IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment

IEEE Power Engineering Society

Sponsored by the
Insulated Conductors Committee

400.3™

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

5 February 2007

IEEE Std 400.3™-2006

IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment

Sponsor
Insulated Conductors Committee
of the
IEEE Power Engineering Society

Approved 15 September 2006

IEEE-SA Standards Board

Abstract: This guide covers the diagnostic testing of new or service-aged installed shielded power cable systems, which include cable, joints, and terminations, using partial discharge (PD) detection, measurement, and location. Partial discharge testing, which is a useful indicator of insulation degradation, may be carried out on-line or off-line by means of an external voltage source. This guide does not include the testing of compressed gas insulated systems or continuous on-line monitoring at normal service voltage.

Keywords: cable system testing, cable testing, diagnostic testing, off-line partial discharge testing, on-line partial discharge testing, partial discharge testing

---

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Print: ISBN 0-7381-5221-8 SH95571
PDF: ISBN 0-7381-5222-6 SS95571

Introduction

This introduction is not part of IEEE Std 400.3-2006, IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment.

Cable systems need to be tested after installation, periodically during their service life, occasionally after frequent failures in specific types of cables or accessories, and whenever a decision needs to be made about cable repair or replacement. The main purpose of testing is to provide a high degree of service reliability in the most economic fashion. To guarantee optimum performance of the power cable system, standards and guidelines have been developed that address the specific testing requirements for newly installed and service-aged extruded and laminated dielectic insulation.

This guide was prepared by working group C-19W of the IEEE Insulated Conductors Committee.

Notice to users

Errata

Errata, if any, for this and all other standards can be accessed at the following URL: http://standards.ieee.org/reading/ieee/updates/errata/index.html. Users are encouraged to check this URL for errata periodically.

Interpretations

Current interpretations can be accessed at the following URL: http://standards.ieee.org/reading/ieee/interp/index.html.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents or patent applications for which a license may be required to implement an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Participants

At the time this guide was completed, the C-19W Working Group had the following membership:

Matthew S. Mashikian, *Chair*
Willem Boone, *Vice Chair*

Nezar Ahmed
Lawrence W. Bobb
Steven A. Boggs
Arvid J. Braun
John R. Densley
Swapan K. Dey
Craig Goodwin
Edward Gulski
Richie Harp
Stanley V. Heyer
John Hinkle
William Larzelere
Rachel I. Mosier
Ralph E. Patterson
Johannes Rickmann
Dirk Russworm
Lawrence Salberg
Albert Spear
William A. Thue

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Roy W. Alexander
Butch Anton
Ali Al Awazi
Saber Azizi-Ghannad
Michael P. Baldwin
Earle C. Bascom III
Martin Baur
Michael G. Bayer
Steven A. Boggs
Kenneth E. Bow
Chris Brooks
Kent W. Brown
William A. Byrd
Jim Y. Cai
Mark S. Clark
John H. Cooper
Tommy P. Cooper
Jorge E. Fernandez Daher
J. P. Disciullo
Gary L. Donner
Randall L. Dotson
Dana S. Dufield
Donald G. Dunn
Gary R. Engmann
Robert B. Fisher
Rabiz N. Foda
Marcel Fortin
Carl J. Fredericks
Edgar O. Galyon
R. B. Gear Jr.
David L. Gilmer
Steven N. Graham
Randall C. Groves
Ajit K. Gwal
Adrienne M. Hendrickson
Lauri J. Hiivala
Ajit K. Hiranandani
David A. Horvath
Dennis Horwitz
David W. Jackson
A. S. Jones
James H. Jones
Gael Kennedy
Joseph L. Koepfinger
Jim Kulchisky
Saumen K. Kundu
Thomas W. La Rose
Solomon Lee
Maurice Linker
William E. Lockley
Lisardo Lourido
William Lumpkins
G. L. Luri
Glenn J. Luzzi
Eric P. Marsden
Matthew S. Mashikan
William M. McDermid
Nigel P. McQuin
John E. Merando Jr.
Gary L. Michel
Rachel I. Mosier
Jerry R. Murphy
Shantanu Nandi
Michael S. Newman
Joe W. Nims
Ralph E. Patterson
Allan D. St. Peter
Johannes Rickmann
Michael A. Roberts
Robert L. Seitz
David Singleton
Michael J. Smalley
James E. Smith
S. Thamilarasan
James E. Timperley
Joseph J. Vaschak
Waldemar G. Von Miller
Edward E. Walcott
Carl T. Wall
Mark D. Walton
William D. Wilkens
James W. Wilson Jr.
Luis E. Zambrano
Donald W. Zipse

When the IEEE-SA Standards Board approved this application guide on 15 September 2006, it had the following membership:

Contents

IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment

1. Overview

This guide is one of a series of guides introduced in IEEE Std 400™-2001.[1] It is divided into 10 clauses, as follows:

- Clause 1 provides the scope and the purpose of the guide.
- Clause 2 lists the references to other standards or guides that are useful in applying this guide.
- Clause 3 provides definitions that are of particular importance for the understanding of this guide and lists a glossary of abbreviations and acronyms.
- Clause 4 provides basic interpretation of partial discharge (PD) data.
- Clause 5 describes the different types of PD detection methods.
- Clause 6 briefly describes the voltage sources available commercially.
- Clause 7 offers useful practical testing guidelines.
- Clause 8 discusses the expected test results and recommendations.
- Clause 9 is devoted to the safety precautions to be observed during testing.
- Clause 10 provides conclusions.

This guide also contains four annexes. Annex A expounds, in some detail, on the question of water treeing and partial discharge in cables with extruded dielectrics. Annex B shows how the partial discharge inception voltage changes with the cavity shape, location, and material. Annex C discusses in greater detail the subjects of PD calibration and location accuracy. Annex D is the bibliography.

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

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 PD detection, measurement, and location. Partial discharge testing, which is a useful indicator of insulation degradation, may be carried out on-line or by means of an external voltage source. This guide does not include the testing of compressed gas insulated systems or continuous on-line monitoring at normal service voltage.

1.2 Purpose

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

1.3 Background

PDs are small electric sparks or discharges that occur in defects in the insulation, or at interfaces or surfaces, or between a conductor and a floating metal component (not connected electrically to the high-voltage conductor nor to the ground conductor), or between floating metal components if the electric field is high enough to cause ionization of the gaseous medium in which the components are located. The discharges do not bridge the insulation between conductors, and the defects may be entirely within the insulation, along interfaces between insulating materials (e.g., at accessories) or along surfaces (terminations or potheads).

Partial discharge characteristics depend on the type, size, and location of the defects, insulating material, applied voltage, and cable temperature, and they vary with time. The damage caused by PD depends on several factors and can range from negligible to causing failure within days to years.

Advances in digital (electrical) measurement technology, both in the time and frequency domains, have improved the sensitivity of PD measurements. This has led to an increasing number of PD measurements on cable systems, particularly on medium-voltage systems. The purpose of such measurements is to assess the current condition of a cable circuit. At the current state-of-the-art, very good cables and very bad cables can generally be identified. It is the remaining life of the cables between these two extremes that cannot be predicted with great accuracy. As well, 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.

2. Normative references

The following referenced documents are indispensable for the application of this document. 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 C-2, National Electrical Safety Code® (NESC®).[2]

ICEA T-24-380-1994, Guide for Partial-Discharge Test Procedure.[3]

IEC 60270, High-voltage test techniques—Partial discharge measurements.[4]

IEC 60885-2, 1987, Electrical test methods for electric cables—Part 2: Partial discharge tests.

IEC 60885-3, 1987, Electrical test methods for electric cables—Part 3: Test methods for partial discharge measurements on lengths of extruded power cables.

IEEE Std 400™-2001, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems.[5, 6]

IEEE Std 400.2™-2004, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF).

IEEE Std 510™, IEEE Recommended Practices for Safety in High-Voltage and High Power Testing.[7]

NFPA-70E, Standard for Electrical Safety Requirements for Employee Workplaces.[8]

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B18][9] should be referenced for terms not defined in this clause.

[2] ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).
[3] ICEA publications are available from the Insulated Cable Engineers Association, P.O. Box 20048, Minneapolis, MN 55420, USA (http://www.icea.org/).
[4] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
[5] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08855, USA (http://standards.ieee.org/).
[6] The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.
[7] IEEE Std 510-1983 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).
[8] NFPA publications are available from Publication Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (http://nfpa.org/codes/index.html).
[9] The numbers in brackets correspond to those of the bibliography in Annex D.

3.1.1 electrical trees: Tree-like growths consisting of non-solid or carbonized microchannels, which can occur at electric field enhancements such as protrusions, contaminants, voids, or water trees subjected to electrical stress for extended time periods. Partial discharges are responsible for electrical tree growth.

3.1.2 extruded insulation: Insulation such as high-molecular-weight polyethylene (HMWPE), crosslinked polyethylene (XLPE), tree-retardant XLPE (TRXLPE), ethylene propylene rubber (EPR), etc. applied using an extrusion process.

3.1.3 laminated insulation: Insulation formed in layers typically from tapes of either cellulose paper or polypropylene or a combination of the two. An example is the PILC (paper insulated lead covered) cable design.

3.1.4 partial discharge (PD) pulse: A current or voltage pulse that results from a partial discharge. In a cable, the pulse propagates away from the PD source in both directions.

3.1.5 pulse sequence: The occurrence of partial discharge (PD) pulses as a function of time that can be used to determine statistical correlations such as the amplitude of one pulse and the time to the next pulse.

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

3.2 Acronyms and abbreviations

CAIFI	customer average interruption frequency index
DAC	damped ac voltage
E_d	stress in the insulation adjacent to the cavity
EPR	ethylene propylene rubber
FTRC	frequency tuned resonant circuit
HMWPE	high-molecular-weight polyethylene
ITRC	inductively tuned resonant circuits
MAIFI	momentary average interruption frequency index
n	partial discharge pulse repetition rate
PD	partial discharge
PDEV	partial discharge extinction voltage, V_e
PDIV	partial discharge inception voltage, V_i
PILC	paper insulated lead covered
PPE	personal protective equipment
q	apparent discharge magnitude
SAIDI	system average interruption frequency index
SOV	system operating voltage
T	period of the test voltage
t_i	time measured from the preceding positive going transition of the sinusoidal test voltage through zero to the PD pulse
TDR	time domain reflectometry
TRXLPE	tree-retardant crosslinked polyethylene
V_o	nominal operating voltage to ground
VLF	very low frequency
XLPE	crosslinked polyethylene
Φ	phase angle of PD pulse given by $\Phi_i = 360\ (t_i/T)$

4. Partial discharge data interpretation

Partial discharges are a consequence of local breakdown either as a result of (a) an electric field enhancement within or on the surface of the insulation, or (b) a region of low breakdown field. PDs appear as individual events of very short duration; are always accompanied by emissions of light, sound and heat, as well as electromagnetic pulses; and often result in chemical reactions.

The PD parameters that are usually measured during tests on installed cable systems are as follows:

- PD inception voltage, PDIV (off-line tests).
- PD extinction voltage, PDEV (off-line tests).
- PD location.
- PD magnitude (q).
- PD repetition rate (n).
- PD density—the density of discharges measured per unit of time and per unit of length (pC/m.s) (laminated cable only).
- Phase angle of PD pulse (Φ) given by $\Phi_i = 360\ (t_i/T)$, where t_i is the time measured from the preceding positive-going transition of the sinusoidal test voltage through zero to the PD pulse, and T is the period of the test voltage.
- Phase resolved PD plot (n vs. Φ vs. q).
- PD magnitude vs. voltage plot (q vs. V), (off-line tests).

The characteristics of the PD parameters depend on

- Type and location of defects, i.e., PD sources, in the insulation system.
- Insulating material.
- Operating conditions such as applied voltage, load, and time.
- On-line tests can measure q, n, and Φ at operating temperature, whereas off-line tests are performed on cable systems that have cooled down.

Each of these characteristics affects the interpretation of PD data and will be discussed separately in 4.1, 4.2, and 4.3.

Water treeing is an important form of degradation that can afflict older HMWPE and XLPE extruded cables. At the site of a water tree, the insulation is degraded, i.e., has a higher dielectric constant and lower dielectric strength than the original insulation. The water tree growth under service conditions is a very slow process, and usually it takes many years to completely penetrate the insulation. Water trees do not generate partial discharge. However, water trees can lead to electrical trees when subjected to high electrical stresses as a result of a lightning impulse, a switching or dc overvoltage, a high ac voltage, or when the tip of the water tree approaches a conductor or insulation shields. There is no evidence of water treeing being an important issue with EPR or TRXLPE cables.

A more comprehensive treatment of the subject of water trees and PD is provided in Annex A.

The existence of PD does not indicate the likelihood of the PD to cause failure without additional information concerning the source of the PD. Although discharge-free cables manufactured since 1994 have less than 5 pC at 8 kV/mm (200 volts/mil), cables made prior to 1987 may have partial discharge above 5 pC as allowed by industry specifications (AEIC) at the time of manufacturing. Measurement of partial discharge in the field above 1 V_o, where V_o is the nominal operating voltage to ground of the cable system, does not necessarily indicate that these cables have developed partial discharge due to in-service aging.

The detected apparent discharge magnitude, q, may or may not play a significant role in determining the severity of the defect, particularly when comparing different defects. For example, a few picoCoulombs detected from an electrical tree in an extruded insulation may require an immediate repair or replacement; however, thousands of picoCoulombs of partial discharge between the cable neutral and ground shield is tolerable in that same extruded insulation. If the defect type is known, the PD magnitude, along with other parameters, may give a general indication of the condition of a defect in both extruded and fluid impregnated cables. There is usually a statistical variation in the PD magnitudes when measurements are made over a short time for a particular defect site. Variations of PD magnitude of up to 100% for a particular discharge site are neither uncommon nor usually significant.

Numerous studies have attempted to correlate PD characteristics with various defect types in extruded cables and accessories to determine whether a particular type of defect has unique PD characteristics (Kreuger [B20], Suzuki and Endoh [B29], Gulski [B13]). Earlier studies tried to relate quantities such as discharge magnitude and discharge power to damage caused by PD without success. However, phase-resolved PD plots, which provide more complete characterization of the PD, have only become available in the last five to ten years. Much of this later work is proprietary as it is used by PD testing companies to determine the type of defect, the amount of damage caused by PD at the defect, and to assess the condition of the cable system. Experience developed by correlating PD data with physical examination or dissection of cable PD sites forms the basis of the know-how used to make PD severity assessments. The voltage V_i at which a discharge is initiated (PDIV) and the voltage V_e at which a discharge is extinguished (PDEV) are critical values for extruded cables. The PDEV can be significantly less than the PDIV. In practice, the extinction voltage V_e is often the lowest voltage at which the magnitude of a PD pulse becomes equal to or less than the sensitivity of the measuring equipment, and the inception voltage V_i is often the lowest voltage at which the magnitude of a PD pulse quantity becomes equal to or exceeds the sensitivity of the measuring equipment..

For laminated cables and their accessories, where PD can be tolerated for a long time due to the high PD resistance of impregnated paper, the use of so-called guidelines (van Schaik et al. [B31]) can be an effective tool to improve data interpretation. These guidelines describe the typical behavior of materials or a combination of different materials under a discharge regime. For some components, 100 pC or 200 pC may already be a dangerous level, for example, if carbonized tracks have developed, whereas for others, 104 pC or more will probably not affect the future performance. These guidelines form the basis of “objective” recommendation criteria (van Schaik et al. [B31]).

There is a significant level of uncertainty in the interpretation of PD data with respect to predicting the future performance of cable systems due to the statistical behavior of PD:

- Some data are obtained from accelerated aging tests in the laboratory. There is always a question of the validity of accelerated aging test data to predict the performance under normal service conditions. This introduces some uncertainty in the application of accelerated aging data to field test data.
- Aging tests are usually performed on a limited number of test cables and accessories, with or without artificial defects, so that not all types of cables, accessories, and defects are tested.
- There is usually a significant variation in the PD characteristics among similar test cables and accessories, with or without artificial defects, which have been subjected to the same aging test conditions. For example, it is not unusual in tests on five or more identical test samples to have an order-of-magnitude variation in the time to failure.

Apart from the scatter in the PD characteristics for "identical" defects in the same cable system, there is further variation in the PD characteristics with time under voltage.

The precision in interpretation of PD data varies with the defect type; for example, it is usually easier to predict the damage and assess the condition of a cable for an electrical tree than for a cavity or void.

As a general rule, the accuracy in interpretation is good when testing "very good" or "very bad" cable systems.

- Very good cable systems will exhibit low levels of PD activity; for example, the PDIV will be typically greater than 2 V_o. This, of course, assumes that the background noise is low and that the sensitivity of the measurements is good (better than 5 pC or equivalent mV reading). It should be noted that a cable system with a measured PDIV above 2 V_o does not guarantee a long life. For example, a lightning surge could initiate an electrical tree and cause rapid failure or it could initiate an otherwise intermittent PD that was extinguished at the time of the test. The probability of these conditions occurring is small but not zero.
- Very bad cable systems will typically exhibit a low PDIV with well-defined PD characteristics such as easily recognizable phase-resolved PD patterns similar to those known to occur at defects that degrade the cable system (e.g., improperly installed accessories). It should be noted that recognizing phase-resolved patterns is not always accurate and the wrong identification of defects can sometimes occur. However, these occurrences should decrease as more experience is gained.

The accuracy in interpretation is lower for cables between the "very good" and "very bad" conditions. The accuracy is often affected by the sensitivity of the measurement, which varies from location to location and also with time. For example "false positives" can occur when the PD detected is incorrectly identified as occurring within the cable system when it is actually originating from an external source, or the defect causing the PD has been incorrectly identified due to too high or too low measurement sensitivity and/or high background noise. "False negatives" can occur if PD signals were missed, for example, by insufficient sensitivity of the detection system, high background noise, operator error, or high pulse attenuation along the cable system. As a PD pulse propagates along a cable, it suffers increasing attenuation with frequency, which results in an increasing width of the PD pulse and decreasing amplitude as a function of the distance propagated away from the PD source. However, the total area under the pulse, which is proportional to charge, remains relatively constant. Repeating the measurements on the same cable circuits can sometimes reduce the risk of incorrect interpretation.

The accuracy in interpretation can be increased if the following criteria are met:

- All relevant information about the cable system is known. This includes the age and type of cable(s) under test (insulation type, presence of jacket, cable design, etc.), the number and types of accessories in the circuit of the cables, and the operating conditions (duct, direct buried, wet, dry or both, incidence of surges, load conditions, previous failure behavior, etc.).
- Cable dissections are carried out on failed cable. This will help in the correlation between possible failure mechanisms and the measured PD characteristics.
- Additional testing and eventual dissection are performed on cables and accessories removed from service to establish correlations between PD characteristics and cable system performance such as time to failure.
- As more data are collected on cable systems in service, better correlations between PD measurements and future performance may be established.
- Measurements are repeated periodically to obtain trends in the data. In this way the rates of change of the PD characteristics can be determined, for example, changes in the phase-resolved PD patterns, discharge magnitudes, PDIV, and so on.

— Standardized test and analysis procedures are developed. When standardized test and analysis procedures have been developed, these will aid the comparison of databases of different PD service providers and also from different utilities.

Some PD testing companies store their field test data in a data bank that classifies PD characteristics according to the different defects in order to establish "knowledge rules." As more tests are performed, more data are accumulated and can be compared with the future performance of the cable system. This builds up a library of data and should gradually improve the accuracy in the interpretation of PD measurements.

Thus, with the current level of knowledge of the interpretation of PD data, the accuracy in estimating the future performance of a cable system varies according to the cable condition. As mentioned, the accuracy is reasonably good for very good or very bad cables, but it is lower for cable systems between these conditions. The accuracy can be further improved as more data are accumulated. Greater confidence in the accuracy in the data interpretation on particular cable circuits can be gained if periodic measurements are made so that trends in the data can be established. When properly implemented PD testing is very useful to rank cables, i.e., to determine whether one cable will perform better than another and to prioritize cable replacement.

4.1 Type and location of defects

The type and location of defects affect 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 may be inadvertently introduced into cables or accessories during manufacture, storage, handling, transportation, and installation, or they may develop as the cable system ages in service while exposed to electrical, mechanical, thermal, and environmental stresses. Some defects do not produce partial discharges. Typically, defects will cause PD only if the local electric stress at the defect exceeds the inception stress.

4.1.1 Typical partial discharge sources in extruded cables

Typical defects in extruded cable systems that can be sources of PD are as follows:

— Voids or cavities within the insulation or at interfaces between the insulation and the semiconducting shields. This includes knife cuts, gouges, or cracks in the insulation shield.

— Interfacial cavities in cable and accessory interfaces.

— High-resistance insulation shield or broken neutral.

— Electrical trees initiated from protrusions, voids, or water trees.

Several PD characteristics are usually used to assess the severity of a PD source. These characteristics include, but are not limited to, detailed measurements of its statistical properties (discharge magnitude, repetition rate, phase, etc.) and inception and extinction voltages.

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

The PDIV of a void or cavity will depend on the shape, size, and position of the cavity within the insulation, and the type of gas and its pressure inside the cavity. Annex B shows examples of how the shape of a cavity affects the magnitude of the electrical stress in the cavity. The PDIV for a spherical cavity in XLPE is about twice that for a flat cavity, for example, at a loose insulation shield and almost three times the value for the same cavity shapes in EPR insulation. If the flat cavity is aligned in the direction of the applied electrical stress, i.e., usually radially, the PDIV will be between 20% and 30% greater than that for a spherical cavity of similar size and location.

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 increase, the multiple discharges can merge into a smaller number of larger magnitude pulses. The PD magnitude will also increase with cavity depth. Thus, any thermal expansion and contraction with cable loading that affects the cavity dimensions will affect the PD characteristics (e.g., PDIV, PDEV, q, and n). In smaller diameter spherical cavities, the discharge may cease as the walls of the cavity become conductive or if the pressure of the gas in the cavity increases. Raising the test voltage will re-ignite the discharges. PDs from cavities are identified through phase angle, pulse sequence, and pulse height distribution data.

As the insulation thickness increases for cables with larger voltage ratings, the discharge magnitude in a cavity of the same depth will decrease at the PDIV for a particular cable. For example, a 0.5 mm spherical cavity at the conductor shield in a 15 kV cable will have a magnitude of about 10 pC, but about 5 pC in a 35 kV cable. Typical magnitudes in voids in extruded insulation systems are less than 100 pC for test voltages up to twice the operating voltage.

Cavities, usually flat, can also occur at interfaces, such as the insulation/semiconducting shields. At voltages well above the PDIV, discharge in such flat cavities may consist of a large number of spatially distributed discharges. With wideband detection in such a situation, the individual discharges can be seen to occur almost simultaneously. With conventional low-frequency, narrow-bandwidth PD detectors, the individual discharges cannot be distinguished, and pulse superposition may 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 usually have larger magnitude discharges in one half cycle of the applied voltage than the other.

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 electrical trees, which grow relatively rapidly to complete the failure. The approximate size or the stage of progression can sometimes be determined from the PD magnitude and repetition.

4.1.1.2 Cavities between cable and accessory interfaces (interfacial cavities)

Cavities between the insulation interfaces of cables and their accessories (i.e., interfacial cavities) may occur if there is bad workmanship while removing the insulation shielding, insufficient pressure to maintain good contact, or if silicone grease has migrated from the interface. The cable loading could affect the pressure and thus the cavity dimensions and PD characteristics (PDIV, PDEV, q, and n).

Interfacial discharges or tracking in cavities located at insulation interfaces between the cable and its accessories are often identified from their pulse height distribution, which tends to progress through three stages. At early stages, both PD magnitude and repetition rate are small. As the tracking progresses, both the magnitude and the repetition rate increase. During the final pre-failure stage, the PD magnitude will decrease while the PD repetition rate increases significantly. Therefore, the severity of the tracking is determined by examining the data of both the PD magnitude and the repetition rate.

4.1.1.3 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, so that PD can occur between the neutral wires/tapes and the outer insulation semiconducting shield. This type of PD is identified through the pulse repetition rate, phase angle, dominant polarity, pulse sequence, and pulse height distribution with magnitudes often in the range of hundreds to thousands of pC. Such discharges, although of large magnitudes, seldom result in cable failure. Therefore, trending is beneficial for this type of defect. External PD can also occur if the neutral wires are broken due to corrosion; in which case, a continuity test of the cable neutral may also be performed. Damage to the cable due to external discharges of this type has been reported (Abdolall [B1]). However, such PD is not likely to occur for a jacketed cable, unless the integrity of the jacket has been compromised.

4.1.1.4 Electrical trees initiated from protrusions, voids, or water trees

Protrusions or contaminants within the insulation or at the insulation/semicon interface produce local increases in the electrical stress. If the stress becomes sufficiently large, an electrical tree can be initiated. At the site of an electrical tree, the insulation is damaged irreversibly, partial discharge may be present, and complete insulation breakdown is only a question of time for non-laminated insulation. In general, electrical trees are more difficult to initiate than to grow, so that an electrical tree, once initiated, tends to grow to failure by partial discharge whenever the PD inception voltage is exceeded. The PD magnitudes from an electrical tree depend mainly on the length of the tree in the direction of the electric field and the magnitude of the applied electric field. In some electrical trees the PD magnitudes increase gradually with the increasing length of the tree channels. These discharge magnitudes are larger than those found in spherical cavities. In other electrical trees the magnitudes stay relatively constant but the repetition rate changes as the tree grows.

Cavities generally generate electrical trees prior to failure. An electrical tree, once initiated, often grows rapidly if partial discharges persist, leading to a failure in a relatively short time ranging from minutes to some weeks, depending on the insulation material and operating conditions. A positive detection of an electrical tree should require immediate replacement or repair.

Although partial discharges do not occur during the initiation and growth of water trees, partial discharges do occur when a water tree leads to an electrical tree. The likelihood of causing a water tree to lead to an electrical tree during a field PD test increases with the test voltage magnitude and the test duration. Any partial discharge at a water tree implies the existence of one or more electrical trees at that water tree. An electrical tree initiated from a water tree may be either from an overvoltage such as lightning, a switching surge, or a field test. Alternatively, at operating voltage, the properties of the insulation surrounding the water tree may be such that it leads to the initiation of an electrical tree. Immediate failure of the cable circuit may not result, but failure can occur several hours to several months after electrical tree initiation.

4.1.2 Typical partial discharge sources in fluid-impregnated cables

Fluid-impregnated [paper insulated lead covered (PILC)] cables are more resistant to PD than XLPE cables. Typical sources of PD are as follows:

- Fluid-deficient butt gaps, soft areas of the insulation, and voids or cavities due to poor impregnation.
- Dry, brittle, and cracked paper.
- Waxing of the fluid.(wax formation due to degradation hinders fluid flow that can lead to void formation).
- Sites of carbonized tracks (e.g., treeing).
- Water in the insulation.
- Leakage of fluid at gaskets or due to holes in the sheath.

Cavities in fluid-impregnated (laminated) insulation can be formed by expansion of the lead sheath during repeated loading, thereby increasing the volume of the cable, waxing of the fluid due to aging, holes in the sheath that allow the egress of fluid, or leakage of fluid at gaskets. PD in gas-filled bubbles will generate additional gases changing the shape of the bubble, which in turn affect the PD characteristics. Thus, it is not unusual for PD in laminated insulation to move from one location to another due to the transient behavior of gas bubbles. Repeated discharges in one location will cause carbonization of the paper and the initiation of tracking. The tracking may follow the interfaces between paper layers, cross the butt gaps, and thus extend axially along the cable.

In belted cables, mainly for the lower class voltages, where the cores are not individually screened as they are in the higher voltage cables, the area between the three cores becomes a high risk for deterioration due to PD. This happens particularly during heavy loading, which may cause core separation. Another problem with this type of belted cable at higher voltages is the high tangential stress causing discharge activity between the layers and finally resulting in a failure. Typically, the application of individual screening of the cores (Hochstaedter layer or H-type cable), which transforms the electric field into a completely radial field, solves this problem in an effective way.

The discharge magnitudes are significantly larger in laminated insulations ranging up to more than 10 000 pC. Finally it should be noted that there is no reference PD data on new laminated cables as PD testing is not required as part of routine factory testing. Newly produced laminated cable, contrary to extruded cable, is never tested for PD behavior, because discharge activity has not been considered to be a relevant quality standard for new laminated cable, as it certainly is for extruded cable. Although newly produced laminated cable is subjected to dissipation factor (tan delta) testing, this test is not as sensitive a tool for measuring PD activity as a conventional PD testing procedure. The use of PD testing as a diagnostic tool for laminated cable is relatively recent. As there is no obvious standard, the interpretation of test results has to be developed in an empirical way.

4.1.3 Typical partial discharge sources in accessories

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

- Voids in molded products due to improper shrinkage of accessory components or poorly shrunk layers in heat-shrink and cold-shrink products.
- Loose insulation-joint interfaces (tracking), especially in the absence or migration of silicone grease, and at indentations made into the insulation during joint installation.
- Incorrectly assembled joints, e.g., misalignment, improper positioning, installation scratches, contamination, and voids.
- Contamination such as moisture, metal oxide, and so on may also leak into interfaces.
- Poorly installed terminations (incorrect positioning of stress relief devices), surface tracking, cuts into the insulation at the edge of the cable semiconducting shield, or corona from terminal hardware.
- Knife cuts or bruises produced by splicing tools, especially at the edges of semiconducting shield cut-backs, and voids in the insulation, mostly along knit lines or at interfaces.
- No contact made between the connector and the semicon or if the neutral wire is not properly connected to the outer semicon of the splice body.
- Terminal connector hardware and contaminated surfaces.

Differences in thermal expansion of the cable and accessory components may cause the generation of cavities at high temperatures.

Discharges resulting from a discontinuity in the connector or shield of a splice or a cable often resemble a corona discharge. This type of discharge is often identified from its pulse height distribution. As the problem progresses, the PD magnitude often remains unchanged while the PD repetition rate increases.

The assessment of the condition of a splice with PD is very complex and often inconclusive, as it depends on the particular type of splice. Phase-resolved PD displays may be able to differentiate between tracking-type defect and void-type defect.

However, more experience in interpreting PD results is needed by carefully testing, dissecting, or leaving in service until failure large numbers of splices of different designs. Past research in this area has not been successful. In general, any tracking-type PD that occurs continuously at operating voltage should be considered as severe and warranting early repair, whereas PD sources that extinguish at a voltage above operating level need not be considered as candidates for immediate repair. Periodic monitoring can help establish trends and help to better assess the severity.

4.2 Insulating materials

It is important to know the materials being tested to better interpret PD data as the resistance to damage by PD depends on the insulating material. The order of PD resistance is XLPE << EPR << Laminated (i.e., fluid-impregnated paper). Cable accessories, often made with filled rubber, may have a high endurance to PD activity, provided this does not occur adjacent to extruded cable insulation.

Shielded distribution cables fall into two classes: PD-free and PD-resistant. PD-resistant cable can sustain substantial amounts of PD over long periods of time without failure. PD-free cable can be formulated with a range of dielectrics, having low PD resistivity. However, for both types of cable, certain forms of PD will eventually cause failure, whereas other forms of PD can continue almost indefinitely without failure. Knowledge rules, which give objective guidance for the interpretation of measured data for the different materials in use, are necessary.

4.3 Operating conditions

Operating conditions also influence PD characteristics. The electric stress to initiate PD in cable systems comes from the operating voltage and transient overvoltages such as lightning or switching surges. The occurrence rate and the magnitude of voltage transients depend on the structure of the electrical system and its geographic location. A cable operating in Florida is exposed to more severe lightning surges than a cable operating in California. A system where frequent switching of capacitor banks is required tends to be exposed to more severe switching transients than a system without capacitor banks. The quality of surge protection affects the transient voltage impressed on a cable during a lightning storm. Selection of adequate arrester characteristics, proper grounding, and judicious placement of surge arresters affect the quality of lightning protection. These, in turn, bear an influence on the rate at which PD sources may be created or existing PD sources may deteriorate in distribution cable. The maximum test voltage selected is influenced by the quality of insulation coordination. Cables with defects are, therefore, exposed to PD events with probabilities that depend on the operating environment.

Another operating environment affecting the relative severity of a PD causing defect is the cable loading during service. If an XLPE insulated cable is operated at very high temperatures, significantly higher than the crystalline melting temperature, mechanical and structural changes could occur in the insulation. These, in turn, may affect the PD characteristics. The size of some defects varies with cable loading so that the PD magnitude varies with the cable loading. PD in some cases might disappear (extinguish) as load conditions change. For a laminated cable, long-term operation at high temperatures may cause the insulating fluid to migrate. The extent of this depends on the viscosity of the impregnating fluid. This can affect the PD-producing defect, which may either improve or further deteriorate depending on the cable topography. This type of operation may also produce unexpected failure due to thermal instability.

In testing three-core cables, care must be taken to identify the correct phase in which the PD is occurring. PD may occur in more than one phase, and cross-talk between phases may give misleading results.

When a cable circuit is taken out of service for off-line PD testing, the PD activity is extinguished when the voltage is removed. To re-initiate PD that can continue at normal operating voltage, a voltage of up to ~1.5 V_o may have to be applied for some minutes, as the PD inception voltage (PDIV) may be greater than the voltage required to maintain PD (PDEV) once it is initiated. A test duration of some minutes is required to ensure that there is an electron to initiate the discharge. Although in theory the PDIV may be two times the PDEV, in practice it is usually about 1.3 to 1.5 times. Thus, in off-line PD testing, the test voltage should be raised above normal operating voltage to initiate PD that was probably already active before the cable was taken out of service. If the cable is tested on-line without removing the voltage prior to testing, then those PD sources that are likely to be active during normal service are probably already in PD at the time of the test, although intermittent PD can occur if the PDEV is close to the service voltage.

Defects that have both the PDIV and the PDEV below the system operating voltage (SOV) will produce PD once the cable system is energized. The PD will be maintained during operation of the cable. Both on-line and off-line methods will detect these defects provided the PD detection system has the required sensitivity. As there is a high risk of failure when there is continuous PD in an electrical tree in an extruded cable, it is unlikely that PD observed at the operating voltage is coming from an electrical tree. It is not unusual to have partial discharges up to thousands of pC in laminated cable, particularly during changes in temperature and pressure.

Defects that have their PDIV > SOV and their PDEV < SOV will not produce PDs at normal operating voltage unless they are triggered by transient overvoltages. However, once triggered, they may be self-sustaining until the voltage is removed, or they could become intermittent or be extinguished completely. If the PD activity does not induce further damage at the defect, these sites will require a system overvoltage to initiate PD each time system voltage is restored. Both on-line and off-line methods will pick up these defects provided that, for the on-line test, a surge has already initiated the PD.

Defects that have both their PDIV and their PDEV above the SOV can initiate PD by transient overvoltages, but the PD will usually extinguish quickly after some cycles of the AC voltage. PD could also be generated by off-line tests, particularly if the test voltage is >2 V_o (see 7.4). These defects are normally harmless during normal system operation, but there is a possibility that an electrical tree could be initiated having PD that could persist below the SOV, i.e., PDEV < SOV due to the high electric field at the tips of the trees.

For most PD sources, both the magnitude and the repetition rate increase as the excitation voltage is increased. If the PD source generates low magnitude pulses, for example, in spherical cavities or in cables with thicker insulation, high sensitivity detection needs to be used and the PDIV may then depend on the detection sensitivity.

In a complex cable system such as network feeders, the network can consist of a mixture of cables with different insulations, constructions, and load capabilities. Discharge can occur at the locations where the ground system of two cable sections operates at different ground potentials. In three-conductor cables, discharge can also occur between the shields of the individual phases and the overall cable shield when the shield is not connected properly. This often occurs when two cable sections with different constructions are spliced together. The voltage build up in the ground system is induced by the current being conducted and is therefore a strong function of the cable loading. In some cases, if an inadequate grounding is employed, the ground potential difference is caused by imbalance between the cable phases. The imbalance between the currents carried by the cable phases is more pronounced as the cable loading increases. For this type of discharge, testing under heavily loaded conditions is essential.

5. Partial discharge detection

PD pulses are very short, typically 1 ns to 5 ns wide, and they can have significant frequency components up to 1 GHz at its source. Two general approaches are available to detect PD pulses in installed cables, which is referred to as off-line and on-line detection (Ahmed and Srinivas [B3]). Off-line testing is normally carried out using a separate voltage source after the cable has been removed from service (see

Mashikian [B22] and CIGRE WG D1.33 Task Force 05 [B10]). On-line (in-service) testing is carried out during normal operation of the cable system (Ahmed and Srinivas [B2]).

Some advantages of off-line PD testing are as follows:

- PDIV and PDEV can be measured if a variable voltage source is used.
- PD characteristics can be obtained at different voltages, which can aid in the identification of certain types of defects.

Some advantages of on-line PD testing are as follows:

- PD characteristics can be obtained under different load conditions, which can aid in the identification of certain types of defects.
- Tests can be performed without having to take an outage.

Some PD test equipment and methods are designed to only detect the existence of partial discharges and not locate their sites. This type of equipment is used to test lumped components such as switchgear or capacitors. Other PD test equipment and methods can detect and locate PD sites. Only the latter are covered in this guide.

Two important factors in PD testing are detection sensitivity and condition assessment from the interpretation of the data. PD test methods vary significantly in their detection sensitivity, and the PD test providers use different criteria to assess the insulation condition posed by the source of the detected PD.

Cable users often rely on economic considerations when they select a test method. The following considerations are recommended to aid cable users in weighing the advantages and disadvantages of the available test methods:

- The detection sensitivity should be given a high priority. Poor sensitivity may result in fewer problems being detected.
- The test methods should be capable of providing pattern recognition to identify the types of PD.
- The operating conditions of the cables, for example, the level of surge protection and the load history, as well as the planned load in the future should be taken into consideration when assessing the risk associated with the detected PD.
- The test method should not induce or aggravate degradation of the system.

5.1 General test setup

An off-line test is generally conducted according to the test setup shown in Figure 1. The cable is disconnected from the network at both ends and properly isolated. A voltage source and a coupling device, or sensor, are connected at one of the ends (near end), whereas the remote end is left open. The coupling device could be capacitive or inductive. The coupling device is connected to the PD detecting and processing systems. Variations of this setup include a measuring system with sensors at both ends and means to communicate the far end data to the near end processing devices or, in the case of a branched system, sensors placed at the end of each branch. Multi-terminal testing also has the advantage of greater sensitivity in the PD testing of very long cable lengths as the pulse travel distances are considerably shorter and consequently the related attenuation of pulse amplitude will be less.

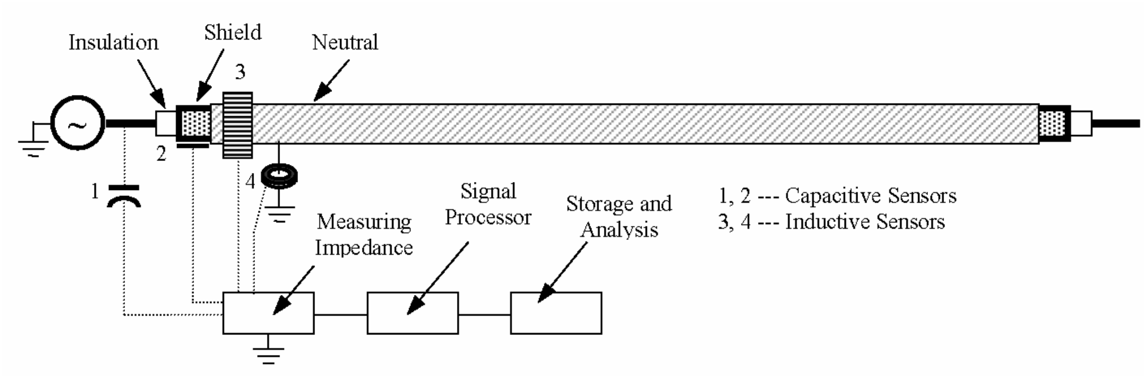
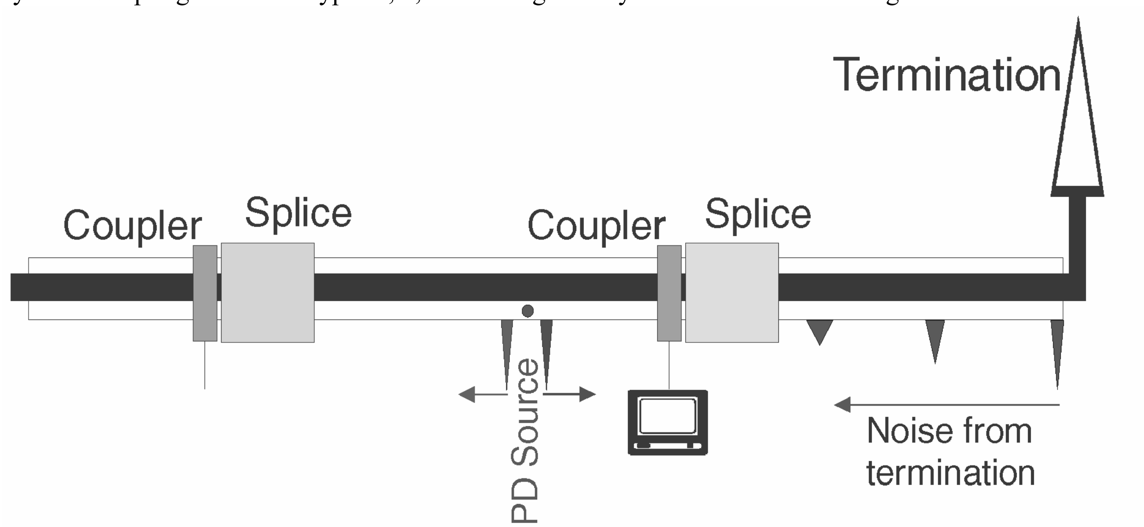


Figure 1—Typical test setup for off-line PD testing

In an on-line measuring system (Figure 2), the cable remains in service with both ends connected to the system. Coupling devices of types 2, 3, and 4 are generally used as illustrated in Figure 1.



NOTE—The termination is connected to the power system.

Figure 2—Typical test setup for on-line PD testing

5.2 Partial discharge detection methods

For PD assessment to be a useful diagnostic tool, the PD detection system should be capable of measuring a wide range of PD characteristics, including PD location, required to identify the types of defects that produce PD in the cable system.

In general, broad categories of detection are electromagnetic and acoustic. Acoustic detection is sometimes used in compressed gas (SF_6) filled lines, transformers, and on cable accessories to determine the exact location of PD activity. The prevalent detection method is electromagnetic. This is accomplished by coupling the cable to the detection instrument either capacitively or inductively, as illustrated in Figure 1 and Figure 2. Each method has advantages and limitations, which are beyond the scope of this guide to discuss. The user of such a test method should be concerned about the overall sensitivity and PD location resolution of the test method.

5.3 Partial discharge detection sensitivity

The detection sensitivity in any field test method is dominated by external noise in the operating environment. Noise suppression through analog techniques, e.g., frequency filtering, seldom results in detection sensitivity better than a few tens of picoCoulombs. Such sensitivity is acceptable for laminated cable but not for extruded dielectric cables for which a higher sensitivity is preferred. However, frequency filtering by modern digital filters can improve the sensitivity.

With regard to extruded dielectric cables having PD activity in the range of several picoCoulombs, inadequate detection sensitivity may mask the existence of serious defects with low PD magnitudes. Inability to detect low levels of PD may result in "false-negative" situations that are expected to lead to unexpected post-testing service failures. In addition incorrectly identified PD may lead to "false-positive" situations leading to unnecessary cable replacement.

The detection sensitivity is usually expressed by the minimum magnitude of apparent partial discharge, in picoCoulombs or the equivalent millivolts (equivalence to be provided by the tester), which the instrument is capable of resolving under existing field conditions. As the cable length and the environmental noise conditions increase, the sensitivity tends to decrease. Cable construction, such as size, type, and the condition of the neutral conductor, and the properties of the semiconducting shields, have a significant influence on PD pulse propagation velocity, and attenuation. The latter, in turn, affects the detection sensitivity. Internally generated noise can also limit the sensitivity of an instrument. High sensitivity is crucial when testing extruded cables where detrimental PD magnitudes are known to be relatively low. Detection sensitivity and PD location accuracy must not be confused with each other, although the effectiveness of noise mitigation can influence both quantities. The following three cable conditions may arise in a test situation:

a) A circuit under test may contain cables made of the same material, but different conductor cross sections, connected in series. In such a case, the estimated cable length, the attenuation, and the calculated discharge magnitude may be slightly affected.

b) A circuit under test may contain cables using different insulating materials or constructions (mixed cable systems). In such a case, both the detection sensitivity and the PD location accuracy may be adversely affected.

c) A circuit under test may contain new and service aged cables with different water content and different wave propagation characteristics. In such a case, the PD location accuracy may be adversely affected.

If the cables are tested in sections, the above conditions do not apply.

The instrument sensitivity can be checked by injecting a calibration pulse, such as 10 pC, 20 pC, 50 pC, or 100 pC, into the cable and determining the ability of the instrument to resolve the response of the cable to the smallest pulse. Calibration is discussed in Annex C.

5.4 Partial discharge location

The location of PD sites is accomplished either in the time domain or in the frequency domain. Each category will be described in turn. PD measuring systems capable of good location resolution on installed cables usually have bandwidths of several megahertz, typically in the 5–20 megahertz range. Note that the bandwidth in IEC 60270 is defined by an upper, f_2, and a lower frequency, f_1, limit at which the transfer impedance has fallen by 6 dB from the peak pass-band value. Note also that the frequency range defined in IEC 60270 for "wideband" PD detection systems is 30 kHz to 500 kHz as lower and upper frequency limits, respectively, with a Δf ($=f_2 - f_1$) of 100 kHz to 400 kHz.

5.4.1 Time-domain partial discharge detection and location

Time-domain testing is usually performed off-line, although on-line with multiple sensors is also possible. Individual pulses are measured if a wide bandwidth detector of at least several tens of megahertz is used. Lower bandwidth detectors may result in the superposition of pulses. When using low bandwidth detectors, for example, as per IEC 60270, the superposition of pulses can be checked by using a double pulse calibrator with an adjustable pulse sequence from 1 μs to 100 μs according to IEC 60885-3. The phase positions, magnitudes, and repetition rates of the pulses can be measured.

A common method of estimating the location of a PD in a cable uses the principle of reflectometry, as illustrated in Figure 3 (Mashikian et al. [B21]). The excitation and measurement are implemented from one cable end (near end). A PD signal splits into two equal signals that travel in opposite directions. The direct signal traveling toward the near end is recorded first as pulse A. The horizontal axis represents time. The signal traveling in the opposite direction is reflected at the remote end and travels back to the near end where it is recorded as pulse B. Using the difference t between the arrival times of these two pulses and the velocity of pulse propagation, the PD location can be estimated. In this figure, the third pulse C represents the recording of pulse A after it has undergone successive reflections at the near and remote cable ends. Its time difference with respect to pulse A is the cable round-trip time.

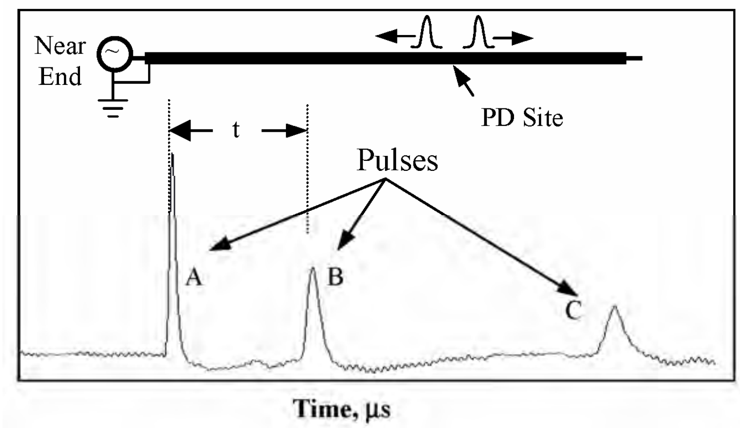


Figure 3—Reflectogram illustrating PD location in the time domain

A simultaneous measurement of pulses at the near and remote ends is possible if a PD detector is installed at each end, and the detectors are provided with means to synchronize their recordings and transmit them to a measuring station where they are processed. The PD location is determined as a function of the PD pulse arrival time at the various sensors. This method is useful for PD measurements on branched circuits and for very long cable lengths. Technical and economic considerations may limit the number of branches that can be tested simultaneously (van Schaik et al. [B30]).

For direct buried cables, an estimate of the PD site is not sufficient to locate it exactly. Several instruments are commercially available to match the above-ground location with the actual PD location along the cable, as estimated by the methods described previously. Once the cable is unearthed, it is possible to pinpoint the exact PD site by means of specialized instruments, provided the external metal shields or sheaths are removed. For cables buried in ducts, these steps are unnecessary, as an entire section between two manholes will have to be pulled out.

Termination discharges can be identified by time-domain location methods and by means of special probes, although some instruments have been developed to isolate these discharges by means of very high-frequency amplifiers/filters. These would detect signals emanating only from within short distances, as cables rapidly attenuate very high-frequency signals.

In high-voltage cable applications, PD detection in joints and terminations can also be accomplished by means of sensors capacitively coupled to individual joints and connected to very high-frequency bandpass filters.

5.4.2 Frequency-domain partial discharge detection and location

Frequency-domain testing, which can be performed either off-line or on-line, is based on measuring the frequency components of the PD pulses (Ahmed and Srinivas [B2]). The frequency spectrum of the time-varying PD pulses can be obtained either digitally (mathematical conversion) or through the use of analog swept filters as in a spectrum analyzer. For both analog and digital frequency-domain PD detection, the outcome depends on the setting of the measuring device used (parameters such as sample rate in the case of digital conversion, filter bandwidth, and sweep rate in the case of analog conversion).

In general, the detected frequency components of a PD signal are in the range of a few hundreds kilohertz to up to 1 GHz depending on the location of the PD with respect to the measuring point. However, a frequency range of a few hundred kilohertz to 300 MHz is more practical due to limitations imposed by the frequency bandwidth of the PD detection sensors. Frequency-domain testing normally is conducted in both full and zero-span modes. In the full span mode, the frequency range scanned can be adjusted to examine signals in narrow-frequency bands as well as wide-frequency bands. Measurement made using narrow-frequency bands significantly enhances the resolution in locating the PD sites. PD energy versus frequency is a strong function of distance from the PD source. The zero-span mode is used to examine PD pulses in a time domain as measured in a relatively narrow bandwidth at a center frequency, which provides good detection sensitivity (i.e., within a frequency range where little interference occurs).

The zero-span mode is used to find PD pulses occurring at one or more cycles of the operating voltage of a specific frequency. The signal from the zero-span mode is often coupled to a pulse phase analyzer. The pulse-phase analyzer is capable of recording PD pulses sorted by their phase angle and magnitude relative to the power frequency excitation.

The frequency-domain technique does not usually provide a direct basis for calibration of the resulting data in terms of apparent charge (pC). PD sources are recognized on the basis of their spectral characteristics and through the use of the zero-span mode of the spectrum analyzer to provide a correlation between the signal in the selected spectral region and power frequency. For such systems, the relationship between the measured signal and the “severity” of PD source is based on subjective information, such as experience, and the results of laboratory testing.

Unlike the time-domain methods, the frequency-domain methods are more immune to interference from external noise, provided means are procured to prevent stray signals from being coupled into the cable tested, when testing is performed on-line. However, a skilled operator is needed to collect and analyze the data. A high sensitivity can be achieved with adequate sensors and if the distance between the test points is kept below 150 m (500 ft).

PD location is estimated by measuring the energy versus frequency of the PD pulses. The accuracy of the location depends on two factors:

- The frequency range of the pick up sensors (greater bandwidth results in improved accuracy).
- The distance between two consecutive test points (shorter distance improves accuracy).

PD location is often judged from the frequency content of the PD-induced signal in combination with knowledge of the cable type (i.e., the high-frequency attenuation of the cable). If the PD-induced signal is sufficiently large, the location can be determined using time-domain approaches.

5.4.3 Location resolution

The resolution with which PD can be located is affected by the bandwidth and internal noise of the measuring instrument, the attenuation of the cable, the soundness of cable terminations, the number and quality of splices, the physical obstacles encountered at the cable termination sites which interfere with proper connections, the analysis methods and procedures used to assess PD site location, and very importantly, the background noise and its mitigation (Zhifang et al. [B33]). As the instrument bandwidth decreases or the cable attenuation and length increase, the PD location resolution decreases. In time-domain PD testing, the exact time of arrival of a pulse cannot be measured accurately either by locating the beginning or the peak of a pulse, so that sophisticated methods are required to perform a measurement with high sensitivity and high resolution under adverse test conditions. In frequency-domain testing, the location resolution is mainly influenced by the distance between two consecutive test points (shorter distance improves accuracy). Annex B discusses in greater detail the conditions affecting PD site location results.

5.4.4 Splice location

Prior to performing high-voltage PD testing, the cable splices need to be identified and located in order to differentiate between PD signals emanating from a cable and PD signals from a splice. This is necessary because of the differences in the insulating materials of cables and splices and, therefore, their relative resistance to PD degradation.

A low-voltage pulse is sent from the near end of a cable and all its reflections are recorded. A mismatch between the characteristic impedances of the cable and splices causes these reflections. An impedance mismatch may also be due to impedance changes caused by extensive physical deformations, corroded neutrals, or heavy moisture absorption. The principle of time-domain reflectometry (TDR) is used to locate the sites of abrupt impedance changes. In on-line testing, the same technique is employed with the exception that the low-voltage pulse is injected into the energized cable via a current transformer.

5.5 Test limitations

PD testing limitations may be caused by the following:

- Lack of detection or location sensitivity (for example, taped insulation shields in older cables can greatly attenuate PD pulses).
- Defective neutral conductor (excessively corroded, cracked wire/tapes, etc.).
- Inability to energize a long length of cable for off-line testing.
- Inability to properly locate the source of PD in a long buried cable section for frequency-domain testing.
- Presence of dominant extraneous sources of partial discharge that may be coupled to the measuring system.
- Poorly trained test operators.
- Inaccessible cable or its components.

Limitations associated with each type of PD test method or voltage source have already been discussed. An assessment of these limitations and their consequences on the test results should be made preferably before initiating the test; however, if the limitations are discovered during the tests, they should be reported in the test report. Of course, a correct interpretation of the results is essential. Under certain conditions, the exact level of PD severity may not be assessable. This should be clearly pointed out in a test report.

6. Voltage sources

The purpose of the test voltage is to produce partial discharges at locations where there are defects in the cable, terminations, and splices. On-line testing uses the system voltage of a constant fixed magnitude, The desired characteristics of off-line voltage sources for field partial discharge measurements are as follows:

- The applied voltage should cause partial discharges in the cable, terminations, and splices that have characteristics close, if not identical, to those that occur when the cable system is in service.
- It should cause no appreciable damage to the cable system during the time required to perform the measurements.
- In the case of off-line testing, the maximum voltage applied should be variable.
- The size and weight of the equipment to produce the voltage should facilitate field transportation.

Voltage sources that are used for commercially available field partial discharge measurement systems fall into the general categories of power frequency and alternative voltage sources. A summary of these voltages sources as well as some of their advantages and disadvantages are contained in the following sections.

6.1 Sinusoidal power-frequency voltage sources

Constant amplitude, power-frequency, sinusoidal voltage sources have the advantage of duplicating the cable system operating voltage. This type of voltage source also has the advantage that the partial discharge measurement results are directly comparable with partial discharge measurement results from routine production tests for extruded dielectric cable systems as long as the PD detection equipment comply with industry standards for measurement and calibration as used in the factory. For the purpose of this guide, power-frequency voltage sources refer to sinusoidal voltages with a frequency ranging from 20 Hz to 300 Hz.

One special case of this category of voltage source is on-line testing, where the power system provides the rated 50 Hz or 60 Hz voltage during the partial discharge measurements. On-line partial discharge measurements require a minimum of equipment to perform the measurements and may eliminate cable system downtime; however, it is not possible to vary the magnitude of the test voltage to determine the PDIV and PDEV. On-line partial discharge measurements may reduce the possibility of extinguishing partial discharges during removal of the operating voltage to perform subsequent off-line measurements. However, this temporary extinction of partial discharges to prepare for off-line measurements generally is not a problem if the off-line test voltage is significantly higher than rated cable system voltage. On-line measurements do not cause any damage to the cable system during the partial discharge measurements.

To obtain the added flexibility of performing partial discharge measurements at voltage magnitudes above and below rated voltage, field transportable power frequency test equipment has been developed for commercial applications. To keep the size and weight suitable for field transportation, resonant test sets are generally used. Two types of power frequency resonant test systems are commercially available for field partial discharge measurements:

a) Frequency tuned resonant circuits (FTRCs).

b) Inductively tuned resonant circuits (ITRCs).

6.1.1 Frequency tuned resonant circuits

FTRC systems have the advantage (compared with ITRC systems) of having no moving parts, which results in less susceptibility to damage during transportation.

A disadvantage of FTRC systems is that they employ high-power electronic converters that lead to the introduction of noise pulses. It is necessary to filter the noise pulses out of any PD measuring system. As the noise pulses may coincide with PD current pulses in the cable, it may be difficult to detect certain cable defects.

6.1.2 Inductively tuned resonant circuits

An advantage of ITRC systems over FTRC systems is that they use variable auto-transformers that do not produce interference pulses that affect partial discharge measurements. Voltage variation is gradual and smooth and facilitates an accurate determination of PDIV.

ITRC systems contain moving parts, which require periodic maintenance. Both the FTRC and the ITRC test sets are generally heavier than equipment required by other alternative voltage sources.

6.2 Alternative voltage sources

For the purpose of this guide, alternative voltage sources refer to sources used for field partial discharge measurements that are non-sinusoidal and/or have frequencies other than power-frequency voltages.

6.2.1 Very low-frequency voltage

Commercially available VLF voltage sources are low in weight and low in capacitive power demand compared with power-frequency excitation sources. Unlike dc voltage, VLF test voltage is less likely to produce harmful space charge because of its continuous polarity changes (Steennis et al. [B28]). Some commercially available VLF voltage sources employ mechanical switches in the high-voltage circuit and thus are not PD free in these portions of the voltage cycle.

Depending on the type of defect, VLF voltage sources, usually 0.1 Hz, for extruded-dielectric cable systems may require a higher test voltage to generate the same partial discharge level compared with tests performed with power-frequency voltages. For example, the conductivity of the surface of a cavity that has been exposed to PD increases, which allows any charges deposited on the surface by PD to leak away and thus lowers the electric field in the cavity. As more charge can leak away between polarity reversals at VLF than at power frequency, the PDIV at VLF will be larger than that at power frequency. If there has been no previous PD activity to increase the conductivity of the cavity surface, the PDIV at VLF and power frequency will be similar. Also, as more charge on electrical tree channels can leak away between polarity reversals under VLF than at power frequency, the tree growth rates at the two frequencies will be different. It is not possible to determine the change in surface conductivity and thus the difference in the PDIV between power frequency and VLF. In addition, the PDIV and PD patterns produced with VLF excitation may deviate from those produced with power-frequency voltage sources.

At low frequency, PD pulse reflection patterns are better separated, which makes site location of the PD easier for the test engineer when testing cables producing discharges with high repetition rates, for example, laminated cables and its accessories (Hetzel and MacKinlay [B15]).

It has been reported that the growth rate of electrical trees undergoing partial discharge can be higher for 0.1 Hz than for power frequency. Once an electrical tree has been initiated during VLF testing, there is a higher likelihood of failure; however, there is no evidence that VLF testing has a lower electrical tree initiation voltage. It should be noted that this concern does not apply to laminated cable systems. For more details on VLF testing, refer to IEEE Std 400.2-2004.

6.2.2 Damped alternating voltage

The generation of a damped AC voltage (DAC) can also be used as an alternative to other methods of generating an ac test voltage on site (Gulski et al. [B14]). The voltage sources are low in weight and have low power requirements compared with power-frequency excitation sources.

A typical test circuit consists of a direct voltage source, which charges the cable capacitance with continuously increasing voltage (no steady state situation). After reaching the desired peak voltage, a switch short-circuits the cable through a wave-shaping circuit. The wave-shaping circuit can be adjusted to produce the desired test frequency. The frequency of the damped oscillation varies from some tens of hertz to a few kilohertz depending on the type of wave-shaping circuit used.

Test systems using damped alternating voltage usually require repeated applications of the test voltage. The short dwell time at peak voltage level of the test voltage may be viewed as both an advantage and a possible disadvantage. The small number of cycles reduces the risk of damage to the cable system when the peaks of the test voltage are higher than rated voltage. However, discharges associated with certain types of cable system defects may require a longer voltage application time to initiate.

With damped alternating voltage in the range of kilohertz, the PD inception and occurrence may differ from those for power-frequency voltage.

6.2.3 Impulse voltage

An impulse voltage may also be used as a voltage source for field partial discharge measurements. The use of impulse voltages with a very fast rate of rise and a decay rate equivalent to power frequency has been reported. Its main advantage is its lighter weight.

A disadvantage of the impulse voltage test is the difficulty in accurately determining the PDIV. As cables tend to highly attenuate high-frequency voltage pulses, the test voltage pulse tends to be attenuated and distorted as a function of cable length. Therefore, the voltage stresses in the cable system may differ significantly with distance from the voltage source.

It is also difficult to relate partial discharge values measured with this type of voltage to partial discharge values from routine factory tests.

7. Practical testing guidelines

7.1 Pre-test owner information

To facilitate the testing process, detailed information needs to be obtained from the cable owner. This information includes the following.

7.1.1 Cable characteristics

These include conductor and neutral sizes, type and condition of neutral, rated voltage, insulation type, cable age and operating history, cable dimensions or total capacitance, cable length, and type and location of joints. If multiple cable types exist within a given test span, the above information should be provided for each type of cable in the span, along with the locations at which the different cable types are spliced together.

7.1.2 Cable configuration

This includes information on whether the system is single or three-phase (is each phase individually shielded or is there one single shield over all three phases), whether the system is radial or looped, whether the system is direct buried or in duct, and other information pertaining to the cable routing, particularly with branched circuits.

7.1.3 Termination type and accessibility

Information is needed on whether the termination is live or dead-front, in a switching cabinet or substation housing, on a pole-top, in SF_6 or other. It is also necessary to know whether terminations are accessible, whether arresters and transformers can be disconnected, and whether any switch permanently connected to the cable can take the maximum test voltage without discharging or flashing over.

7.2 Preliminary inspection and/or testing

A physical inspection by the testing organization of the system to be tested is helpful and is highly recommended. A relatively quick and inexpensive preliminary test is recommended, including a sensitivity test, to determine whether (a) the cables to be tested are insulated with certain old-vintage rubber compounds that cannot be tested; (b) the cable construction is such that very high attenuation is expected; or (c) the neutral is suspected of not being continuous or of being ineffective. The preliminary test can be effectively performed by means of low-voltage reflectometry. If the attenuation is so high that the reflected pulse is hardly visible or if the neutral is not continuous, a high-voltage PD test may not be warranted, as PD signals, especially those with low magnitude, may go undetected. Such a preliminary screening test can be technically and economically justified.

7.3 Pre-test conference

Prior to PD testing, a conference with the cable operator is useful and recommended. During this conference, the following items should be discussed.

7.3.1 Test protocol

The PD test protocol and the results of any preliminary screening tests shall be reviewed. Specifically, the test voltage level shall be discussed and an agreement reached for its maximum allowable value and the duration of its application. The advantages and limitations of the particular PD test method used must be clearly conveyed to the cable owner. The cable owner must approve the test protocol and clearly state any conditions that would require its revision.

7.3.2 Safety

The safety procedures, as described in Clause 9, should be reviewed and agreed upon. This includes safety equipment, switching and blocking practices, grounding, responsibility for control of the cable under test, and safety of the public.

7.4 Test conditions (voltage levels and duration)

On-line tests use the system voltage. The duration of the test should be until sufficient data are collected (see 9.2), up to a maximum of 15 min.

Off-line tests can be carried out using different voltage sources; see Clause 6. There is a solid technical rationale of testing up to 1.5 V_o to 2 V_o to ensure that the PDEV of the cable system is greater than 1 V_o.

There is an increased risk of initiating damage at defects in aged cable systems that are innocuous at operating voltage if testing is carried out at voltages greater than 2 V_o. There is also an increased risk of failures during the PD testing. However, some utilities will request testing up to a maximum of 3 V_o on new cables, either on the reel or newly installed, to ensure that there was no damage during transportation or installation. In addition, some utilities will test up to 3 V_o even though there is a significantly higher probability of failure during the testing of the following:

- Cable circuits with generic defects that may cause high failure rates, e.g., some silane-cured cables can cause severe corrosion of aluminum conductors.
- Cable circuits that are being considered for silicone injection, the rationale being that all cables with electrical trees will fail at higher test voltages. The higher test voltages could also initiate new electrical trees.
- Cable circuits that may have suspect accessories and/or cables to ensure operation during high load periods, e.g., during the summer months in some urban areas.

The voltage in power frequency tests may be applied for up to a maximum of 15 min to ensure that electrons are available in cavities to initiate PD. However, once PDs are detected, the voltage should be applied long enough to collect sufficient data up to a maximum of 15 s. Some PD testing organizations will decrease the voltage very soon after the onset of steady PD when testing extruded dielectric cable circuits.

In summary it is not possible to standardize a specific test protocol at the current time for either on-line or off-line tests. This may become possible as more data are collected. For off-line tests, the amplitude of the test voltage can be varied. For heavily aged systems, a maximum test voltage of 2 V_o is suggested. As the anticipated condition of the cable improves, the test voltage may be increased to as much as 2.5 V_o. New cables, either on the reel or newly installed, may be tested to a maximum of 3 V_o at the concurrence of the cable owner and cable manufacturer. The test duration should be long enough to allow the availability of electrons to initiate PD, but once PDs are detected, the voltage should be applied long enough to collect sufficient PD data.

8. Test results and recommendations

Regardless of the test method or voltage source utilized, the following results are expected:

a) Detection of the existence, if any, of any significant PD above a specified detection sensitivity.

b) Identification of the location of each PD site.

c) Assessment of the severity of the defect associated with each PD site.

When comparing PD test results obtained with different voltage sources but equivalent detection sensitivity and the same applied voltage level, the lack of identical results is not unusual and should not be surprising. The PD inception voltage levels of certain defects may be significantly affected by the type of voltage source.

8.1 Interpretation of test results—recommendations and implications

Interpretations of PD data from both extruded and laminated cable systems are already available; however interpretation is still developing and knowledge is continuing to be accumulated (Boone et al. [B9]). Many organizations and companies have data banks of PD characteristics for different defects and have created knowledge rules to improve data interpretation. New test data are compared with these stored data to identify the type, location, and severity of the defect. The measured PD characteristics, for example, phase-resolved PD patterns (pulse repetition rate vs. phase angle vs. magnitude), can be analyzed in various ways based on experience and knowledge of the types of defects anticipated in the cable and accessories to provide insight into the condition of the cable system.

As examples, for extruded cable systems, PD characteristics are being obtained for internal cavities in the insulation, interfacial cavities between the shields and the insulation, broken shields, electrical trees from cavities, protrusions or water trees, knife cuts, contaminants, and poorly installed accessories. Similarly for laminated cable systems, PD data are being obtained on fluid-deficient butt gaps, soft areas of the insulation with poor impregnation, dry and brittle paper, carbonized tracking, moisture in the insulation, and the leakage of fluid from gaskets or holes in the sheath. The PD characteristics are dependent on the cable design, the materials used, and the operating conditions. For example, cavities can change size or migrate with temperature and thus the load on the cable. This could result in significant changes in the PD activity and thus the measured PD characteristics.

Data interpretation for both extruded and laminated cable systems is difficult and is discussed more fully in Clause 4. The PD characteristics produced by most defects usually exhibit significant variations over both the short and the long term. The magnitudes of the variations depend on the type and location of the defects, the type of cable system, and the operating conditions. Low magnitude discharges may not be measured if there is high background noise during the PD measurement.

In general the accuracy in interpretation of PD data is good when testing "very good" (low levels of PD activity) or "very bad" cable systems with, for example, low PDIV with well-defined PD characteristics. The accuracy in interpretation is less when testing cable systems between "very good" and "very bad" conditions. Cable attenuation and background noise affect the PD detection and measurement sensitivity of every circuit. Thus, there is a risk of not being able to detect PD pulses or wrongly identifying pulses as PD pulses, according to the test conditions. This could lead to the risk of an incorrect assessment of the cable circuit. This risk must be recognized by everyone involved in the cable testing, the cable owner, and the test provider.

The accuracy in condition assessment may improve as

- More data are collected and are compared with actual cable system performance.
- Data are compared with information from the results of dissections of cable parts or accessories, which were recommended to be replaced.
- Additional testing is carried out on cables and their accessories that were recommended to be replaced.
- Periodic measurements are made on the same circuits, i.e., trending,. When available, data from previous PD tests on the same circuit will be very helpful in diagnosing the implications of detected PD sources.
- All relevant information about the cable system is known, such as the age type and design of cables and accessories, operating conditions, and so on.
- Standardized test and analysis procedures are developed. This will aid the comparison of data bases of different PD service providers and from different utilities.

Based on the interpretation of the PD test data, the cable user has to make decisions regarding re-use, replacement, repair, or refurbishment or retesting within a specified period to be determined. The reliability impact of this decision depends on the criticality of the affected circuit—the potential for personal injury, damage to facilities/property, and/or impact on reliability performance metrics such as System Average Interruption Frequency Index (SAIDI), Customer Average Interruption Frequency Index (CAIFI), and Momentary Average Interruption Frequency Index (MAIFI). The economic impact of this decision depends in part on the construction (direct buried vs. conduit system), the importance of the circuit, and the potential lost revenues or customer claims. In a conduit system, for instance, if a termination shows unacceptable discharge, it may be cheaper to replace the termination and the first section of cable rather than just the termination. Likewise, if a cable is direct buried, it may be more cost-effective to replace a short segment of the cable rather than the entire section.

8.2 Partial discharge test documentation

The PD test provider should provide cable users with a report of the cables tested and the PD test results, and in a quotation to provide such services or in standard marketing documentation, the PD test service provider should make clear the type of documentation that is provided. The PD test provider should give the cable user recommendations on possible corrective action to be taken. The report of the test results should include the value of PD detection sensitivity and a reference to the method used in obtaining this value. The PD site location results must also be provided with an assessment of the accuracy limits within which these results can be interpreted under the conditions of the specific test. This becomes critical where the location is at or near a splice.

Details to be included in the report are as follows.

8.2.1 Cable system identification

The following information is desirable:

- Name of cable manufacturer.
- Cable section identification (i.e., substation name, from switch No. to switch No.).
- Cable voltage class.
- Cable insulation (if mixed, specify).
- Operating voltage (phase-to-neutral).
- Conductor type and size (if mixed, specify).
- Cable length.
- Location of splices.
- Cable vintage or year placed in service.
- Neutral type, for example, concentric wires, metal tapes, or flat strap, and size, for example, full or one third.
- Type of construction, i.e., direct buried, duct, aerial, jacketed, unjacketed, and so on.
- Splice type, if available.
- Termination type, i.e., pole-top, switching cabinet live-front/dead front, premolded, heat-shrink, and so on.

8.2.2 Partial discharge test results

The following information is recommended:

- Test date.
- Date of the most recent previous test.
- Estimated cable length.
- Splice location.
- Background noise level.
- Minimum resolvable PD signal pC magnitude (sensitivity) and how it was determined. If the sensitivity is lower than expected, provide the reason(s).
- Test voltage levels.

- At each test voltage level, the location of each PD site, along with the limits of accuracy.
- At each voltage and site location, the number of PD events per second or per cycle of a sinusoidal excitation voltage.
- At each voltage and site location, a phase-resolved PD representation (pC versus phase angle for each PD event recorded), provided the excitation voltage is sinusoidal. Specify the number of cycles included in the phase-resolved diagram.
- For a frequency-domain measurement, describe the spectral characteristics and the estimated location for each PD site. Specify the limits of accuracy.
- Any other diagnostic results pertinent to the test method used.
- An indication of the severity of the PD behavior, if PDs are detected, and recommendations on possible corrective action to be taken.

The format of data reporting may vary. For instance, some prefer reporting individual PD events in a three-dimensional (3-D) form with location, picoCoulomb level, and phase angle at which each PD is initiated. Variations of this three-dimensional representation are also possible. Others prefer a set of two-dimensional representations, showing PD location with PDIV, and apparent charge (pC) versus phase angle for each PD site, at each voltage level, and PD repetition rate for each PD site at each voltage level.

8.2.3 Time-domain partial discharge tests with sinusoidal voltage

For a PD test based on a sinusoidal voltage and time domain PD pulse measurements, documentation should, ideally, be based on a 3-D plot, or equivalent representation, showing PD repetition rate (or Number of PD Pulses over a stated time) vs. PD Magnitude and PD Phase relative to the applied voltage for each PD site detected, or a set of two-dimensional representations, showing PD location with PDIV, and pC versus phase angle for each PD site, at each voltage level, and PD repetition rate for each PD site at each voltage level. If the test provider and user agree to limit the test duration once PD has been detected to below that for which the data necessary for a useful 3-D plot can be obtained, a plot of the number of PD pulses vs. PD magnitude may be appropriate. These data will be very useful to the system owner as a basis for comparison with future PD tests on the same circuit, which might be carried out by a different PD test provider. For this reason, a measurement that provides the industry standard “apparent PD charge” to within reasonable accuracy is important. In all cases, the documentation should include an interpretation of the data, including accuracy, in terms of implications for system reliability and the need to replace or repair the circuits tested.

8.2.4 Time-domain partial discharge tests with non-sinusoidal voltage

Some field PD test apparatus use a low-frequency ac or unipolar test waveform with a rapid change in voltage that simulates the time-rate of voltage variation (dV/dt) of power frequency voltage. For such test waveforms, PD is usually only measured during the rapid discharge phase of the waveform, and reported results should include, at least, Number of PD vs. Magnitude of PD for various locations at which PD is detected, along with an appropriate interpretation of the data in terms of implications for system reliability and the need to replace or repair the circuits tested.

8.2.5 Frequency-domain partial discharge tests

Reports of PD testing based on frequency-domain PD tests should provide the user with useful documentation of the measured data along with meaningful interpretation, including accuracy, in terms of implications for system reliability and the need to replace or repair the circuits tested. This may involve presentation of a radio-frequency spectrum for each measured PD source along with an interpretation of that spectrum or similar objective documentation as well as appropriate interpretation of the data in terms of implications for system reliability and the need to replace or repair the circuits tested.

9. Safety

The use of safety procedures is a routine practice whenever high-voltage testing is performed [refer to the National Electrical Safety Code® (NESC®) (Accredited Standards Committee C-2) and IEEE Std 510]. High-voltage withstand testing, such as dc hi-pot, is commonly practiced by cable owners whose staff is trained to observe the necessary safety procedures. Partial discharge testing is typically performed by the service provider. The safety practices of the two organizations must, therefore, be critically reviewed and a common set of safety procedures agreed upon.

While testing, one or more cable ends will be remote from the testing site, therefore, before testing is begun:

a) Cable ends under test must be cleared and guarded.

b) Cables must be de-energized and grounded.

The specific topics to be discussed and agreed upon include, but are not limited to, personal protective equipment, switching and blocking practices, grounding and responsibility for control of the cable, public safety, and daily meetings.

9.1 Personal protective equipment

The use of basic personal protective equipment (PPE), such as hard hats, safety glasses, hard-toe shoes, or flame or arc-resistant clothing, is normally required by employer work rules and regulations such as NFPA-70E. PPE requirements must be discussed and agreed upon before testing begins, and they must be complied with rigorously during work around energized equipment.

9.2 Switching and blocking practices

Prior to undertaking the testing, the cable owner and the service provider shall review the owner's switching and blocking practices in order to ensure the safety of the test personnel and the test equipment.

9.3 Grounding and responsibility for control of cable

Grounding and other safety-related procedures at utility locations are governed by the NESC and local utility rules, and they must be adhered to. All parties must familiarize themselves with these rules and requirements prior to proceeding with a testing program. In particular, the general steps involved in passing control of the cable during the test are spelled out as follows:

The owner and the testing organization must carefully coordinate the control of the cable under test. For off-line testing, the owner removes the cable from service and grounds it, following generally accepted safety procedures. The control of the cable is, then, turned over to the testing organization, making sure that the transfer of responsibility is acknowledged. The testing organization connects the necessary test leads to the cable and, only prior to energizing the cable for testing, the grounds are removed. The initiation of the test must be clearly announced and a visible indicator light illuminated to indicate that the cable is energized for testing. After the test is completed, the grounds are reapplied to the cable, the test leads are removed, and the responsibility of the cable returned to the owner. No one is allowed to touch a test lead until the grounds are reapplied. The procedures and tools used by the testing organization to disconnect and reconnect the grounds must be acceptable to the cable owner.

9.4 Safety of the public

Prior to starting a test, a visit to the test site by representatives of the cable owner and the test provider takes place. The placement of any test vehicle, the test leads, and the power source are discussed and agreed upon. Consideration is given to vehicular and pedestrian traffic, and means are provided to ensure the safety of everyone involved. Test leads may be a hazard both with respect to tripping and exposure to voltage. Safety cones and ribbons are, therefore, used to prevent any such hazard. Whenever portable generator sets are used, the impact of noise should be seriously considered and mitigated.

When tests involve the maneuvering of vehicles within an outdoor substation or near other electrical equipment, inspection of the route in and out of the test site is performed to ensure adequate clearance between any test vehicle and substation equipment, especially any overhead conductors or pipe ways.

9.5 Daily safety meeting

Holding a daily safety meeting is recommended. During the meeting, the safety performance of each day is reviewed, potential weaknesses corrected, and any special conditions that may be encountered during the next test day discussed.

10. Conclusions

Partial discharges, which can occur at some types of defects in high-voltage cable systems, can lead to premature failures. This guide provides information on partial discharge testing and information on the interpretation of test data to assess the condition of the cable.

There are two types of partial discharge testing, on-line and off-line. Both types have advantages and disadvantages. There are also different types of partial discharge detection methods, one using the time domain and the other, the frequency domain. Both types can locate the source of the partial discharge.

The risk of failure during or after the field test increases with the test voltage. For heavily aged systems, a maximum test voltage of 2 V_o is suggested. As the anticipated condition of the cable improves, the test voltage may be increased to as much as 2.5 V_o. New cables, either on the reel or newly installed, may be tested to a maximum of 3 V_o at the concurrence of the cable owner and cable manufacturer.

The ability of partial discharge testing to assess the future performance of a cable system is continuously improving.

The best accuracy in assessing the future performance is achieved on “very good” or “very bad” cable systems.

Further improvements may occur as more data are collected, test and analysis procedures are standardized, and if measurements on particular cable circuits are repeated on a periodic basis, i.e., trending.

Annex A

(informative)

Partial discharge and water trees

Water treeing is the most important form of degradation that may afflict older XLPE and high-molecular-weight polyethylene extruded cables. As a result, the phenomenon of water treeing has been studied extensively, including means by which the degree of water tree-induced degradation can be assessed. Water treeing can be described as a self-propagating dendritic pattern of electro-oxidation, which reduces the ac and impulse breakdown strengths of extruded insulation and is the primary mechanism of degradation of extruded medium-voltage distribution cables. Although studied extensively, the initiation and growth mechanisms of water treeing are not clearly understood; they are not a single mechanism but complex interactions of chemical, electrical, and mechanical phenomena that depend on the material and applied stresses (see Crine [B11], Ross [B26], and Zeller [B32]). The visible manifestation of water treeing is strings of water-filled microcavities. The water-filled microcavities are connected by electro-oxidized tracks, which are usually less than 0.1 µm in diameter, which is too small to see (see Crine [B11], Moreau [B23], and Zeller [B32]).

The detection of water trees has been an important issue for some time, and attempts have been made to relate dielectric loss and partial discharge characteristics to water treeing in both laboratory and field tests on cable insulation (see Bahder et al. [B4] and Hvidsten et al. [B17]). Greater partial discharge detection sensitivity can usually be achieved in laboratory tests with the result that many tests have been performed on cables removed from the field or on insulation samples molded and aged in the laboratory. Numerous researchers have attempted to detect partial discharge from water trees using both electrical and optical techniques. The laboratory electrical partial discharge detection systems often had sensitivities in the range of 0.01 pC to 0.1 pC (see Bahder et al. [B4]). Measurements have also been made on cables removed from service after 5 to 13 years (see Kirkland et al. [B19]). In no case has partial discharge been detected from water trees, either using electrical or optical detection (see Bahder et al. [B4], Bamji et al. [B5], Hvidsten et al. [B17], Kirkland et al. [B19], Nitta [B24], and Steennis and Kreuger [B27]), unless an electrical tree formed from the water tree (see Rasikawan et al. [B25]).

The above results indicate that despite extensive efforts to find partial discharges from growing water trees, none has been found. This is not surprising given the relatively low electrical field necessary for water tree initiation and growth, typically 1 kV/mm to 2 kV/mm (25 V/mil to 50 V/mil). Even allowing for some stress enhancement at the tip of a water tree, the electric stress at operating voltage will not be sufficient to sustain partial discharges in the microcavities found in typical water trees [<50 µm, (<2 mils)].

Water trees do not generate partial discharge. However water trees can lead to electrical trees as a result of a lightning impulse (see Boggs et al. [B7] and Hopkinson [B16]) or as a result of AC voltage (see Bamji et al. [B5] and Steennis and Kreuger [B27]). The likelihood of causing a pre-existing water tree to lead to an electrical tree during a field PD test increases with the test voltage and the test duration. In general, electrical trees are more difficult to initiate than to grow, so that an electrical tree, once initiated, tends to grow to failure by partial discharges. Thus one can conclude that growing water trees do not generate partial discharge signals, unless they give rise to an electrical tree. Any partial discharges at a water tree imply the existence of one or more electrical trees at that water tree.

Annex B

(informative)

Effect of cavity shape on partial discharge inception voltage

The PD inception voltage (PDIV) of a void or cavity will depend on the shape, size, and position of the cavity within the insulation and the type of gas and its pressure inside the cavity.

Table B.1 shows examples of how the shape of a cavity affects the magnitude of the electrical stress in the cavity.

Table B.1—Values of electric stress and PDIV for different cavity shapes and locations in 15 kV, 250 mm^2 (500 kcmil) cable

XLPE		**PDIV in kV for 0.5 mm (20 mil) cavity**		
Cavity shape	**Electric stress in cavity**	**Cavity at conductor shield**	**Cavity in middle of insulation**	**Cavity at insulation shield**
Spherical	$1.23E_d$[a]	11.7	13.8	16.0
Flat longitudinal	$2.3E_d$	6.3	7.4	8.6
Flat radial	E_d	14.0	17.0	20.0
EPR		**PDIV in kV for 0.5 mm (20 mil) cavity**		
Cavity shape	**Electric stress in cavity**	**Cavity at conductor shield**	**Cavity in middle of insulation**	**Cavity at insulation shield**
Spherical	$1.31E_d$	11.0	13.0	15.0
Flat longitudinal	$3.5E_d$	4.1	4.8	5.6
Flat radial	E_d	14.0	17.0	20.0

[a]E_d is the stress in the insulation adjacent to the cavity.

For example, the electrical stress inside a spherical cavity in XLPE insulation will be about half that in a flat cavity such as a loose insulation shield. Thus, the PDIV for a spherical cavity in XLPE is about twice that for a flat cavity and almost three times the value for the corresponding flat longitudinal cavities in EPR insulation. If the flat cavity is aligned in the direction of the applied electrical stress, i.e., usually radially, the stress inside the cavity will be the same as that in the adjacent insulation so that the PDIV will be 20% to 30% greater than that for a spherical cavity of similar size and location.

Annex C

(normative)

Partial discharge calibration and location accuracy

C.1 Introduction

This guide covers devices and techniques to measure and to locate partial discharge activity. There are many types of PD detection and location equipment, generally categorized as “wide band” or “narrow band.” Some types indicate values in the time domain, and some types indicate values in the frequency domain. Due to the differences in measuring technique, there can be great differences in sensitivity of partial discharge detection.

Partial discharge measurements are not absolute in the sense that the measured PD magnitude, PDIV, PDEV, and other properties are a function of defect size, position of the defect within the sample, and so on. For example, the measured PD magnitude is generally inversely proportional to sample size. Thus, the purpose of calibrating PD measurements is not to provide absolute accuracy but to assure that PD measurements yield the same result under the same circumstances. Calibration is also a convenient method to check the detection sensitivity, which is an important parameter in PD measurements. It can also be used to verify that the test equipment is functioning normally or has changed during a test or series of tests.

C.2 Partial discharge calibration

Cable standards, ICEAT24-380, IEC 60270, IEC 60885-2, and IEC 60885-3, contain calibration methods that are used in factory tests. The standards stipulate maximum acceptable PD magnitudes in new cables; these specified maximum magnitudes have decreased over time so that a cable installed 30 years ago might not meet the current standards. The calibration methods described in the standards are valid for low- or narrow-bandwidth measurements, but they do not address wide-band measurements. In general, if the measurement of partial discharge activity is to be compared with values obtained in the factory where tests are done according to ICEA or IEC norms, a standardized calibration method should be used. If other methods are used to calibrate PD measuring systems, they should be documented in the field test reports. The calibration will be affected by attenuation in the cable, which is usually larger in aged cables and is dependent on cable length.

For off-line PD testing in the field, the following calibration procedure may be used that follows the narrow-band measurement procedure described in the standards. A voltage pulse of short duration (in the order of several tens of nanoseconds) and known pC magnitude is applied across the cable insulation at the remote cable end. This procedure is not trivial as stray capacitance effects can influence the actual pulse magnitude applied to the cable. The pulse received at the near end is integrated with respect to time. For analog integration, the gain is adjusted until the pC value read is equal to that of the calibration pulse. For digital integration, a constant multiplier is adjusted until the pC obtained is the same as that of the calibration pulse. The PD test instrument is now calibrated to measure with relatively good accuracy the apparent charge of the PD pulse. Once calibrated, the calibration remains valid for future tests as long as the cable characteristic impedance and the reflection coefficients at the accessories remain unchanged, and the characteristics of the detection and measuring circuits have not changed. Periodic calibration is recommended to ensure that all equipment is working satisfactorily.

In some on-line PD testing, the relative magnitude of the PD pulse is provided in units of voltage rather than in pC. Some HV cable joints are built with extra electrodes where calibration signals can be injected during on-line PD measurements in the joints. During on-line testing, a sensitivity of about 1 pC is achievable if the distance between two consecutive test points is kept less than 150 m (500 ft).

A note of caution needs to be made concerning the pC values provided by limited bandwidth (30–400 kHz) instruments, such as those commonly used in cable manufacturing plants, and the values obtained by large bandwidth (several megahertz) instruments, such as those used in field PD location. Because of the different measurement and calibration methods used in these two applications, the pC values reported may be different.

C.3 Partial discharge location accuracy

This subclause discusses the major conditions affecting the accuracy of PD location.

PD site location is normally performed using wide-band systems that have good distance accuracy and lower background noise susceptibility. The major site-specific parameters affecting PD location include wave-propagation characteristics, cable length, number, quality and spacing of splices, quality of terminations, and noise level. The major non-site-specific parameters include PD instrument performance, noise mitigation schemes, analysis methods and procedures, and operator competence.

The wave-propagation characteristics of a cable, namely attenuation and wave velocity, are strongly affected by cable neutral size and configuration, semiconductor shield characteristics, and cable homogeneity. Attenuation tends to reduce the amplitude and increase the duration (width) of a PD pulse as it travels along a cable. Amplitude reduction adversely affects the ability of the instrument to detect the existence of a PD, whereas the broadening of the pulse adversely affects its location accuracy. A neutral completely surrounding a cable, such as a continuous metal tape or housing, yields low attenuation and offers an ideal condition for accurate PD location, provided its electrical conductivity is not impaired by corrosion. In the case of concentric neutral wires, attenuation increases as the percent neutral is decreased. The minimum percent neutral size recommended with respect to acceptable attenuation is 25%. Highly reduced neutral size, such as 10%, produces unreasonably high attenuation and lower than expected velocity. For the same neutral size, a flat strap configuration tends to produce less attenuation than a round conductor. In frequency-domain PD location, high frequencies tend to attenuate over relatively shorter distances with reduced neutral size. The role of cable construction in location accuracy becomes, therefore, more important than in time-domain PD location.

Cable neutral size and configuration can act in combination with the electrical characteristics of the semiconducting shields to play an important role in wave velocity and attenuation and, therefore, in PD location accuracy. If the length of a cable is known, the propagation velocity has to be adjusted accordingly. Otherwise, the assumed velocity should take into account the cable construction. Non-homogeneous cable systems exist when cable constructions are mixed (i.e., mixed extruded and laminated, or mixed conductor sizes or insulation thickness). Non-homogeneous situations also arise when a cable section contains new and service-aged cables with different water content and non-uniform wave propagation characteristics. The foregoing conditions tend to decrease the PD location accuracy.

For equivalent propagation characteristics, long cables attenuate more than short cables and tend to produce less accurate PD location results. The presence of a large number of splices, especially when they present abrupt impedance changes, adversely affects attenuation and spatial resolution. Closely spaced splices tend to create pulses resulting from multiple reflections, distorting the original PD pulse and causing an apparent shift in location.

Ambient (background) noise can mask PD pulses totally or create distorted pulses with resulting errors in location assessment. A robust PD locating instrument, with effective noise mitigation measures, should circumvent this undesirable situation. PD analysis can be totally automated, partially automated or placed totally under human control. The effectiveness of each of these schemes significantly affects the PD location accuracy. The bandwidth of a PD locating instrument influences the location accuracy. As the bandwidth increases, the PD pulses tend to be sharper and crisper, tending to improve accuracy. However, frequency-dependent noise may increase, and interfere with this accuracy, unless the noise mitigation measures prevent it.

Annex D

(informative)

Bibliography

[B1] Abdolall K., Halldorson G., and Green D., "Condition assessment and failure modes of solid dielectric cables in perspective," *IEEE Transactions on Power Delivery*, vol. 17, no. 1, pp. 18–24, 2002.

[B2] Ahmed, N. H. and Srinivas, N. N., "On-line partial discharge detection in cables," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 2, pp. 181–188, 1998.

[B3] Ahmed, N. H. and Srinivas, N. N., "On-line versus off-line partial discharge testing in power cables," *2001 IEEE Transmission and Distribution Conference and Exposition*, vol. 2, pp. 865–870, Nov. 2001.

[B4] Bahder, G., Katz, C., Lawson, J., and Vahlstrom, W., "Electrical and electrochemical treeing effect in polyethylene and cross-linked polyethylene cables," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-93, no. 3, pp. 979–990, 1974.

[B5] Bamji, S., Bulinski, A., Densley, J., Garton, A., and Shimizu, N., "Water treeing in polymeric insulation," *Conference Internationale des Grandes Reseaux Electriques Haute Tension (CIGRE)*, 1984, Paper 15-07.

[B6] Bamji, S., Bulinski, A. T., and Densley, J., "Final breakdown mechanism of water treeing," *1991 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena*, pp. 298–305.

[B7] Boggs, S. A., Densley, R. J., and Kuang J., "Mechanism for Conversion of Water Trees to Electrical Trees under Impulse Conditions," *IEEE Transactions on Power Delivery*, vol. PD-13, no. 2, pp. 310–315, 1998.

[B8] Boggs, S. and Densley, R. J., "Fundamentals of partial discharge in the context of field cable testing," *IEEE Electrical Insulation Magazine*, vol. 16, no. 5, pp. 13–18, 2000.

[B9] Boone, W., van Schaik, N., and Schacker, M. S., "Reliability improvement of underground cable circuits by condition based maintenance programs," *NETA Conference*, San Antonio, TX, March 15–16, 2004.

[B10] CIGRE WG D1.33 Task Force 05, "Experiences in partial discharge detection of distribution power cable systems," *Electra*, vol. 208, pp. 35–43, June 2003.

[B11] Crine, J.-P., "Electrical, chemical and mechanical processes in water treeing," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 5, pp. 681–694, 1998.

[B12] Dorris, D. L., Pace, M. O., Blaleck, T. V., and Alexeff, I., "Current pulses during water treeing, procedures and results," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. DEI-3, no. 4, pp. 523–528, 1986.

[B13] Gulski, E., "Digital analysis of partial discharges," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 2, no. 5, pp. 822–837, 1995.

[B14] Gulski, E., Wester, F. J., Smit, J. J., Seitz, P. N., and Turner, M., "Advanced partial discharge diagnostic of MV power cable system using oscillating wave test system, *IEEE Electrical Insulation Magazine*, vol. 16, no. 2, pp. 17–25, 2000.

[B15] Hetzel, E. and MacKinlay, R., "Diagnostic field testing of PILC MV cable," *Jicable*, pp. 472–475, 1995.

[B16] Hopkinson, R. H., "Better surge protection extends cable life," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, pp. 2827–2834, 1984.

[B17] Hvidsten, S., Ildstad, E., and Sletbak, J., "Understanding water treeing mechanisms in the development of diagnostic test methods," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 5, pp. 754–760, 1998.

[B18] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition, New York, Institute of Electrical and Electronics Engineers, Inc.[10]

[B19] Kirkland, J. W., Thiede, R. S., and Reitz, R. A., "Evaluating the service degradation of insulated power cables," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 7, pp. 2128–2136, 1982.

[B20] Kreuger, F. H., Gulski, E, and Krivda, A., "Classification of partial discharges," *IEEE Transactions on Electrical Insulation*, vol. 28, no. 6, pp, 917–931, 1993.

[B21] Mashikian, M. S., Luther, R., McIver, J. C., Jurcisin Jr., J., and Spencer, P. W., "Evaluation of field-aged crosslinked polyethylene cables by partial discharge location," *IEEE Transactions on Power Delivery*, vol. 9, no. 2, pp. 620–628, 1994.

[B22] Mashikian, M. S., "Preventative maintenance testing of shielded power cable systems," *IEEE Transactions on Industry Applications*, vol. 38, no. 3, pp. 736–743, 2002.

[B23] Moreau, E., Mayoux, C., Laurent, C., and Boudet, A., "The structure characteristics of water trees in power cables and laboratory specimens," *IEEE Transactions on Electrical Insulation*, vol. EI-28, no. 1, pp. 54–64, 1993.

[B24] Nitta, Y., "A possible mechanism of water trees from water electrodes," *IEEE Transactions on Electrical Insulation*, vol. EI-9, no. 3, pp. 109–112, 1974.

[B25] Rasikawan, S., Ishihara, H., and Shimizu, N., "Comparison between water-treed and deteriorated regions. Electrical tree precursor," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. DEI-1, no. 4, pp. 597–603, 1994.

[B26] Ross, R., "Inception and propagation mechanisms of water treeing," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 5, no. 5, pp. 660–680, 1998.

[B27] Steennis, E. F., and Kreuger, F. H., "Water treeing in polyethylene cables," *IEEE Transactions on Electrical Insulation*, vol. 25, no. 5, pp. 989–1028, 1990.

[B28] Steennis, E. F., Hetzel, E., and Verhoeven, C. W. J., "Diagnostic medium voltage cable test at 0.1 Hz," *Jicable*, pp. 408–414, 1991.

[10] IEEE publications are available from the Institute of Electrical and Electronics Engineers Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[B29] Suzuki, H. and Endoh, T., "Pattern recognition of partial discharges in XLPE cables using a neural network," *IEEE Transactions on Electrical Insulation*, vol. 27, pp. 550–556, 1992.

[B30] van Schaik, N., Steennis, E. F., Boone, W., and van Aartrijk, M., "Partial discharge diagnostics on very long and branched cable circuits," *Nordic Insulation Symposium*, Tampere, June 11–13, 2003.

[B31] van Schaik, N., Steennis, E. F., and Kruithof, M. G., "Partial discharge diagnostics as part of condition based maintenance on MV power cables: yes or no?" *Jicable*, pp. 241–246, 2003.

[B32] Zeller, H. R., "Noninsulation properties of insulation materials," *1991 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena*, pp. 19–47.

[B33] Zhifang D., Willet, P. K., and Mashikian, M. S., "Performance limits of PD location based on time-domain reflectometry," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 4, no. 2, pp. 182–188, 1997.