



IEEE Guide for Partial Discharge Field Diagnostic Testing of Shielded Power Cable Systems

IEEE Power and Energy Society

Developed by the
Insulated Conductors Committee

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STANDARDS

IEEE Guide for Partial Discharge Field Diagnostic Testing of Shielded Power Cable Systems

Developed by the

Insulated Conductors Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

Abstract: The diagnostic testing of new or service-aged, installed shielded power cable systems, which include cable, joints, and terminations, using electrical partial discharge (PD) detection, measurement, and location is covered by this guide. PD testing, which is a useful indicator of insulation degradation, may be carried out online or by means of an external voltage source. The testing of compressed gas insulated cable or termination systems is not covered by this guide.

Keywords: accessory, cable, cable system testing, cable testing, commissioning, condition assessment, diagnostic testing, field test, IEEE 400.3™, partial discharge testing

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Introduction

This introduction is not part of IEEE Std 400.3-2022, IEEE Guide for Partial Discharge Field Diagnostic Testing of Shielded Power Cable Systems.

This document is intended to provide cable system owners and test operators a working understanding of partial discharge (PD) testing and guidance on performing PD tests on cable systems in the field. The discussion includes the theory and background on the generation and detection of PD, descriptions of common defect types, and information on sensors and detection equipment used to identify and localize PD sources. These PD sources can be excited by subjecting the cable system to voltages generated under normal operation (online) as well as by external voltage sources with various waveshapes.

Of significance since the 2006 edition are the recommended test protocols, including pass criteria, for PD testing of extruded cable systems. These protocols were developed based on typical practices employed with commercially available test-voltage sources, for both new and aged cable components. While the test protocols do not cover every situation and there continues to be debate over voltage-source equivalence, this guide represents a reasonable set of parameters based on the working group's considerable experience.

Acknowledgments

The following individuals have provided substantial contributions to this document but were not members of the working group at time of ballot: Peter Coors, John Densley, Ed Galski, Eberhard Lemke, Frank Petzold, and Mark Walton. The working group is grateful for their efforts.

[Figure 5](#), [Figure 7](#), and [Table 3](#) are from CDFI Phase 2 Final Report and reprinted with permission from Georgia Tech NEETRAC, Chapter 7, “Medium Voltage Cable System Partial Discharge,” © 2015.

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IEEE Guide for Partial Discharge Field Diagnostic Testing of Shielded Power Cable Systems

1. Overview

1.1 Scope

This guide covers the diagnostic testing of new or service-aged, installed shielded power cable systems, which include cable, joints, and terminations, using electrical partial discharge (PD) detection, measurement, and location. PD testing, which is a useful indicator of insulation degradation, may be carried out online or by means of an external voltage source. This guide does not cover the testing of compressed gas insulated cable or termination systems.

1.2 Purpose

This guide describes diagnostic methods capable of detecting and locating PD from defects and damage in installed shielded power cable systems. The results of PD tests can be used to assess the condition of cables and accessories.

1.3 Word usage

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

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

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

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

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

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

1.4 Background

PDs are small electric sparks or discharges that may occur at defects in the insulation, at interfaces or surfaces, between a conductor and a floating conductive component (not connected electrically to the high voltage conductor or to the ground conductor), or between floating conductive components. PD occurs if the electric field is high enough to cause ionization of the medium in which the components are located. The discharges do not bridge the insulation between conductors completely, and the defects may be entirely within the insulation, along interfaces between insulating materials (e.g., at accessories), or along insulation surfaces (terminations or potheads).

PD characteristics depend on the type, size, shape, and location of defects, the insulating material, the applied voltage, and the cable temperature, and they can vary in magnitude or repetition rate with time. The potential damage caused by PD depends on several factors and can range from negligible to causing failure within seconds to years.

Advances in digital (electrical) measurement technology, both in the time and frequency domains, have improved the effectiveness of PD measurements, especially in environments where high background noise levels exist that are in the same frequency band as that of the PD. This has led to an increasing number of PD measurements being performed on cable systems in the field, particularly on medium-voltage systems.

The purpose of such measurements is to use PD characteristics (such as location, extinction voltage, etc.) as a tool for assessing the conditions of the cable and accessories. The remaining life of the cables cannot be predicted with great accuracy; however, new cable systems are expected to be free of PD. This technology cannot determine with complete confidence that a specific cable is in very good condition with essentially no probability of failure in the near future, as failure can be caused by phenomena that do not generate PD. However, the PD measurement can, at times, predict with a high level of confidence that a given cable is in very poor condition and is likely to fail in the near future.

This guide provides background information on PD detection and location techniques for users of PD testing services of cables with laminated or extruded insulations, and it provides background information on the interpretation of PD data. In this guide, *cable* may also refer to a cable system that includes cables and accessories.

PD measurements are used in a variety of environments (field, laboratory, and factory) and for multiple purposes (qualification, quality assurance, and condition assessment). It is important to understand the basic differences between these environments, as the metrics and noise mitigation strategies are quite different. These differences are discussed in [Table 1](#).

Table 1—Testing environments and their respective objectives

Location	Test type	Description
Laboratory	Research	Tests conducted on new or aged accessories and cable together as a cable system to study the interactions between them from a research perspective. The research is commonly focused on investigating design issues and/or estimation of the aging and degradation mechanisms that a cable system as a whole experiences during its service life.
	Qualification	Industry standard tests completed <i>to</i> ensure the effectiveness of the manufacturing processes, equipment, and procedures used to produce cable system components for field use.
Factory (manufacturer)	Quality assurance (factory or routine tests)	Tests carried out on new accessories or cable to verify that they comply with industry standards. Tests are performed routinely as part of the production line.
Field (utility, generation, or industrial)	Commissioning	Tests deployed to check the integrity of the individual components (cable and accessories), their interfaces, and the cable system as a whole, including damage that could have occurred during installation and/or workmanship issues.
	Maintenance	Tests intended to detect deterioration and to verify the serviceability of cable systems in service for some length of time.

The primary difference between field and factory tests is that factory tests are performed on unaged cable or accessories, while field tests are performed on complete cable systems that include both cable and accessories installed together as a system. Field tests are performed on systems with new and aged components, thus making them the more challenging to undertake.

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.

IEC 60060-3, High-voltage test techniques—Part 3: Definitions and requirements for on-site testing.⁸

IEC 60270, 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.

IEEE Std 4TM, IEEE Standard for High-Voltage Testing Techniques.^{9,10}

IEEE Std 400.2TM, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz).

IEEE Std 400.4TM, IEEE Guide for Field Testing of Shielded Power Cable Systems Rated 5 kV and Above with Damped Alternating Current (DAC) Voltage.

⁸IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

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

charge magnitude: *See:* **partial discharge (PD) magnitude.**

commissioning test: Test applied to a newly installed cable circuit to verify that the cable circuit is installed correctly and is able to work satisfactorily.

damped ac (DAC): Starting from a (negative or positive) maximum voltage level and having damped sinusoidal oscillations around the zero level. It is characterized by the peak value, V_{DAC} , the circuit natural frequency, f_n , and the damping factor, D_f .

maintenance test: Test made during the operating life of a cable circuit in order to detect deterioration in the cable circuit or to check workmanship after a repair.

narrow band (NB): Partial discharge (PD) detection circuit with a midband frequency between 50 kHz and 1 MHz and bandwidth in the range of 9 kHz to 30 kHz.

near power frequency (NPF): Continuous sinusoidal voltages in the frequency range from 20 Hz to 300 Hz. Frequencies as low as 10 Hz may be used for very long cable lengths, for example, submarine cables.

partial discharge extinction voltage (PDEV): The applied voltage at which repetitive partial discharges (PDs) cease to occur in the test object when the applied voltage is gradually decreased from a higher value at which PD pulse quantities are observed.

partial discharge inception voltage (PDIV): The applied voltage at which repetitive partial discharges (PDs) are first observed in the test object when the applied voltage is gradually increased from a lower value at which no PDs are observed.

partial discharge (PD) magnitude: Magnitude associated with a PD pulse received and recorded by a measuring system. This may be reported as a voltage or charge. In the case of a reported charge, a suitable pulse injector is used to inject pulses of known charge into the cable system and measuring system to establish the scaling for the measuring system.

partial discharge (PD) repetition rate: The total number of PD pulses recorded in a selected time interval or number of cycles divided by the duration of this time interval or number of cycles. Usually, only pulses above a specified magnitude or within a specified range of magnitudes are considered.

phase-resolved partial discharge (PRPD) pattern: A visual representation of partial discharge (PD) pulse activity (number and magnitude) during a specified time relative to the ac cycle phase position.

prestress test: A test or part of a test during which a high enough voltage is applied for a sufficient time to initiate partial discharges (PDs) in potentially life-limiting insulation defects.

NOTE—This is the highest applied voltage for a particular PD test sequence and should never be greater than the specified withstand level of the component with the lowest withstand rating.¹²

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

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

pulse height distribution: Number of pulses within a series of equally spaced windows of pulse magnitude during a specified measuring time.

temporary overvoltage (TOV): An oscillatory overvoltage associated with switching or faults (e.g., load rejection and single-phase faults) and/or nonlinearities (e.g., ferroresonance effects and harmonics) of relatively long duration, which is undamped or slightly damped.

time-domain reflectometry: A technique whereby one or more fast low energy pulses are injected into the cable system and the resulting reflections from changes in characteristic impedance are recorded. This provides information on system configuration, length, and potential diagnostics.

U_0 : Phase-to-ground voltage based on component rating for acceptance tests or system nominal voltage for maintenance tests.

ultra-wideband (UWB): Partial discharge (PD) detection circuit with a detection bandwidth greater than 500 kHz with no specific definition. No direct correlation with apparent charge level can be established.

very low frequency (VLF): Continuous, alternating sinusoidal or cosine-rectangular voltage with a recommended fundamental frequency of 0.1 Hz.

wideband (WB): Partial discharge (PD) detection circuit with a lower-limit frequency in the range of 30 kHz to 100 kHz, an upper-limit frequency less than 500 kHz, and bandwidth in the range of 100 kHz to 400 kHz.

withstand test: A test on a cable/accessory/circuit at a particular voltage for a specified time under specified conditions. To pass the test, the object under test shall not fail or flashover.

3.2 Acronyms and abbreviations

DAC	damped ac
EHV	extra-high voltage
EPR	ethylene propylene rubber
FTRC	frequency tuned resonant circuit
HV	high voltage
ITRC	inductively tuned resonant circuit
NB	narrow band
NPF	near power frequency
PD	partial discharge
PDEV	partial discharge extinction voltage
PDIV	partial discharge inception voltage
PRPD	phase-resolved partial discharge
TOV	temporary overvoltage
UWB	ultra-wideband
VLF	very low frequency
WB	wideband
XLPE	cross-linked polyethylene

4. Overall PD process

Partial discharges (PDs) are a consequence of local breakdown, either as a result of an electric field enhancement within or on the surface of the insulation or from a region of low breakdown strength such as an air void or cavity (throughout this document *void* and *cavity* are used interchangeably). PDs appear as individual events of very short duration that are always accompanied by emissions of light, sound, and heat as well as electromagnetic pulses. They also often result in chemical reactions (see Boggs and Densley [B10]¹³).

The overall process for determining a cable system condition assessment based on PD tests includes the following elements:

- a) Initiation: Generation of a PD when a sufficiently large defect present in the cable system, filled with gas at an appropriate pressure and exposed to an electric field close to the dielectric strength of the gas, experiences a momentary breakdown
- b) Propagation: The process by which an electrical signal generated by a PD event is altered by the cable system (via dispersion and attenuation) as the signal travels away from the PD source along the cable system length
- c) Detection: The use of a sensor and measurement system with sufficient sensitivity to detect the signal produced by a PD source within the cable system
- d) Interpretation: Knowledge rules and tools used to locate and identify the PD source as well as a means of assessing the severity/criticality of the defect
- e) Reporting: The conveyance of results of a PD test to the cable system owner with enough information for the owner to decide on any remediation to be pursued

The PD process elements described above constitute the primary structure of this guide. The focuses of this guide are the practices used in the detection, interpretation, and reporting of PD tests conducted in the field. The inclusion of the generation and propagation elements are meant to provide the user with sufficient background knowledge to understand the issues surrounding PD testing practices. This should aid the user in determining which approaches he/she wishes to undertake in assessing his/her cable system.

5. PD initiation

5.1 General

In cable systems, PD occurs in voids or interfaces between insulating and semiconducting surfaces. These are generally considered to be of the Townsend type of discharge. Such a discharge requires the following conditions to occur:

- A gas-filled void of sufficient size
- Low enough pressure within the void
- Electric field greater than the breakdown strength of the gas (inception stress)
- An available free electron

The process requires a free electron (e.g., from cosmic rays) to be accelerated through the void by an electric field with sufficient energy to cause additional electrons to be freed when it collides with another molecule. This sets off an avalanche that progresses across the void, generating a discharge, local heating, and erosion of the surrounding material. The void must be large enough so that it can catch a free electron, but once discharges are established, there will be electrons available to initiate a discharge from the charges deposited on the

¹³The numbers in brackets correspond to those of the bibliography in Annex C.

surface by previous PD. The pressure inside the void must also be low enough so that there is enough distance between molecules for the electron to achieve enough kinetic energy to start the avalanche. The electric field must also be sufficiently high (inception) to accelerate the electron fast enough so that its energy is able to break loose additional electrons upon collision. All these conditions are interdependent and, therefore, allow for a variety of conditions that can generate discharge.

This basic description encompasses a variety of defect types that can be found at accessory locations and in extruded and laminated cable systems. The following discussion provides additional information on the specific types of defects that can be identified using PD measurements.

5.2 Type and location of defects

The type of defect and the nature of the insulation structure in which the defect is located affect the discharge signal that is generated and, therefore, the interpretation of PD data. It is well known that defects in cable systems can result in premature failure, so it is important to be able to locate the defects and to determine the type of defect. Defects can be inadvertently introduced into cables or accessories during manufacture, storage, handling, transportation, and installation, or they can develop as the cable system ages in service while exposed to electrical, mechanical, thermal, and environmental stresses. Some defects do not produce PDs. Typically, defects will cause PD only if the local electric stress at the defect exceeds the inception stress in that particular material and geometry.

5.2.1 Typical PD sources in accessories

Less than ideal conditions during installation can lead to the inclusion of defects within accessories in the field. Typical defects that can result in PD are as follows:

- Loose insulation-joint interfaces, especially in the absence or migration of silicone grease, and at indentations made into the insulation during joint installation
- Incorrectly assembled accessories (e.g., misalignment, improper positioning, installation scratches, contamination, and voids)
- Knife cuts or bruises produced by splicing tools, especially at the edges of semiconducting shield cut-backs
- Incorrectly positioned termination stress relief components
- Contamination such as moisture, metal oxide (sandpaper grains), or insulation shield material
- Voids in molded products due to manufacturing issues or improper shrinkage of accessory components
- Insufficient electrical contact between the cable connector and the inner semiconducting layer or between the ground/neutral bond and the outer semiconducting layer
- Contaminated outer surfaces
- Terminal connector hardware (corona)

Modern accessories are designed to have a mechanically stable dielectric interface, but if the device is the wrong size or there is a significant installation defect, differences in thermal expansion and contraction of the cable and accessory components can cause interfacial cavities at high or low temperatures and especially during cooldown periods after high-temperature operation. The cable loading further affects the pressure and, thus, the cavity dimensions as well as PD characteristics: partial discharge inception voltage (PDIV), partial discharge extinction voltage (PDEV), magnitude, and repetition rate. Different types of discharges can be identified by their phase-resolved partial discharge (PRPD) patterns, but it is not an exact science. For example, discharges resulting from a discontinuity in the connector or shield of a splice or a cable can resemble a corona discharge.

5.2.2 Typical PD sources in extruded cables

Typical defects in extruded cable systems that can be sources of PD include the following:

- Voids or cavities within the insulation or at interfaces between the insulation and the semiconducting shields, including knife cuts, gouges, cavities due to poor extrusion, or cracks in the insulation shield
- High-resistance insulation shield or broken neutral
- Electrical trees initiated from protrusions, voids, or water trees

These defects are discussed in more detail below.

5.2.2.1 Voids/cavities within the insulation or at interfaces between the insulation and the semiconducting shields

These defects are characterized as gas-filled holes within either insulation or between the insulation and semiconducting shields. The gas is typically air but can also include gaseous byproducts from the cross-linking process (methane, acetophenone, etc.). The type of gas, shape, size, location, and pressure conditions within the void all affect the discharge behavior of these defects.

The conditions within voids and cavities change in time as the discharge process erodes the walls and increases the pressure (temporarily) within the defect. This, in turn, produces different pulse shapes and can impact the inception stress. Discharges detected at lower stresses can disappear temporarily unless the stress is increased to reignite the process.

Both the PD magnitude and the repetition rate increase with cavity surface area. Multiple discharges can occur within the same cavity if the surface area is large; with time, however, as the conductivity of the cavity surfaces increases, the multiple discharges can merge into a smaller number of larger magnitude pulses. The PD magnitude will also increase with cavity depth. Therefore, any thermal expansion and contraction with cable loading that affects the cavity dimensions will affect the PD. In smaller diameter spherical cavities, discharges can cease with time as the walls of the cavity become conductive or if the pressure of the gas in the cavity increases. Raising the test voltage can reignite the discharge sites.

Flat cavities can occur at interfaces, such as the insulation/semiconducting shields. At voltages well above the PDIV/PDEV, discharge in such flat cavities can consist of a large number of spatially distributed discharges. Wideband detection can be able to resolve them in time as separate events. With conventional low-frequency, narrow-bandwidth PD detectors (midband frequency between 50 kHz and 1 MHz and bandwidth in the range of 9 kHz to 30 kHz; see IEC 60270:2000 [B21]), the individual discharges cannot be distinguished, and pulse superposition can take place, resulting in a much greater measured PD magnitude and much lower PD repetition rate than actually occurs. Cavities adjacent to a semiconducting shield or a conductor can have a polarity bias on the PRPD pattern (larger or more pulses on the positive or negative half cycle).

The usual progression of damage in cavities due to PD is the gradual erosion of the surfaces, the creation of pits, and the eventual formation of surface tracks or electrical trees, which can grow relatively rapidly to breakdown and failure of the cable.

5.2.2.2 High-resistance insulation shield or broken neutral

The resistivity of the semiconducting insulation shield of an unjacketed extruded cable can increase significantly if the shield becomes contaminated with an organic liquid such as transformer oil, gasoline, or the preservatives used in some wood utility poles. Such contamination is most likely to occur at the base of a utility pole, where the cable enters the ground, or in industrial chemical plants. A high resistivity insulation shield causes an increase in the electric stress at the neutral wires/tapes; consequently, PD can occur between the neutral wires/tapes and the outer insulation semiconducting shield.