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IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems

IEEE Power Engineering Society

Sponsored by the
Insulated Conductors Committee

IEEE

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Approved 29 April 2002

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Abstract: This Guide lists the various field test methods that are currently available or under development with guidance on HOW to perform each test. The Guide covers shielded, insulated power cable systems rated 5 kV through 500 kV unless these voltages are modified by the specific "point" document.

Keywords: alternating-polarity dc-biased ac voltage, dissipation factor testing, field tests, high-voltage dc testing, low-voltage dc testing, oscillating wave, partial discharge, propagation characteristics spectroscopy, underground residential distribution, very low frequency

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Introduction

(This introduction is not part of IEEE Std 400-2001™, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems.)

This is a new omnibus Guide that has been in preparation for nine years. It 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. 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 nor the specification of test voltage levels nor time of application.

Additional details will be provided in “point” documents (that are presently under preparation), such as IEEE P400.1™, direct voltage testing; IEEE P400.2™, very low frequency testing; and IEEE P400.3™, dissipation factor testing.

Participants

At the time this Guide was completed, the Working Group on Field Testing and Evaluation of Shielded Power Cable Systems had the following membership. Voting members at the time of publication are marked with an asterisk (*).

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IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems

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 with guidance on HOW to perform each test. The Guide covers shielded, insulated power cable systems rated 5 kV through 500 kV unless these voltages are modified by the specific "point" document. 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 available for evaluating the insulation of cable systems in the field, and to set the stage for a series of guides covering each test method.

2. References

This Guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

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 4-1995™, IEEE Standard Techniques for High-Voltage Testing.[3]

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

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

IEEE P400.1™, IEEE Draft Guide for Making High-Direct-Voltage Tests on Shielded Power Cable Systems in the Field.[4]

IEEE Std 404-2000™, 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 510-1983™ (Reaff 1992), IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.

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[1] AEIC publications are available from the Association of Edison Illuminating Companies, 600 N. 18th Street, P. O. Box 2641, Birmingham, AL 35291-0992, USA (http://www.aeic.org/). AEIC publications are also available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112-5704, USA (http://global.ihs.com/).

[2] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

[3] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[4] This 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.

3. Definitions

For the purposes of this Guide, the following terms and definitions apply. IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms and Definitions*, Seventh Edition [B30][5] should be referenced for terms not defined in this clause.

3.1 acceptance tests: A field test made after cable system installation, including terminations and joints, but before the cable system is placed in 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™).[6]

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 1.2×50 µs 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.

3.4 maintenance tests: 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.

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

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[5] The numbers in brackets correspond to those in the bibliography in Annex B.

[6] Information on references can be found in Clause 2.

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.

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 δ) 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 δ) 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. 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).

$$S = VI = 2\pi fCV^2 \times 10^{-12} \quad (1)$$

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.[7]

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 CENELEC standards.[8]

$$R = K \log_{10}(D/d) \tag{2}$$

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.

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[7] 1 800 m is approximately 6 000 ft.

[8] 305 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.
- Extensive history of successful testing of laminated dielectric cable systems and well-established data base.
- It is effective when the failure mechanism is triggered by conduction or by thermal consideration.
- It is effective on interface problems of joints and terminations and surface problems of terminations.
- Purchase cost is generally lower than that of non-dc test equipment for comparable kilovolt output.

5.5.2 Disadvantages

- It is blind to certain types of defects, such as clean voids and cuts.
- It may not replicate the stress distribution existing with power frequency ac voltage. The stress distribution is sensitive to temperature and temperature distribution.
- It may cause undesirable space charge accumulation, especially at accessory to cable insulation interfaces.

- It may adversely affect future performance of water-tree-affected extruded dielectric cables.
- Leakage current readings may have wide variations due to atmospheric conditions and lack of control of charges at termination lugs.

6. Power frequency testing

6.1 Introduction

As the name implies, these test methods are based on using alternating current at the operating frequency of the system as the test source. These methods have the advantage, unique among all test methods described in this Guide, of stressing the insulation comparably to normal operating conditions. It also replicates the most common method of factory test on new cables and accessories.

In the past, a bulky and expensive test generator was required when a capacitive load such as a cable system was stressed above normal operating levels. This has been offset by the use of variable inductance and variable frequency resonant and pulsed resonant test sources.

A further advantage of power frequency testing is that it allows partial discharge and dissipation factor (tan δ) testing for diagnostic purposes. Some other test sources also permit these measurements, but give rise to some uncertainty in interpretation, because the measurements are then made at a frequency other than the normal operating frequency. The factory quality tests on new cable are almost invariably made at the power frequency on which the cable will operate in service.

The size of the necessary equipment can be substantially reduced by using the principle of resonance. If the effective capacitance of the cable is resonated with an inductor, the multiplying effect of the resonant circuit (its Q factor, presently between 50 and 120) will allow the use of a smaller test source. In the ideal case of a perfect resonance, the test source will only be required to supply energy to balance the true resistive loss in the inductor and cable system. One of two resonant circuits is normally used, either series or parallel. Other hybrid arrangements of series-parallel combinations can be used with advantage in special circumstances, but are unusual and will not be considered here. In practical resonant test systems, provision is made for varying both the magnitude of the inductance and the system voltage. Figure 1 shows a series resonant circuit.

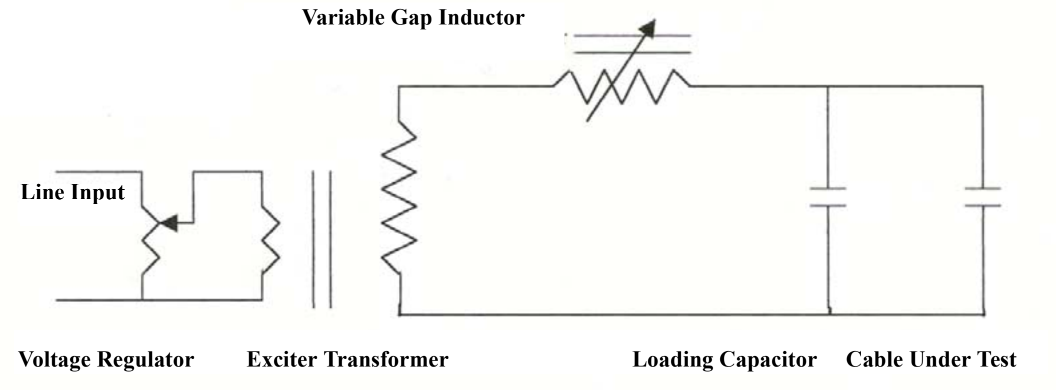

Figure 1—Series resonant circuit

A further and significant reduction in size and weight of the test voltage generator can be achieved by use of the pulsed resonant circuit. See Figure 2 for the shape produced by this type of test circuit.

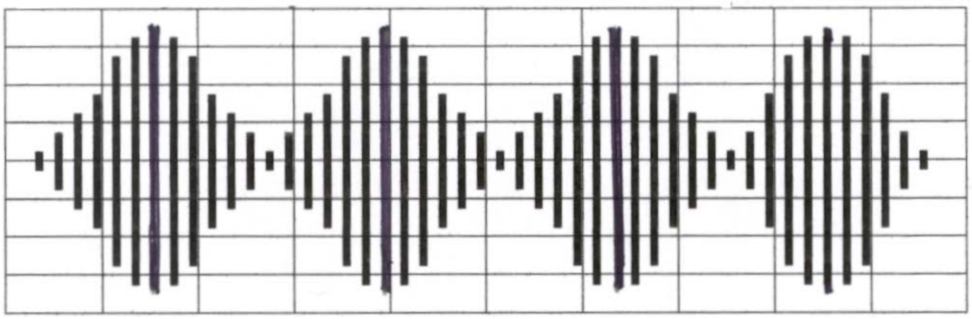

Figure 2—Four complete output cycles of pulsed resonant system

6.2 Test apparatus requirements

The following requirements are common to all three types of line frequency and resonant testing systems:

- The apparatus should be provided with an output voltmeter which responds to the test waveform. See IEEE Std 4-1995™.
- The output waveform should be sinusoidal and should contain minimum line frequency harmonics and noise. This is of particular importance if diagnostic measurements (partial discharge, dissipation factor, etc.) are to be performed. See IEEE Std 4-1995™ for a discussion of harmonic distortion. It should be noted that older types of voltage regulators using inductive methods for regulation tended to produce large amounts of harmonic distortion.
- The test system should be equipped with a means of controlling the output voltage smoothly and linearly. The resolution of the voltage adjustment should be not more than 1% of the maximum output voltage.
- For withstand tests, the detection and indication of the point at which breakdown occurs is determined by the overcurrent protective device of the test system. For this reason, a high-speed and repeatable electronic circuit may be used to operate the system circuit breaker as fast as practical. Disconnection of the cable from the test system should occur in less than two cycles of input frequency.
- It is desirable that the output voltage be controlled by an automatic voltage regulator to maintain the constant voltage for the duration of the test.
- In resonant systems, it is convenient to have an automatic resonance control that operates initially to resonate the test system and cable system under test.
- If the test system is to be used for diagnostic measurements, the internal partial discharge should be low; less than 5 pC is normally acceptable.

6.3 Characteristics of test systems

- The operating characteristics of a conventional test transformer are similar to a power transformer, although significant differences exist in the design.

- Resonant systems operate differently than do conventional transformers, in that they have a specific tuning range for the capacitance of the cable under test. Capacitance outside of this range cannot be energized. The minimum cable capacitance that can be energized can be reduced to zero, in the series resonant system, by using an auxiliary capacitor of appropriate rating in parallel with the test sample. The parallel resonant test system can be energized with no connected capacitance. The maximum value is independent of the current or thermal rating of the test system and cannot be exceeded. A typical tuning range is of the order of 20:1, maximum to minimum capacitance.
- Both conventional and resonant test sets provide an output that stresses the cable system under test identically to that under normal operations.

The output of a pulsed resonant test system consists of a power line frequency modulated at a low frequency, such as 1 Hz (see Figure 2). The stress distribution in the cable system under test is therefore almost identical to that under normal operation. The only difference is that the magnitude of the stress varies periodically. The duration of the test must therefore be extended so that the cable under test is subjected to the same volt-time exposure as with a constant amplitude line frequency test.

6.4 Test procedures

6.4.1 Conventional transformers

When the cable has been prepared and appropriate safety precautions have been taken, the test set is energized and the voltage is increased at a slow, constant rate until the specified test voltage is achieved. It is then held constant for the specified test period. At the conclusion of the test period, it is reduced to zero at the same rate as that used for raising the voltage.

6.4.2 Resonant systems

Proceed as in 6.4.1, except that the voltage is first raised to approximately 5% of the specified test voltage. The system is then tuned, either manually or automatically if the facility is available. The tuning may also require minor adjustment when specified voltage is achieved.

6.4.3 Rate of change of voltage

The recommended rate-of-rise and rate-of-decrease of the test voltage is approximately 1 kV/s at power frequency. In the VLF test mode, the applied voltage will be reached immediately after switching on the test set.

6.4.4 Time period

The duration of an acceptance test on a new cable system is normally 15 min at specified voltage. Maintenance tests may be 5 to 15 min. Any diagnostic tests (such as partial discharge or dissipation factor) may be performed during this period. The voltage should be maintained at the specified value to within ±1%.

6.4.5 Testing with system voltage (medium voltage)

It has been the utility practice for field crews to reclose an overhead circuit after visually inspecting the circuit. The visual inspection is important in order to verify that any damaged equipment has been removed, downed lines have been restored, and feeds from alternate circuits have been disconnected. Fusing used in these operations is normally the size and type that was originally found in the switch.

This practice has been carried over to the underground residential distribution (URD) circuits by the same operating crews that switched the overhead system. URD circuits have been re-energized either by the overhead fuse connection or by the use of a separable connector (elbow). In some cases, continual reclosing and sectionalizing have been used to isolate a failure. This practice should not be used because it may be damaging to the underground system. Reclosing in this manner may cause high-voltage transients to be generated and, hence, subject the circuit to excessive current surges. Both of those conditions may reduce the life and reliability of the underground circuit.

Devices have been developed to eliminate the need to re-energize a faulted underground circuit. With the use of a standard operating tester, a high-voltage rectifier, the correct adapters, and an ac system source, a test can be applied to the underground circuit that will indicate whether a circuit is suitable for re-energization. A voltmeter phasing tester, in common use for overhead testing, can be modified to test underground circuits with the application of a high-voltage rectifier and proper adapters. The voltmeter indicates the amount of charging current that is on the circuit being tested. Because the underground cable is a good capacitor, an unfaulted circuit would give a high reading when the tester is first connected to the circuit. As the capacitance charges, the reading on the voltmeter will decrease. If the reading fails to decrease, a faulted circuit is indicated.

6.5 Advantages and disadvantages

6.5.1 Advantages

- Readily available at V_0

6.5.2 Disadvantages

- Heavy equipment and expensive above V_0
- Does not assess condition of insulation

7. Partial discharge testing

7.1 Introduction

Partial discharge measurement is an important method of assessing the quality of the insulation of power cable systems, particularly for extruded insulation materials.

This Guide considers partial discharge from two points of view: the measurement of all partial discharges occurring within the cable system and the location of individual partial discharge sites.

7.2 Fundamentals

A partial discharge is an electrical discharge (formation of a streamer or arc) that does not bridge the entire space between two electrodes. The discharge may occur in a gas-filled void within the extruded cable insulation, at the interface between a shield protrusion and the insulation, at a shield skip, at the boundaries of a contaminant, or at the tip of a well-developed water tree when a cable is subjected to moderately high voltage. Partial discharges can also occur in a cable termination, in a joint, in air, or within a cable.

7.3 Partial discharge characterization

Voltage excitation by ac produces, during each half cycle, a series of PD pulses. The rise time of these pulses is in the range of nanoseconds to tens of nanoseconds. At the measuring end, these pulses tend to become wider because of the wave propagation characteristics of the cable and the bandwidth of the measuring circuit. The narrower bandwidths produce a broader and more rounded pulse. The time interval between pulses varies randomly and can range from 10 to over 200 ms.

Another important aspect of partial discharge is the fact that under dc voltage excitation conditions, the charging of the capacitor containing the defect is affected by the very high resistance of the cable insulation. The recharging time constant of the cavity can be several hours, thus, limiting the repetition rate of the PD pulses to one per several hours. It follows that the repetition rate at 0.1 Hz is slower than at 50 or 60 Hz.

As the PD pulse is of a very short duration, it tends to set up an electromagnetic field that propagates in both directions along the cable with a velocity of propagation that is dependent on the dielectric constant of the cable insulation (generally, 146 to 171 m/ms in a 15-kV URD cable).[9]

7.4 Measurement of partial discharge

Perhaps the most significant factory test made on the insulation of full reels of extruded cable is the partial discharge test. This is usually done at power frequency, but it can also be carried out at VLF and at some voltage significantly higher than normal working voltage to ground. Experience has shown that this test is a very sensitive method of detecting small imperfections in the insulation such as voids or skips in the insulation shield layer.

It would therefore seem logical to repeat this test on installed cables to detect any damage done during the shipping or laying or any problems created by jointing and terminating the cable. Unfortunately, this is a difficult measurement to perform in the field because of the presence of external noise. In spite of the difficulty, this test has been performed in the field, where some special circumstances suggest it is worth the time and expense involved. Typically, this may be when damage or faulty installation is suspected or the cable route requires it to be of the highest possible reliability.

Once the necessary steps are taken to reduce the noise level below the partial discharge level to be measured, the test can provide a great deal of useful diagnostic data. By observing the magnitude and phase of the partial discharge signals and how they vary with increasing and then decreasing the test voltage, results will disclose information on the type and position of the defects and their probable effect on cable life.

Noise reduction methods necessary for field tests of partial discharge usually include the use of an independent test voltage source such as a motor-generator, power line and high-voltage filters, shielding, and sometimes bridge detection circuits. The references that follow provide information on noise reduction methods and the interpretation of the results.

Partial discharges can also be detected at system voltage with special sensors connected to a splice or termination, using the frequency spectrum of the discharges.

In summary, if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory tests on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.

7.5 Advantages and disadvantages

7.5.1 Advantages

- Modest size, weight, and cost
- Useful for both laminar and extruded dielectrics

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[9] 146 to m/μs is approximately 480 to 560 ft/μs.

- Frequencies from 0.1 to 60 Hz available
- Measures and pinpoints defects

7.5.2 Disadvantages

- Trained operators required
- One large PD site may mask others
- Mixed dielectrics confuse results

8. Very low frequency (VLF, less than 1 Hz) testing

8.1 Introduction

Medium- and high-voltage power cables are carefully tested by the manufacturer before shipment with ac or dc voltages to ensure conformance with published specifications and industry standards. During transport, installation, and backfilling, cables are vulnerable to external damage. Therefore, cables may be tested prior to placing them in service to locate any external mechanical damage and to ensure that jointing and terminating work has been satisfactory. Periodic testing of service-aged cables may also be performed with the desire to determine system degradation and to reduce or eliminate service failures. VLF testing describes a testing technique for testing of service-aged or new cable systems in the field.

VLF testing methods can be categorized as withstand or diagnostic. In withstand testing, insulation defects are caused to break down (fault) at the time of testing. Faults are repaired, and the insulation is retested until it passes the withstand test. The withstand test is considered a destructive test. Diagnostic testing allows the identification of the relative condition of degradation of a cable system and establishes, by comparison with figures of merit, if a cable system can or cannot continue operation. Diagnostic testing is considered nondestructive.

In extreme cases, when the cable system insulation is in an advanced condition of degradation, the diagnostic tests can aggravate the condition of the cable and cause breakdown before the test can be terminated.

The VLF Withstand Test Methods for Cable Systems are

- VLF Testing with Cosine-Pulse Waveform
- VLF Testing with Sine Waveform
- VLF Testing with Square Wave with Programmable Slew Rate

The VLF Diagnostic Test Methods for Cable Systems are

- VLF Dissipation Factor (tan δ) Measurement
- VLF Partial Discharge Measurement

Field testing techniques frequently employ a combination of diagnostic and withstand test methods. They are selected based on their ease of operation and cost/benefit ratio. The various VLF test methods described are in commercial use and are accepted as alternative test methods in international standards. Table 1 is included as an aid to identifying the effectiveness of the VLF test for various cable insulation problems.

Table 1—Tree growth rates as a function of voltage and frequency

Test voltage factor (V/V_0)	Growth rate at 50-Hz test voltage (mm/h)	Growth rate at 0.1-Hz sinusoidal test voltage (mm/h)	Growth rate at 0.1-Hz VLF Cos-Rectangular voltage (mm/h)
2	1.7–2.4	2.3	1.4
3	2.2 –5.9	10.9–12.6	3.4–7.8
4	175–611	58.3–64.2	22.2–30.3
5		336	125
Channel tree growth rate on field aged samples of XLPE at different test voltage levels and waveforms where V is test voltage and V_0 is operating voltage to ground.			

Average channel growth rate on partial discharge defects using different types of XLPE cable samples at different test voltage levels and waveforms where V is test voltage and V_0 is operating voltage to ground.

The fastest tree growth is shown in millimeters per hour.

8.2 VLF testing with cosine-pulse waveform

8.2.1 Method

The VLF cable test set generates a 0.1-Hz bipolar pulse wave that changes polarity sinusoidally. Sinusoidal transitions in the power frequency range initiate a partial discharge at an insulation defect, which the 0.1-Hz pulse wave develops into a breakdown channel. Within minutes, a defect is detected and forced to break through. It can then be located with standard, readily available cable fault locating equipment. Cable systems can be tested in preventive maintenance programs or after a service failure. Identified faults can be repaired immediately, and no new defects will be initiated during the testing process. When a cable system passes the VLF test, it can be returned to service.

8.2.2 Measurement and equipment

A dc test set forms the high-voltage source. A dc to ac converter changes the dc voltage to the VLF ac test signal. The converter consists of a high-voltage inductor (choke) and a rotating rectifier that changes the polarity of the cable system being tested every 5 s. This generates a 0.1-Hz bipolar wave. A resonance circuit, consisting of a high-voltage inductor and a capacitor in parallel with the cable capacitance, assures sinusoidal polarity changes in the power frequency range. The use of a resonance circuit to change cable voltage polarity preserves the energy stored in the cable system. Only leakage losses have to be supplied to the cable system during the negative half of the cycle.

The 0.1-Hz test set is easily integrated into a standard cable fault locating and cable testing system by making use of available dc high potential test sets. Stand-alone VLF systems should be supplemented by cable fault locating equipment. See Figure 3 for a simplified schematic of a VLF test set.

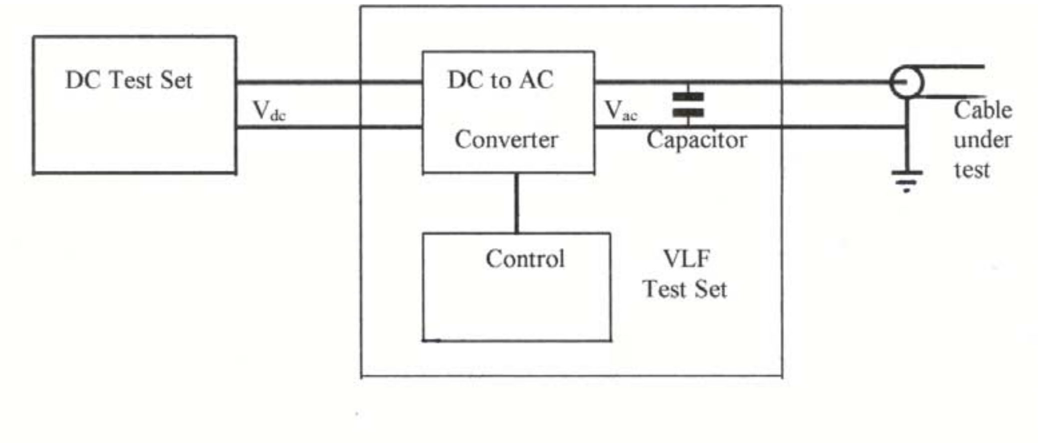

Figure 3—VLF test set generates a 0.1-Hz bipolar wave with cosine-shaped transitions between positive and negative pulse amplitudes

The cable system to be tested is connected to the VLF test set. In three to four steps, the test voltage is regulated to the test voltage level up to 3 V_0 (V_0 is rated phase-to-ground voltage). The recommended testing time is 15 to 60 min. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the cable and test set are discharged and grounded. When a cable fails the test, the VLF test set is turned off to discharge the system. The fault can then be located with standard cable fault locating equipment.

8.2.3 Advantages and disadvantages

8.2.3.1 Advantages

- The VLF test uses a 0.1-Hz square wave or cosine-rectangular wave that changes polarity sinusoidally. The sinusoidal transitions in the power frequency range may initiate a partial discharge at a defect that the 0.1-Hz pulse wave may develop into a breakthrough channel.
- Due to sinusoidal transitions between the HV pulses, traveling waves are not generated.
- Due to continuous polarity changes, space charges cannot develop.
- Cables can be tested with an ac voltage up to three times the normal phase-to-ground voltage with a device comparable in size, weight, and power requirements to a dc test set.
- The VLF test can be used on extruded as well as on fluid impregnated paper insulations.
- The VLF test with cosine-rectangular pulse waveform works best when eliminating a few singular defects from an otherwise good cable insulation. The VLF test is used to "fault" the cable defects without jeopardizing the cable system integrity.
- When a cable passes the recommended 0.1-Hz VLF test, it can be returned to service.

8.2.3.2 Disadvantages

- When testing cables with extensive water tree damage or ionization of the insulation, VLF testing alone is often not conclusive. Additional tests that measure the extent of insulation losses will be necessary.
- Present limitations are the maximum available test voltage of 56 kV.
- A long testing time may be seen as an inconvenience rather than as a limitation.

- Due to the layout of cosine-rectangular test voltage generation, the waveform is dependent on the cable length being tested. A dc offset or bias may be possible.
- The discharge and polarity switching mechanism over a spark gap may cause higher harmonics and transients on the cable under test.

8.2.4 Caution

Withstand testing is considered a destructive test. Cable fault locating will be required when the cable fails the test.

8.3 VLF testing with sinusoidal waveform

8.3.1 Method

The VLF test set generates sinusoidally changing waves that are less than 1 Hz. When the local field strength at a cable defect exceeds the dielectric strength of the insulation, partial discharge starts. The local field strength is a function of applied test voltage, defect geometry, and space charge. After initiation of partial discharge, the partial discharge channels develop into breakthrough channels within the recommended testing time. When a defect is forced to break through, it can then be located with standard, readily available fault locating equipment. Cable systems can be tested in preventive maintenance programs or after failure. Identified faults can be repaired immediately. When a cable passes the VLF test, it can be returned to service.

8.3.2 Measurement and equipment

The VLF test set is connected to the cable or cable system to be tested. The test voltage is regulated to the test voltage level of approximately 3 V_0. VLF testing guides usually recommended a test time duration of 60 min or less. VLF sets have to have sufficient capacity to be able to supply and dissipate the total cable system charging energy. When the cable system passes the VLF voltage test, the test voltage is regulated to zero and the test set and cable system are discharged and grounded. When a cable fails the test, the VLF test is turned off to discharge the cable system and test set and the cable fault can then be located with standard cable fault locating equipment.

In addition to standard 0.1-Hz sinusoidal VLF test sets, which have been in use for many years for VLF testing of electrical machines, see IEEE Std 433-1974™ [B31], where several variations are also available to meet specific cable system test requirements:

a) VLF, less than 0.1-Hz, high-voltage generator with programmable test voltage waveforms for cable systems with mixed insulation:
    1) Sine wave test voltage.
    2) Bipolar pulse wave with defined slew rate.
    3) Regulated dc test voltage with positive and negative polarity.
    4) Programmable step test for all voltage waveforms.
b) VLF, 0.1-Hz, high-voltage generator with dissipation factor (tan δ) measurement capability (see 8.5).
c) Partial discharge free, VLF, 0.1-Hz, high-voltage generator for partial discharge testing.
d) Partial discharge free, VLF, bipolar pulse with defined slew rate, high-voltage generator for partial discharge testing.

8.3.3 Advantages and disadvantages

8.3.3.1 Advantages

- Cables are tested with an ac voltage up to three times the normal phase to ground voltage. After initiation of a partial discharge, a breakthrough channel at a cable defect develops very rapidly.
- Due to continuous polarity changes, dangerous space charges do not develop in the cable insulation.
- Test sets are transportable, and power requirements are comparable to standard cable fault locating equipment.
- The VLF test can be used on extruded as well as on fluid impregnated paper type cable insulations. The VLF test with sinusoidal waveform works best when eliminating a few defects from an otherwise good cable insulation. The VLF test is used to “fault” the cable defects without jeopardizing the cable system integrity. When a cable passes the recommended 0.1-Hz VLF test, it can be returned to service.
- Due to the sinusoidal regulated waveform and to the highest electrical tree growth rate as compared to the cosine-rectangular waveform, electrical trees will be initiated at a defect within minutes.
- The test voltage level and waveform is defined as RMS voltage and is completely independent of the cable length.

VLF test sets with 0.1-Hz dissipation factor (tan δ) measurement capability for identifying cables with highly degraded cable insulations are available and can be used with a 0.1-Hz withstand test. This test is described in 8.4.

8.3.3.2 Disadvantages.

When testing cables with extensive water tree damage or ionization of the insulation, VLF withstand testing alone is often not conclusive. Additional tests that measure the extent of insulation losses will be necessary.

Limitations are the maximum available test voltage of 57 kV rms and the maximum capacitive load of approximately 3 mF at 0.1 Hz (30 mF at 0.01 Hz). The total charging energy of the cable has to be supplied and dissipated by the test in every electrical period. This limits the size of the cable system that can be tested. A long testing time must be seen as an inconvenience rather than as a limitation.

8.3.4 Caution

Withstand testing is considered a destructive test. Cable fault locating will be required if the cable fails the test.

8.4 Dissipation factor testing with VLF (0.1-Hz) sinusoidal waveform

8.4.1 Method

Bahder, et al. [B8] first used dissipation factor (tan δ) measurements to monitor aging and deterioration of extruded dielectric cables. Bach, et al. [B7] reported a correlation between an increasing 0.1-Hz dissipation factor and a decreasing insulation breakdown voltage level at power frequency. The 0.1-Hz dissipation factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of the dissipation factor with a 0.1-Hz sinusoidal waveform offers comparative assessment of the aging of fluid impregnated paper, PE, XLPE, and EPR type insulations. The test results permit differentiation between new, defective, and highly degraded cable insulations. The dissipation factor with a 0.1-Hz sinusoidal waveform can be used as a diagnostic test. Cables can be tested in preventive maintenance programs and returned to service after testing. The dissipation factor measurements at VLF can be used to justify cable replacement or cable rejuvenation expenditures.

8.4.2 Measurement and equipment

A programmable high-voltage VLF, 0.1-Hz test generator with dissipation factor measurement capability is connected to the cable system under test. See Figure 4. The dissipation factors of tan δ at V_0, tan δ at 2 V_0, and the differential dissipation factor Δ tan δ (tan δ at 2 V_0 minus tan δ at V_0) are measured. The measured values are used as figures of merit to grade the condition of the cable insulation as good, defective, or highly deteriorated. See ASTM D 150-1995 [B1].

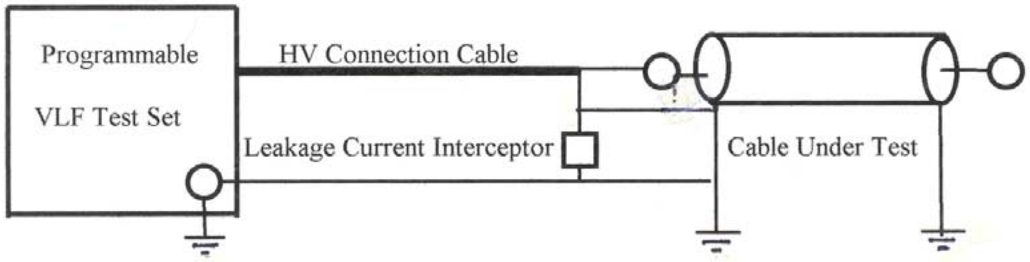

Figure 4—VLF (0.1-Hz) test set for dissipation factor measurements of cable insulation

For example, when XLPE insulation is tested at 0.1 Hz with a test voltage of V_0, service-aged cable should be replaced when the dissipation factor (tan δ) is greater than 2.2×10^{-3}.

If for a 0.1-Hz test voltage of 2 V_0, the dissipation factor is less than 1.2×10^{-3} and the differential dissipation factor Δ tan δ is less than 0.6×10^{-3}, the service-aged cables can be returned to service but should be monitored periodically.

If for a 0.1-Hz test voltage at 2 V_0, the dissipation factor is greater than 2.2×10^{-3} and the differential dissipation factor is Δ tan δ is greater than 1.0×10^{-3}, the cable is highly degraded.

It must be understood that for different insulations, installations, and cable types, dissipation factor (tan δ) figures of merit can vary significantly from the values listed above. The test gives the best results when comparing present measurements against established historical figures of merit for a particular cable.

No side effects have been reported that would restrict 0.1-Hz VLF tan δ testing of service-aged cables with extruded dielectric insulation or that would indicate that the 0.1-Hz VLF test voltage levels used during dissipation factor testing adversely affect the cables' life expectancy. See Table 2.

8.4.3 Advantages and disadvantages

8.4.3.1 Advantages

- This test is a diagnostic, nondestructive test. Cable systems are tested with an ac voltage equal to the line to ground voltage.
- Cable system insulation can be graded between good, aged, and highly degraded.
- Cable system insulation condition can be monitored over time, and a cable system history can be developed. Cable replacement and cable rejuvenation priority and expenditures can be planned.

Table 2—Table of criterion

Tan δ at $2V_o$	**Differential of Tan δ** tan δ $2V_o$ – tan δV_o	**Assessment**
Less than 1.2×10^{-3}	Less than 0.6×10^{-3}	Good
Greater than or = 1.2×10^{-3}	Greater than or = 0.6×10^{-3}	Aged
Greater than or = 2.2×10^{-3}	Greater than or = 1.0×10^{-3}	Highly degraded

NOTE—It has been found that copolymer dielectric materials such as TR-XLPE or silicon fluid-treated insulations exhibit different tan δ characteristics; therefore, other criteria are valid.

- Test sets are transportable, and power requirements are comparable to standard cable fault locating equipment.
- The diagnostic test results represent global, integral information about the aging condition of the cable insulation. A dielectric withstand test can only give information about the weakest point (see Gnerlich [B25]).
- The aging characteristic measured with a dissipation factor test at VLFs (less than 1 Hz) show more significant results as compared with power frequencies of 50 to 60 Hz.

8.4.3.2 Disadvantages

- For a 0.1-Hz VLF test set, the maximum presently available test voltage is 57 kV RMS and the maximum capacitive load is approximately 3 mF at 0.1 Hz.
- Historical comparative cable system data should be accumulated before the test becomes really useful.

8.5 Conclusions

The suitability, practicality, and effectiveness of these testing methods for service-aged power cables with extruded dielectric insulation will have to be determined based on several criteria:

a) At what voltage level can a defect be detected?
b) Is it possible to miss a defect that will fault when the cable is returned to service?
c) Does the test aggravate what was a negligible defect so that it will fault when the cable is returned to service?

VLF test techniques are effective for testing of service-aged shielded power cables with extruded dielectric insulation.

9. Dissipation factor testing

NOTE—Some of this material is also included in Clause 8 above, but is left here to aid in an understanding of this method.

9.1 Introduction

Periodic testing of service-aged cables is practiced with the desire to determine system degradation and to reduce or eliminate service failures. Dissipation factor testing describes a diagnostic testing technique for field testing of service-aged shielded cable systems.

9.2 Dielectric loss

Service-aged, shielded cable can be described by an equivalent circuit, as shown in Figure 5. For lossless insulation, the cable capacitance per unit length C is shown in Equation (3).

$$C = 2\pi k e_o \ln(d_i/d_c) \tag{3}$$

where

e_o is the permittivity of free space = 8.85×10^{-12} F/m,

k is the dielectric constant of the insulation,

d_i is the diameter over the insulation,

d_i is the diameter under the insulation (over the conductor shield),

ln is the natural logarithm (loge).

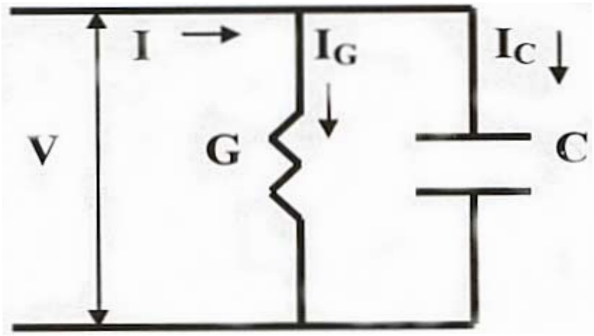

Figure 5—Equivalent circuit of a high loss portion of a power cable

If the space between the coaxial conductors is filled with a conventional insulating material, the cable conductance per unit length G is shown in Equation (4).

$$G = 2\pi f C \tan\delta \tag{4}$$

The quantity tan δ is a measure of the losses of the insulating dielectric in an ac electric field. This is called dissipation factor or the tangent of the loss angle δ of the material. Typical values of k and tan δ are shown in Table 3.

For an applied voltage V, the current through the loss-free dielectric is I_C and the current due to the losses of the insulation is I_G (see Figure 6). The angle formed by the current $I = I_C + I_G$, and the current I_C is δ.

Table 3—Typical values of dissipation factor (tan δ) and dielectric constant (K)

Type of insulation	K	tan δ
Impregnated paper	3.5	2.3×10^{-3}
Impregnated PPP	2.7	0.7×10^{-3}
XLPE	2.3	0.1×10^{-3}
HDPE	2.3	0.1×10^{-3}
EPR	2.8	3.5×10^{-3}

The angle formed by the current $I = I_C + I_G$, and the voltage V is θ and cos θ is the power factor. I, I_C, and I_G are phasor quantities.

For an applied voltage V, the current through the loss-free dielectric is I_C and the current due to the losses of the insulation is I_G (see Figure 6). The angle formed by the current $I = I_C + I_G$, and the current I_C is δ. The angle formed by the current $I = I_C + I_G$, and the voltage V is θ and cos θ is the power factor. I, I_C, and I_G are phasor quantities.

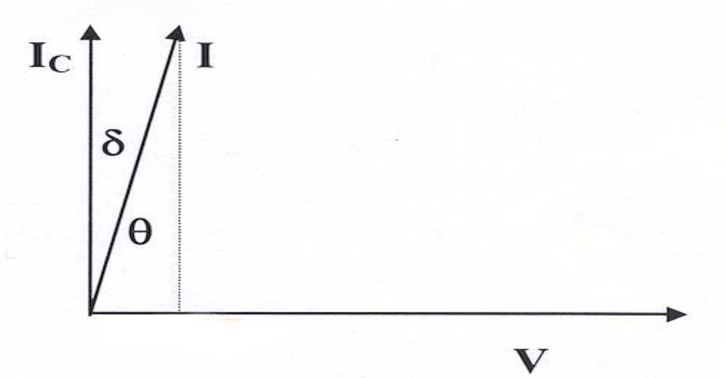

Figure 6—Phasor diagram for high loss dielectric material

9.3 Method

The dissipation factor (tan δ) test is a diagnostic test that allows an evaluation of the cable insulation at operating or test voltage levels. The test is conducted at operating frequency or at the VLF frequency of 0.1 Hz. When the tan δ measurement exceeds a historically established value for the particular insulation type, the cable is considered to be defective and may have to be scheduled for replacement. If the tan δ measurements are below a historically established value for a particular insulation type, additional tests have to be performed to determine whether the cable insulation is defective.

Tests conducted on 2 400 km of XLPE-insulated cables have established a figure of merit for XLPE, tan $\delta = 2.2 \times 10^{-3}$. If the cable's measured tan δ is greater than 2.2×10^{-3}, the cable insulation is contaminated by moisture (water trees). The cable may be returned to service, but it should be scheduled for replacement as soon as possible.[10]

If the cable's measured tan δ is less than 2.2×10^{-3}, the general condition of the insulation is probably good; however, the cable insulation could have many small defects; in which case, the cable may operate satisfactorily for many more years. The tan δ should be monitored regularly, and upon further deterioration of the dissipation factor, proper action should be taken. However, the cable could have only a few isolated large defects, which could cause it to fail upon returning it to service or within days after it has been re-energized. Therefore, if the measured tan δ is greater than 2.2×10^{-3}, it is recommended that a VLF test at 3 V_0 be performed to identify the large defects, remove them, and repair them.

9.4 Measurement and equipment

Bridge type circuits are used to measure cable capacitance and tan δ. The most common are the Schering bridge and the transformer ratio arm bridge. Both test sets require an ac HV source and a loss-free capacitor standard. For balanced bridges, the dissipation factor and cable capacitance are shown in Equation (5) through Equation (8).

- Schering Bridge

$$\tan \delta = 2\pi f C_1 R_1 \tag{5}$$

$$C_X = C_N(R_1/R_2) \tag{6}$$

- Transformer Ratio Arm Bridge

$$\tan \delta = 2\pi f C_1 R_1 \tag{7}$$

$$C_X = C_N(W_1/W_2) \tag{8}$$

9.5 Advantages and disadvantages

9.5.1 Advantages

- Tan δ measurements are diagnostic tests that permit assessment of the state of aging or damage of the cable insulation.
- Cables are tested with an ac voltage at operating voltage at diagnostic levels or with levels up to 3 V_0.
- The tests are performed at operating or at VLF frequencies.
- The dissipation factor test is suitable for extruded dielectric as well as for laminar type insulations.
- When a cable fails the dissipation factor test, it can still be returned to service until repair or replacement has been scheduled.
- Monitoring of the dissipation factor will establish a cable history, and deterioration will be observed.

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[10] 2 400 km is approximately 1 500 miles.

9.5.2 Disadvantages

- When a cable passes the dissipation factor test, it is not possible to declare the cable insulation sound because a localized defect in a long cable may not be detected.
- A breakdown test will have to be performed to identify any large defects in the cable system insulation.

9.6 Method and assessment

The test sample is connected to a VLF generator producing a sinusoidal HV output. The test voltage and current are measured and correlated with Fourier analysis. The tan δ output is calculated as a time difference between the voltage and the current signals.

9.7 Dissipation factor with VLF sinusoidal waveform

9.7.1 Method

Bach, et al. [B7] reported that dissipation factor (tan δ) measurements at VLF (0.1-Hz sinusoidal) can be used to monitor aging and deterioration of extruded dielectric cables. The 0.1-Hz dissipation factor is mainly determined by water tree damage of the cable insulation and not by water along the conducting surfaces. The measurement of dissipation factor with a 0.1-Hz sinusoidal waveform offers comparative assessment of the aging condition of PE, XLPE, and EPR type insulations. The test results permit differentiating between new, defective, and highly degraded cable insulations. The dissipation factor with a 0.1-Hz sinusoidal waveform is a diagnostic test. Cable systems can be tested in preventive maintenance programs and returned to service after testing. The dissipation factor measurements at VLF can form the basis for the justification of cable replacement or cable rejuvenation expenditures.

9.7.2 Measurement equipment

A programmable high-voltage VLF test generator with dissipation factor measurement capability is connected to the cable under test. If, for a test voltage of V_0, the tan δ is greater than 4×10^{-3}, the service-aged cables should eventually be replaced. The test voltage should not be raised above V_0 in order to prevent insulation breakdown. If for test voltage of V_0 the tan δ is less than 4×10^{-3}, the service-aged cables should additionally be tested with VLF at 3 V_0 for 60 min. When the cable passes this test, it can be returned to service without reservation. Dissipation factor measurements at VLF may form the basis for the justification of cable replacement or cable rejuvenation expenditures.

9.8 Advantages and disadvantages

9.8.1 Advantages

- The test is a nondestructive, diagnostic test.
- Cables are tested with an ac voltage equal to the phase-to-ground voltage at which they operate.
- Cable system insulation can be graded as excellent, defective, or highly deteriorated.
- Cable system insulations can be monitored and history developed. Cable replacement and rejuvenation priority can be planned.
- Test sets are transportable, and power requirements are comparable to standard cable fault locating equipment.

9.8.2 Disadvantages

- The maximum available test voltage is 57 kV RMS, and the maximum capacitive load is about 3 mF at 0.1 Hz.
- The test works best after comparative cable system data have been developed.

10. Oscillating wave testing

10.1 Introduction

This clause presents information with respect to oscillating wave testing. This method was selected by a CIGRE task force “alternative tests after laying” (see Auclair, Boone, and Papadopoulos [B2], and Aucort, et al. [B3]) as an acceptable compromise using the following criteria:

- The ability to detect defects in the insulation that will be detrimental to the cable system under service conditions, without creating new defects or causing any aging
- The degree of conformity between the results of tests and the results of 50- or 60-Hz tests
- The complexity of the testing method
- The commercial availability and costs of the testing equipment

The purpose of the oscillating wave (OSW) testing method is to detect defects that may cause failures during service life without creating new defects that may threaten the life of the cable system.

Although OSW testing does not have a wide reputation with respect to cable testing, it is already used for testing in metal-clad substations (see Eager and Bahder [B18]) and is being recommended for gas insulated cable testing (see Aucourt, et al. [B4]).

10.2 General description of test method

The test circuit consists of a dc voltage supply that charges a capacitance C_1 and a cable capacitance C_2. After the test voltage has been reached, the capacitance is discharged over an air core coil with a low inductance. This causes an oscillating voltage in the kilohertz range (see Aucourt, et al. [B4]). The choice of C_1 and L depends on the value of C_2 to obtain a frequency between 1 and 10 kHz.

10.3 Advantages and disadvantages

10.3.1 Advantages

- The OSW method is based on an intrinsic ac mechanism.
- The principal disadvantages of dc (field distribution, space charge) do not occur.
- The method is easy to apply.
- The method is relatively inexpensive.
- For both HV and MV cable systems, f* OSW/DC is low (0.2 to 0.8), indicating the superiority of OSW over dc voltage testing.

10.3.2 Disadvantages

- The effectiveness of the OSW test method in detecting defects is better than with dc but worse when compared with ac (60 Hz).
- In particular for medium-voltage cable systems, the factor f* OSW/60-Hz voltage is approaching 1, indicating the mutual equivalence.
- For HV cable systems, f* OSW/60 Hz is significantly higher (1.2 to 1.9), which means that OSW is less effective than 60 Hz.

NOTE—f* OSW/60 Hz is the ratio of breakdown values for a dielectric containing a standard defect when using, respectively, OSW voltage and 60-Hz voltage.

10.4 Test apparatus

The cable is charged with a dc voltage and discharged through a sphere gap into an inductance of appropriate value so as to obtain the desired frequency. The voltage applied to the cable is expressed in Equation (9).

$$V(t) = V_1 e\exp[-\alpha t\sqrt{LC}]\cos(2\pi f t) \qquad (9)$$

where

V_1 is the charging voltage provided by the generator,

a is the damping ratio,

C is $C_1 + C_2$,

f is the $\left(\frac{1}{2}\pi\sqrt{LC}\right)$.

Other test circuits are described in more detail in Bertani, et al. [B12], which gives alternative solutions that use different circuit configurations.

10.5 Test procedure

Most of the tests carried out so far are of an experimental nature. Artificial defects like knife cuts, wrong positions of joints, and voids in the insulation were created and subjected to different testing procedures of which one method was the OSW testing (see Auclair, Boone, and Papadopoulos [B2], Aucort, et al. [B3], and Bertani, et al. [B12]).

These test procedures were intended to obtain breakdown as a criterion for comparison. The general testing procedure is as follows:

- Start to charge the cable with a dc voltage of about one or two times the operating voltage.
- Increase with steps of 20 to 30 kV.
- Produce 50 shots at each voltage level.
- Time interval between shots to be 2 to 3 min.
- Proceed until breakdown occurs.

In one case, the Dutch testing specification for HV extruded cables (Dutch Test Specification for HV Extruded Cables, NEN 3630 [B17]), the OSW method, is mentioned as a withstand test to be used as an after laying (installation) test. The test procedure is as follows:

- Charge the cable slowly, using the dc power supply.
- After reaching the value of 3 V_0, the dc source will be disconnected and the rapid closer activated.
- The cable circuit will be discharged through a reactor, causing the OSW testing voltage.
- This procedure should be repeated 50 times.

In The Netherlands, the OSW testing method is applied several times as an after laying test for HV extruded cable systems. Details are given in Koevoets [B33].

10.6 Safety precautions

No special precautions need to be taken other than the usual grounding when the test procedure is completed.

10.7 Further development work

Because the effectiveness of the OSW testing method is not as high as would be desired, it may be very attractive to combine OSW with partial discharge (PD) site detection as an additional source of information. In Plath [B43], details are given of an automatic PD measurement system, enabling statistical analysis and generating phase, time, and amplitude resolved PD fingerprints. Compared with ac (50/60-Hz) generated PD fingerprints, additional information results from the decreasing voltage amplitude of each OSW pulse. For medium-voltage cable systems according to Plath [B43], this measuring system looks feasible.

Annex A

(informative)

Power frequency testing

A.1 Introduction

Testing with alternating current (ac) may be accomplished in the field without the use of conventional test equipment. A testing setup may be assembled using various pieces of equipment and voltage available to the technician. Existing voltages may be 0 to 1 000 V (secondary class) or distribution voltages ranging from 4 kV to 35 kV (medium voltage, MV). AC available from field sources is normally sinusoidal and has a frequency of 50 to 60 Hz. Alternative waveforms and frequencies, normally generated by special equipment, are addressed in other sections.

A.2 Alternating current (ac)

Wave shape of the ac voltage available from the field is sinusoidal. This means that each cycle will have a positive and negative maximum of approximately 1.4 times the RMS value of the circuit. Example: A circuit operating at 7 200 V RMS to ground will have a peak negative and positive voltage of $1.4 \times 7\ 200 = \ 10\ 000$ V approximately.

A.3 Field sources: Voltage and current

Current available from primary, medium-voltage circuits in the field is many magnitudes higher than those available from testing instruments. Circuits may have anywhere from 100 to 40 000 amperes. With this amount of current operating at system voltage, the energy available makes it essential to protect the equipment and personnel when performing any field tests. Fast-acting fusing is commonly used to provide this protection. This technique is used when overhead and underground circuits are energized in the restoration of service after outages have occurred.

A.4 Testing with system voltage (MV)

It has been the practice for overhead operating crews to reclose a circuit without testing to restore service to customers. Normally, this procedure is followed after a visual patrol is conducted to verify that all wires are up and cleared of any tree limbs. The energization is accomplished with a fused switch, and replacement fuses are of the type and size used to coordinate the circuit.

This practice has been carried over to the URD circuits by the same operating crews that switch the overhead system. In most cases, the operating personnel have not been trained properly in the operating procedures required for URD, and they have not been given the test equipment to accomplish testing procedures. Use of separable connectors (loadbreak elbows) as a switching device has allowed crews to isolate defective system sections. In doing this, the crews have unknowingly exposed the circuits to excessive currents and damaging transients. Although the preceding procedure has been used, it is strongly recommended that it not be continued without adequate circuit protection.

Many underground circuits are normally fed from an overhead system. Testing, following an outage, can be accomplished by using a small, fast-acting fuse (e.g., current limiting) in the same fuse switch normally utilized. This reduces the energy fed into the system and thus reduces damage to system components.

A.5 Low-voltage sources

Low-voltage testing is normally accomplished in the field by energizing the circuit through a distribution transformer. Transformers installed and operating are readily available for use as a testing source. Voltage checks and phasing, where required, can be made before additional testing is started.

Figure A.1 and Figure A.2 show how a low-voltage source may be obtained from an overhead and an underground circuit:

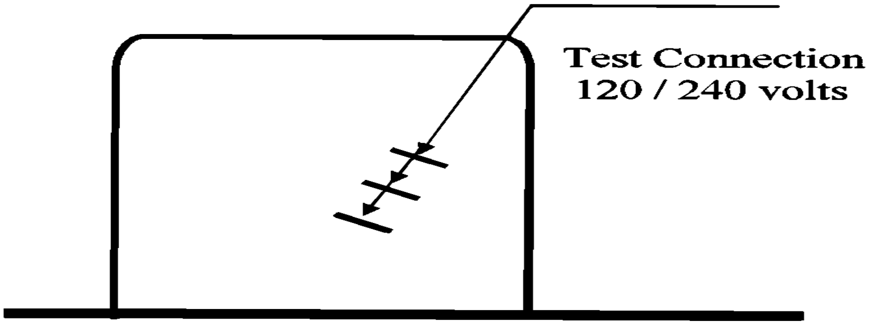

Figure A.1—URD transformer

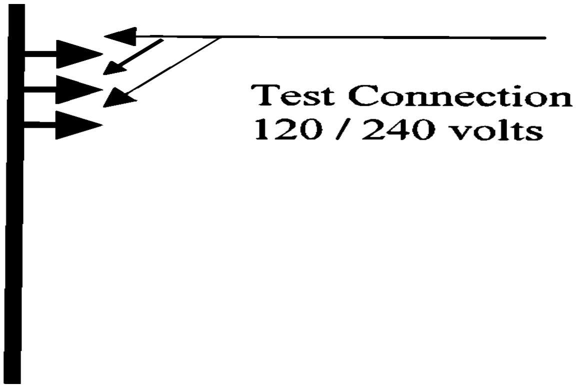

Figure A.2—Overhead secondary

Annex B

(informative)

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