is small and easy to handle.</p> <p>Long lengths can be tested.</p> <p>Can be integrated with insulation resistance or leakage current.</p>	<p>Testing voltage waveform is not the same as the operating voltage.</p> <p>Should not be used for extruded cables.</p> <p>Cable system needs to be taken out of service.</p> <p>Requires a higher test voltage level than AC voltage.</p>

Table 3 — Advantages and disadvantages of dielectric response methods

Advantages	<p>Provides an overall condition assessment of a cable system.</p> <p>Can be a relevant indicator for the overall degree of water treeing in PE cable.</p> <p>The methods are generally sensitive to low impedance/conductive type defects such as dirty terminations, some improperly installed accessories, and extreme overheating.</p> <p>Comparison can be made for adjacent phases with the same configuration (including T-branched or complex circuits).</p> <p>Periodic testing has the potential to provide historical data, which can enhance future testing assessment through trending. Measurements over time can show some cable system defects progressing to failure.</p> <p>Data obtained at low voltages ($<U_0$) can also be used for diagnostic purposes. Depending on the type of defect, the effect of electrical stresses as produced at different test voltage levels can have influence on the diagnostic results and can be used as a diagnostic tool.</p>
Disadvantages	<p>Cannot locate discrete defects. Identification of defects from the measurements is difficult.</p> <p>Cannot detect defects in cable systems that do not have significant dielectric losses contribution to the overall response.</p> <p>A cable system can have a high dielectric response (tan delta or other measurement) not leading to failure.</p> <p>Accessory behavior has to be taken into account in order to properly assess cable system insulation condition.</p> <p>Environmental influences (humidity, temperature, etc.) can affect measurements and cannot always be eliminated or separated.</p> <p>Neutral corrosion (wire or tape) is likely to perturb measurement interpretation.</p> <p>Cable needs to be taken out of service for testing.</p> <p>Difficult to interpret results for hybrid circuits (similar adjacent phases can help).</p> <p>Relationship between the measured loss on the entire system and the local loss difficult to establish.</p> <p>Skilled operators are required for testing and post analysis.</p>

6.2.1 Dissipation factor (tan delta)

6.2.1.1 Description

The dissipation factor measurement (tan delta) (IEEE Std 400.2-2004 [B60], IEEE P400.4 [B62], Bartnikas and Srivastava [B10], Thue [B92], Plath [B86], Wester [B97], Gulski, et al. [B36]) can be used for the

determination of the loss factor of the insulation material, see ASTM D 150-2004 [B6]. Due to the fact that this factor increases during the aging process of the cable, the tan delta measurement can be used as a diagnostic.

The dissipation factor, at a frequency ω and voltage V , can be defined as the ratio of the resistive (I_R) and the capacitive (I_C) currents and the angle delta is the phase angle between the capacitive current and the total current according to Equation (1).

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

where

DF is the dissipation factor

I_R is the resistive current

I_C is the capacitive current

V is the applied voltage

R is the insulation resistance of the cable system under test

C is the insulation capacitance of the cable system under test

ω is the frequency of the applied voltage

The tan delta is measured by applying an AC voltage at a given frequency and measuring the phase difference between the voltage waveform and the resulting current waveform. This phase angle is used to resolve the total current (I_T) into its charging (I_C) and loss (I_D) components. The tan delta is the ratio of the loss current to the charging current, as shown in Equation (2).

$$\tan \delta = \frac{I_D}{I_C} = \frac{\sqrt{I_T^2 - I_C^2}}{I_C} \quad (2)$$

where

I_D is the loss component

I_C is the charging current

I_T is the total current

Using damped AC (DAC) voltages and based on the resulting natural frequency, the cable capacitance C can be calculated and an estimation of the dissipation factor can be derived from the decay characteristics of the damped sinusoidal voltage wave (Seitz, et al. [B88], Plath [B86], Wester [B97], Gulski, et al. [B36]).

It is clear that tan delta is most useful if the specific cable and accessory technologies are known, as this assists in making the appropriate comparisons. In addition to the absolute value of tan delta, the increment of tan delta (Δ tan delta or tip-up) measured at two designated voltages or the variability (which can be quantified using the standard deviation or the inter quartile range) of tan delta values with time at constant voltage can be used for condition assessment (Ward, et al. [B95]). Measurements can also be made at different frequencies and would then be referred to as dielectric spectroscopy (see 6.2.5).

To enhance the effectiveness of the tan delta test in assessing cable degradation, the tan delta values should be observed over time when test is repeated, to observe trends. In general, an increase in the tan delta in comparison to previously measured values indicates additional degradation has occurred (Moh [B78]; Gnerlich [B32]; Eager, et al. [B27]; Voigt and Mohaupt [B94]; Gulski, et al. [B37]; Wester, et al. [B98]; Plath [B86]; Farneti, et al. [B29]; Aucourt and Louis [B8]; Koevoets [B70]; Farneti, et al. [B28]; Thomson [B91]; Ward and Steiner [B95]; Gulski, et al. [B36]; CIGRE WG D1.33.03 [B19]; and CIGRE WG D1.33.03 [B20]).

Cable systems that are in good condition have tan delta values that are independent of time and voltage. Thus, changes in tan delta either with voltage or time can indicate that aging has occurred.

6.2.1.2 Application

This method is conducted offline. In the case of continuous AC or DAC (Gulski, et al. [B35]) generation, the frequency is between 20 Hz and 300 Hz (see IEEE P400.4 [B62]). In the case of VLF, a frequency of 0.1 Hz is preferred (see IEEE Std 400.2-2004 [B60]).

It is important to recognize that tan delta values obtained using different test voltages at different frequencies, mainly 50/60 Hz AC, 20–300 Hz AC, VLF, and DAC (20–300 Hz), cannot be compared. The results for the cables tested have shown that the tan delta values change with frequency. This is to be expected as the degradation components in the insulation that contribute to polarization behave differently at different frequencies.

Establishing the tan delta acceptable values for a cable system is complicated by the fact that the values depend not only on the cable system quality but also on the cable and accessory technologies employed.

The tan delta should only vary slightly between different voltage levels. The tan delta of oil/paper insulation, which will normally go through a minimum with increasing voltage, is more temperature sensitive than that for extruded insulations. An increase in tan delta with increasing voltage can have different physical origins. It can indicate the presence of high intensity of or severe partial discharge in PILC cable systems, the presence of water treeing in extruded dielectric cable systems or other defects. The variation of tan delta with time at constant voltage can also indicate water treeing. Meanwhile, a decrease in tan delta can indicate moisture problems in accessories. Such variation in tan delta can be on the order of less than 0.1%. Results are reported in terms of the temporal stability of tan delta, the increase of loss (“tip up”) at selected electrical stresses, and/or the absolute tan delta at a specific voltage. The data should be reported to make further analysis (e.g., track trends, compare with adjacent cable lengths, and/or reinterpret data in the light of new knowledge).

IEEE Std 400.2-2004 [B60] provides criteria for tan delta analysis under VLF application.

6.2.1.3 Advantages and disadvantages

Table 4 lists the advantages and disadvantages of tan delta methods. Table 5 lists the advantages and disadvantages of different voltage sources for tan delta measurements.

Table 4 — Advantages and disadvantages of tan delta^a

Advantages	Measurement can be simple and quick to perform using a stable, low distortion, stand alone power supply. Minimal influence from external electrical fields/noise. Data obtained at low voltages ($<U_0$) can be used for diagnostic without the need to test at higher voltages.
Disadvantages	Tan delta measurement on EPR cables is difficult to interpret due to different behaviors of losses across EPR formulas and, for discharge-resistant designs, nonlinear loss characteristics. Its values change with frequency of the testing voltage. So does the tan delta criteria. Tan delta reflects only the volume effect of the test object as a whole and do not locate areas of defects.

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 3.

Table 5—Advantages and disadvantages of tan delta measurements for different voltage sources^a

Source Type	Advantages	Disadvantages
AC Offline Sinusoidal Continuous (20 Hz to 300 Hz)	Measurements can be made at power frequency (50/60 Hz)	Tan delta is more difficult to measure at 50/60 Hz than at lower frequencies due to the increased magnitude of the capacitive current.
AC Very Low Frequency (VLF 0.01 Hz to 1.0 Hz)	By varying the testing voltage at VLF, dependency of tan delta can be established. Insulation aging changes are more visible by applying tan delta measurements at lower frequencies than power frequency.	The loss mechanism at VLF is different from that under service voltage at AC 50/60 Hz and should be taken into consideration when evaluating the test results.
Damped AC (DAC 20 Hz to 500 Hz)	Results are an approximation of the dissipation factor to those obtained from continuous AC voltages (20 Hz to 300 Hz) (DAC voltages decay is directly related to dielectric losses in the cable insulation) that can be comparable (within some DAC test frequencies).	Approximation of the dissipation factor values with a measuring threshold is in the range of 1×10^{-3} (0.1%). In the case of a very short cable an additional capacitive load (with very low losses) is recommended to assure that voltage frequency remains in the appropriate range.

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 2.

6.2.2 DC leakage current

6.2.2.1 Description

DC leakage current tests consist of the application of DC voltage (lower than that used in the withstand tests of 6.1) with the simultaneous measurement of the current flowing through the tested insulation. They can be applied to all cable systems; however, HVDC is not recommended for aged extruded cable systems, see 6.1.2.

6.2.2.2 Application

This method is performed offline. It is primarily intended to measure the overall condition of the cable insulation (Buchholz, et al. [B16]), but it can also be useful for measuring tracking currents at insulation interfaces or on the external surface of terminations (Yamaguchi, et al. [B99]).

A DC test voltage is applied between the conductor and the insulation shield. The measurement of the DC current is performed after the voltage has reached its steady-state value. It is the leakage current. The test voltage level is increased stepwise, dwelling for a short period on each step, to a maximal value.

If the DC portion of cosine-rectangular VLF waveform is sufficiently flat and ripple free then it could also be used for leakage current measurement, see IEEE Std 400.2-2004 [B60].

6.2.2.3 Advantages and disadvantages

Table 6 lists the advantages and disadvantages of leakage current measurement technique.

Table 6 — Advantages and disadvantages of DC leakage current^a

Advantages	Easy to employ. The method can be automated.
Disadvantages	Pass or fail criteria are not established. High DC voltages can create space charge accumulation in extruded materials if the local electrical stresses exceed 10 kV/mm. Application of high voltage DC on aged XLPE cables can cause the cable to prematurely fail after returning to service. Before and after each test, cable should be completely discharged. The time required for a complete discharge can be four times the test duration or longer. Duration of voltage application is not well established.

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 3.

6.2.3 Recovery voltage

6.2.3.1 Description and application

The recovery voltage, see Figure 1, is a method whereby the cable circuit is charged using DC voltage for a given time. After the circuit is charged, it is discharged for a very short period of time through a ground resistor. The open circuit voltage is then recorded versus time. This voltage is known as the recovery voltage. Multiple intermediate short circuits (Patsch and Jung [B83]) can be performed during the measuring process.

This method (see Ildstad and Gubanski [B68], Kuschel and Plath [B73], Oyegoke, et al. [B80], Jung, et al. [B69], Hvidsten, et al. [B46], and Patsch and Jung [B83]) can be applied to all cable systems. It is sensitive to moisture ingress in PILC cables (see Buchholz, et al. [B16]). It can be used to indicate the level of water tree degradation in extruded insulation (see Ildstad, et al. [B68] and Hvidsten, et al. [B46]). Hvidsten, et al. [B45] indicates that this evaluation can require the measurement of polarization current.

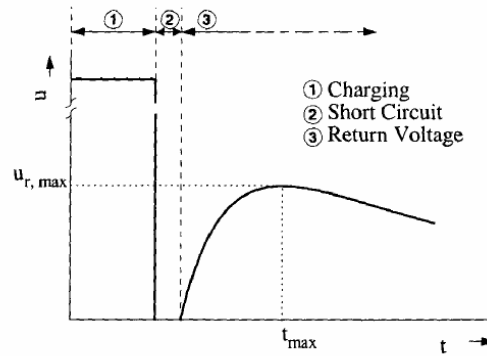


Figure 1 — Recovery voltage (also known as return voltage) measurement (Patsch and Jung [B83])

The level of maximum recovery voltage is the parameter most used to determine the condition of the cable (Oyegoke, et al. [B81]). Other parameters can include the following:

- The ratio of recovery voltage measurements of two different voltage level applications
- The ratio of recovery voltage slopes of two different voltage level applications
- The nonlinearity of the recovery voltage at its maximum value (Jung, et al. [B69])

6.2.3.2 Advantages and disadvantages

Table 7 lists the advantages and disadvantages of recovery voltage measurement technique.

Table 7 — Advantages and disadvantages of the recovery voltage measurement^a

Advantages	It is sensitive to moisture ingress in PILC cables. The method could be fully automated. Test equipment is small.
Disadvantages	High DC voltages can create space charge accumulation in extruded materials if the local electrical stresses exceed 10 kV/mm. Application of high voltage DC on aged XLPE cables can cause the cable to prematurely fail after returning to service. Due to frequency dependence of polarization effects interpretation can be complicated. Cable needs to be completely discharged after each test. Assessment criteria need to be developed for different polymeric cables.

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 3.

6.2.4 Polarization/Depolarization current

6.2.4.1 Description and application

These methods, see Figure 2, are performed offline by applying a relatively low DC voltage to the cable system under test for a preset duration. The current during voltage application (charging current) is measured and recorded. This current is called the polarization current. After the charging period the cable system is short circuited for a few seconds to discharge the capacitive current. The discharging current (the

depolarization current) is then measured and recorded for a preset time under short circuit condition, usually about the same time as the charging time with the application of a DC voltage.

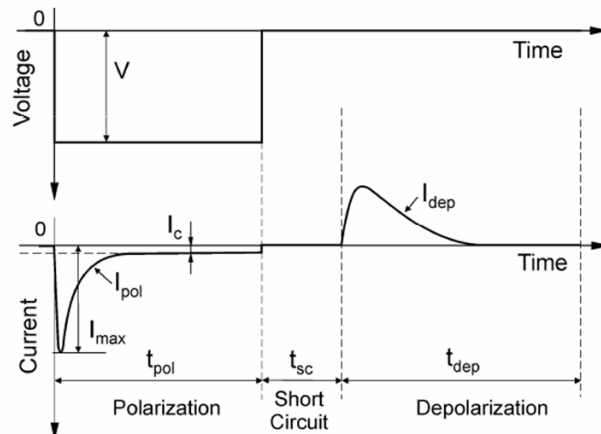


Figure 2 — Representation of polarization and depolarization current (Dakka et al. [B23])

The measured charging current consists of the absorption current, which decays relatively quickly after the voltage reaches the test value; the polarization current, which decreases more slowly with time; and the resistive (or conduction) current, which is due to the resistance of the insulation system.

The discharging current consists of desorption current, which decreases relatively rapidly with time (similar to the absorption current during charging) and depolarization current, which decays more slowly. The depolarization component results from the relaxation of the polarization process after the voltage has been removed. This process can be modified by degradation of the insulation. Polarization and depolarization currents can be used to monitor degradation.

Polarization/depolarization currents can be measured and analyzed in the time domain to evaluate the overall degradation of cable systems in the field. Different analysis methods are possible: polarization index, polarization current (Buchholz, et al. [B16]), depolarization current (Birkner [B11], Hoff and Kranz [B42], Buchholz, et al. [B16], Dakka, et al. [B22]), or a combination of polarization and depolarization currents (Oyegoke, et al. [B80]).

The following different analyses have been used to interpret the results of such tests to assess the cable system degradation:

- Comparing the total polarization current per unit length of new and aged cables. This method and others described in Buchholz, et al. [B16] have demonstrated a good indication of aging of laminated insulation cables.
- Comparing the total depolarization currents at two different voltages. Doubling the test voltage should also double the measured current. Aged cables have ratios of current greater than two (Zaengl [B100]).
- Separating the depolarization current into three different components and comparing the ratios of these current (Birkner [B11], Hoff, et al. [B42], Buchholz, et al. [B16]). The components separation is carried out with an assumed model that considers three exponential currents, each with a different time constant. These three currents are current associated with the cable insulation, current associated with the semi-conductive layer, and current associated with insulation defects.
- Calculating the polarization index. The insulation resistance is measured after 1 minute of voltage application and after 10 minutes. The polarization index is the ratio of insulation resistance value

measured at 10 minutes divided by the value measured at 1 minute. Other time ratios can be used. The index should be higher or close to unity. An index of less than one would indicate an abnormal condition.

6.2.4.2 Advantages and disadvantages

Table 8 lists the advantages and disadvantages of Polarization/Depolarization current methods.

Table 8 — Overall advantages and disadvantages of the Polarization/Depolarization current methods^a

Advantages	Some methods are simple and can be automated.
Disadvantages	<p>Small currents are affected by environment.</p> <p>Cable neutral usually needs to be ungrounded.</p> <p>Long length is usually required to get sufficiently large signal.</p> <p>Assessment criteria have not been widely accepted.</p> <p>Cables need to be energized prior to measurement for adequate polarization.</p> <p>Cable needs to be completely discharged after each test.</p>

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 3.

6.2.5 Dielectric spectroscopy

6.2.5.1 Description and application

Dielectric spectroscopy is a method whereby the real and imaginary components of a cable system leakage (displacement and loss) current through the insulation are measured at a range of frequencies of 0.001 Hz to 100 Hz (Werelius, et al. [B96], Hvidsten, et al. [B44], Drapeau, et al. [B26], Buchholz, et al. [B16]). As stated previously in 6.2.1, these current components enable the calculation of tan delta. The process of measuring at different frequencies supplies additional information on the condition of the insulation.

In general, the tan delta varies inversely with frequency and will therefore be larger at lower frequencies. The benefit of this approach is the significant reduction in power supply size and cost compared to a 50/60 Hz power supply. Also, there is an increase in the sensitivity and lower signal-to-noise ratio, due to the increased currents that result.

Therefore, it is becoming increasingly attractive to perform the measurement at frequencies lower than 50/60 Hz. However, the data is essentially frequency spectra that contain a lot of information, and consequently require more careful interpretation. Successful application has been reported in Werelius, et al. [B96] and Hvidsten, et al. [B44].

Dielectric spectroscopy can also be performed in the time domain (Drapeau, et al. [B26]) and translated into tan delta vs. frequency using the Hamon approximation (only valid for linear systems in which there is no voltage dependence of the dielectric response). In the time domain, the losses are measured both in the polarization and depolarization modes.

6.2.5.2 Advantages and disadvantages

Table 9 lists the advantages and disadvantages of Dielectric Spectroscopy measurement technique.

Table 9 — Advantages and disadvantages of the Dielectric Spectroscopy measurement technique^a

Advantages	Measurement at different frequencies brings more information about cable systems than single frequency measurements The method can be automated.
Disadvantages	In frequency domain: Testing at multiple very low frequencies can take longer time than time domain. In time domain: Use of the Hamon approximation is only valid for linear systems in which there is no voltage dependence of the dielectric response. Small currents are affected by environment. Assessment criteria have not been widely accepted.

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 3.

6.3 Partial discharge

6.3.1 Partial discharge—electrical measurement

6.3.1.1 Description

PD testing of cable systems in the field has been used since the mid 1970s (Mashikian, et al. [B77], Mashikian, et al. [B76], Gillespie, et al. [B31]). A large amount of work (Voigt, et al. [B94]; Mashikian and Szatkowski [B75]; Bartnikas [B9]; Kreuger [B71]; Sahoo, et al. [B87]; Contin, et al. [B21]; CIGRE TF D1.02.05 [B18]; Boggs, et al. [B13]; Kreuger, et al. [B72]; Gulski, et al. [B37]; IEEE Std 400.3™-2006 [B61]; Boggs and Densley [B14]; and Wester, et al. [B98]) has been published over the past decade regarding characterization of partial discharge sources and measurements in power cable systems.

Partial discharge testing can indicate discharge locations (e.g., voids, sharp points/edges, floating parts, electrical treeing, and tracking) as possible weak spots in a cable system. Partial discharges are initiated in localized areas of the cable insulation, joints, or terminations under electrical stress (during overvoltage, steady state conditions in service, or by an external test voltage). Partial discharges are described by many important parameters such as PD inception and extinction voltages, PD pulse magnitudes, PD patterns, and PD site location in a power cable circuit. PD field measurements can be performed either online at U_0 or offline at higher than U_0 . Performing field PD measurements at test voltages higher than U_0 can be considered for the following two reasons:

- To evaluate if there are discharging insulation defects with PD inception voltage above normal operating voltage. Such defects can initiate insulation failure in the case of temporary AC overvoltages. However, too high a test voltage can initiate PD from defects that would not initiate insulation failure under normal operating conditions that include temporary AC overvoltages.
- To verify after an acceptance test that there is no PD detected up to a voltage higher than normal operating voltage. This will indicate that during the service operation the power cable insulation is free of discharging defects at the time of the test within the sensitivity limit of the test.

PD is a stochastic process. A suitable initiatory electron is required; the pressure within the void needs to be low enough and the electrical stress high enough. Thus, a no-PD result can mean either that no voids are present or that a void is present but discharge has not occurred. The latter is a more critical issue for short measurement durations or low test frequency. This process creates considerable scatter in the measurements over time and also between identical cable systems operating under similar conditions.

A number of technical articles have described the phenomenon where PD pulses (at most a few nanoseconds wide) spread and reduce in magnitude as they propagate away from the PD source as a result of high-frequency attenuation in the cable and dispersion (frequency-dependence of the propagation velocity) (CIGRE TF D1.02.05 [B18], Boggs, et al. [B13]). The loss of high-frequency energy from the PD pulse reduces its magnitude and distorts its shape. A false negative can result if the PD is sufficiently attenuated so that it is not detected by the PD sensor. False positives can occur if the PD does not cause any significant degradation to the cable system insulation over the in-service period of time observed. These circumstances make it more difficult to measure the PD pulses and accurately identify the source and type of the PD. Thus, the accuracy in evaluating risk from the presence of PD should be considered carefully.

PD measurement characteristics strongly depend on the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type of insulation material (EPR, XLPE, PILC, etc.) and ambient noise (Kreuger, et al. [B72]). Therefore, accurate interpretation of the PD data requires sound knowledge of temporal PD behavior (Hernandez, et al. [B41]).

Cable system components are often tested for PD in the factory prior to shipping and the test results are available to the buyer. Although field measurements data can, in principle, be compared to factory values, making such a comparison is difficult. Depending on the field environment, the performance in noise mitigation utilized and the type of power supply used for the field test, electromagnetic interferences usually adversely affects the sensitivity of PD detection.

6.3.1.2 Application

PD detection on power cables (IEEE Std 400.3-2006 [B61]) can be done in the following two ways:

- Offline PD detection (Mashikian, et al. [B77], Kreuger, et al. [B72], Brettschneider, et al. [B15], Galski, et al. [B34], Takahashi, et al. [B90]), the test object is energized from external voltage sources with voltage levels higher, lower than or equal to the nominal voltage level.
- Online PD detection (Ahmed, et al. [B1], Cantin, et al. [B17], Yamaguchi, et al. [B99], CIGRE WG D1.33.03 [B19], Stennis, et al. [B89]), the test object is energized from the network with nominal voltage level (and current since the load remains connected).

The voltage sources for offline PD measurements can be power frequency, DAC, VLF voltage power supplies, or resonant test sets. As PD measurement characteristics strongly depend on the type (magnitude, frequency, and waveform) of testing voltage, users should carefully review Table 11. It is important that the voltage source be stable and free of any noise that would interfere with PD measurements.

Performing adequate sensitivity assessment of the measuring circuit (for a given combination of a sensor, type of cable accessory and signal processing of a particular system) is very important to establish sensitivity level and to validate PD measuring system performance.

While most PD detection techniques currently in practice are in accordance with available standards such as IEEE Std 400.3-2006 [B61], IEC 60270 [B51], IEC 60855-2:1987 [B54], and IEC 60855-3:1987 [B55], non-standardized PD test techniques also exist. The PD sensors used in non-standardized techniques are usually directly coupled capacitive sensors, high-frequency current transformers (CTs), or capacitively coupled voltage sensors. The latter can be built into the accessory during manufacture.

Refer to IEEE Std 400.3-2006 [B61] for more information about test application.

6.3.1.3 Advantages and disadvantages

Table 10 lists the overall advantages and disadvantages of PD measurement methods. Table 11 lists the advantages and disadvantages of different voltage sources for PD measurements.

Table 10 — Advantages and disadvantages of electrical PD measurement

Advantages	<p>A single test can locate singular or multiple weak spots (localized degradation) in cable systems; such weak spots can be due to voids, electrical trees, interface tracking, interfacial cavities in cable and accessory, high-resistance insulation shield, or broken neutral regions, provided the defects produce PD signals at the test voltage level and frequency.</p> <p>Can be employed for all cable types (e.g., XLPE, TR-XLPE, EPR, PILC).</p> <p>Measures magnitude of signals detected and patterns that can indicate defect-type causing signal.</p> <p>Comparison can be made for adjacent phases with the same configuration (including T-branched or complex circuits).</p> <p>Periodic testing has the potential to provide historical data that can enhance future testing assessment through trending. Measurements over time can show some cable system defects progressing to failure.</p>
Disadvantages	<p>Cannot directly identify defects associated with dielectric losses in cable system if these defects are not associated with a significant electrical tree or void. These losses can be discreet or distributed throughout the cable insulation, e.g., resulting from water trees or non-water -treed oxidized insulation.</p> <p>Some defects do not develop a PD signal (ionize) at the test voltage. Some defects produce PD, but do not necessarily lead to failure.</p> <p>Attenuation of the PD signal as it travels along a cable might result in the signal not being detected.</p> <p>On branched circuits, multiple measuring locations may be needed making the method more complex.</p> <p>No uniform Pass/Fail criteria are established for field testing. Interpretation may rely on parameters other than PDIV/PDEV such as phase pattern or surface or internal discharges, etc.</p> <p>Noise should be minimized; accuracy/sensitivity of detection depends on robustness or noise mitigation schemes when performed within ambient noise.</p> <p>Additional post analysis of test data is required.</p> <p>Neutral corrosion (wire or tape) can perturb measurement interpretation.</p>

Table 11 — Advantages and disadvantages of voltage sources for electrical PD measurement^a

Source type	Advantages	Disadvantages
50/60 Hz AC Online	<p>No additional voltage source equipment is needed.</p> <p>No service outages.</p> <p>Trend analysis can be accomplished if continuous monitoring is employed.</p> <p>Extended data acquisition time improves the chance of PD capture under in-service voltage conditions.</p> <p>Since measurement is performed at operating voltage, the test cannot induce dormant defects to become activated (as is theoretically possible when an overvoltage is applied).</p> <p>Since the system is tested while in-service, measurement is performed at operating temperature; hence voids that can be present will remain, and liquids that can be present cannot solidify (as can theoretically occur when testing is performed off-line). Attenuation can be minimized by selecting multiple data point pickup locations.</p>	<p>Requires that sensors be placed at points on the cable system which are not shielded with an acceptable distance between each sensor to assure detection. Multiple point access increases complexity.</p> <p>Cannot initiate PD or detect signals that would occur at voltages above normal operating voltage.</p> <p>Some PD pulse like signals external to the cable system under test could be interpreted as an issue/defect: noise on the network needs to be minimized or techniques that can detect PD signals buried in noise are required.</p> <p>The circuit needs to be de-energized if it is desired to perform calibration and sensitivity assessment.</p> <p>Measures signal/discharge activity between sensors, not the entire cable length.</p>
AC Offline. Sinusoidal Continuous (20 Hz–300 Hz)	<p>Test voltage allows the test to excite PD-producing defects which only appear at elevated voltages. This can enable the test to simulate transient voltage and assess cable system performance under these conditions.</p> <p>Can measure PD Inception Voltage (PDIV) and Extinction Voltage (PDEV); PDIV and PDEV are believed to give an indication of circuit condition.</p> <p>Measurements can be made from a single position on the circuit without the need for multiple accessing points.</p> <p>Short data acquisition time lowers the risk of a cable system failure at high voltage.</p> <p>Test can be stopped if desired (e.g., if what is considered to be unacceptable PD is observed).</p>	<p>Removing the system from service prior to applying the overvoltage test can allow the system to cool down, which can cause voids to disappear or liquids to solidify.</p> <p>Long cable lengths can distort and attenuate the shape of PD pulses, possibly making identification of the PD type and its location difficult.</p> <p>Short data acquisition time can miss PD. Tests can only detect PD if it is present when the test is conducted; thus the statistical nature of PD can complicate detection.</p> <p>On branched circuits, multiple measuring units are required making the method more time-consuming.</p> <p>Test voltage can activate PD defects that can be dormant (indefinitely) under operating voltage.</p>
AC Very Low Frequency (VLF 0.01 Hz to 1.0 Hz)	<p>Frequency dependency (0.01–1 Hz.) of PD can be established if sine wave is used.</p> <p>Test voltage allows the test to excite PD-producing defects, which only appear at elevated voltages. This can enable the test to simulate transient voltage and assess cable system performance under these conditions.</p> <p>Can measure PD Inception Voltage (PDIV) and Extinction Voltage (PDEV) for the frequency of the test voltage; PDIV and PDEV are believed to give an indication of circuit condition.</p>	<p>As compared to 50/60 Hz voltage stresses the PD inception conditions, PD magnitudes and PD patterns can be different.</p> <p>As the frequency decreases, test time needs to increase.</p> <p>Removing the system from service prior to applying the overvoltage test can allow the system to cool down which can cause voids to disappear or liquids to solidify.</p> <p>Long cable lengths can distort and</p>

Source type	Advantages	Disadvantages
	<p>Measurements can be made from a single position on the circuit without the need for multiple accessing points.</p> <p>Test can be stopped if desired (e.g., if what is considered to be unacceptable PD is observed).</p>	<p>attenuate the shape of PD pulses, possibly making identification of the PD type and its location difficult.</p> <p>Short data acquisition time can miss PD. Tests can only detect PD if it is present when the test is conducted; thus the statistical nature of PD can complicate detection.</p> <p>On branched circuits, multiple measuring units are required making the method more time-consuming.</p> <p>Test voltage can activate PD defects that can be dormant (indefinitely) under operating voltage.</p>
Damped AC (DAC 20 Hz to 500 Hz)	<p>Test voltage allows the test to excite PD-producing defects, which only appear at elevated voltages. This can enable the test to simulate transient voltage and assess cable system performance under these conditions.</p> <p>Can measure magnitude of partial discharge: PD Inception Voltage (PDIV) and PD Extinction Voltage (PDEV) that can give an indication of circuit condition.</p> <p>Measurements can be made from a single position on the circuit without the need for multiple accessing points.</p> <p>PD inception behaviors and PD magnitudes can be similar to those of 50/60 Hz voltage stresses.</p> <p>PD patterns show additional information about the PD behavior as a function of the decaying voltages.</p> <p>Test can be stopped if desired (e.g., if what is considered to be unacceptable PD is observed).</p>	<p>Can only control the voltage magnitude of the first half cycle.</p> <p>Due to different decaying characteristics among different types of cable insulation adequate comparison of PD data to continuous AC energizing is limited to the first half of each applied waveform.</p> <p>To obtain PD occurrence conditions (e.g., PD inception, PD level) similar to 50/60 Hz AC voltage stresses, the DAC frequency has to be below approximately 500 Hz.</p> <p>Interpretation of phase-related PD characteristics is more difficult with variable frequency and damping.</p> <p>In the case of a very short cable an additional capacitive load (PD free) is recommended to assure that voltage frequency remains adequate.</p> <p>Removing system from service prior to applying overvoltage test can allow the system to cool down, which can cause voids to disappear or liquids to solidify.</p> <p>Long cable lengths can distort and attenuate the shape of PD pulses, possibly making identification of the PD type and its location difficult.</p> <p>Short data acquisition time can miss PD. Tests can only detect PD if it is present when the test is conducted; thus the statistical nature of PD can complicate detection.</p> <p>On branched circuits, multiple measuring units are required making the method more time-consuming.</p> <p>Test voltage can activate PD defects that can be dormant (indefinitely) under operating voltage.</p>

^aConsider also the general dielectric response measurements advantages and disadvantages listed in Table 2.

6.3.2 Partial discharge—acoustic measurements

6.3.2.1 Description

When a partial discharge occurs, it produces an instantaneous release of energy. This energy release results in a mechanical wave, which propagates through the materials of the device in which it occurred. Thus, the PD site acts like an acoustic wave source. The waves propagate from the PD location and can be externally detected by using the proper equipment. This is known as acoustic partial discharge detection.

Acoustic PD measurement methods increase the possibilities over which PD detection can be applied, and enhance the information that can be obtained. One of the important features of acoustic methods compared to electrical methods is the immunity of the acoustic measurements to electromagnetic interference; therefore, acoustic methods could be applicable to situations in which electrical methods are not effective due to electromagnetic interferences (see Tian, et al. [B93] and Lundgaard [B74]).

Some literature has reported that acoustic methods are not well suited for discharge detection in cables as a result of the large reduction in sensitivity with distance from the source. The absorption in the cable insulation also reduces sensitivity. As a result, the acoustic sensor needs to be in contact with the cable near the PD source to provide a reasonable sensitivity (Lundgaard [B74]). Acoustic methods are therefore usually applied to the detection of PD in terminations, joints, and cable sections that are accessible so that direct contact with the device can be achieved.

Refer to IEEE Std 400.3-2006 [B61] for more information.

6.4 Time-domain reflectometry

Although time-domain reflectometry does not directly measure the dielectric properties of the cable system, it is included in this guide as it is a valuable complementary test to any insulation test.

6.4.1 Description

A time-domain reflectometry (TDR) is used to locate and characterize changes in impedance in a cable system. These changes in impedance can be caused by faults, joints, open connections, taps in the circuit, deteriorated neutrals IEEE Std 1617™-2007 [B67], highly conductive water ingress into insulation material or joints, and bad (high resistance) connectors.

Any other discontinuities along the circuit will also reflect a portion of the incident pulse back to the source. The location of these discontinuities can be determined in the same way as the end of the circuit. The shape of reflected pulses on the instrument's display helps the operator to determine what the discontinuities are.

The magnitude of the reflection at a discontinuity could be calculated using the reflection coefficient or ρ :

$$\rho = \frac{Z_d - Z_o}{Z_d + Z_o} \quad (3)$$

where

ρ is the reflection coefficient

Z_d is the impedance of a discontinuity

Z_o is the characteristic impedance of the cable

Also $V_{ref} = \rho V_{inc}$

where

V_{ref} and V_{inc} are the reflected and incident voltages, respectively.

Values of the reflection coefficient ρ range from 1 (open circuit) to -1 (short circuit). A reflection coefficient of zero would indicate that there is no reflection.

6.4.2 Application

Typically, this method is performed offline. TDR works essentially like a radar system. A fast rise-time, low-voltage pulse is applied between the conductor and the insulation shield of a cable circuit at an elbow or termination. As the pulse travels through the cable circuit, reflections are generated by any mismatches in circuit impedance, for example at cable joints. The reflected pulse components will be positive or negative depending on whether the impedance is more or less than the cable characteristic impedance. The initial and reflected pulses are displayed against time on an oscilloscope-type display and interpreted by the operator. Since the speed of travel of the pulse can be determined, the time can be converted to distance or location. The source of an impedance discontinuity can be determined by the shape of the reflected signal. Identifying as well as locating an anomaly requires an experienced operator to interpret the TDR signals.

The test duration, including interpretation, is on the order of five to ten minutes once the TDR is connected to the cable circuit.

6.4.3 Advantages and disadvantages

Table 12 lists the overall advantages and disadvantages of the TDR technique.

Table 12 — Advantages and disadvantages of TDR

Advantages	<p>Testing is easy to employ. Test equipment is small and inexpensive.</p> <p>Can detect and locate corroded neutral and shields.</p> <p>Test equipment typically uses low test voltage (less than U_0).</p> <p>Locates areas of cable system where there is a sudden impedance change, possibly related to problem conditions.</p> <p>Provides a profile of significant cable system physical features (i.e., locations of joints and overall circuit length) that can be useful for the interpretation of diagnostic test results.</p>
Disadvantages	<p>Blind spots occur at the point where the pulse is injected. The length of cable within the blind spot is dependent on the applied pulse width.</p> <p>Before each test, the cable should be completely discharged. After a HV TDR, the cable needs to be discharged.</p> <p>Noise can interfere with the low-voltage signal of TDR.</p> <p>TDR most likely will not detect even serious insulation defects.</p> <p>Proper interpretation of TDR data can require history of the cable circuit tested.</p> <p>Impedance reflections observable with a HV TDR cannot be visible with a LV TDR.</p> <p>High-frequency content of the TDR pulse is required to resolve defects of small dimensions. Thus, cable systems that cause high pulse attenuation and dispersion can cause anomalies to be masked.</p> <p>Cable needs to be taken out of service for testing.</p>

6.5 Thermal infrared imaging

Although thermal infrared imaging testing does not directly measure the dielectric properties of the cable system, it is included in this guide as it is a very valuable complementary test to any insulation test where the cable system is accessible.

This method (Fournier and Amyot [B30]) can be used to evaluate the condition of accessories by measuring or monitoring their surface temperature. Connector high resistivity and unusual heating of part of the accessory due to localized dielectric losses can be detected. Typical insulation problems found on service-aged joints are shown in Figure 3.

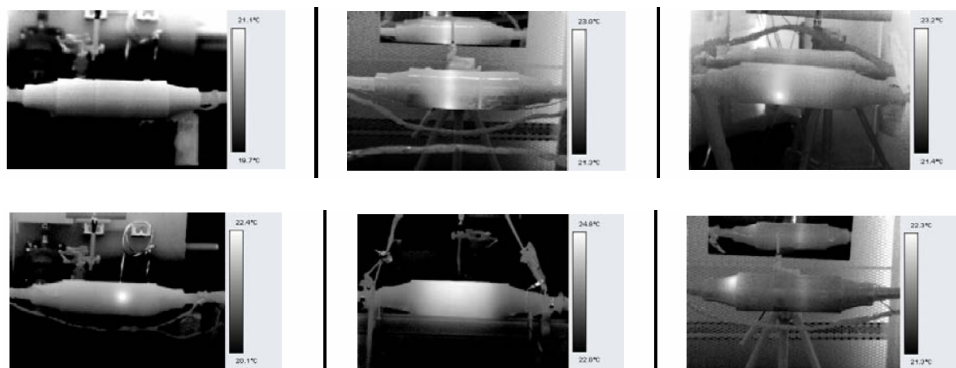


Figure 3 — Examples of thermal infrared measurements of defective components
(top left: no anomaly (reference); top middle: hot circular area with $T^{\circ}\text{rise} > 0.2^{\circ}\text{C}$; top right: hot spot with circular area with $T^{\circ}\text{rise} > 1.0^{\circ}\text{C}$; bottom left: single hot spot with $T^{\circ}\text{rise} > 1.0^{\circ}\text{C}$; bottom middle: hot joint body with $T^{\circ}\text{rise} > 1.0^{\circ}\text{C}$; bottom right: cable adapter with $T^{\circ}\text{rise} < 1.0^{\circ}\text{C}$)⁸

⁸ Reprinted with permission from Hydro-Quebec.

6.5.1 Application

The thermal measurements are made with an infrared camera. A simple infrared pointer can also be used but will provide less information in the same amount of time. The load of the cable and accessory also has to be measured and taken into account as the heat can be related to normal thermal dissipation. In the case where arc proofing tapes are used around the joints, the thermal monitoring is not usually possible.

6.5.2 Advantages and disadvantages

Table 13 lists the overall advantages and disadvantages of the thermal infrared imaging.

Table 13 — Advantages and disadvantages of thermal infrared imaging

Advantages	<p>Can detect unusual thermal behavior such as a high-resistance connector or high dielectric losses. Test equipment is small.</p> <p>This test is conducted while the circuit is energized (online).</p> <p>Non destructive and non invasive technique.</p>
Disadvantages	<p>Skilled operators are required for image interpretation and analysis.</p> <p>Cable system needs to be accessible. This technique is not suitable for direct buried systems except for above ground terminations. In a manhole, some parts of the accessories cannot be observable (e.g., close to a wall).</p> <p>Some defects do not have temperature gradient and cannot be detected with thermal imaging.</p>

7. Applicability of testing methods

This clause is intended to help the reader select one or a combination of testing methods for a specific situation of interest. A combination of testing methods will help to reduce the diagnostic uncertainty when these methods have complementary advantages.

First, the user should consider the intent of the test: installation, acceptance or maintenance test.

Second, the user should review the type of cable and cable accessories to be tested, their electrical characteristics, rate of failure, installation (in duct system or direct buried), and length of the cable system under test. If there is a targeted population of components, known for their high failure rate, it is important that the testing method has the capability to sort these out.

Third, the remediation action to an identified component that did not pass the test is important. If the user wants to repair only the failed point or if replacing sections of cable is preferred, this can orient the choice of a testing method.

Then, the user should review Clause 5 and consider the different advantages and disadvantages. The user should consider the references of this document as many contain real field applications and results. Experience of other users having similar cable systems and issues and expert advice can be very beneficial. Finally, a table is provided in Annex C for the applicability of field testing.

The user should recognize that there is a constant evolution in technical development of testing equipment and scientific knowledge of the relation between diagnostic properties. Not all of the evolutionary steps prove to be robust or useful. Thus the user is recommended to establish the generation of technology being evaluated and review the performance of the generation in an appropriate pilot study.

Annex A

(informative)

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Annex B

(informative)

Test voltage levels and durations

The recommended levels in “point” documents are based on laboratory research and utilities’ experiences and data. Therefore, users should not deviate from these values unless they manage a testing program to demonstrate the benefits of using alternative values. Deviation may be justified if the cable system characteristics or network architecture are different from the cable systems specified in “point documents.”

The testing program should include a large number of cable systems with a reference cable systems set for comparison. This reference set can be similar cable systems untested for the period of time under study and/or similar cable systems tested at recommended levels and duration. Statistical analysis of compared reliability for both systems on an extended period of time can demonstrate the benefits of alternative testing voltage or duration values. Such statistical analysis can be an average time-to-failure after test, SAIDI, SAIFI, other reliability index or any other applicable statistical method IEEE Std 1366-2003 [B66].

Annex C

(informative)

Information on applicability of field testing methods from CDFI

It should be noted that this information is based on information available at the time the information was collected. The user should consider that there is a constant evolution in technical development of testing equipment and scientific knowledge of the relation between diagnostic properties.

NEETRAC (USA), as part of the Cable Diagnostic Focused Initiative (CDFI), has constructed a Knowledge Based System (KBS) to assist users and utilities in selecting a short list of diagnostics that are suitable for their particular circumstances. The KBS combines an Expert System and a Fuzzy Logic Analyzer to interrogate a database of collated experience. The experience database is comprised of inputs from experts and users of diagnostics on cable systems.

In this case, the KBS that has been developed solicits information from the user on the following:

- The age of the cable system to be tested
- The type of insulation system [PE (XLPE, PE, TRXLPE), Paper or EPR]
- Likely remediation actions (replacement of a small section, replacement of accessories, complete new system, etc.)
- Failure Rate (qualitative classification) of the cable components

The experience database has been developed from 35 separate contributors and the inputs have the following distribution:

- 29% were members of IEEE Insulated Conductors Committee (ICC) Working Group F01 for the IEEE Std 400
- 43% from utilities
- 31% from diagnostic equipment or service providers
- 26% from other experts

The breakdown of expertise within the diagnostic equipment or service provider grouping (31% of the total) is as follows:

- Dielectric Response Techniques 18%
- Partial Discharge Techniques 47%
- Withstand Techniques 35%

The contributing experts acknowledge experience of diagnostic tests on cable systems from countries that are included, but not limited to: Austria, Belgium, Canada, Germany, Luxemburg, Malaysia, Netherlands, South Africa, and USA.

The KBS was used to construct Table C.1 included in this annex.

The KBS has the capability of addressing many (>200) scenarios; however the table reported here has been constructed for a general set of conditions (see below). Thus the applicability of the information is intended only as general guidance and the relevance for specific conditions can be quite different from that given in the table.

The assumptions used for Table C.1 are as follows:

- Remedial Action: Unknown
- Age: New ≤ 10 years old, Old ≥ 20 years old
- Hybrid: 33% PE, 33% Paper, 33% EPR, all with an equal sensitivity to failure
- The failure history is known in general
- A TDR measurement is obtained whenever an offline test is carried out

The classifications in the table relate to the distributions for the expert responses and are consistent for all cable system types, i.e., the Useful Class has the same meaning for a New Extruded Distribution Cable System as for an Aged Hybrid Cable System. The classes have been defined as follows:

- Useful: Techniques that have expert recommendations that exceed the upper quartile ($>75\%$) of the responses
- Not Useful: Techniques that have expert recommendations that do not exceed the lower quartile ($<25\%$) of the responses
- Potentially Useful: Techniques that have expert recommendations that are between the lower and upper quartiles ($>25\%$ and $<75\%$) of the responses
- Do Not Use: Techniques where $>50\%$ of the expert recommendations indicate that they believe the technique to be harmful to the cable system
- Not KBS reviewed: No data was collected from experts in this iteration of the KBS

The KBS is an evolving system that incorporates the increasing experience and learning of the participants. Thus as more tests are carried out by more users the outputs are likely to change and become more refined.

Table C.1—Information on applicability of field testing methods from CDFI

Testing Method and Voltage Source	New Transmission Extruded Cable System	New Distribution Extruded Cable System	Aged Distribution Extruded Cable System	Aged Distribution Laminated Cable System	Aged Distribution Hybrid Cable System
Simple Withstand Test					
HVDC Simple Withstand	Not Useful ²	Not Useful ²	Do Not Use ²	Not Useful ²	Not Useful ²
VLF Simple Withstand	Not KBS reviewed	Potentially Useful ³	Potentially Useful ³	Potentially Useful ³	Potentially Useful ³
AC Offline Sinusoidal Continuous (20 Hz–300 Hz) Simple Withstand	Useful ⁶	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
Damped AC Simple Withstand	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
Dielectric Response					
AC Offline Sinusoidal Continuous (20 Hz–300 Hz) tan delta measurements	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
VLF tan delta measurements	Not KBS reviewed	Potentially Useful ³	Useful ³	Potentially Useful ³	Useful ³
Damped AC Monitored Withstand with PD & Tan δ^5	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
VLF Sinusoidal Monitored Withstand with Tan δ	Not KBS reviewed	Potentially Useful ³	Useful ³	Useful ³	Useful ³
VLF Cosine-rectangular Monitored Withstand with Leakage Current	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed ³	Not KBS reviewed ³	Not KBS reviewed ³
HVDC Monitored Withstand with Leakage Current	Not Useful	Not Useful	Do Not Use	Not Useful	Not Useful
DC Leakage Current	Not Useful	Not Useful ²	Not Useful ²	Not Useful ²	Not Useful ²
VLF—Cosine-Rectangular with Leakage Current	Not Useful	Not Useful	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
Recovery Voltage	Not Useful	Not Useful	Not Useful	Not Useful	Not Useful
Polarization/Depolarization Current	Not Useful	Not Useful	Not Useful	Not Useful	Not Useful
Dielectric Spectroscopy	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
Partial Discharge					
AC Online Partial Discharge Electrical Measurement	Potentially Useful ⁴	Potentially Useful ⁴	Potentially Useful ⁴	Not Useful ⁴	Potentially Useful ⁴
AC Offline Sinusoidal Continuous (20 Hz–300 Hz) Partial Discharge Electrical Measurement	Potentially Useful ^{4,6}	Useful ⁴	Useful ⁴	Potentially Useful ⁴	Potentially Useful ⁴
VLF Partial Discharge Electrical Measurement	Potentially Useful ⁴	Useful ⁴	Useful ⁴	Potentially Useful ⁴	Potentially Useful ⁴
VLF Monitored Withstand with Partial Discharge Electrical Measurement	Potentially Useful	Not KBS reviewed	Potentially Useful ³	Not KBS reviewed	Not KBS reviewed
Damped AC Monitored Withstand with PD & Tan δ^5	Potentially Useful	Not KBS reviewed	Potentially Useful	Potentially Useful	Not KBS reviewed
Partial Discharge (PD) Acoustic Measurement	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed
Time-Domain Reflectometry (TDR)					
	Potentially Useful	Potentially Useful	Potentially Useful	Not Useful	Potentially Useful
Thermal Imaging					
	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed	Not KBS reviewed

NOTES: 1—Not KBS reviewed :The test method or test case was not reviewed by the contributors to the version of the KBS used to construct this table, 2—Refer to IEEE Std 400.1 [B59] for testing details, 3—Refer to IEEE Std 400.2-2004 [B60] for testing details, 4—Refer to IEEE Std 400.3 for testing details, 5—Damped AC point document (IEEE P400.4 [B62]) currently under development, 6—Refer to IEC 60267 [B56] for testing details.