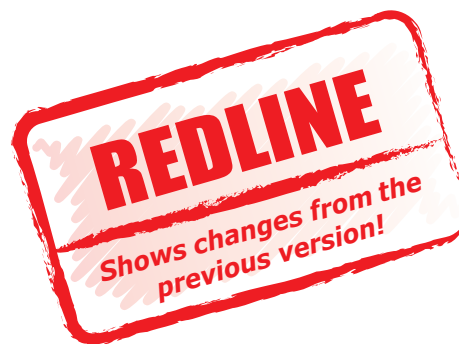


IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above

IEEE Power & Energy Society

Sponsored by the
Insulated Conductors Committee



IEEE
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USA

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

Sponsor

**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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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

~~This omnibus Guide provides an overview of known techniques 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. Field applied tests can be broadly divided into the following categories:~~

- ~~a) Type 1 Field Tests are intended to detect defects in the insulation of a cable system in order to improve the service reliability after the defective part is removed and appropriate repairs are performed. These tests are usually achieved by application of~~

~~moderately increased voltages across the insulation for a prescribed duration. Such tests may be categorized as “pass/fail” or “go/no go.”~~

~~b) Type 2 Field Tests are intended to provide indications that the insulation system has deteriorated, hence, are “diagnostic.” Some of these tests will show the overall condition of a cable system, and others will indicate the locations of discrete defects that may become the sites of future service failures. Both varieties of such tests are usually performed by means of moderately increased voltages applied for relatively short duration, or by means of low voltages.~~

~~This Guide provides a brief description of all known voltage sources used to perform both categories of tests as well as a brief introduction to specific tests. The material presented is descriptive and tutorial and does not address the questions of evaluation of test results nor the specification of test voltage levels. Some of the methods described are well known and widely accepted. Other methods are still in development stages, with limited field experience. Each method described has advantages and disadvantages that are discussed in their respective clauses.~~

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. ~~A complete tutorial or debate forum for one method versus another is not being attempted. A brief listing of “advantages” and “disadvantages” is included, but the users should avail themselves of the technical papers that are referenced, the material listed in the bibliography in Annex B, manufacturers' literature, and recent research results to make decisions on whether to perform a test and which test method to use. In making such decisions, consideration should be given to the performance of the connected cable system, including joints, terminations,~~

~~and associated equipment.~~

~~(The manufacturers of the associated equipment should be consulted, or their instruction bulletins read, for the applicability of the chosen test to that particular type of equipment.)~~

~~This Guide does not propose to cover, but may apply to, communication cables, control cables, high frequency cables, and other special purpose cables, or unshielded power cables.~~

1.2 Purpose

The purpose of this guide is to provide an overview of the various ~~tests~~ test methods available for evaluating the insulation of shielded cable systems in the field, and to ~~set the stage~~ assist cable owners in selecting one or more appropriate tests for a ~~series of guides covering each test method~~ 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.

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Accredited Standards Committee IEEE C2, National Electrical Safety Code®
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IEC 61230, Live Working—Portable Equipment for Earthing or Earthing and Short-

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

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

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

~~AEIC G7-90 (1st Edition), Guide for Replacement and Life Extension of Extruded Dielectric 5-35 kV Underground Distribution Cables, May 1990.¹~~

~~ASTM D 150-1998, Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Dielectric Insulation.²~~

~~IEEE Std 4TM-1995, IEEE Standard Techniques for High Voltage Testing.^{3, 4}~~

~~IEEE Std 48TM-1996, IEEE Standard Test Procedures and Requirements for Alternating Current Cable Terminations 2.5 kV Through 765 kV.~~

~~IEEE Std 62TM-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors.~~

~~IEEE P400.1TM, IEEE Draft Guide for Making High Direct Voltage Tests on Shielded Power Cable Systems in the Field.⁵~~

~~IEEE Std 404TM-2000, IEEE Standard for Cable Joints for Use with Extruded Dielectric Cable Rated 5000–138,000 V and Cable Joints for Use with Laminated Dielectric Cable Rated 2500–500,000 V.~~

~~IEEE Std 510TM-1983 (Reaff 1992), IEEE Recommended Practices for Safety in High Voltage and~~

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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.

~~IEEE 100TM, The Authoritative Dictionary of IEEE Standards Terms and Definitions, Seventh Edition [B30]~~⁶ 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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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.

~~The test is intended to further detect installation damage and to show any gross defects or errors in installation of other system components. (IEEE Std 48-1996 and IEEE Std 404-2000).⁷~~

~~**3.2 basic impulse level (BIL):** Impulse voltage that electrical equipment is required to withstand without failure or disruptive discharge when tested under specified conditions of temperature and humidity. They are designated in terms of crest voltage of $1.2 \times 50 \mu\text{s}$ full-wave impulse voltage test. (IEEE Std 4-1995).~~

~~**3.3 installation tests:** Field tests that are conducted after cable installation but before jointing (splicing) or terminating. The test is intended to detect shipping, storage, or installation damage.~~

~~**:** A field test made during the operating life of a cable system. It is intended to detect deterioration of the system and to check the serviceability so that suitable maintenance procedures can be initiated.~~

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

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

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.

4. Introduction

4.1 Environmental influences

4.1.1 Temperature

The dielectric strength of some cable insulation is reduced at increased temperatures. This may necessitate a reduction of the test voltage at those higher temperatures. Temperature gradients in the cable system insulation, caused by heat dissipation from the conductor, can result in abnormal potential distribution upon application of voltage, especially with direct voltage.

4.1.2 Atmospheric conditions

High humidity or other conditions favoring condensation on exposed surfaces can affect test results to a marked degree. Contamination of termination surfaces can greatly increase conduction current and reduce flashover levels. Relative air density affects the measurement of test voltage by gaps or similar means and the flashover at terminations. At elevations higher than 1 000 m, additional insulation at terminations is required to withstand both working voltages and prescribed test voltages. Wind can cause erroneous leakage current readings, as described in IEEE Std 48-1996, IEEE Std 62-1995, and IEEE P400.1. The bibliography, Annex B, provides some specifics for cables and cable systems.

4.1.3 Other energized conductors

Precautions should be taken to allow adequate voltage clearance when testing conductors in close proximity to other energized conductors. Failure to maintain safe clearances may lead to flashover between the test conductor and other live conductors, particularly when test voltages above the rated operating voltage are used. This consideration must be made for dc, ac, or very low frequency (VLF) test voltages. When spacing is marginal, special precautions may be required

to prevent flashover.

⁶The numbers in brackets correspond to those in the bibliography in Annex B.

⁷Information on references can be found in Clause 2.

4.2 Summary of direct voltage testing

DC testing has been accepted for many years as the standard field method for performing high-voltage tests on cable insulation systems. Whenever dc testing is performed, full consideration should be given to the fact that steady-state direct voltage creates within the insulation systems an electrical field determined by the geometry and conductance of the insulation, whereas under service conditions, alternating voltage creates an electric field determined chiefly by the geometry and dielectric constant (or capacitance) of the insulation. Under ideal, homogeneously uniform insulation conditions, the mathematical formulas governing the steady-state stress distribution within the cable insulation are of the same form for dc and for ac, resulting in comparable relative values; however, should the cable insulation contain defects in which either the conductivity or the dielectric constant assume values significantly different from those in the bulk of the insulation, the electric stress distribution obtained with direct voltage will no longer correspond to that obtained with alternating voltage. As conductivity is generally influenced by temperature to a greater extent than the dielectric constant, the comparative electric stress distribution under dc and ac voltage application will be affected differently by changes in temperature or temperature distribution within the insulation. Furthermore, the failure mechanisms triggered by insulation defects vary from one type of defect to another. These failure mechanisms respond differently to the type of test voltage utilized. For instance, if the defect is a void where the mechanism of failure under service ac conditions is most likely to be triggered by partial discharge, application of direct voltage would not produce the high partial discharge repetition rate that exists with alternating voltage. Under these conditions, dc testing would not be useful. However, if the defect triggers failure by a thermal mechanism, dc testing may prove to be effective. For example, dc can detect the presence of contaminants along a creepage interface.

In the case of joints and accessories, their dielectric properties may differ from that of the cable with regard to conductivity. This may result in a dc stress distribution at the interfaces between the cable and the accessory that is very different from the stress under ac voltage. A careful examination of the system is necessary prior to a dc test in order to avoid difficulties.

Testing of cables that have been service aged in a wet environment (specifically, XLPE) with dc at the currently recommended dc voltage levels (see IEEE P400.1) may cause the cables to fail after they are returned to service (see Fisher, et al. [B23], and Stennis, et al. [B48]). The failures would not have occurred at that point in time if the cables had remained in service and not been tested with dc (see Eager, et al. [B21], and Srinivas, et al. [B47]). Furthermore, from the work of Bach, et al. [B7], we know that even massive insulation defects in extruded dielectric insulation cannot be detected with dc at the recommended voltage levels.

After engineering evaluation of the effectiveness of a test voltage and the risks to the cable system, high direct voltage may be considered appropriate for a particular application. If so, dc testing has the considerable advantage of being the simplest and most convenient to use. The value of the test for diagnostic purposes is limited when applied to extruded insulations, but it has been proven to yield excellent results on laminated insulation systems.

4.3 Summary of alternative testing

Alternating voltage tests at power line frequencies stress the insulation in a similar manner to normal operation, and the test is similar to that used in the factory on new reels of cable.

A serious disadvantage of power frequency ac tests at increased voltage levels is the requirement for heavy, bulky, and expensive test transformers that may not be readily transportable to a field site. This problem may be mitigated through use of resonant (both series and parallel) test sets, compensated (gapped core) test sets that are designed to resonate with a cable of average length at power frequency, the range of resonance being adjustable to a range of cable lengths through a moderate change of the excitation voltage frequency, or a pulse resonant system. Power

frequency ac tests are ideally suited for Type 2 Field Tests, such as partial discharge location, and dissipation factor ($\tan \delta$) evaluation.

Some of the practical disadvantages of power frequency tests are reduced while retaining the basic advantages by the use of VLF (0.1 Hz) voltage or by the use of other time-varying voltages. Examples of these latter are the oscillating wave (OSW, Clause 10) and the alternating polarity dc-biased ac voltage (APDAC). When such variations of power frequency test sets are used for conducting Type 1 Tests, it is necessary to establish the equivalence of the results obtained at various voltage levels and test durations with corresponding results obtained by testing at power frequency.

A major objection to Type 1 Field Tests is the concern that application of increased voltages without any other accompanying diagnostic measurements triggers failure mechanisms that will not show during the test but that may cause subsequent failures in service. The selected test voltages can be used not only to force cable systems to fail at the sites of defects, but also to provide a useful evaluation of the condition of the insulation system.

As cable system insulations age, their dielectric properties undergo characteristic changes. These can be used to perform various Type 2 (Diagnostic) Field Tests. A brief overview of the known methods follows:

- For defective cable insulation, the dc leakage current versus voltage plot departs from linearity as the voltage is increased beyond some threshold value (tip-up curve), allowing a simple diagnostic test to be performed in the field.
- Another set of tests consists of applying a moderately elevated direct voltage across the cable insulation, removing the voltage source, shorting the cable while monitoring the short-circuit current as a function of time (depolarization current test), or measuring the voltage buildup as a function of time after the removal of the short (return voltage test). The rate of depolarization current decay or the rate of return voltage buildup can be used

as indicators of the degree of insulation aging. Measurement of polarization index (Ratio of insulation resistance after 10 min to resistance after 1 minute of a voltage application) can also be utilized as an insulation diagnostic test.

— As a cable deteriorates, its dissipation factor ($\tan \delta$) versus voltage plots can assume a gradually higher rate of increase (tip up) beyond some threshold voltage. This test can be conducted either by means of a power frequency voltage or by means of a VLF voltage.

— Water treeing in extruded cables causes a slight rectification of the ac voltage impressed across their insulation, producing a very small dc component in the ac leakage current. The magnitude of this component has been shown to increase with the severity of treeing.

— Another developing diagnostic test, propagation characteristics spectroscopy (PCS), monitors the changes in the wave propagation characteristics (attenuation versus frequency spectrum) of a cable by means of a low voltage pulse that can be applied while the cable is energized and in service. Experiments have shown that the attenuation spectrum changes characteristically as the insulation ages.

The Type 2 Field Tests previously described are intended to monitor the overall condition of a cable insulation throughout its length. At least two additional diagnostic methods are intended to identify the locations of discrete defects that may be the sites of future failures in service. Service aged cables with water trees have been shown to produce partial discharge (PD) signals from the tips of their longest trees when subjected to time varying voltage in the range of one to three times service level. The exact identification of these discharge sites is now possible by means of equipment capable of functioning even in high ambient noise environments. The severity of defects is assessed by the closeness of the PD inception voltage to service voltage. Partial discharge location in installed cables is usually performed by means of power frequency excitation voltage sources, but it also has been shown to be possible by means of APDAC, VLF, impulse voltage, or oscillatory voltage. A guide covering the use of this method using VLF voltage will be provided in the future. Another diagnostic test, known as the DIACS

method, identifies the location of discrete impedance discontinuities or anomalies in the cable insulation through low voltage reflectometry. Water trees are reported to act as discontinuities after the cable has been preconditioned for some length of time by means of unipolar high dc and impulse voltages. The ability of this method to assess the severity of anomalies and to identify defective joints has yet to be demonstrated.

4.4 Need for testing

Although medium and high voltage power cables are carefully tested by the manufacturer before shipment with alternating or direct voltage, some defects may not be detected or, more likely, damage during shipment, storage, or installation may occur. Additional testing of completed installations including joints and terminations prior to being placed in service may be conducted. Additionally, many users find that with time, these cable systems degrade and service failures become troublesome. The desire to reduce or eliminate those failures may lead cable users to perform periodic tests after some time in service. As well, cable users need special diagnostic tests as an aid in determining the economic replacement interval for deteriorated cables.

AEIC G7-90 states that "There are no field tests available that will provide an exact measurement of remaining service life in an operating cable system." Users may mix cable types on a system, and a need exists to base the test voltages and time on the circuit basic impulse level (BIL) rather than on the type and thickness of the insulation.

The traditional method of factory testing the insulation of medium voltage cable systems has been to subject it to high alternating potential followed by direct potential. Because of the previous unavailability of compact ac field test equipment, many systems have been field tested with dc or no field testing has been performed. Experience with paper insulated, lead covered cable systems that have been tested in the field with dc for over 60 years has shown that testing with the recommended dc voltage does not seem to deteriorate sound insulation, or if it does, it is at a very

slow rate of degradation.

The decision to employ maintenance testing must 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. As proven nondestructive diagnostic test methods become available, the users may want to consider replacing withstand-type voltage tests with one or more of these methods.

CAUTION

The consequences of experiencing a failure during the performance of a maintenance test should be considered prior to undertaking any such test. A faulted circuit would be out of service until repairs can be completed.

4.5 Safety awareness

WARNING

For all tests involving hazardous voltage levels, special attention must be paid to ensure the safety of personnel. Refer to Clause 6, Safety Procedures in the Field, IEEE Std 510-1983, equipment makers' instructions, and all applicable regulations.

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 must 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 ensure 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 may be used to indicate that the circuit is completely de-energized before application of safety grounds.~~

~~Cables have high capacitance and dielectric absorption characteristics. Particular attention must be directed to the special techniques required for discharging cables after testing to eliminate personnel hazards.~~

CAUTION

~~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

5. Direct voltage testing

5.1 Introduction

The use of direct voltage has a historical precedent in the testing of laminated dielectric cable systems. Its application for testing extruded dielectric cable systems at high voltage is a matter of concern and debate. IEEE P400.1 contains information relevant to these concerns.

This section presents the rationale for using dc testing, including the advantages and disadvantages and a brief description of the various dc field tests that can be conducted. These are generally divided into two broad categories, delineated by the test voltage level: low voltage dc testing (LVDC) covering voltages at and above 5 kV and high voltage dc testing (HVDC) covering voltage levels above 5 kV.

5.2 Rationale for using dc

Ideally, the field testing of cable systems is best performed by means of ac voltages at power frequency; however, the size and input power required for such tests using conventional transformers led to impractically large and costly test transformers. The apparent power rating of these transformers is given by Equation (1).

$$S = VI = 2\pi fCV^2 \times 10^{-12}$$

(1)

where

S is the apparent power of the transformer in voltamperes,

V is the maximum test voltage level phase to ground in volts,

I is the current in amperes,

f is the power frequency in hertz,

C is the total capacitance of the cable to be tested in pF.

As an example, to test a 1 800-m-long 35-kV cable system (20-kV phase-to-ground) having a capacitance of 330 pF/m would require a conventional transformer rated at 80 kV, 1 500 kVA. If this transformer is fed from a 480-V source, the primary current would be over 3 000 amperes. This set is not readily transportable to a field location; it is costly and requires an unreasonably high primary current supply. See Clause 6 for a discussion of resonant equipment.⁸

Testing with a dc voltage source requires that only the dc conduction current be supplied rather than a continuous capacitive charging current utilized in Equation (1).

A 10-W (10-VA) dc test set should be satisfactory for testing the cable mentioned in the previous example. Such a test set is relatively small, easy to handle, and reasonably inexpensive.

5.3 Performing LVDC tests

Equipment for producing these voltages is typified by commercially available insulation resistance testers. Some have multivoltage range capability.

Cable phases not under test should have their conductors grounded. Cable ends, both at test location and remote, should be protected from accidental contact by personnel, energized equipment, and grounds.

Apply the prescribed test voltage for a specified period of time. It may be advantageous to conduct the test with more than one voltage level and record readings of more than one time period.

5.3.1 Insulation resistance test

Such test equipment provides measurements of the insulation resistance of the cable system as a function of time. Interpretation of the results, covered in greater detail in IEEE P400.1, usually makes use of the change in resistance as testing progresses. A value of polarization index can be obtained by taking the ratio of the resistance after 10 min to the resistance after 1 minute.

ICEA provides values of minimum insulation resistance K in megohms for 305-m [Equation (2)], which are found in the applicable cable standards. These are based on new single conductor cable after an ac voltage test in the factory, at 500 V dc for 1 min, corrected to a base temperature of 15.6 °C. Also refer to the CEN ELEC standards.⁹

$$R = K \log_{10}(D/d)$$

(2)

where

R —is the megohms for 305 m of cable,

K —is the constant for specific insulating material,

D —is the outside diameter of insulation,

d —is the diameter over conductor shield.

⁸1 800 m is approximately 6 000 ft.

⁹305 m is approximately 1 000 ft.

5.4 Performing HVDC tests

Equipment for producing these voltages is typified by rectification of an ac power supply. Output voltage is variable by adjusting the ac input voltage. Output current, i.e., current into the cable system under test, may be measured on the HVDC side or ratio transformation of the ac input. For the latter case, the test equipment leakage may mask the test current and the interpretation of results. Apply the prescribed test voltage for the specified period of time. IEEE P400.1 provides guidance for the selection of test voltage and time.

The following three general types of tests can be conducted with this equipment.

5.4.1 DC withstand test

~~A voltage at a prescribed level is applied for a prescribed duration. The cable system is deemed to be acceptable if no breakdown occurs. This may be categorized as a "pass/fail" or "go/no-go" test (Type 1 Field Test).~~

5.4.2 Leakage current—time tests

~~Total apparent leakage output current is recorded as a function of time at a prescribed voltage level. The variations of leakage current with time (rather than its absolute value) provide diagnostic information on the cable system.~~

5.4.3 Step-voltage test or leakage current tip-up tests

~~The voltage is increased in small steps while the steady-state leakage current is recorded, until the maximum test voltage is reached or a pronounced nonlinear relationship between current and voltage is displayed. Such departures from linearity may denote a defective insulation system.~~

5.5 Summary of advantages and disadvantages

Some of the advantages and disadvantages of dc testing are listed below.

5.5.1 Advantages

- ~~—Relatively simple and light test equipment, in comparison to ac, facilitate portability.~~
- ~~—Input power supply requirements are readily available.~~