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IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)

IEEE Power and Energy Society

Sponsored by the
Insulated Conductors Committee

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Abstract: Very low frequency (VLF) withstand and other diagnostic tests and measurements that are performed using VLF energization in the field on shielded power cable systems are described in this guide. Whenever possible, cable systems are treated in a similar manner to individual cables. Tables are included as an aid to identifying the effectiveness of the VLF ac voltage test for various cable system insulation problems.
Keywords: cable fault locating, cable system testing, cable testing, condition assessment, dielectric spectroscopy, grounding, hipot testing, IEEE 400.2™, partial discharge testing, proof testing, safety, tangent delta testing, very low frequency testing, VLF ac voltage testing

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Introduction

This introduction is not part of IEEE Std 400.2-2013, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz).

A significant investment with respect to electric power systems is underground cables. A high degree of reliability and reasonable life expectancy of cable systems are necessary. In order to get the optimum performance, standards and guidelines have been developed which address the specific testing requirements for new and service-aged extruded and laminated dielectric cable insulations. This Guide is one part of a series of guides that discuss known diagnostic techniques for performing electrical tests in the field on shielded power cable systems. An omnibus guide (IEEE Std 400™) provides a general overview of all technique classes. It is intended that the technique-specific guides provide the definitive information on voltages, times and criteria.

Ideally, field withstand testing of cable systems would be done using the same power frequency as would normally applied to the cable under operating conditions, but at higher test voltage. However, because of the inherent capacitance of long runs of medium-/high-voltage concentric shielded cable, the excessive charging current is beyond the limits of normally available power sources and test equipment found in the field, except costly ac resonant test systems.

High-voltage dc testing would eliminate the charging current issue associated with ac tests, but would not subject the cable system to the voltage stress distribution that it is exposed to under normal operating conditions. Furthermore there are significant negative issues affecting the integrity of aged cross linked polyethylene (XLPE) cable after it is exposed to high-voltage dc tests and then placed back into service. There is also the unknown influence of elevated dc voltage on other extruded cables such as mineral-filled EPR. In addition, dc is not effective in detecting many forms of gross defects that may be present in a cable system that will otherwise be detected by VLF or at operating frequency.

When required to perform field testing on long lengths of medium-/high-voltage cable with an alternating current source, an alternative to applying power frequency is very low frequency (VLF, 0.01 to 1 Hz). The charging current at a very low frequency of 0.1 Hz is only 1/500 or 1/600 of that at 50 Hz or 60 Hz respectively so that significantly smaller and more portable VLF power sources have the capability to test cable systems of relatively long lengths.

This guide provides a definition of VLF, a description of the wave-shapes and their magnitudes and frequencies that can be applied as a source for overvoltage field testing, the issues with different wave shapes, the duration of testing and what diagnostic information can be learned when these VLF voltages are applied.

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1. Overview

This guide provides a description of the methods and practices to be used in the application of very low frequency (VLF) ac high-voltage excitation for field testing of shielded power cable systems (Bach [B1][1] and [B2]; Baur, Mohaupt, and Schlick [B6]; Gnerlich [B11]). VLF ac voltage testing is an alternative method of continuous ac voltage testing and is used for a broad range of accessory and cable types (Kobayashi, et al. [B26], Steennis, Boone, and Montfoort [B32]) as well as testing of rotating machinery, see IEEE Std 433™. It provides a method of evaluation, and helps to fill the need for more complete information on the cable system condition while minimizing or eliminating some potential adverse charging effects of the direct voltage high-potential test method (commonly known as the dc hi-pot test) (Srinivas and Bernstein [B31]; Eager, et al. [B8]; Hampton, et al. [B19]; Groenefeld, von Olshausen, and Selle [B14]; Steennis, Boone, and Montfoort [B32]; Gockenbach and Hauschild [B12]). This guide addresses VLF ac voltage withstand and dielectric loss testing in the frequency range from 0.01 Hz to 1 Hz. The guide does not focus on the effects of insulation materials parameters: the nature of the differences between insulation materials, the subject of the peroxide crosslinking agent by-products, or on the influence of the VLF stress application on the cable system. Therefore, caution is recommended in interpretation of results.

[1] The numbers in brackets correspond to those of the bibliography in Annex A.

The information contained in this guide is intended to provide the methodology, voltages, and factors to be considered when utilizing VLF ac voltage testing, whether as a withstand test or as a diagnostic test. For general information regarding other field testing methods, refer to the omnibus standard, IEEE Std 400™.[2]

1.1 Scope

This guide describes VLF withstand and other diagnostic tests and the measurements that are performed in the field on service-aged shielded medium and high-voltage cables rated 5 kV through 69 kV with extruded and laminated insulation. VLF test methods utilize ac signals at frequencies less than 1 Hz. The most commonly used, commercially available, VLF test frequency is 0.1 Hz. Whenever possible, cable systems are treated in a similar manner to individual cables. Tables are included of the recommended test voltage levels for installation, acceptance, and maintenance tests.

1.2 Purpose

This guide is intended to provide troubleshooting and testing personnel with information to test shielded medium- and high-voltage cable systems rated 5 kV through 69 kV using VLF ac techniques.

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.

Accredited Standards Committee IEEE C2, National Electrical Safety Code® (NESC®).[3]

ANSI/NETA ATS: Standard for Acceptance Testing Specifications for Electrical Power Equipment and Systems (Section 7.3.3: Cables ,Medium, and High Voltage).[4]

ANSI/NETA MTS: Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems (Section 7.3.3: Cables ,Medium, and High Voltage).

IEC 60060-3, High Voltage Test Techniques: Definitions and requirements for on-site tests.[5]

IEC 60270-3, High Voltage Test Techniques: Partial Discharge Measurements.

IEC 60885-3. Electrical test methods for electric cables. Part 3: Test methods for partial discharge measurements on lengths of extruded power cables.

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IEC 61230, Live working—Portable equipment for earthing or earthing and short-circuiting.

IEEE Std 400, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems.[6, 7]

IEEE Std 433™, IEEE Recommended Practices for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency.

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

IEEE Std 400.3™, IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment.

IEEE Std 1617™, IEEE Guide for Detection, Mitigation, and Control of Concentric Neutral Corrosion in Medium Voltage Underground Cables.

NFPA 70E, Standard for Electrical Safety in the Workplace.[8]

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[9]

acceptance test: 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 detect installation damage and to show any gross defects or errors in installation of other system components.

cross linked polyethylene (XLPE): A thermoset filled or unfilled polymer used as electrical insulation in cables. If filled, it is referred to as a filled XLPE.

diagnostic test: A field test made during the operating life of a cable system. It is intended to determine and, for some tests, locate degraded regions that may cause cable and accessory failure.

electrical trees: Tree-like growths, consisting of non-solid or carbonized micro-channels, that can occur at stress enhancements such as protrusions, contaminants, voids, or water trees subjected to electrical stress. The insulation is damaged irreversibly at the site of an electrical tree.

ethylene propylene rubber (EPR): A type of thermoset filled polymer used as electrical insulation in cables and accessories.

NOTE—There are several different formulations of mineral-filled EPR and they have different characteristics. For purposes here, the term also encompasses ethylene propylene diene monomer rubber (EPDM).[10]

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[9] *IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.
[10] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

extruded dielectrics: Insulation such as PE, XLPE, TRXLPE, EPR, etc. applied using an extrusion process.

installation test: A field test conducted after cable installation but before jointing (splicing) or terminating or energizing. The test is intended to detect shipping, storage, or installation damage. It should be noted that temporary terminations may need to be added to the cable to successfully complete this test, particularly for cables rated above 35 kV.

laminated dielectrics: Insulation formed in layers typically from tapes of either cellulose paper or polypropylene or a combination of the two. Examples are the paper insulated lead covered (PILC) and mass-impregnated non-draining (MIND) cable designs.

maintenance test: A field test made during the operating life of a cable system. It is intended to detect deterioration and to check the serviceability of the system.

mass-impregnated non-draining (MIND): A cable design using impregnated paper insulation. The impregnating compound has a sufficiently high viscosity at maximum operating temperature to preclude migration or draining of compound.

monitored withstand: A test in which a voltage of a predetermined magnitude is applied for a predetermined time. During the test other properties of the test object are monitored and these are used, together with the withstand results, to determine its condition.

paper insulated lead covered (PILC): A cable design using impregnated paper insulation. The paper tapes are applied unimpregnated, the complete insulation being subsequently dried and impregnated with a compound as a whole.

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

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

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

tree retardant cross linked polyethylene (TRXLPE): A thermoset polymer used as electrical insulation in cables. It is based on XLPE and contains an additive, a polymer modification, or a filler that retards the development and growth of water trees in the insulation.

U_0: Normal phase-to-ground operating voltage.

water trees: Tree-like pattern of electro-oxidation that can occur at stress enhancements such as ionic contaminants, protrusions, or voids in polymeric materials subjected to electrical stress and moisture. Within the water tree the insulation is degraded due to chemical modification in the presence of moisture. There is no evidence of partial discharge (see NOTE) inside the water tree branches. Complete insulation breakdown may subsequently occur if a water tree either induces an electrical tree and the electrical tree grows a channel of sufficient length to fail the insulation or leads to thermal runaway. The water tree growth under service conditions is a very slow process, usually taking many years to completely penetrate the insulation from the inside or outside.

NOTE—There have been no cases documented of partial discharge detectable in the field from water trees. Water trees can cause electrical trees to form as a result of a lightning impulse, switching surges, or excessive test voltage levels and durations. When this occurs, partial discharge may be detectable.

3.2 Acronyms and abbreviations

EPR ethylene propylene rubber

NOTE—In the cable industry also includes: EPDM (Ethylene-Propylene-Diene) with the "M" referring to the classification in ASTM D-1418 monomers.

MIND mass-impregnated non-draining, a cable design

PE polyethylene

PILC paper insulated lead covered, a cable design

TRXLPE tree retardant crosslinked polyethylene

VLF very low frequency (for the purpose of this guide 0.01 Hz to 1.0 Hz)

VLF-DS very low frequency-dielectric spectroscopy

VLF-LC very low frequency-leakage current

VLF-LCH very low frequency- loss current harmonics

VLF-MW very low frequency-monitored withstand

VLF-PD very low frequency-partial discharge

VLF-PDIV very low frequency-partial discharge inception voltage

VLF-PDEV very low frequency-partial discharge extinction voltage

VLF-TD very low frequency-tangent delta (dissipation factor)

VLF-DTD very low frequency-differential tangent delta (delta tangent delta or tip up)

VLF-TDTS very low frequency-tangent delta temporal stability

XLPE crosslinked polyethylene

4. Safety

4.1 Safety practices

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 recommended and properly authorized. Appropriate safety practices must be followed. The safety practices shall include, but not be limited to, the following requirements:

— Applicable national, state, local, and company safety operating procedures, e.g., National Electrical Safety Code® (NESC®).

- IEEE Std 510, IEEE Recommended Practices for Safety in High Voltage and High Power Testing.
- NFPA 70E—Standard for Electrical Safety in the Workplace.
- ANSI/NETA ATS-2009: Standard for Acceptance Testing Specifications for Electrical Power Equipment and Systems (Section 7.3.3: Cables, Medium and High Voltage).
- ANSI/NETA MTS-2011: Standard for Maintenance Testing Specifications for Electrical Power Equipment and Systems (Section 7.3.3: Cables, Medium and High Voltage).
- Physical protection of utility and customer property.

Prior to testing, determination of safe clearances must consider both the test voltage and voltage of nearby energized equipment:

a) At the one or more cable ends remote from the manned testing site: 1) cable ends under test must be cleared and cordoned off; 2) cables that are de-energized should be grounded when not being tested; and 3) remote cable ends must be marked to indicate a high-voltage test is in progress.

b) When a switch or disconnect type device is used to isolate the cable circuit from the rest of the system, the ability of the device to sustain the VLF ac test voltage and maintain isolation while the other end is under normal operating voltage shall be checked with the manufacturer.

c) When isolation is an air gap, such as when a cable terminator connection is removed, the clearance distance must be sufficient to maintain isolation with the cable system at the VLF ac test voltage and the surrounding equipment at normal line voltage.

d) All ancillary equipment such as lightning arrestors and motors should be disconnected from the cable terminals if possible.

At the conclusion of high-voltage testing, attention should be given to the following:

1) Discharging cables and cable systems including test equipment. The discharging of the cable should be carefully monitored for the time needed to fully discharge.

2) Grounding requirements for cables and test equipment to help eliminate the after effects of recharging the cables due to dielectric absorption and capacitance characteristics.

4.2 Grounding

Cable systems can be de-energized and grounded when, among other things, conductor and metallic shield are connected to system ground at the test site and, if shield continuity has not been confirmed, at the far end of the cable.

When testing, a **single system ground at the test site** is recommended, see Figure 1. The metallic shield of the cable to be tested is connected to system ground. If this connection is missing or deteriorated, it must be replaced at this time. **A safety ground cable must connect all test instrument cases with system ground.** All exposed conductive parts of the test system must be bonded to the common ground point. If the test instrument is a high-voltage device, an external safety ground cable should be used to ground the cable to be tested. This cable should be able to accommodate the fault current of the system. Once the test lead from the VLF test equipment is connected to the cable to be tested, this safety ground can be removed so that testing can commence.

Should a local ground be advisable or recommended for the test equipment, case ground must remain connected to system ground in order to maintain an acceptable single ground potential.

Care should be taken to ensure that all ground connections cannot be disconnected accidentally. Grounding connections that can be securely tightened are recommended. Portable ground clamps and grounding assemblies built and tested per IEC 61230 are recommended.

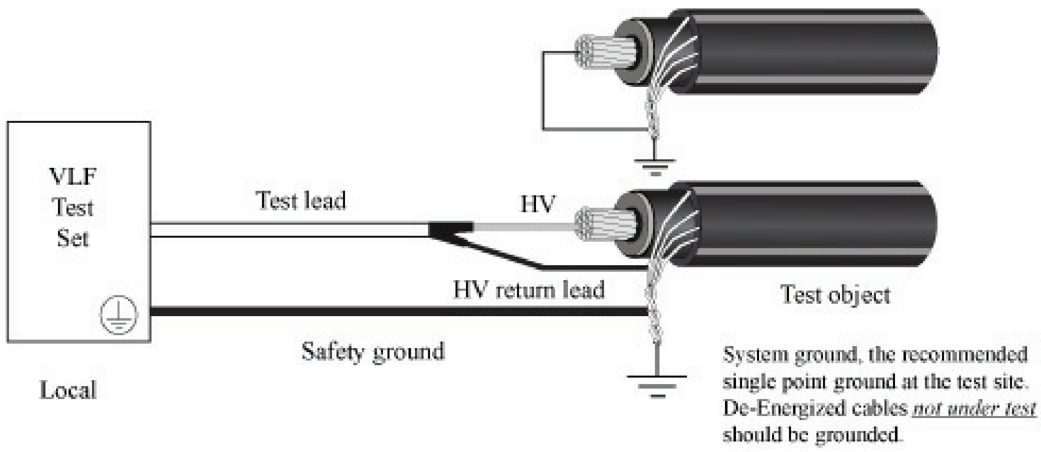

Figure 1—Recommended test hook-up

5. Very low frequency (VLF) ac testing

VLF ac testing methods utilize ac signals in the frequency range from 0.01 Hz to 1 Hz. In withstand testing, (Gnerlich [B11]), the test object must survive a specified voltage applied across the insulation for a specified period of time without breakdown of the insulation (Hampton, et al. [B19]). The magnitude of the withstand voltage is usually greater than the operating voltage. If the accessory or cable insulation is sufficiently degraded a breakdown can occur. The cable system may be repaired and the insulation retested until it passes the withstand test. Diagnostic testing allows the determination of the relative amount of degradation of a cable system section and establishes, by comparison with figures of merit or accumulated data, whether a cable system section is likely to continue to perform properly in service. It should be noted that values of the diagnostic quantity measurements obtained during VLF ac voltage tests may not correlate with those values obtained at other frequencies, for example, the tangent delta is larger at 0.1 Hz than at power frequency and partial discharge (PD) may differ in terms of magnitude and inception voltage.

There are risks associated with high-voltage testing and diagnostics. Diagnostic tests can be non-destructive if they are performed at voltages at or below the normal operating voltage. However, there is a trade-off between gathering additional information about the cable under test and going to elevated voltage levels, with the associated higher risk that the cable may fail as the voltage is increased. It should be noted that at the prescribed withstand levels in Table 3, a failure indicates that the cable is already in a highly compromised condition. In addition, should a failure occur under test, the resultant fault current and collateral damage to the cable and surrounding assets may be limited. This may not be the case should the cable fail under operating conditions.

Examples of the various waveforms (shown in Annex B) are as follows:

- VLF ac voltage testing with cosine-rectangular waveform.
- VLF ac voltage testing with sinusoidal waveform.

The VLF diagnostic test methods of cable systems are as follows:

1) VLF tangent delta measurement (VLF-TD); see 5.4.
2) VLF differential tangent delta measurement (VLF-DTD); see 5.4.
3) VLF tangent delta temporal stability (VLF-TDTS); see 5.4.
4) VLF dielectric spectroscopy (VLF-DS); see 5.6.
5) VLF loss current harmonics (VLF-LCH).
6) VLF leakage current (VLF-LC).
7) VLF partial discharge (PD) measurement (VLF-PD); see 5.5.
8) VLF monitored withstand (VLF-MW).

Methods 5) and 6) are in limited use at present.

Field testing techniques frequently employ a combination of diagnostic test methods. Test methods should be selected based on considerations such as ease of operation, operator training requirements, cost/benefit ratio, the cable system age and condition, and the capability of the cable owner to endure and accommodate a possible cable failure. Diagnostic test results can be used for asset management decision support, e.g., different maintenance activities, replacement, and condition assessment steps.

CAUTION

The potential consequences of a cable system insulation failure during any high-voltage test should be considered prior to undertaking any such test.

The consideration of various VLF ac voltage testing methods should be based upon the following guidelines as tabulated in Table 1.

The density and severity of the defects in a cable system influence the effectiveness of any diagnostic method including the VLF ac voltage test methods (Bach [B1] and [B2]; Baur, Mohaupt, and Schlick, [B6]; Goodwin, Oetjen, and Peschel [B13]; and Hampton, et al. [B17] and [B19]). As a general rule the more severe the defects, the lower the ac dielectric strength. Typical defects for fluid-impregnated and extruded cable systems are listed in Annex C.

In extruded cable systems severe defects are, for example, large water trees, large contaminants, large voids, or large sharp protrusions that can initiate partial discharges and/or electrical trees at test voltages. The loss and harmonic loss currents increase with the severity of water treeing. Less severe defects—those that have a longer elapsed time to failure—are, for example small water trees, small contaminants or voids, and less sharp protrusions that may not initiate partial discharges and/or tracking or electrical trees at test voltages.

Table 1—Criteria considerations: various VLF ac voltage testing methods

Comparison	Withstand test methods		Other diagnostic test methods	
Equipment	VLF Cosine-Rectangular/Bipolar Pulse power source	VLF Sinusoidal power source	VLF power source plus one or more of the following measuring equipment: VLF-TD/VLF-DTD/VLF-TDTS/VLF-LCH, VLF DS, VLF-LC, VLF-MW	VLF power source plus PD measuring equipment VLF PD
Ease of operation	Connect HV power supply and apply voltage of specified magnitude for specified time		Connect HV power supply and ancillary equipment, if recommended, to make diagnostic measurements. The effectiveness of these methods relies on the effectiveness of noise filtering of the test equipment.	
Detect overall condition/ localized defect	Localized defect in insulation or at interface		Overall condition of insulation	Localized defect in insulation or at interface

All types of VLF ac voltage tests are applicable to jacketed and unjacketed cable systems with all types of shields. VLF withstand, tangent delta, and partial discharge tests can also be applied to extruded cables with bare metallic shields. Corrosion of the metallic shield can limit the sensitivity of PD tests due to the attenuation of high frequency signals. If the corrosion is so severe that there is no continuity, the tests are not valid. Refer to IEEE Std 1617 for guidance to determine the extent of metallic shield corrosion. The usefulness of various VLF ac voltage testing methods for selected cable and/or insulation conditions is tabulated in Table 2.

Table 2—Usefulness of VLF ac voltage testing methods for selected cable and/or insulation conditions

Cable condition	Diagnostic test methods				
	Simple withstand test methods	**VLF-MW**	**VLF-TD VLF-DTD VLF-TDTS VLF-DS**	**VLF-PD**	**VLF-LC VLF-LCH**
Cables with metallic shield corrosion	Acceptable	Acceptable	Acceptable	Poor (see Note 1)	Poor
Extensive water treeing	Acceptable	Good	Good	Poor (See Note 2)	Good
Few large defects or few localized electrical trees	Good	Acceptable/ Good (see Note 3)	Acceptable/ Good (see Note 2)	Acceptable/ Good	Acceptable/ Good (see Note 3)
Defective splices and terminations	Acceptable/ Good (see Note 4)	Acceptable/Good (see Note 3)	Acceptable (see Note 3)	Acceptable (see Note 2)	Acceptable (see Note 3)
Mixed insulation (extruded and/or laminated)	Good	Good (see Note 4)	Poor/Good (see Note 4)	Good (See Note 5)	Poor/Good (see Note 4)

NOTE 1—PD testing can be less sensitive on aged taped shielded cables due to corrosion of the shield overlaps that causes attenuation of the PD signals (Guo and Boggs [B15]). PD sensitivity can decrease with increasing length of the cable under test.
NOTE 2—PDs are detectable only if there are one or more active electrical trees or tracking sites or there are gas-filled voids in the cable insulation or accessories. Moreover it should be noted that PD inception conditions at VLF can be different from those at other frequencies.

NOTE 3—Supplemental testing is recommended to distinguish a severe localized defect from general overall deterioration.
NOTE 4—As this test technique measures the average of all the insulations under test, supplemental testing is recommended to measure individual sections of the insulation. VLF-TD, VLF-DTD, VLF-TDTS, VLF-DS, or non-VLF techniques can be used to differentiate mixed cable insulations. If the individual sections cannot be measured, the test method may not be useful.
NOTE 5—The different propagation characteristics of the various cable sections (different sizes and/or insulations) may make it difficult to locate the PD.

5.1 General VLF ac withstand voltage testing

5.1.1 VLF ac withstand voltage test parameters

The purpose of a withstand test is to verify the integrity of the cable under test. If the test cable has a defect severe enough at the withstand test voltage, an electrical tree will initiate and grow in the insulation. Inception of an electrical tree and channel growth time are functions of several factors including test voltage, source frequency and amplitude, and the geometry of the defect. For an electrical tree from the tip of a needle in PE insulation in laboratory conditions to completely penetrate the insulation during the test duration, VLF ac voltage test levels and testing time durations have been established for the two most commonly used test voltage sources, the cosine-rectangular and the sinusoidal wave shapes. However, the time to failure will vary according to the type of insulation such as PE, paper, and rubber. Thus the electrical tree growth rate is not the same for all materials and defects.

The voltage levels (installation and acceptance) are based on the most used, worldwide practices of from less than 2 U_0 to $3U_0$, where U_0 is the rated rms phase to ground voltage, for cables rated between 5 kV and 69 kV. The maintenance test level is about 75% of the acceptance test level. One can reduce the test voltage by another 20% if the voltage is applied for longer times (Bach [B2]; Baur, Mohaupt, and Schlick, [B6]; Krefter [B27]). Evidence (Hernandez-Mejía, et al. [B21]) indicates that increasing the voltage above $3U_0$ to compensate for reduced test cycles (time) does not replicate performance either on test or in service as compared to the lower voltage, longer time tests.

Table 3 lists voltage levels for VLF withstand testing of shielded power cable systems using cosine-rectangular and sinusoidal waveforms (Bach [B2]; Eager, et al. [B9]; Krefter [B27]; Moh [B28]). For a sinusoidal waveform the rms is 0.707 of the peak value, assuming the harmonic distortion is less than 5%. The rms and peak values of the cosine-rectangular waveform are assumed to be equal.

It should be noted that terminations may need to be added to avoid flashover for installation tests on cables rated above 35 kV.

Regarding the test times:

- The recommended minimum testing time for a simple withstand test on aged cable circuits is 30 min at 0.1 Hz (Goodwin, Oetjen, and Peschel [B13]). If a circuit is considered as important, e.g., feeder circuits, then consideration should be given to extending the testing time to 60 min at 0.1 Hz (Hampton, et al. [B19].
- The recommended minimum testing time for an installation and/or acceptance withstand test on new cable circuits is 60 min at 0.1 Hz.
- A test time within the range 15–30 min may be considered if the monitored characteristic remains stable for at least 15 min and no failure occurs. **It should be noted that the recommended test time for a withstand test is 30 min.**

If the circuit fails during the test, it should be repaired or replaced and then retested using a complete 30-minute test, preferably a monitored withstand test. It is recommended to retest each section with VLF-TD, VLF-DTD, VLF-TDTS, or VLF-PD before the repair to get an assessment of the cable before repair. It is also recommended to retest with VLF-TD, VLF-DTD, VLF-TDTS, or VLF-PD after repair to assess the workmanship of the repair. Monitoring cannot be used to reduce the testing time for retests as the cable system has already been shown to be potentially weak by the prior failure.

Table 3—VLF withstand test voltages for sinusoidal and cosine-rectangular waveforms (see Note 1)

Waveform	Cable system rating (phase to phase) [kV]	Installation (phase to ground)		Acceptance (phase to ground)		Maintenance[2] (phase to ground) (see Note 2)	
		[kV rms]	[kV peak]	[kV rms]	[kV peak]	[kV rms]	[kV peak]
Sinusoidal	5	9	13	10	14	7	10
	8	11	16	13	18	10	14
	15	19	27	21	30	16	22
	20	24 (Note 3)	34 (Note 3)	26	37	20	28
	25	29 (Note 3)	41 (Note 3)	32	45	24 (Note 3)	34 (Note 3)
	28	32	45	36 (Note 3)	51 (Note 3)	27	38
	30	34	48	38	54	29 (Note 3)	41 (Note 3)
	35	39	55	44	62	33	47
	46	51	72	57	81	43	61
	69	75	106	84	119	63	89
Cosine-Rectangular	5	13	13	14	14	10	10
	8	16	16	18	18	14	14
	15	27	27	30	30	22	22
	20	34	34	37	37	28	28
	25	41	41	45	45	34	34
	28	45	45	51	51	38	38
	30	48	48	54	54	41	41
	35	55	55	62	62	47	47
	46	72	72	81	81	61	61
	69	106	106	119	119	89	89

NOTE 1—If the operating voltage is a voltage class lower than the rated voltage of the cable, it is recommended that the **maintenance** test voltages should be those corresponding to the operating voltage class.

NOTE 2—The maintenance voltage is about 75% of the acceptance test voltage magnitude.

NOTE 3—Some existing test sets have a maximum voltage that is up to 5% below the values listed in the table. These test sets are acceptable to be used. However, there is a risk that the cable may be “undertested” due to a combination of lower test voltage and allowed uncertainty of the measuring circuit.

VLF ac voltage testing methods utilize ac signals at frequencies in the range of 0.01 Hz to 1 Hz. The most commonly used, commercially available VLF ac voltage test frequency is 0.1 Hz. VLF ac test voltages with cosine-rectangular and the sinusoidal wave shapes are most commonly used. While other wave shapes are available for testing of cable systems, recommended test voltage levels have not been established.

Other commercially available frequencies for dielectric spectroscopy are in the range of 0.001 Hz up to 1 Hz. Frequencies lower than 0.1 Hz may be useful for diagnosing cable systems where the length of the cable system exceeds the limitations of the test equipment at 0.1 Hz. However, if withstand tests at frequencies below 0.1 Hz are carried out, consideration should be given to extending the test duration so that there are a sufficient number of cycles to cause breakdown if an electrical tree is initiated.

5.1.2 Testing considerations

Testing considerations are as follows:

- Details about the cable including cable capacitance and a route map should be available so that personnel will be familiar with the cables involved, the location of open points, where the cables or joints may be accessible and the types of cable constructions used. Time domain reflectometry may be used to determine the location of accessories, open points and the length of the circuit.
- The test set used must be sufficiently powerful to supply and dissipate or recover the total cable system charging energy during every test and monitoring cycle.
- If the accessory or cable insulation is in an advanced condition of degradation, the test can cause breakdown before it can be terminated when using test voltages above the operating voltage.
- Crews should be prepared to install a new splice, cable or termination if failure unexpectedly occurs during the test.
- If a cable circuit has failed and a new section of cable installed, an installation test can be performed on the new length before it is spliced and a maintenance test carried out on the complete circuit after it is installed.
- An issue can arise while testing existing circuits according to their cable rating or according to normal circuit voltage. For example, utilities sometimes install a higher rated cable in a circuit that is energized at a lower voltage in preparation for a later upgrade of the circuit. It is prudent to test according to the full cable rating for the installation test before the circuit is connected to equipment with lower voltage rating but to test according to the present circuit voltage rating afterwards.
- At the conclusion or at an interruption of a VLF ac voltage test, the test object should be discharged and then grounded.
- The voltage application in some equipment has two components: the ramp up and the hold portions, whereas in other equipment the voltage reaches the test voltage during the first cycle. At the present time any failure that occurs during the test is considered to have occurred at the test voltage (the hold portion). Some additional useful information may be collected by collecting the ramp and hold portions separately, see Annex D.

5.2 VLF ac withstand voltage testing with cosine-rectangular/bipolar pulse waveform

5.2.1 Measurement and equipment calibration

Some VLF cable test sets provide a cosine-rectangular voltage waveform. A typical waveform is shown in Figure B.1, Annex B. A dc test set forms the high-voltage source and a dc-to-ac converter changes the dc voltage to the VLF ac test signal. The converter consists of a high-voltage inductor and a switching rectifier. Changing the polarity of the cable system being tested every 5 s generates a 0.1 Hz bipolar pulse waveform.

The measurement of the test voltage should be made with an approved and calibrated measuring system as described in IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of ± 5% and the response time of the measuring system should not be greater than 0.5 s. It should be verified that positive and negative peaks do not differ by more than 2%. It is important that all measuring equipment is under a valid calibration.

5.2.2 Method

The cable or cable system to be tested is connected to the VLF ac voltage test set and the cosine-rectangular test voltage raised to a value up to that specified in Table 3. During the test cycle the leakage current may be monitored and recorded if the necessary equipment is available. The current may be converted to tangent delta using an approximation technique (Hamon [B16]). When the cable or cable system passes the VLF voltage test, the test voltage is regulated to zero and cable and test set are discharged and grounded. The cable or cable system can be returned to service. If a cable or cable system fails the test, the test voltage collapses. The VLF ac voltage test set is turned off to discharge the cable and test set; the cable is then grounded. The cable fault may be located with standard cable fault locating equipment. After the fault has been located and repaired, the circuit should be retested.

5.2.3 Advantages

The advantages are as follows:

— Simple withstand tests are usually straightforward and may not require an expert to interpret the results.

— The 0.1 Hz cosine-rectangular waveform changes polarity in the frequency range 30 Hz to 250 Hz. Because of the sinusoidal transitions between the positive and negative polarities, traveling waves are not generated, and because of continuous polarity changes, space charges are not likely to be developed in the insulation unless the frequency is less than 0.01 Hz and the electric stress is > 10 kV/mm (Takada [B33]; Dissado, et al. [B7]). The electrical stresses given by the voltages in Table 3 are below 10 kV/mm. The actual stress for space charge trapping will be related to the degree and nature of the degradation.

— Insulation resistance/leakage current can be measured if the necessary equipment is available.

— Cable systems may be tested with an ac voltage greater than the rated conductor to ground voltage with a device comparable in size, weight, and power requirements to a dc test set.

— The VLF ac voltage test can be used to test cable systems with extruded and laminated dielectric insulation.

— Monitored withstand testing, e.g., leakage current, monitors the effect of the test on the cable system during voltage application and may be able to detect possible defects or failure sites that do not fail during the test.

5.2.4 Disadvantages

The disadvantages are as follows:

— When testing cable systems with extensive insulation degradation, simple VLF withstand testing alone may result in repeated failures, although this rarely occurs in practice. Additional diagnostic tests, such as leakage current measurements that measure the extent of insulation losses, are recommended.

— Cable systems must be taken out of service for testing.

— Only gross workmanship defects are likely to be detected on new cable systems.

— Simple withstand testing does not monitor the effect of the test on the cable during the voltage application and can fail to detect a potentially destructive defect.

— Diagnostics methods such as tangent delta measurements are currently not available with this voltage waveform.

5.3 VLF ac withstand voltage testing with sinusoidal waveform

5.3.1 Measurement and equipment calibration

The VLF cable test sets provide sinusoidal ac output voltages, see Annex B, Figure B.1.

The measurement of the test voltage should be made with an approved and calibrated measuring system as described in IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of ± 5% and the response time of the measuring system should not be greater than 0.5 s. If the ratio of peak to rms values is not within $\sqrt{2} \pm 5\%$, it should be verified that positive and negative peaks do not differ by more than 2%. It is important that all measuring equipment is under a valid calibration.

5.3.2 Method

The VLF ac voltage test set is connected to the cable system to be tested and the test voltage raised or preset to a value up to that specified in Table 3. When the cable or cable system passes the VLF voltage test, the test voltage is regulated to zero, the cable or cable system and test set are discharged and the cable or cable system is grounded.

If a failure occurs during the test, the test voltage collapses. The VLF ac voltage test set is turned off to discharge the cable system and test set. The breakdown voltage and the testing elapsed time are recorded. During the test cycle the leakage current may be monitored and recorded. The cable is then grounded. When a defect has caused breakdown, the latter can then be located with standard fault locating equipment. Cable systems can be tested after installation, for acceptance, or in preventive maintenance programs or after outages. Identified faults can be repaired or faulted cable sections replaced. Once a cable system passes the VLF withstand test, it may be returned to service.

5.3.3 Advantages

The advantages are as follows:

- Simple withstand tests are usually straightforward and may not require an expert to interpret the results.
- Because of continuous polarity changes, space charges are less likely to form in the cable insulation unless the frequency is less than 0.01 Hz and the electric stress is > 10 kV/mm. (Takada [B33]; Dissado, et al. [B7]). The electrical stresses given by the voltages in Table 3 are below 10 kV/mm. The actual stress for space charge trapping will be related to the degree and nature of the degradation.
- Insulation resistance/leakage current can be measured if the necessary equipment is available.
- Cable systems may be tested with an ac voltage greater than the rated conductor to ground voltage with a device comparable in size, weight, and power requirements to a dc test set.
- The VLF ac voltage test can be used to test extruded, laminated, and mixed dielectrics.
- VLF ac voltage test sets with 0.1 Hz tangent delta, insulation resistance/leakage current or dielectric spectroscopy measurement capability for diagnostically identifying cable systems with range (low, medium, or high) levels of degradation are available.
- Partial discharge-free VLF high-voltage generators for diagnostic testing of cables are useful to monitor and locate single and multiple defects. These tests are described in 5.5.
- Monitored VLF withstand testing can measure tangent delta, insulation resistance, and partial discharge characteristics.

— Monitored withstand testing monitors the effect of the test on the cable system during voltage application and can pick out defects that do not fail during the test.

5.3.4 Disadvantages

The disadvantages are as follows:

— When testing cables with extensive insulation degradation, simple VLF withstand testing can result in repeated failures, although this rarely occurs in practice. Additional diagnostic tests that measure the extent of insulation losses is recommended, see 5.4.

— Cable systems must be taken out of service for testing.

— Only gross workmanship defects are likely to be detected on new cable systems.

— Simple withstand testing does not monitor the effect of the test on the cable during the voltage application and can fail to detect a potentially destructive defect although practical experience has shown that this rarely occurs.

5.4 Tangent delta/differential tangent delta/tangent delta stability/leakage current/harmonic loss current tests with VLF sinusoidal waveform

5.4.1 Measurement and equipment

VLF Tangent delta, differential tangent delta, tangent delta stability, leakage current, and loss current harmonics measurements may be used to monitor aging and deterioration of cable systems (Werelius [B35]). However, tangent delta (VLF-TD), differential tangent delta (VLF-DTD), and tangent delta stability (VLF-TDTS) measurements are the most commonly used methods in the field. A correlation between an increasing 0.1 Hz tangent delta and a decreasing insulation breakdown voltage level at power frequency has been reported (Bach, Kalkner, and Oldehoff [B3]; Hvidsten, et al. [B24]; Hernandez-Mejía, et al. [B21]) for PE and cross linked polyethylene (XLPE) cables. The 0.1 Hz tangent delta, differential tangent delta, and tangent delta stability are mainly determined by degradation of the cable insulation (water-trees), corroding metallic shields, insulation moisture, and degraded accessories. The measurement of the tangent delta, differential tangent delta and/or tangent delta stability with a 0.1 Hz sinusoidal waveform offer comparative assessment of the aging of PE, XLPE, TRXLPE, EPRs, and paper-type insulations and can be used as a diagnostic test. The test results permit differentiating between new, defective, and highly degraded cable systems (Baur, Mohaupt, and Schlick, [B6]; Hernandez-Mejía, et al. [B21]; Hampton, et al. [B20]; Hampton and Patterson [B18]).

Cable systems can be tested in preventive maintenance programs and returned to service after testing. The measurements at VLF can be used to make decisions on cable/accessory replacement, cable rejuvenation, or repair expenditures.

The measurement of the test voltage should be made with an approved measuring system as described in IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of ± 5% and the response time of the measuring system should not be greater than 0.5 s. The positive and the negative halves of the output waveform should be symmetrical.

5.4.2 Method

A VLF generator with tangent delta/differential tangent delta/tangent delta stability and/or harmonic loss current measurement capability is connected to the cable under test. At least one end of the cable must be accessible**. In common with all practical field diagnostics it is good practice to ensure that the terminations are clean and in good repair prior to commencing the test program.** If tangent delta, differential tangent delta and/or tangent delta stability tests are going to be made, they should be carried out before a simple or monitored withstand test. The results of these tests will assist in assessing the severity of the cable condition and give guidance in determining the duration of the withstand test.

The tangent delta (TD) at 0.5 U_0, U_0, and 1.5 U_0, are measured and the differential tangent delta or tip up, DTD = TD(1.5 U_0) – TD(U_0) is calculated. In addition the variation of tangent delta with time at a particular voltage (TDTS), usually over a period of some minutes, can be measured and from which the mean and standard deviation of the readings can be calculated. The tangent delta values of aged extruded and oil-paper insulations usually increase with time but occasionally a decrease occurs. The mechanisms for the increase or decrease in tangent delta are not fully understood at this time, but the greater the change in tangent delta the more severe is the insulation aging. A decrease has been attributed to wet splices in paper insulated lead covered (PILC) cable systems. The voltage should be set at 0.5 U_0 and raised to 1.5 U_0 in steps of 0.5 U_0. The maximum withstand value may also be used as a final step. Although the criteria for the TDTS listed in Table 5 to Table 7 are given for measurements at U_0 it is a good practice to make measurements in steps of 0.5 U_0 so that severely aged cables can be identified sooner without going to elevated voltage levels. Each step should include at least six single TD measurements at intervals of 10 s between each measurement at 0.1 Hz. The intervals will be correspondingly longer at lower frequencies. The average TD value and the stability of each TD or DTD measurement in each step should be calculated. Alternatively, the stability values can be calculated from tangent delta measurements taken at each voltage level and at the end of the 30-minute withstand period.

The tangent delta stability refers to the variation of tangent delta with time at constant voltage. In this document, the tangent delta stability is defined as the measurement of the standard deviation of tangent delta with time at a particular voltage (U_0):

$$STDEV = \sqrt{\frac{\sum\left(TD - \overline{TD}\right)^2}{(n-1)}}$$

where

TD is tangent delta

$\overline{TD}$ is the mean or average value

The tangent delta stability can also be measured in other ways, e.g., using the inter-quartile range or the trend with measurement time. The change in the tangent delta with time at constant voltage increases with degree of aging of the insulation. However, it can also be affected by the duration of the voltage interruption experienced by the cable system.

5.4.3 Assessment criteria—aged cable systems

The measured values of VLF-TD, VLF-DTD, and temporal stability (VLF-TDTS) are primarily influenced by the condition (age, contamination, and moisture ingress) of the various cable system components (accessories, cable insulation, and metallic shield). In addition, some utilities may have components connected to the cable circuit being measured, e.g., oil-filled switches, that cannot be removed but can influence the test results. Most users of dielectric response techniques choose to measure the entire cable system response that would include the responses from all terminations, cable, and joints within the circuit.

If a high value of VLF-TD, VLF-DTD, and/or VLF-TDTS is detected then a user has a number of choices as follows:

- The user can compare results between different phases of the same segment or sequential sections to better place the result in context.
- The user can divide circuits into subsections and retest, perform a visual analysis of circuit components where accessible and replace suspect parts, or replace the accessories, especially if they appear to be old, and re-measure.
- The user can perform additional testing in the form of a monitored withstand, non-monitored withstand, or partial discharge test should they wish to identify a localized problem.
- The user may separate the response of terminations and other components if connected from cables plus splices, by, if practical, adding guard circuits at the terminations.

Tangent delta measurements provide a global assessment of the dielectric loss. Thus a single region of high loss such as a region of severe water treeing, degraded accessory, area of high moisture or different cable insulation can cause the measured value to rise even though the bulk loss of the majority of the system will be lower. The measured value will be less than the actual loss of the high loss region. A comparison of results between different phases of the same segment or sequential section will help identify if this is the case.

A comparison of data from similar cable systems should improve the usefulness of tests. For example, comparisons of the phase or voltage dependencies of the tangent delta can increase the diagnostic efficiency (Fletcher, et al. [B10]; Goodwin, Oetjen, and Peschel [B13]). Statistical comparisons of many results increase the security of criteria levels established. Dielectric losses can be affected by insulation material parameters such as different materials and the cross-linking by-products, although in older cables the concentration of the latter will be negligible. Data from VLF diagnostics may not be comparable with data at higher frequencies, e.g., power frequency.

Partial discharges produced by the accessories may influence the VLF-TD, VLF-DTD, or VLF-TDTS results; this can be easy to recognize by highly increased tip up of TD at increasing voltage levels. With the exception of wet accessories, VLF-TD, VLF-DTD, and VLF-TDTS cannot detect singular defects in extruded cable insulation and requires hundreds of large water trees to be present to cause the smallest indication (Baur [B5]). A hybrid cable system with multiple insulation types can give VLF-TD/VLF-DTD/ /VLF-TDTS results that will be related to the relative lengths of each type of insulation.

The absolute VLF-TD, the VLF-DTD, and the temporal stability (VLF-TDTS) values are used as figures of merit (see also Annex E) or compared to historical data to grade the condition of the cable insulation as:

- No action required
- Further study advised, or
- Action required

If there is a significant difference, as defined by Table 4 through Table 7, in tangent delta with increasing and decreasing voltage (VLF-DTD) or a significant variation of tangent delta with time (VLF-TDTS), there may be a section of severely damaged insulation in the cable insulation or accessory.

The *no action required* condition assessment means that, although the cable system can be returned to service, the cable system may be retested at some later date to observe the trend of the tangent delta.

The *action required* condition assessment means that the cable system has an unusually high set of tangent delta characteristics that may be indicative of poor insulation condition and should be considered for replacement or repair immediately after the test or in the near future. These results may also be used to trigger further testing.

The *further study advised* condition assessment means that additional information is needed to make an assessment, the additional information could come from previous circuit failure history or additional assessment from an additional diagnostic test; for example, a monitored withstand test can be performed after the VLF-TD, VLF-DTD, VLF-TD stability or VLF DS test, the information from the monitored withstand test could be used to enhance the diagnostic and leading eventually to a condition assessment of *no action required* or *action required*.

If there is a significant increase in tangent delta during the test with increasing voltage from 0.5 U_0 to U_0, there may not be a need to raise the voltage to test at 1.5 U_0, as the significant increase is an indication that the cable system is highly degraded and thus there is a danger of initiating electrical trees in the severely damaged insulation. In this case, the cable system condition is assessed as *action required*.

More importantly, it must be understood that, for different insulations, installations, and cable types, tangent delta, differential tangent delta and tangent delta stability figures of merit can vary significantly from each other. Therefore, the tangent delta tests—TD, DTD, and/or TDTS—work best when comparing present measurements against established historical figures of merit for a particular cable system type as a whole (i.e., including the cable, terminations, and joints). Table 4 to Table 7 show historical figures of merit (see also Annex E) that could be used for condition assessment for aged PE-based (e.g., PE, XLPE, TRXLPE cables), aged filled insulations (e.g., EPR cables), and aged oil impregnated paper (e.g., PILC cables) respectively. In Table 4 to Table 7, U_0 is the cable phase to ground operating voltage. The values given in Table 4 to Table 7 can also be given in percentage, in which case the values are multiplied by 100, for example, 0.1×10^{-3} becomes 0.01%. The columns in Table 4 to Table 7 are arranged in the order of sensitivity of the measurements to insulation deterioration, i.e., the time stability is the most sensitive followed by the voltage stability followed by the actual value of TD.

The values in Table 4 to Table 7 were derived from empirical cumulative distribution functions (CDF) for the data consisting of data points obtained for aged cable systems, mainly in utilities from North America, i.e., the data are from maintenance tests. The tables use the probability criteria of 80% (selected based on the Pareto principle where the best ranked 80% of the population only account for 20% of the issues) and 95% of the poorest values. The figures of merit are constructed so that they may be used with the basic insulation system information available to test engineers at the time of the field investigations. More details of how the figures of merit are derived are given in Annex E and Annex H.

There are some circumstances where the precise cable design (e.g., shielded or belted, conducting or non-conducting shield), system composition, insulation material, or vintage is known. In these cases the figures of merit are useful guides. However, an owner can develop his or her own “cable system specific” criteria to provide better discrimination, using the approach detailed previously. These nuances are not included in these tables due to the fact that only a small number of installations are precisely identified to enable the discrimination. Furthermore, the differences that have been identified are not statistically significant for the data available. As an example, several formulations of EPR (the mineral-filled class) have been used; however, the formulations that may be definitively identified represent 2% of the filled data.

Some comments on data interpretation and subsequent performance after simple or monitored withstand test are given in Annex F.

Annex I gives the equivalent tables for cable systems installed and used outside North America. The inputs for these tables have been collected from different sources and it cannot be established if the criteria in the tables were derived in the same way as those listed in Table 4 to Table 7 for North America.

It should be noted that Table 4 to Table 7 apply to maintenance tests on cable systems that have been in operation for five or more years, i.e., the cables can be considered to be aged.

Table 4—Historical figures of merit for condition assessment of service-aged PE-based insulations (e.g., PE, XLPE, and TRXLPE) using 0.1 Hz

Condition assessment	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0, $[10^{-3}]$		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 $[10^{-3}]$		Mean VLF-TD at U_0 $[10^{-3}]$
No Action Required	< 0.1	**and**	< 5	**and**	< 4
Further Study Advised	0.1 to 0.5	**or**	5 to 80	**or**	4 to 50
Action Required	> 0.5	**or**	> 80	**or**	> 50

Table 5—Historical figures of merit for condition assessment of service-aged filled insulations (e.g., mineral-filled EPR) using 0.1 Hz

Condition assessment	Filled insulation system	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0 [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No action required	**If it is not possible to definitively identify a Filled Insulation**[a]	**< 0.1**	and	**< 5**	and	**< 35**
	Carbon-filled (Black) EPR	< 0.1		< 2		< 20
	Mineral-filled (Pink) EPR	< 0.1		< 4		< 20
	Discharge resistant EPR[b]	< 0.1		< 6		< 100
	Mineral-filled XLPE[b]	—		—		< 100
Further study advised	*** If it is not possible to definitively identify a Filled Insulation**[a]	**0.1 to 1.3**	or	**5 to 100**	or	**35 to 120**
	Carbon-filled (Black) EPR	0.1 to 2.7		2 to 120		20 to 100
	Mineral-filled (Pink) EPR	0.1 to 1		4 to 120		20 to 100
	Discharge resistant EPR[b]	0.1 to 1		6 to 10		100 to 350
	Mineral-filled XLPE[b]	—		—		100 to 350
Action required	*** If it is not possible to definitively identify a Filled Insulation**[a]	**> 1.3**	or	**> 100**	or	**> 120**
	Carbon-filled (Black) EPR	> 2.7		> 120		> 100
	Mineral-filled (Pink) EPR	> 1		> 120		> 100
	Discharge resistant EPR[b]	> 1		> 10		> 350
	Mineral-filled XLPE[b]	—		—		> 350

[a] Experience has shown that it is quite difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect or missing records, obliterated or obscured markings on the cable jacket, indistinct coloring, etc. In these cases, it is recommended to use the criteria for the collated data sets.

[b] Insufficient data have been collected to make precise estimates of criteria, consequently the criteria are likely to contain considerable errors, see Annex G and Annex H. However, they are included here to provide some guidance to engineers encountering these insulation systems in the field.

Table 6—Historical figures of merit for condition assessment of service-aged paper insulations (e.g., PILC) using 0.1 Hz

Condition assessment	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0 $[10^{-3}]$		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 $[10^{-3}]$		Mean VLF-TD at U_0 $[10^{-3}]$
No action required	< 0.1	**and**	–35 to 10	**and**	< 85
Further study advised	0.1 to 0.4	**or**	–35 to –50 or 10 to 100	**or**	85 to 200
Action required	> 0.4	**or**	< –50 or > 100	**or**	> 200

The condition assessment for the cable system may be undertaken by considering the VLF-TD characteristics in the sequence VLF-TD Temporal Stability, then Differential VLF-TD, and finally Mean VLF-TD. The condition assessment is given by the most serious condition of any of the features. Any prioritization or extra differentiation between tested cable system portions may be accomplished by looking at the assessments for different features. Examples of condition assessment of cable systems are shown in Table 7.

Table 7—Examples of condition assessment of service-aged cables based on VLF-TD measurements using 0.1 Hz

Cable system insulation	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0 $[10^{-3}]$	Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 $[10^{-3}]$	Mean VLF-TD at U_0 $[10^{-3}]$	Condition assessment
PE	0.1	2	3.5	No Action Required
Paper	0. 35	–50	90	Further Study Advised
Filled	2.5	30	120	Action Required

The values given in Table 4 to Table 7 are based on data collected from North American cable designs and installations.

5.4.4 Assessment criteria—effect of cable length

As a tangent delta measurement gives the average value of the dielectric loss for the whole cable circuit tested including the cable and the accessories, it does not give information about how much variation in the loss there is along the cable length. Tangent delta tests can be conducted on cable system lengths from 30 m (100 ft) to > 3 km (> 10000 ft) with a mean length of 180 m (600 ft). For example, a short length of cable or an accessory could have a high loss whereas the rest of the circuit has low losses, or severe metallic shield corrosion could affect the tangent delta measurements. One way to overcome this is to compare the tangent delta results with the physical characteristics of the individual circuits, such as the cable length and the number of accessories in the circuit and then plotting the data graphically (tangent delta vs. cable length), preferably on logarithmic scales if there are large variations in the lengths tested or in the tangent delta values measured. Table 8 lists the possible diagnoses based on the slope of the tangent delta vs. cable length curves obtained from extensive measurements.

Table 8—Interpretation of the slopes of the tangent delta vs. cable length plot

Slope of tangent delta vs. length	Possible diagnosis
Flat (loss independent of length)	Uniform loss for all parts of the cable system
Random (no clear length dependence)	No clear pattern of loss. Each length tested is different from others in the same area. Could be local variations between lengths
Positive slope (loss increasing with length)	Corrosion of the metallic shield or poor contact between the metallic shield and the insulation shield. Isolated loss regions such as lossy accessories.
Negative slope (loss decreasing with length)	Isolated loss regions such as lossy accessories or heavily water treed regions within a large proportion of low loss cable

5.4.5 Assessment criteria—new cable systems

Withstand tests (installation and/or acceptance) on new cable systems can be carried out using the test voltage levels listed in Table 3. The recommended test duration is 60 min. **Note that the figures of merit from diagnostic tests on aged cable systems that are listed in Table 4 to Table 7 should not be applied to new cable systems.** It should also be noted that tangent delta measurements in aged cable systems are sensitive to water tree degradation; whereas, such measurements in acceptance tests on new cable systems are looking for contamination, etc.

As the data available in 2010 from VLF diagnostic tests on the different types of newly installed cable systems are limited, the figures of merit for new cable systems are listed in Table G.1and Table G.2 in Annex G. The values given in the tables may change as additional data are accumulated. For new cable systems, the voltage sensitivity of the tangent delta, the differential tangent delta (DTD), is expected to be small, as should the temporal stability of tangent delta at constant voltage (TDTS). Annex G also gives an example of the values of VLF-TD and VLF-DTD for new cables with one type of mineral-filled EPR insulation. The values of VLF-TD are less than 0.012, below the no action required value given in Table G.2, and the values of VLF-DTD ($2U_0 – U_0$) are less than the 0.005 limit given in Table G.2.

5.4.6 Advantages for tangent delta measurements

The advantages are as follows:

— The measurement of the bulk properties of extruded insulation is an indicator of the severity of water treeing.

— On highly degraded cables, tangent delta diagnostic tests can be performed at or below operating voltage U_0 of the cable, yielding good information about the condition of the cable, without the need to raise the voltage above the operating voltage.

— Cable system insulation condition can be graded among *no action required*, *further study advised*, or *action required*.

— Cable system insulation can be monitored over time by means of periodic tangent delta measurements and a cable system history developed.

— VLF-TD, VLF-DTD, and VLF-TDTS tests provide an overall condition assessment on a given phase when compared to adjacent phases, so long as the phases have the same configuration. This also applies to T-branched or complex circuits.

- Measurements are simple and quick to perform.
- Minimal influence from external electric fields/noise.
- Basic results available at end of test.
- If there is no metallic shield corrosion, cable replacement, repair, and cable rejuvenation priorities and expenditures can be planned.
- Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.
- Monitored VLF withstand, with tangent delta and partial discharge measurement capabilities, may be used to monitor the tangent delta and/or partial discharge activity during a 30 min to 60 min withstand test procedure.
- Periodic measurements or reference data are useful to accurately assess the condition of cable systems.

5.4.7 Disadvantages for tangent delta measurements

Disadvantages are as follows:

- Data from diagnostic tests may not be comparable with power frequency data.
- Cables must be taken out of service for testing.
- Higher cable temperatures are expected to influence the VLF-TD, VLF-DTD, or VLF TDTS results in XLPE, MIND, and PILC cables, i.e., after switching off of the system, the cable temperature can influence the test results. Measuring and recording the cable temperature are recommended.
- VLF-TD, VLF-DTD, and VLF-TDTS cannot locate singular defects in extruded insulation. However, the test may detect a wet or lossy accessory in new (Baur [B5]) or aged cable systems.
- Some utilities may have components connected to the cable circuit being measured, e.g., oil-filled switches that cannot be removed but can influence the test results.
- The measurement of the response of terminations, if needed, from that of the cables plus splices, may require the addition of guard circuits.

5.4.8 Open issues

Open issues are as follows:

- VLF-TD, VLF-DTD, and VLF-TDTS are effective tests for mixed dielectric if the cables are correlated with the relative lengths of each type of cable.
- On hybrid cables with different insulation types, the operator should not consider the TD value itself unless it is excessively high, but rather the TD gradient and standard deviation.
- The tangent delta should be observed over time, preferably over several years. In general, an increase in the tangent delta in comparison to previously measured values indicates additional degradation has occurred.
- Measurements can be made even when there is significant metallic shield corrosion. Generally, the measured loss is increased under this circumstance; however, the precise impact on the loss is not clear.
- It remains unclear as to how different frequencies of the applied voltage affect the tangent delta condition assessment criteria.

5.5 Partial discharge (PD) test with VLF sinusoidal waveform

NOTE—This subclause describes the partial discharge (PD) test with VLF sinusoidal waveform only. Partial discharge testing is covered in detail in IEEE Std 400.3. VLF-PD tests should be performed according to IEEE Std 400.3.

5.5.1 Measurement and equipment

PD measurements to monitor aging and degradation of paper-insulated cables have been reported (Baur, Mohaupt and Schlick [B6]; Hetzel and MacKinlay [B22]). The described method is based on the application of a pure, sinusoidal 0.1 Hz wave to the cable system. The applied voltage of up to two times the rms system line-to-ground voltage may generate partial discharges at insulation defect sites. A traveling wave method may be used to measure the magnitude of PD, locate, and record the partial discharges from the various defect locations in the cable, splices, or terminations. VLF-PD measurements are a diagnostic tool used to detect, in a nondestructive manner, the location and severity of an insulation defect. There may be differences in the PD characteristics measured at VLF and power frequency. The measurement of the test voltage should be made with an approved measuring system, as described in IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of ± 5% and the response time of the measuring system should not be greater than 0.5 s.

It is recommended that test procedures be followed according to IEC 60885-3 where possible, to aid in consistency of results.

5.5.2 Method

A transportable VLF sine wave generator is connected to an isolated cable system. The VLF-PD can be used as a monitoring tool during a withstand test. Test times and maximum voltages are recommended in Table 3. An alternative test procedure is to raise the voltage slowly to the withstand test level while monitoring the PD activity. If PDs occur, the voltage at which they initiate is the partial discharge inception voltage (PDIV). The voltage can either be kept at this level or raised to the withstand level for 20 s to 50 s (2 cycles to 5 cycles) where the PD activity is measured before being slowly reduced until the PD extinguish. This voltage is the partial discharge extinction voltage (PDEV). If no PDs are observed up to the withstand voltage, the voltage is maintained at this level for a maximum of 30 min unless PDs occur. If PDs occur, the voltage is maintained for an additional 30 s to 60 s and then slowly reduced until the PDs extinguish. After the initiation of PDs (PDIV), an electrical tree may form that can develop into a breakdown channel within minutes. Every detectable partial discharge generated during the testing time is recorded in a computer-based system by magnitude and location of its origin. The information of all recorded discharges is presented in a “PD Map.” The total number, the phase, and the magnitude of the partial discharges displayed along the cable system route diagram may provide information as to the severity and location of the various defects. Recommendations about repair or replacement of cable system sites, cable sections, or complete cable systems can be made. However, as with all PD diagnostic test methods, it should be noted that there is insufficient data to allow an accurate interpretation of PD results from either extruded or PILC cables. For example, some sites with high PD activity have not failed and there have been some failures at sites with little or no PD activity. Caution is advised in the interpretation of PD data. The test is diagnostic; after the test, the cable system can be returned to service until such time when repairs or replacements will be made.

5.5.3 Advantages

The advantages are as follows:

— Cables are tested with an ac VLF voltage up to the partial discharge inception voltage, VLF-PDIV, or during a withstand test voltage level.

— The location of PD activity can be detected and measured.
— Cable system insulation condition can be graded as no further action required, further study required, or action required when the measurement data are compared against historically established cable system PD data.
— Cable system repairs and/or replacements can be made when schedules permit.
— Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.
— In monitored VLF ac withstand test systems, partial discharge detection may be used to monitor partial discharge activity during a 30 min to 60 min withstand test procedure.
— The test becomes more useful after historical comparative cable system data have been accumulated.

5.5.4 Disadvantages

The disadvantages are as follows:

— The PD detection test may be of limited use when evaluating water treed insulation unless the electric stress created by a water tree is sufficiently severe to initiate an electrical tree and there is PD activity at the test voltage.
— External surface discharges, PDs in joints and accessories, corona discharge, and cable attenuation may have a great influence on the PD test results.
— Cable systems must be taken out of service for testing.
— Some utilities may have components connected to the cable circuit being measured, e.g., oil-filled switches, that cannot be removed but can influence the test results.
— PD testing can be less sensitive on aged taped shielded cables due to corrosion of the shield overlaps that increases the impedance of the tape and increases the attenuation of the PD pulses (Guo and Boggs [B15]).

5.6 Dielectric spectroscopy with VLF sinusoidal waveform

5.6.1 Measurement and equipment

Measurements over a range of frequencies and voltages, e.g., dielectric spectroscopy, provide information about the status of the insulation. A programmable high-voltage generator and an active bridge have been used to measure loss currents in medium-voltage cables at high voltages and frequencies from 0.1 mHz to 1 kHz (Hvidsten, et al. [B24]).

The loss currents at frequencies below 1 Hz are sensitive to degradation due to water trees in extruded XLPE cables. The loss currents also offer a comparative assessment of the aging of paper/oil cables (Hyvoenon, Oyegoke, and Aro [B25]). No work has been reported on mineral-filled EPR cables.

The test is a diagnostic test that uses rms voltages up to 14 kV and can be used as a preventive maintenance test where cables can be returned to service after testing.

In common with all practical field diagnostics it is good practice to ensure that the terminations are clean and in good repair prior to commencing the test program.

The measured value is primarily influenced by the condition (age, contamination, and moisture ingress) of the various cable system components (accessories, cable insulation, and metallic shields). In addition, some utilities may have components connected to the cable circuit being measured, e.g., oil-filled switches, that cannot be removed but can influence the test results. Most users of dielectric response techniques choose to measure the entire cable system response that would include the responses from all terminations, cable, and joints within the circuit. If a high value of loss is detected, then a user has a number of choices as follows:

a) The user can compare results between different phases of the same segment or sequential sections to better place the result in context.

b) The user can replace the terminations, especially if they appear to be old, and re-measure.

c) The user can perform additional testing in the form of a monitored withstand, non-monitored withstand, or partial discharge test should they wish to identify a localized problem.

d) The user may separate the response of terminations and other components if connected from cables plus splices, by, if practical, adding guard circuits at the terminations.

The measurement of the test voltage should be made with an approved measuring system as described in IEC 60060-3. The peak value of the test voltage should be measured with an overall uncertainty of ± 5% and the response time of the measuring system should not be greater than 0.5 s.

5.6.2 Method

A programmable high-voltage generator with a variable frequency between 0.001 Hz to 1 Hz is connected to the cable system to be tested. Once the test ranges of frequencies and voltages have been defined, the active bridge automatically measures the complex dielectric constant and the tangent delta at each voltage and frequency by measuring accurately the voltage across and the loss and capacitive currents in the cable under test with a voltage divider and an electrometer. Typical measurement times take less than 15 min.

For hybrid circuits, the tangent delta should be observed over time, preferably over several years. In general, an increase in the tangent delta in comparison to previously measured values indicates additional degradation has occurred.

5.6.3 Advantages

The advantages are as follows:

— The test is a diagnostic test that can be effective using voltage levels up to the operating voltage.

— When loss and capacitive currents increase together, the tangent delta, which is the ratio of these currents, may be less sensitive in detecting cable degradation. Therefore, both the loss and capacitive currents can be plotted separately as a function of voltage and frequency.

— Periodic measurements allow the condition of the cable system to be monitored with time and a cable history developed.

— Cable system insulation condition can be graded as no further action required, further study required, or action required when the measurement data are compared against historically established cable system VLF-DS data.

— Cable replacement and cable rejuvenation priorities and expenditures can be planned.

— Test sets are transportable and power requirements are comparable to standard cable fault locating equipment.

5.6.4 Disadvantages

The disadvantages are as follows:

— At present, the maximum commercially available test voltages at a particular VLF frequency and the maximum cable capacitance that can be tested limits the application of dielectric spectroscopy to the testing of medium voltage cable systems.

— The technique measures the average condition of the insulation.

— At very high test voltage levels and frequencies below 0.01 Hz, space charges might be produced in extruded cable insulation.

— Cables must be taken out of service for testing.

— Difficult to interpret results for hybrid circuits.

— Some utilities may have components connected to the cable circuit being measured, e.g., oil-filled switches, that cannot be removed but can influence the test results.

— The measurement of the response of terminations, if needed, from that of the cables plus splices, may require the addition of adding guard circuits.

5.6.5 Open issue

There is one open issue, as follows:

— Cable circuits with healthy cables that have accessories, which utilize stress grading materials with non-linear voltage characteristics, may exhibit characteristics of degraded cables.

6. Conclusions

VLF ac testing uses frequencies of the applied voltage in the range of 0.01 Hz up to 1 Hz. There are two main wave shapes presently in use, the sinusoidal and cosine-rectangular waveforms. This guide addresses the use of VLF non-monitored (simple) and monitored withstand and other diagnostic field testing of installed shielded power cable systems covering voltage classes from 5 kV up to 69 kV. Non-monitored and monitored withstand, tangent delta, differential tangent delta, tangent delta stability, and partial discharge tests at VLF are used as diagnostic tools to assess the condition of cable systems.

Tables of test voltage levels are included for installation, acceptance, and maintenance tests on cable systems up to 69 kV. Also included are tables giving limits of the temporal stability of tangent delta, differential tangent delta (difference in tangent delta at two test voltages), and absolute values of tangent delta for new and service-aged cable systems. The values of the test voltages and tangent delta criteria listed are based on laboratory and field test results and experience gained over many years.

The tangent delta criteria have been taken as the 80% and 95% values of the cumulative measurement data and assume the higher the tangent delta reading the worse the performance. Users may use their own cumulative measurement data and percentile values to develop their own figures of merit for the different types of cable systems. There is evidence of a correlation between the tangent delta criteria and subsequent cable performance, as shown in Figure F.1 in Annex F. Monitoring the future performance of tested circuits will help to strengthen or modify the correlations as more data are collected. As more data are acquired, the values may change and these changes will be introduced in future editions of this guide.

The guide describes the methodology (data driven, consistent percentiles, percentile estimates, etc.) for the selection of the critical levels. Important benefits of using this methodology are the availability of a framework with which to rapidly and transparently update criteria as more data become available, and the flexibility in the methodology to be adapted to the needs of the user.

The variation of tangent delta with time at constant voltage is the most sensitive technique to detect insulation aging of cable systems. The variation of tangent delta with test voltage is also sensitive to insulation aging. Both measurements are significantly more sensitive to aging than the measurement of the absolute value of tangent delta.

The advantages, limitations, and open issues with respect to VLF ac testing of cables and accessories are discussed. VLF ac voltage testing techniques, along with other test techniques, are continuing to develop.

Annex A

(informative)

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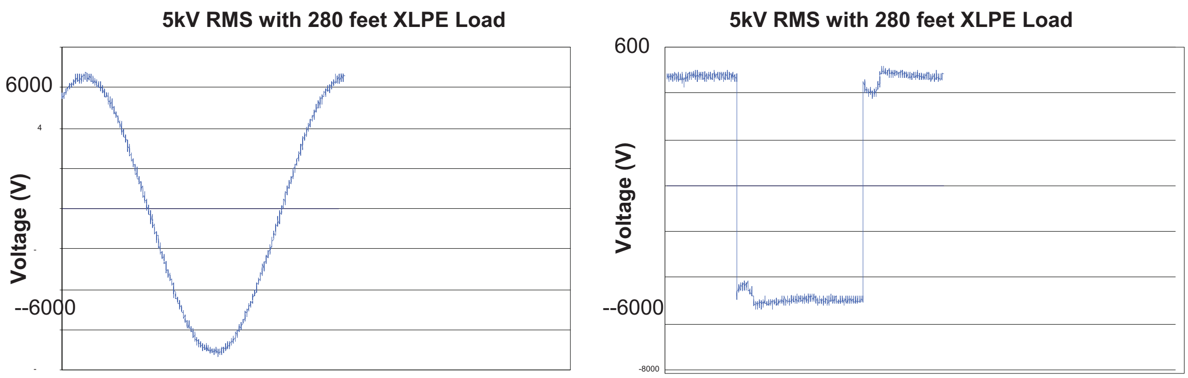
Annex B

(normative)

Wave shapes of VLF ac voltage testing voltages



0.1 Hz Sinusoidal Waveform **0.1 Hz Cosine Rectangular Waveform**

Figure B.1—Withstand voltages waveforms

Annex C

(informative)

Typical defects in fluid-filled and extruded cable systems

Typical defects in fluid-filled and extruded cable systems are listed in Table C.1.

Table C.1—Typical defects in fluid-filled and extruded cable systems

Fluid-filled cable systems	
Typical defects	**Defect causes**
Decreased oil level in accessories	Operation, leaks
Drying out of insulation	Operation, leaks, cracks in sheath
Moisture ingress	Operation, cracks in sheath, environment
Cavities	Operation & workmanship
Contaminations	Workmanship, Operation
Bad hardened resin	Workmanship
Asymmetrical conductor positioning	Workmanship, operation, environment
Conductor problems	Workmanship, operation environment
Faulty materials	Manufacture
Extruded cable systems	
Typical defects	**Defect causes**
Interface problems	Workmanship, operation
Protrusions on connectors	Workmanship, manufacture
Moisture penetration	Operation, environmental, manufacture
Water trees	Manufacture, environment
Contaminants	Workmanship, manufacture, environment
Cavities/delamination of shield	Workmanship, manufacture
Incorrect assembly of accessories	Workmanship, manufacture
Conductor problems	Operation, Workmanship, environment
Metallic shield corrosion	Manufacture, environment
Faulty materials	Manufacture, workmanship

This table has been modified from Wester [B36].

Annex D

(informative)

Effect of initial increase in voltage (ramp up)

The voltage application during a withstand test has two components—the ramp up and the hold portions. In some equipment, voltage reaches the test voltage in the first cycle so that the ramp is a quarter cycle of the voltage waveform. At the present time, any failure that occurs during the test is considered to have occurred at the test voltage (the hold portion). If more engineering information is required, failures during the ramp up and hold portions can be collected separately as follows:

— Test times are specified for the hold portion.

— The ramp up process should be defined by the user and consistent from one test to another.

— Records of all successful and unsuccessful tests (simple and monitored withstands) form a valuable diagnostic resource (Hampton, et al. [B20]) and should be retained.

— If a failure occurs during the voltage ramp up stage then the VLF voltage, U_f, (not the instantaneous voltage) should be recorded; see Figure D.1.

— If a failure occurs during the hold period, the time, t_f, into the hold period should be recorded; see Figure D.2. In equipment that allows the voltage to reach the test voltage in the first cycle the ramp is a quarter cycle of the voltage waveform and the instantaneous breakdown voltage is recorded.

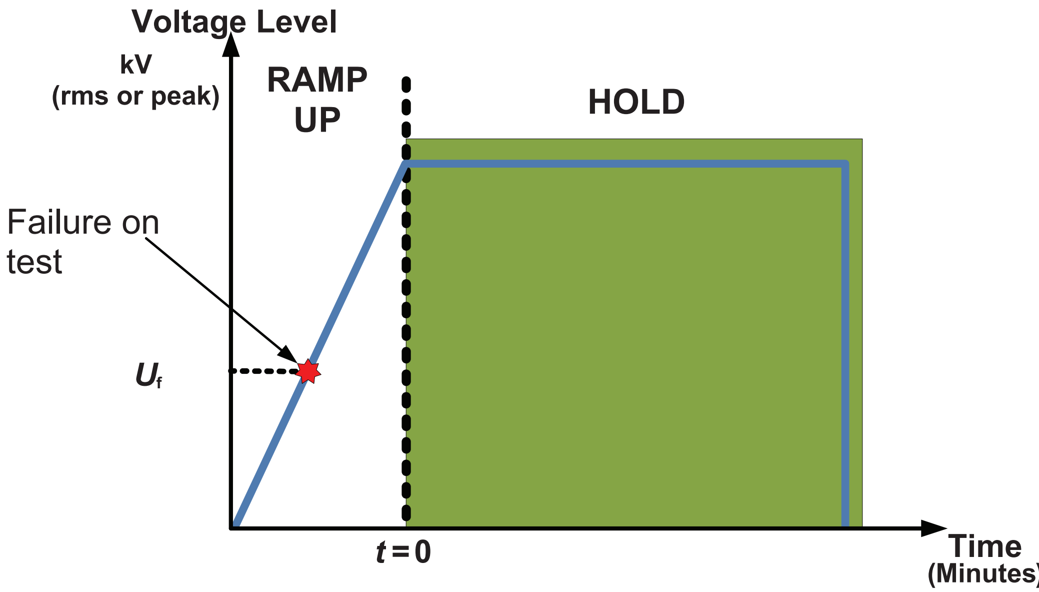


Figure D.1—Failure during ramp up period
[Record voltage at which failure occurs (U_f).]

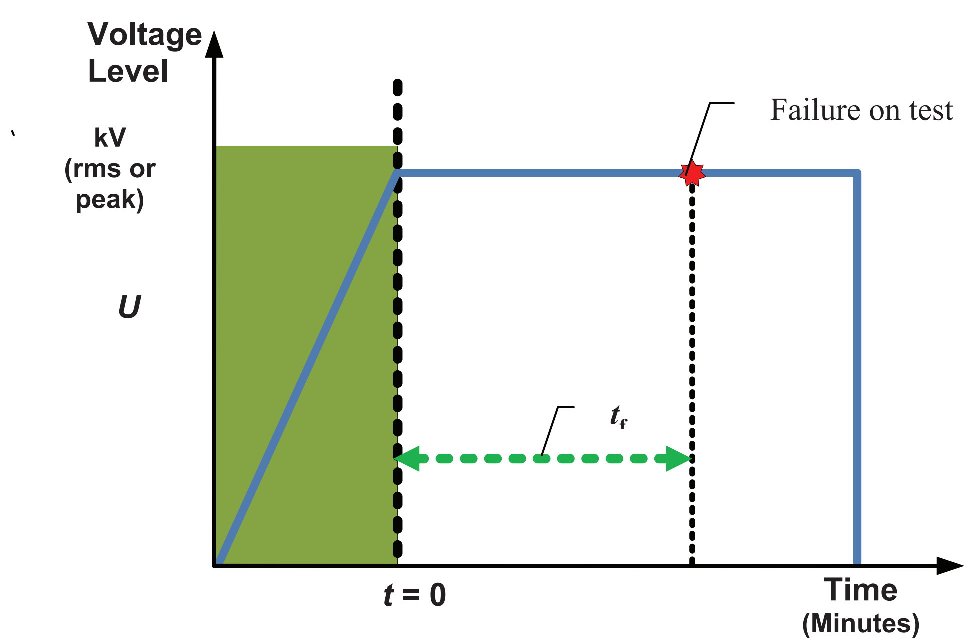


Figure D.2—Failure during hold period
[Record time on test (t_f).]

Annex E

(informative)

Figures of merit and range of available tangent delta and differential tangent delta (tip up) data

Recently collated (March 2011) data are available for measurements made on a range of utility systems. These data have been segregated for cable system type. The behavior of the measured Cable System Tangent Delta stability, Tip Up ($1.5U_0$ to $0.5U_0$), and Tangent Delta (U_0) is shown in Figure E.1 to Figure E.3, respectively. The recommended critical assessment levels of further study required and action required are derived from these data by taking the values at the 80% (following the Pareto Principle) and 95% probabilities, respectively.

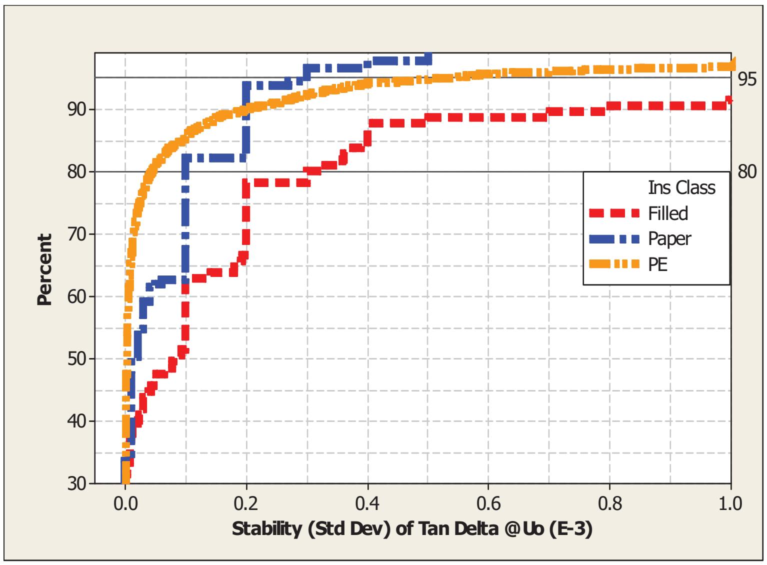


Figure E.1—Cumulative distribution of all cable system tangent delta stability values at U_0

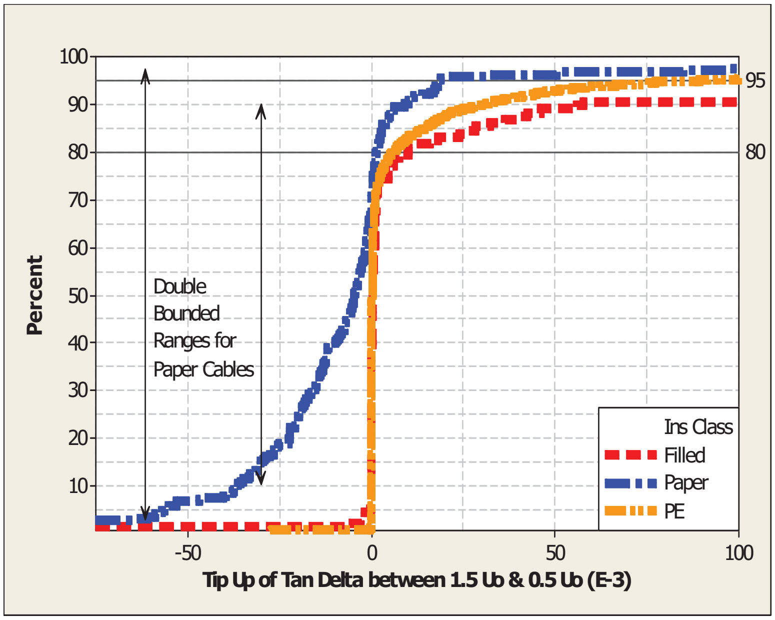


Figure E.2—Cumulative distribution of all cable system tangent delta tip up criteria

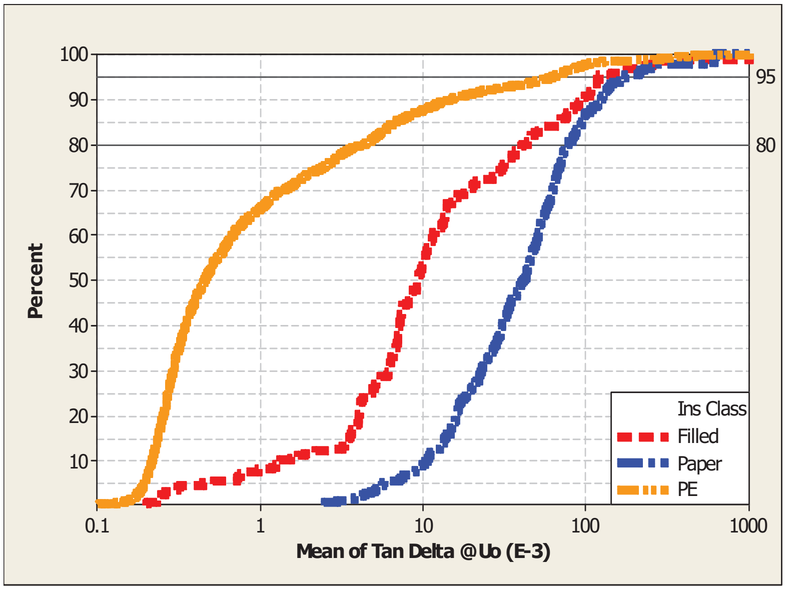


Figure E.3—Cumulative distribution of all cable system tangent delta at U_0

Annex F

(informative)

Comments on data interpretation and performance

Some comments on the risk of failure under a simple withstand test can be made based on data collected from approximately 16000 km (10000 miles) of cable systems since 2000 from several North American utilities (Hampton, et al. [B20]; Hampton, et al. [B19]; NEETRAC [B29]). However, the risk of failure on test does not relate to the whole population but the smaller/older/concerning subset that utilities subject to a condition assessment. Thus, this overestimates the risk of failure for new or well- maintained circuits but may underestimate the risk for particularly poorly performing circuits. VLF withstand tests can be performed on a large range of cable lengths [~75 m (~250 ft) to ~4.5 km (~15000 ft)]. Thus, the risk of failure on test can be considered on the following two levels as shown in Table F.1:

a) Risk of failure on test as a function of cable length.

b) Risk of failure on test for a specific length of cable, e.g., 300 m (1000 ft).

Table F.1—Risk of failure on test as function of cable system length for simple withstand tests for 30 minutes and recommended maintenance voltages

Risk of failure on test of cable systems with typically > 25 years of service or showing evidence of poor performance		
	First failure	**Second failure**
Any length of cable system	10%–30%	< 2%
Cable system length of 300 m (1000 ft)	4%	< 0.5%

The failure rates in service after the completion of a successful VLF test are low, with > 90% of the cable systems surviving longer than 5 years after the test. Cable systems that fail on test and are then repaired have a 5 year survival rate > 95%.

Overall **insulation failures on test** account for between 1% and 2%, see Figure F.1, of the number of cable systems tested according to the recommended voltage step protocol.

There is evidence of a correlation between the tan delta criteria and subsequent cable performance (Perkel, et al. [B30]). Some tested cable systems, which were already known to have questionable (due to age or failures in service) service performance, were monitored for a number of years to determine their service performance. Figure F.1 shows an example of the performance in service of PE-based insulations up to five years after testing. The times are shown in Weibull format segregated by the action classes: no action required, further study, and action required. If left unaddressed following a diagnosis, it has been estimated that for these PE-based cable systems ~7.5% [(0.8 × 6), from no action required plot; + (0.15 × 13), from further study plot; + (0.05 × 20), from action required plot, from Figure F.1] of the tested cable systems would fail in service within 5 years. It should be noted that these results do not apply to cable systems at large but to the small subset that have already come to the user’s attention due to age, criticality, poor service performance, or combinations of these factors. Monitoring the future performance of tested circuits will help to strengthen or modify the correlations as more data are acquired. The new data will be included in future revisions of this document.

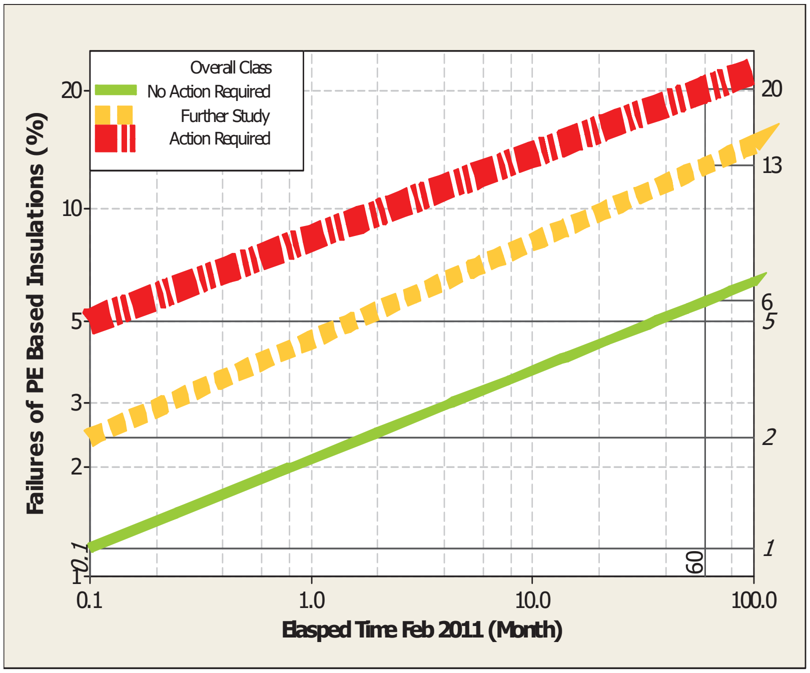


Figure F.1—Diagnostic performance curves for tan delta measurements on cable systems with questionable performance using PE-based insulations

(Values on right hand side are the number of failures at 60 months for the different plots.)

Annex G

(informative)

Tan delta results of new cable systems

The data available in 2010 from VLF diagnostic tests on the different types of newly installed cable systems are limited so the values given in Table G.1 to Table G.2 may change as additional data are accumulated. For new cable systems, the differential tan delta (DTD) is expected to be small, i.e., the voltage sensitivity of the tan delta should be small, as should the temporal stability of tan delta at constant voltage (TDTS). The tangent delta, DTD, and the TDTS values on new cables often approach the sensitivity limits of the measuring equipment.

An example of the values of VLF-TD and VLF-DTD for new cables with one type of mineral-filled EPR insulation is shown in Figure G.1 and Figure G.2. The values of VLF-TD are less than 0.012, significantly below the no action required value given in Table G.1, and the values of VLF-DTD ($2U_0 - U_0$) are less than the 0.02 limit given in Table G.1.

Table G.1—Criteria for assessment of newly installed cables with PE-based insulations (XLPE and TRXLPE)
Provisional due to sparse data—For engineering information only

Condition assessment	Tangent delta stability at U_0 [10^{-3}]		Tip up ($2.0U_0 - 1.0U_0$) [10^{-3}]		Tangent delta at U_0 [10^{-3}]
Acceptable	< 0.1	**and**	< 0.8	**and**	< 1.0
Further study advised	> 0.1	**or**	> 0.8	**or**	> 1.0

Table G.2—Criteria for assessment of newly installed conventional mineral-filled EPR cables
Provisional due to sparse data—For engineering information only

Condition assessment	Tangent delta stability at U_0 [10^{-3}]		Tip up ($2.0U_0 - 1.0U_0$) [10^{-3}]		Tangent delta at U_0 [10^{-3}]
Acceptable	< 0.1	**and**	< 5	**and**	< 10
Further study advised	> 0.1	**or**	> 5	**or**	> 10

CAUTION

The limited data in Table G.1 and Table G.2 were available in 2010 from VLF diagnostic tests on different types of newly installed cable systems. The values may change as additional data are accumulated.

The values in Table G.1 and Table G.2 should be derived by the same method as was used to get the values listed in Table 4 to Table 6, except that the percentiles of the cumulative distributions of the data from measurements on the particular type of newly installed cable systems should be used. Refer to Annex H for discussion on determining the percentiles, the confidence limits and the limitations on these percentiles when the data sets are small. At the present time, there are insufficient data to set criteria to assess PILC and non-conventional EPR cables.

Figure G.1 and Figure G.2 show the tangent delta as a function of length and the differential tangent delta measured at $2U_0$ and U_0 measured on one type of new (unaged) mineral-filled EPR cable from one manufacturer. The cables were manufactured between 1987 and 2007 the cables were rated at 5 kV and 8 kV and had 133% insulation thickness. The cables had a taped copper shield over the insulation and were jacketed. The tests were performed after installation with no terminations and also after being terminated before being put into service.

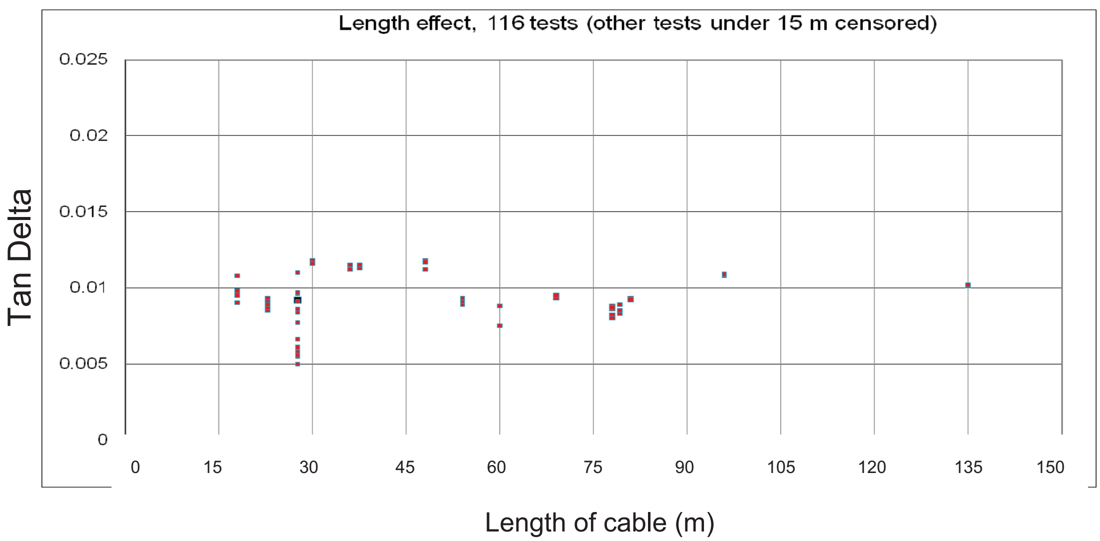


Figure G.1—Effect of length of cable on tangent delta measured at $2U_0$ of one type of new EPR cable

The results in Figure G.1 show that tangent delta is less than 0.012 and is independent of length. There were no joints in the cable circuits. The results indicate that the tangent delta criterion for no action required for installation and acceptance tests should be less than that for aged cables given in Table 5.

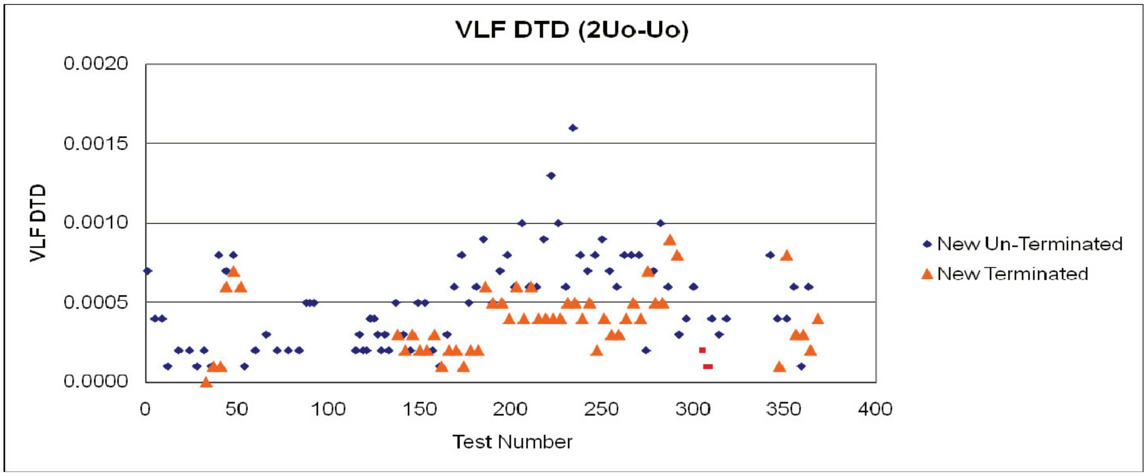


Figure G.2—Differential tangent delta of one type of new mineral-filled EPR cable

Figure G.2 shows the differential tangent delta (VLF-DTD) of newly installed mineral-filled EPR cables before and after being terminated. The majority of the test values are below 0.001, the criterion for acceptable given in Table G.2. Note, however, that the data in Figure G.2 were taken at $2U_0$ and U_0; whereas, the test voltages in Table 5 are $1.5U_0$ and $0.5U_0$.

Table 4 to Table 7 list the figure of merit values obtained during maintenance tests on different types of aged cables.

Annex H

(informative)

Development of utility/application specific criteria

In many cases, the criteria (the divisions between No Action Required to Further Study and Further Study to Action Required) have to be estimated from a smaller set of data than that used to develop the tables in the body of the standard. When the data are limited, experience has shown that a number of issues need to be considered by the engineer. These are set out below, using the filled insulation, and its sub-classes, as an example.

Sufficient information is required to determine the desired percentiles selected for the critical levels. In this document, the 80^{th} and 95^{th} percentiles have been selected through analogy with the Pareto Principle and Shewart Charts. In these cases it has been found that reasonable estimates can be developed with sample sets of the order of 100 separate entries. The process can be applied with lower numbers; however, the estimates are much coarser (see 95% confidence limits for Discharge Resistant and Mineral Filled XLPE in Table H.1), and subject to much larger changes as more data become available at later dates. Obviously the 95^{th} percentile (Action Required) is the level that is most sensitive to this issue as this is at the extreme of the data distribution.

As already mentioned, this document has, for consistency across insulation classes, selected the 80^{th} and 95^{th} percentiles as the critical levels. These are not the only levels that a user may select; for example 75^{th} and 90^{th} percentiles may be equally valid and the choice is often guided by the remediation and risk strategies of the user. However, care should be exercised to make sure that unreasonably low or high values are not selected, e.g., 50^{th} or 99^{th} percentiles. The 80^{th} and 95^{th} percentiles were guided by the cusps or split points in the distributions of data (see the distribution for mineral-filled EPR shown in Figure H.1). In this case, there is no precise agreement with the percentiles but their adoption is reasonable to enhance consistency across all insulation systems and to provide a framework for the consistent upgrading of criteria.

Inherent in any estimate of criteria is the error introduced by the data. A convenient way to determine and represent this is through the confidence limits associated with fits of statistical distributions. Thus the engineer may choose either the percentile estimate or the lower (most common) or upper confidence limits on the estimate for the critical levels. Again this is a judgment guided by the remediation and risk strategies. In the case of the VLF tangent delta features (stability, tip up, and tangent delta) this is complicated for service-aged data by the fact that no single distribution can adequately fit the data over the whole range for all insulations. The following figures show the issues to be faced by the engineer.

The mineral-filled EPR data (Figure H.1) clearly have multiple modes (represented by the straight line segments and cusps) such that an adequate fit cannot be attained for the whole data even when a sophisticated three parameter Weibull distribution is used. Whereas, the data for discharge-resistant mineral filled EPR (Figure H.2) appears to be well fitted by the three-parameter Weibull distribution (it is not clear if this level of fit is an attribute of the sparse data on this material). In this case then it is rather straightforward to develop the confidence limits for the percentiles. For example, at the 80^{th} percentile in Figure H.2, the user may choose to use 80 E-3 or 150 E-3 as the division between the No Action or Further Study areas (see Table H.1). The dearth of data leads to the issue faced at the 95^{th} percentile where the data would suggest an upper limit at 540, while the distribution argues for 250. In these situations it would seem prudent to recognize the limitations in the data and weight the limit towards the data; in this case 515. However, in this case, the issue carries less sensitivity in that it refers to the upper limit, which is rarely used to determine criteria.

The situation is more complicated for the filled insulation—mineral-filled EPR and carbon-black filled EPR categories—as a single distribution does not provide an adequate fit for any of the features. In these cases, it is necessary to recognize the constraint of the Weibull approach in that it is designed to be applied to a single mode at a time. Therefore it is necessary to segregate the complete datasets into smaller subgroups and then apply a distribution approach. The segregation is straightforward and can be accomplished by inspection of the empirical distributions; to date it has not been found necessary to use any optimization tools. The outcome of this approach is shown for the tip up data for the mineral-filled EPR class (Figure H.3). In this case three separate distributions (1, 2, and 3) have been used; of these distributions #3 is of most interest for the criteria at the 80th and 95th percentiles. As can been seen, the distribution fit is adequate over the area of interest and thus the confidence range for the tip up can be established—No Action Required to Further Study, 3.7 to 6.75, and Further Study to Action Required, 74 to 135. The outcome for all features and types of filled insulation class are shown in Table H.1.

The revision of this document has clearly demonstrated the benefits of clearly establishing the methodology (date driven, consistent percentiles, percentile estimates, etc.) for the selection of the critical levels. The chief among these benefits is the availability of a framework with which to rapidly and transparently update criteria as more data become available.

The criteria used for the historical figures of merit provided in this document have been selected using the estimate of the 80th and 95th percentiles, not the lower confidence limits.

Many users will find the ranges provided in Table H.1 cumbersome to use and will prefer the clarity of the percentile estimates in the main document. However, there is a benefit in recognizing the probabilistic nature of the criteria.

Table H.1—Historical figures of merit for condition assessment of service-aged filled insulations using 0.1 Hz including the upper and lower 95% confidence limits

Condition assessment limits	Filled insulation systems	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0 $[10^{-3}]$		Differential VLF-TD (VLF-DTD) (difference in meanVLF-TD) between 0.5 U_0 and 1.5 U_0 $[10^{-3}]$		Mean VLF-TD at U_0 $[10^{-3}]$
No action required to further study	**If it is not possible to definitively identify a filled insulation**	**0.08 < 0.1 0.13**	and	**3.7 < 5 6.75**	and	**30 < 35 41**
	Carbon-filled (Black) EPR	— < 0.1 —		1.64 < 2 2.43		14 < 20 29
	Mineral-filled (Pink) EPR	— < 0.1 —		3.6 < 4 4.5		19 < 20 24
	Discharge resistant EPR	— < 0.1 0.15		5.1 < 6 7.4		80 < 100 150
	Mineral-filled XLPE	—		—		60 < 100 165
Further Study to Action Required	**If it is not possible to definitively identify a Filled Insulation**	**0.97 > 1.3 1.75**	or	**74 > 100 135**	or	**102 > 120 141**
	Carbon-filled (Black) EPR	0.75 > 2.7 9.8		81 > 120 177		66 > 100 151
	Mineral-filled (Pink) EPR	0.68 > 1 1.7		82 > 120 175		75 > 100 133
	Discharge resistant EPR	0.2 > 1 6.4		7.5 > 10 14.1		237 > 350 515
	Mineral-filled XLPE	—		—		212 > 350 576

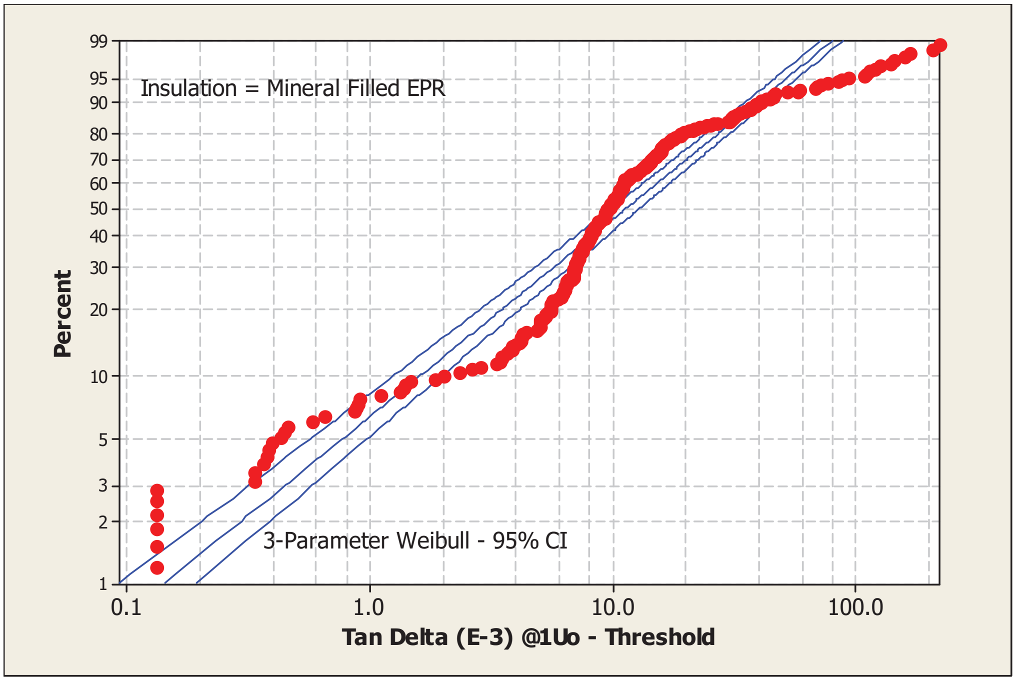


Figure H.1—Three parameter Weibull fit to the available tangent delta data collected at U_0 segregated for mineral-filled EPR

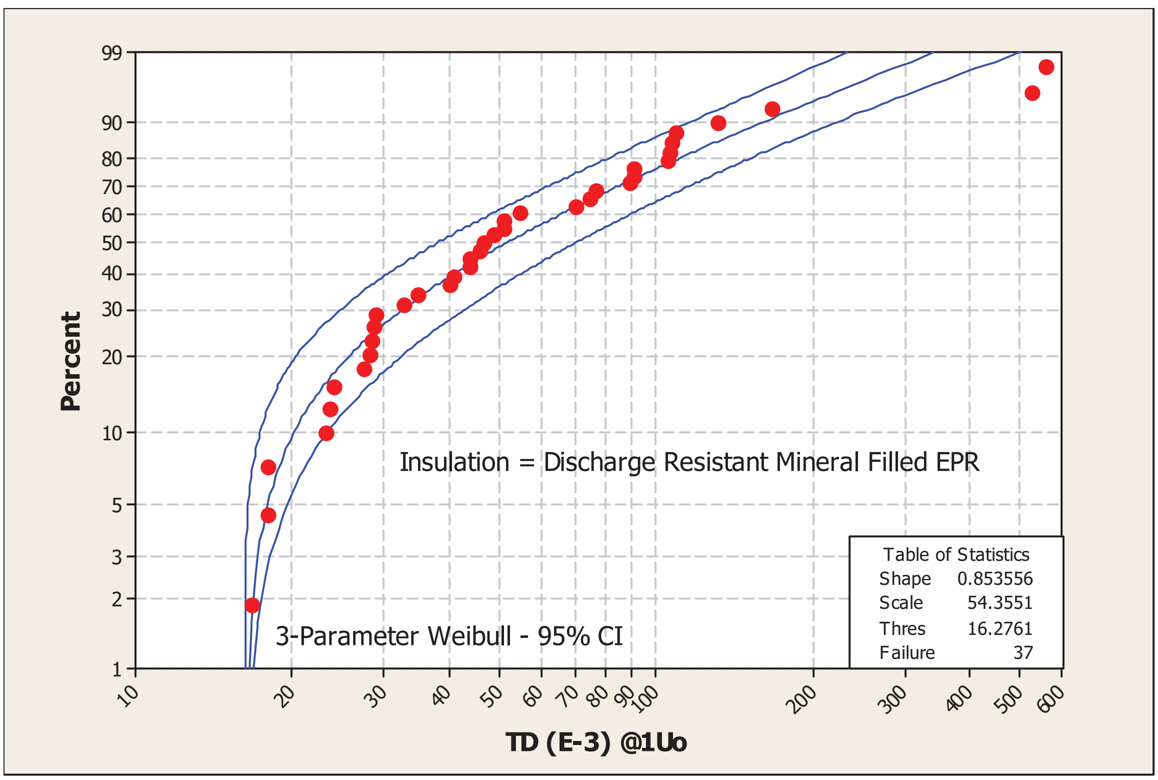


Figure H.2—Three parameter Weibull fit to the available tangent delta data collected at U_0 segregated for discharge resistant mineral-filled EPR

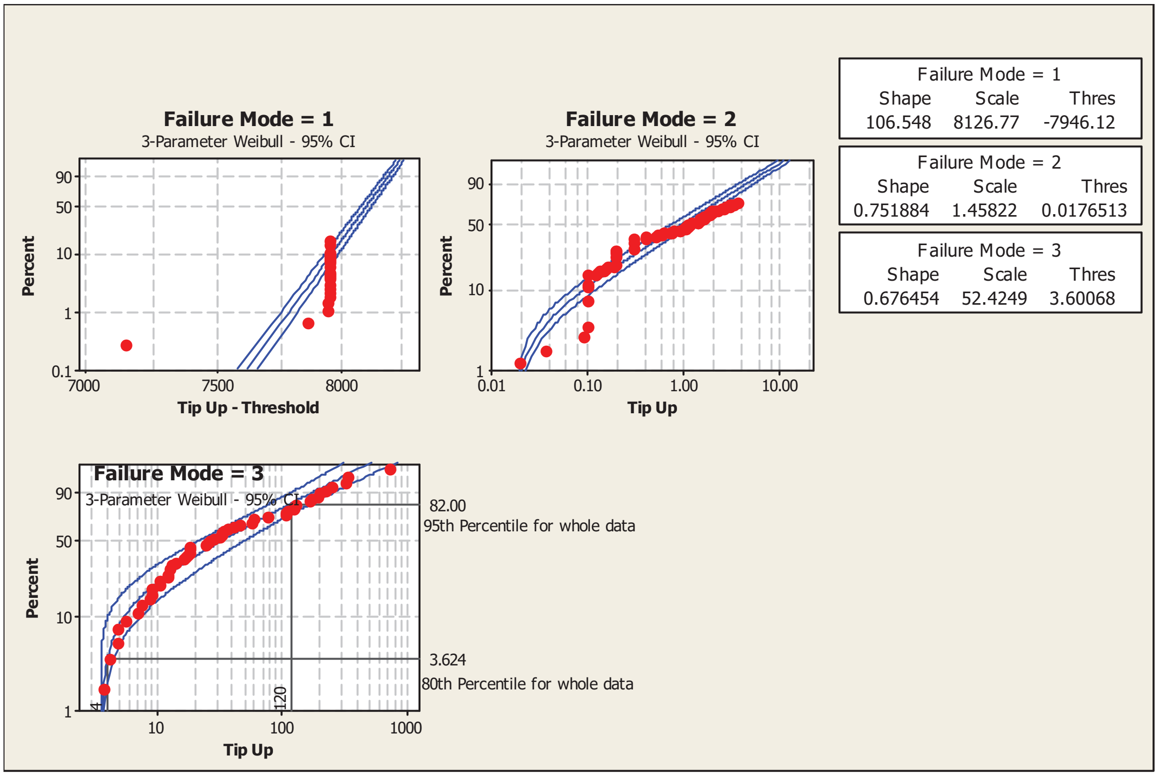


Figure H.3—Three parameter Weibull fits to the different modes within the tip up (tangent delta @ 1.5 U_0 – tangent delta @ 0.5 U_0) data for mineral-filled EPR. Mode 3 is used to establish the confidence limits at the 80th and 95th percentiles of the whole (not segregated into modes) distribution of data

Annex I

(informative)

Tangent delta criteria used outside North America

Table 4 to Table 6 in this guide are based on data obtained on North American cable designs and installations.

Table I.1, Table I.2, Table I.3, and Table I.4 list the ranges in the TD assessment criteria for different cable insulations used in different countries outside North America by industry and utilities. Lower and upper TD and differential TD limits are individually applied. The number of utilities or countries is not known and no information is available about failure occurrences or service conditions.

Table I.1—Alternate figures of merit for condition assessment of PE-based insulations (i.e., PE, XLPE)

Condition assessment	**TD stability (measured by standard deviation) at U_0 [10^{-3}]**		**Differential TD (difference in mean TD) between $2U_0$ and U_0 [10^{-3}]**		**Mean TD at $2U_0$ [10^{-3}]**
No Action Required	< 0.1	**and**	< 0.6	**and**	< 1.2
Further Study Advised	0.1 to 0.5	**or**	0.6 to 1	**or**	1.2 to 2
Action Required	> 0.5	**or**	> 1	**or**	> 2

Table I.2—Alternate figures of merit for condition assessment for PE-with additives based insulations (i.e., TRXLPE, co-polymers), see table note

Condition assessment	**TD stability (measured by standard deviation) at U_0 [10^{-3}]**		**Differential TD (difference in mean TD) between $2U_0$ and U_0 [10^{-3}]**		**Mean TD at $2U_0$ [10^{-3}]**
No Action Required	< 0.5	**and**	< 1.5	**and**	< 8
Further Study Advised	0.5 to 1	**or**	1.5 to 3	**or**	8 to 10
Action Required	> 1	**or**	> 3	**or**	> 10

NOTE—Due to a long term polymerization effect the mean TD results at $2U_0$, immediately after production of co-polymers insulations may be measured significantly higher. After one or two years, the absolute TD values may decrease close to levels similar to XLPE or PE insulations.

Table I.3—International figures of filled insulations (i.e., mineral-filled EPR)

Condition assessment	TD stability (measured by standard deviation) at U_0 $[10^{-3}]$		Differential TD (difference in mean TD) between $2U_0$ and U_0 $[10^{-3}]$		Mean TD at $2U_0$ $[10^{-3}]$
No Action Required	< 0.5	**and**	< 4	**and**	< 10
Further Study Advised	0.5 to 1	**or**	4 to 10	**or**	10 to 80
Action Required	> 1	**or**	> 10	**or**	> 80

Table I.4—International figures for condition of paper insulations (i.e., PILC)

Condition assessment	TD Temporal stability (measured by standard deviation) at U_0 $[10^{-3}]$		Differential TD (difference in mean TD) between $2U_0$ and U_0 $[10^{-3}]$		Mean TD at $2U_0$ $[10^{-3}]$
No Action Required	< –0.5	**and**	–20 to 20	**and**	< 50
Further Study Advised	0.5 to 1	**or**	–20 to –50 or 20 to 50	**or**	50 to 100
Action Required	> 1	**or**	< –50 or > 50	**or**	> 100