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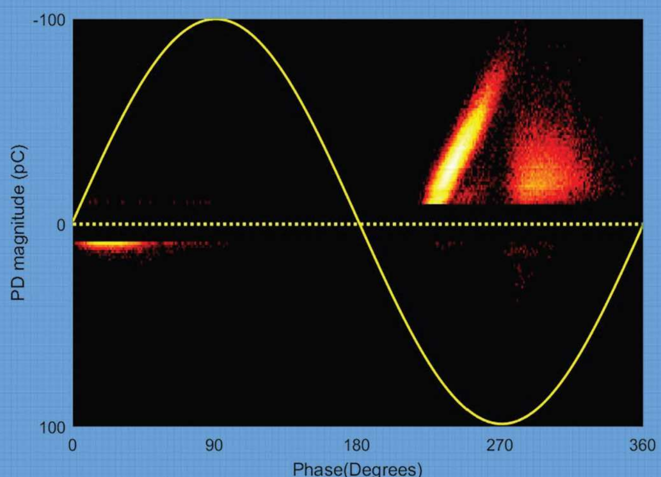
Practical Partial Discharge Measurement on Electrical Equipment

Greg C. Stone, Andrea Cavallini, Glenn Behrmann, Claudio Angelo Serafino



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This book is dedicated to the engineers and scientists who took a scientific curiosity of the 1890s and built a measurement technology that is now an essential tool for factory quality control tests on new high-voltage electrical equipment, as well as a widely used technology to help determine when maintenance is needed on such equipment.

Although thousands have worked in this field, we would like to acknowledge the seminal contributions of some of its leading engineers and scientists who are no longer with us:

Ray Bartnikas (Canada)
Steve Boggs (Canada/USA)
Frederik Kreuger (The Netherlands)
Bernd Fruth (Germany)
Jitka Fuhr (Switzerland)
George Mole (UK)
Lutz Niemeyer (Germany)

Some of us have had the privilege of working with and being guided by them over the years; they are sorely missed. This book is dedicated to them, especially their willingness to share their knowledge and inspire us.

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About the Authors

Greg C. Stone was one of the developers of a widely used online partial discharge test method to evaluate the condition of the high-voltage insulation in stator windings. Except for a one-year period at Canada Wire and Cable, from 1975 to 1990, he was a Dielectrics Engineer with Ontario Hydro, a large Canadian power generation company. From 1990 to 2021 he was employed at Iris Power L.P. in Toronto Canada, a motor and generator winding condition monitoring company he helped form, and one of the largest manufacturers of partial discharge measurement equipment in the world. He has published two books on motor and generator winding maintenance, contributed the machine insulation chapters to three technical encyclopedias/handbooks, and authored >200 papers concerned with partial discharge measurement and rotating machine condition assessment. Since 1980 he has also been active in creating and updating many IEEE and IEC standards. Dr. Stone has been and continues to be active in the IEEE Dielectrics and Electrical Insulation Society for his entire career, serving as its president in 1989 and 1990. He has been chosen for the IEEE Kaufmann, Dakin and Forster Awards; the CIGRE Technical Committee Award; the IEC 1906 Award; and the US-based EPRI Principal Investigator Award. Greg Stone has BASc, MASc, and PhD degrees in electrical engineering from the University of Waterloo, is a fellow of the IEEE, a fellow of the Engineering Institute of Canada, and a licensed professional engineer in Ontario, Canada.

Andrea Cavallini is a professor at the University of Bologna. In 2000, he invented the TF map, a revolutionary method to process partial discharge signals allowing noise rejection and the individual analysis of multiple partial discharge sources simultaneously active in the same equipment. From 1999 to 2012, he cofounded and collaborated with Techimp Srl, now a part of the Altanova group. During this time, he was actively involved in testing all types of apparatus used in power systems: cables, generators, transformers, and motors. He has worked on electrical as well as ultra-high frequency detection of partial discharges; in particular, he was among the first to use ultra-high frequency detection of partial discharges on inverter-fed machines, a technique that later became the state of the art. He has published more than 250 papers, most of them in the IEEE. He is member of the IEC TC 2 Rotating Machinery MT 10 concerned with the qualification, testing and diagnostics of winding insulation systems. He is active in CIGRE where he has convened D1 working groups. He has BASc, MASc, and PhD degrees in electrical engineering from the University of Bologna in Italy and is a fellow of the IEEE.

Glenn Behrmann began work in radio-frequency design and signal processing for military applications at MIT Lincoln Laboratory, the MITRE Corporation, and Signatron. After working in EMC, he began his work in PD in 1992 at ABB Corporate Research (Baden) under Bernd Fruth and Lutz Niemeyer, first in the insulation materials lab, later on site, on transformers, HV cable accessories, and GIS, playing a key role on the first large-scale UHF PD monitoring systems for 400 kV GIS in Singapore. During a two-year stint at the Paul Scherer Institute, he worked on RF beam-diagnostics for the European Free Electron Laser (X-FEL, Hamburg). In 2008, he returned to PD diagnostics of rotating machine insulation and online monitoring systems at Alstom (GE). In 2011, he rejoined ABB, focusing on all aspects of PD detection and monitoring in GIS using both conventional and UHF techniques. This included sensor development, detailed investigations of RF signal behavior, lots of onsite PD diagnostics, and a key role in PXIPD (pulsed X-ray-induced partial discharge) for detecting voids. He has authored many papers and holds patents in the field. He is an active member of CIGRE (presently secretary of D1.66, Requirements of UHF PDM systems for GIS) and IEC TC42 (including the latest revision of IEC 60270) and is chair of the IEEE PES/SA group revising IEEE 454 on PD measurement. Glenn received a BSEE from Union College (Schenectady) in 1979. Although just retired, he remains active doing onsite PD assessments and consulting.

Claudio Angelo Serafino has more than 40 years of experience in measurements and tests on high voltage equipment. He carries out commissioning and routine tests on high-voltage equipment, including circuit breakers, disconnectors, surge arresters, gas-insulated systems, current transformers, and voltage transformers. He also has experience in commissioning and routine tests on protection systems for high-voltage plants, large power generators, and transformers. He is an expert in PD measurements on large power and high-voltage transformers, performed both in the manufacturers' test labs and onsite, with the aim to investigate faults. He gained his experience working in two companies. From 1982 until 2000, he worked at ENEL, the integrated Italian electrical utility. Since 2000 he is working in the Italian TSO Terna as an expert in medium and large power transformer tests and technical specifications.

Preface

Partial discharge (PD) testing is widely used as a quality assurance test for the electrical insulation in medium- and high-voltage equipment. Owners of high-voltage equipment such as transformers, switchgear, power cables, and rotating machines are also using PD testing as a tool to determine if there is a risk of insulation failure in equipment that has been in service. This latter application has exploded in the past decade with the availability of PD test systems that measure PD during normal operation of medium- and high-voltage apparatus.

There are now dozens of vendors of PD testing systems, and many IEC and IEEE standards have been published that present the basics of PD measurement on various types of high-voltage apparatus. Also, books have been published that go into the details of both the physics of PD and PD detection theory, in addition to thousands of technical papers. These have been mainly written for researchers on the subject.

This book has a different aim. It is written for those who work for electrical equipment manufacturers and owners of medium- and high-voltage equipment who preform PD testing as only one part of their job, and who want to understand better the information from vendors and the relevant standards. Although we discuss some basic information on why PD occurs and PD measurement theory in the first few chapters, the main focus is presenting practical information that even occasional users of PD testing need to know when using commercially available PD measurement systems. There are chapters on the most common ways to detect PD, how to reduce the influence of electrical noise and interference, as well as how PD results are analyzed in general. Then there are chapters for each type of high-voltage equipment that describe the most common PD measurement methods for that equipment, as well as what insulation problems it can detect and how to interpret the PD data. Since there is a broad range of PD system vendors for each type of high-voltage equipment, we have attempted to include the most popular methods applied to each type of equipment. Sometimes, the same PD measuring system is used for different types of electrical equipment. The final chapters are brief introductions to the rapidly evolving techniques to measure PD under DC excitation and short-risetime voltage impulses.

The authors have a diverse range of backgrounds. One of us was formerly with a PD system vendor, one is both an academic researcher and a cofounder of a different PD system vendor. The other two authors are primarily users of PD testing – one mainly working for a high-voltage equipment supplier and the other working for a transmission grid utility. Hopefully, this diversity has resulted in a practical book on PD measurement.

Acknowledgments

The authors would like to thank Ms. Resi Zarb, the founding president of Iris Power L.P. as well as a former co-editor in chief of the *IEEE Electrical Insulation Magazine*. She provided invaluable assistance in reviewing every chapter of this book.

GCS would like to thank his wife, Judy Allan, for her support during this project. He would also like to acknowledge the importance of the late Mo Kurtz and the late Steve Boggs to his comprehension of PD measurement. Many significant discussions with his former colleagues at Iris Power L.P.: Howard Sedding, Mladen Sasic, Connor Chan, Vicki Warren, and Iouri Pomelkov have contributed to his understanding of the measurement and interpretation of PD.

AC would like to thank his colleagues at the University of Bologna: Gian Carlo Montanari for directing his research efforts toward partial discharges, as well as Davide Fabiani and Gaetano Pasini for countless discussions. He is particularly indebted to Alfredo Contin and Francesco Puletti with whom he had many enlightening exchanges of ideas, Fabio Ciani (*sit tibi terra levis*) for his friendly and professional support in the lab, and all the PhD students who worked with him: Carlos Gustavo Azcarraga Ramos, Peng Wang, Fabrizio Negri, Paolo Mancinelli, Luca Lusuardi, and Alberto Rumi. Last but not least, AC thanks his fiancé Violeta Zumeta for her incredible patience.

GB wishes to thank many colleagues in the field, both past and present, for passing on their know-how (or challenging mine) during many fruitful discussions in the lab or on site, often in the evenings after work or at a conference. First and foremost, I must thank the late Bernd Fruth and Lutz Niemeyer for bringing me into this strange and fascinating field, educating me, and igniting my interest in it. Along with them, my sincere thanks to Detlev Gross, Markus Schraudolph, Stefan Neuhold, Uwe Riechert, Ralf Pietsch, Wojciech Koltunowicz, Marek Florkowski, and Maria Kosse (Hering); I'm indebted to them all for their help, wisdom, PD insights, and friendship. In my work in RF propagation, I am grateful to Jasmin Smajic and Daniel Treyer for their lucid explanations of electromagnetics, impedance, and many hours of fun discussions. To anyone I have left out: my sincere apologies.

CAS firstly thanks Fiorenzo Stevanato, Mario Cimini and Diego Bosetto; they have been my teachers and they continue to be a reference. They have the great merit for instilling passion for this profession and the pleasure of increasing knowledge about PD. Many thanks to Dario Gamba, Fabio Marinelli, and Fabio Scatiggio who were with me for long durations as we undertook onsite tests searching for PD, their causes, and their consequences in large power transformers. Finally thanks to Maria Rosaria Guarniere, Evaristo Di Bartolomeo and Roberto Spezie. They demonstrated their belief in this technology and in its benefits to transformer maintenance. They spurred me to grow and to innovate, and they are examples of excellent managers.

Acronyms

ADC	Analog-to-digital converter
AI	Artificial intelligence
AIS	Air-insulated switchgear
ASTM	American Society for Testing of Materials
BDV	Breakdown voltage
BIL	Basic impulse level (lightning impulse voltage)
CIGRE	Conseil International des Grands Réseaux Electriques; Paris-based organizer of power industry conferences and publisher of consensus technical reports
CT	Current transformer
DGA	Dissolved gas analysis (in transformer oil)
EM	Electromagnetic
EMI	Electromagnetic interference
EUT	Equipment under test
FAT	Factory acceptance test
FEM	Finite element method
FPGA	Field programable gate array (type of integrated circuit)
GIL	Gas-insulated transmission line
GIS	Gas-insulated switchgear/substation
GTEM	GigaHertz transverse electromagnetic cell
GVPI	Global vacuum-pressure impregnation (stator winding manufacturing process)
HF	High frequency (3–30 MHz)
HFCT	High-frequency current transformer
HV	High voltage
HVDC	High voltage direct current
IEC	International electrotechnical commission
IEEE	Institute of electrical and electronics engineers
IPB	Isolated phase bus
LF	Low frequency, formally 30–300 kHz, but 30 kHz to 1 MHz in this book
LV	Low voltage
MV	Medium voltage
OCP	Outer corona protection (stator windings)
OEM	Original equipment manufacturer
OIP	Oil impregnated paper
OLTC	Online tap changer (transformers)

PD	Partial discharge
PDEV	Partial discharge extinction voltage
PDIV	Partial discharge inception voltage
PE	Polyethylene
PMT	Photomultiplier tube
PRPD	Phase-resolved partial discharge (plot)
PSH	Peak sample-and-hold (electronic circuit)
PT	Potential transformer
RF	Radio frequency
RFI	Radio frequency interference
RIP	Resin impregnated paper (bushings)
RIV	Radio interference (or influence) voltage
RTS	Resonant test supply/set
SCLF	Space charge limited field
TDR	Time domain reflectometry
UHF	Ultrahigh frequency (300–3000 MHz)
VFTO	Very fast transient overvoltage (GIS)
VHF	Very high frequency (30–300 MHz)
VLF	Very low frequency (AC voltage supply)
VPI	Vacuum pressure impregnation (stator bar and coil manufacturing process)
VSC	Voltage source converter
VZC	AC voltage zero crossing
XLPE	Cross-linked polyethylene (power cables)

1

Introduction

1.1 Why Perform Partial Discharge Measurements?

This book is focused on the practical aspects of the measurement of partial discharge (PD) and corona in 50/60 Hz power system equipment such as generators, motors, power cables, air- and gas-insulated switchgear (GIS), and transformers, all usually rated 3 kV and above. Such electrical equipment uses solid electrical insulation, for example polyethylene, epoxy, and polyester, or insulation composites such as oil–paper, fiberglass-reinforced polymers, or epoxy-mica, to separate high-voltage conductors from ground or to separate one AC phase from another. If this insulation fails, the equipment experiences a phase-to-ground fault or a phase-to-phase fault, which will activate protective relays to isolate the equipment from the power system. Such a failure may manifest itself as a power outage in a residential area or hospital, a loss of electrical power production capacity, or a reduction in power system reliability. In industries such as petrochemical, cement, steel, aluminum, paper, or semiconductor fabrication, these failures can be extremely expensive because modern production processes are continuous; an electrical power failure of even a few minutes may necessitate taking the entire factory out of production for days or weeks. In addition, such insulation failures can cause collateral damage to adjacent components that can greatly increase the cost of repair. For example, a large utility generator or power transformer failure can cost millions to repair, and result in a plant shutdown that can last for months, causing tens of millions of dollars in lost production.

Partial discharges are small electrical "micro-sparks" that can occur in insulation systems operating with high electric fields. The physics of PD and how it is manifested are discussed in Chapters 2, 3, and 5. PD activity can directly lead to insulation degradation and equipment failure. PD is also sometimes a symptom of poor manufacturing and/or aging of the insulation due to high temperature, mechanical forces, contamination, etc. In this case, PD might not directly lead to failure but may indicate that insulation aging due to other mechanisms is occurring and maintenance may be needed. Thus, by measuring PD activity, equipment manufacturers can often determine that the insulation system on the equipment was properly made, and equipment owners can determine if aging is occurring that could lead to failure.

Each partial discharge is accompanied by a current pulse. As presented later in this book, these current pulses can be detected by various types of sensors and measurement instruments. In addition to measuring the PD current, PD can be detected from radio frequency (RF) radiation, light

Practical Partial Discharge Measurement on Electrical Equipment, First Edition. Greg C. Stone, Andrea Cavallini, Glenn Behrmann, and Claudio Angelo Serafino.

emissions, acoustic noise, and by chemical changes in the local environment. PD testing involves the measurement of the PD current pulses and other signals that are produced by PD.

PD testing using 50/60 Hz AC is widely employed as a factory quality assurance (QA) test for all types of high-voltage equipment. Many IEEE and IEC technical standards have been published to indicate how the PD should be measured for each type of equipment, often providing guidance on interpretation, and sometimes providing information on pass/fail criteria. The premise is that if newly manufactured equipment successfully passes the PD test, then premature insulation failure due to electrical stress is unlikely.

In recent decades, with the development of digital hardware, often with powerful disturbance suppression methods and signal processing, PD testing has increasingly been applied to high-voltage equipment that has been installed in the power system or industrial plants with a view to assess if the high-voltage insulation system is degrading and may have a high risk of failure. Thus, the purpose of PD testing, once equipment has entered service, is to help with insulation condition assessment and determining the need for maintenance. There are relatively few IEEE and IEC standards for such PD testing applications. Hence, an important function of this book is to provide information for both onsite (offline) and online PD testing/monitoring of the different types of high-voltage equipment.

In this book, for simplicity, we will use the term "high-voltage insulation system," rather than the more cumbersome "medium- and high-voltage insulation system." What voltage ratings are associated with medium voltage (MV) and high voltage (HV) depends on the type of equipment. A medium-voltage motor is usually rated between 3 and 7 kV, whereas a high-voltage motor is 11 kV or higher. In electrical power transmission systems, there is a wide variation of what is meant by medium and high voltage.

1.2 Partial Discharge and Corona

There are many definitions for partial discharge. Perhaps the most widely used definition of PD comes from IEC 60270, where it is described as "a localized electrical discharge that only partially bridges the insulation between the conductors and which can or cannot occur adjacent to a conductor." That is, PD is a localized electrical breakdown of the insulation that does not immediately progress to a complete breakdown across the insulator (e.g. between the high-voltage conductor and ground). In contrast, a "complete discharge" essentially means a phase-to-phase or phase-to-ground fault has occurred, which would typically trigger protective relaying to open-circuit breakers. As is discussed in Chapters 2 and 3, since gases (and air in particular) have a dielectric strength that is a small fraction of the dielectric strength of a solid or liquid insulation, PD tends to occur where there is a gas under high electrical stress. Thus, PD almost always occurs when there is a gas-filled void within the solid or liquid insulation, or there is gas adjacent to the solid/liquid insulation along a surface. PD can also occur in a gas adjacent to metal conductors where the electric field is rapidly decreasing the greater the distance from the metal conductor. Thus, PD can occur in all types of high-voltage apparatus, regardless of the insulation system, and may even occur at relatively low voltages if distances are small (Chapter 18).

A corona discharge is a particular type of PD. In IEC 60270, corona is described as "a form of partial discharge that occurs in a gaseous media that is around conductors that are remote from solid or liquid insulation." The most common type of corona occurs in overhead electric transmission lines, from which its distinctive crackling sound can often be heard, especially during rainy/snowy/foggy weather. Such corona is caused by localized breakdown of the air due to the high electric field adjacent to the bare aluminum conductors. The corona is very localized, since the electric field more than a few centimeters away from the high-voltage conductors is too low for electrical breakdown to occur. Thus, there is no "complete breakdown" between the transmission line conductors and ground. The term "corona" has been reserved for this type of PD since, on dark nights, the glow of the "corona" surrounding the lines can often be observed visually. To clarify, corona is often visible and caused by nonuniform electric fields in the air or gas. Corona itself does not directly damage the "electrical insulation" since, for the most part, electron and ion bombardment of gas molecules have no lasting effect, and although metals may experience some discoloration and pitting, and corona can produce by-products such as ozone, this usually does not impair the function of the HV apparatus. Also, the glass and ceramic insulators that hold up the overhead transmission lines are inorganic and extremely resistant to corona. In fact, the only real negative impact of corona is the radio and television interference they cause, as well as the energy losses due to corona on the transmission line.

A hundred years ago, the terms "ionization" and "corona" were used for what is now called PD. In the 1920s, the term corona became more popular than ionization. After the 1940s, more and more papers referred to both corona and (partial) discharges interchangeably. Once the definition of corona and partial discharge were clarified by many standard-making organizations in the 1960s, corona and PD should no longer be used as synonyms. In reviewing the literature, Europeans adapted more quickly and tended not to use the corona and PD as synonyms after the 1960s. North Americans tended to use corona and PD interchangeably well into the 1980s (and a few older persons still get mixed up). In this book, PD will refer to all types of incomplete discharges. Corona will be used to refer to a particular type of PD that is associated with highly divergent electric fields around metal conductors in air.

1.3 Categories of PD Tests

PD testing has two main purposes:

- as a factory test on new equipment; and
- as a test to determine if insulation aging is taking place in installed high-voltage equipment.

The first is an offline test (that is an external AC supply is needed to energize the equipment to the test voltage). There are subcategories of factory tests: PD tests during the development stage of new equipment; type tests on a small percentage of test objects to ensure the PD is within requirements; and routine tests (quality assurance or QA tests) done on every new piece of equipment to ensure the that each test object meets manufacturer's production standards, international or national standards, and/or customer specifications. The manufacturer's production standards may exceed the requirements of international or customer requirements.

The second category can be either offline or online testing. In online testing, the test equipment is energized from the power system.

1.3.1 Factory PD Testing

Virtually all electrical equipment that uses at least some solid or liquid insulation and that is rated above about 3 kV (phase-to-phase, rms), may be given a routine factory PD test at rated or higher voltage before the equipment is shipped. Thus, either the original equipment manufacturer (OEM) of power cables, transformers, air- and gas-insulated switchgear will voluntarily perform PD tests as part of their factory quality assurance program, or the end user (eventual owner of the equipment) may require a PD test before shipment.

As mentioned above, and as discussed in some detail in Sections 3.6 and 3.7, PD will damage organic insulation materials such as polyethylene, rubber, epoxy, and oil/paper composites. The electron and ion bombardment of organic materials leads to electrical treeing or surface electrical tracking. With sufficient time, the tree or track will cause a phase-to-ground or phase-to-phase fault, and thus equipment failure. The main purpose of a factory PD test is to ensure that HV equipment using organic insulation has no PD during normal operation, and, therefore, cannot fail prematurely due to PD. In addition, if the PD activity in a specific piece of equipment is higher than occurs in the same equipment made in the past by the OEM, even though it meets requirements, it may be an indication that the components or the manufacturing process has changed. This is a signal to the OEM to investigate the root cause of the increase in PD activity to avoid similar problems with future production. For example, if the partial discharge extinction voltage (PDEV, Sections 3.6.1, 8.7.5, and 10.2) test is lower than normal in a few reels of XLPE power cable, it may mean that the extrusion process is not using the correct pressure, flow rate, etc.; the polyethylene pellets are contaminated; the curing cycle is wrong, etc., and therefore the manufacturing process should be corrected before more cable is made.

The presence of PD-like electrical interference (Chapter 9) that can lead to false indications of high PD levels in onsite or online tests (Sections 1.3.2 and 1.3.3) tends not to be too much of a problem for factory tests. This is because the tests can often be done in an electromagnetically shielded area, use an interference-free AC test supply, and/or the source of the interference can be eliminated by doing the tests when most sources of interference are not operating (e.g. at night or on weekends).

Power cables (PE, XLPE, EPR, EPDM, as well as oil-paper insulated cables), capacitors (using polymer films impregnated with a liquid), and liquid-filled power transformers (mainly oil-paper composites) all use purely organic insulation as the main insulation material. Thus, as far back as 1926, researchers were investigating the use of PD (or as they called it "ionization" testing as a QA tool in factories) [1]. In the 1950s, what today would be recognized as factory PD tests were becoming more established, as discussed by Dakin [2]. Today, most equipment that is primarily insulated with organic insulation has associated standardized PD test procedures, often with minimum acceptable levels of PDIV or PDEV. The standards are prepared by IEEE (Institute of Electrical and Electronic Engineers), IEC (International Electrotechnical Commission), and various national standards bodies. Chapters 12–15 identify the relevant QA test procedures for each type of high-voltage equipment.

Air-insulated metalclad switchgear (AIS) and gas-insulated switchgear (GIS) use air and SF_6, respectively, as the main insulation. However, the high-voltage busbars are usually supported by organic-insulated components such as fiberglass-reinforced polyester boards (AIS) or epoxy spacers (GIS). Such switchgear may also include insulating rods to operate switches, potential transformers (PTs), and current transformers (CTs) that employ molded epoxy. PD tests on these components are essential to ensure that the switchgear does not fail in service. In addition, metallic debris may be present because of the manufacturing process that can lead to corona (and even bouncing metallic particles in GIS). Thus, PD testing has long been required for assembled AIS and GIS in most countries to ensure equipment reliability, using associated standardized tests (Chapters 13 and 14).

Rotating machines have always been in a special class for factory QA testing. As discussed in Chapter 16, the high-voltage insulation in motor and generator stator windings is a composite of mica tapes bonded together with epoxy (epoxy-mica insulation). Mica, being inorganic, is extremely resistant to PD attack, and stator windings using mica tapes have been known to withstand low and moderate levels of PD in service for many decades. As a result, even though there are IEEE and IEC standards for factory PD testing, there are no international standards for acceptable and unacceptable PD activity for new equipment. Instead, OEMs often perform PD testing on newly manufactured stator windings (especially on air-cooled motors and turbine generators), as a means of ensuring the manufacturing process has not changed, rather than as an acceptance test.

1.3.2 Onsite/Offline PD Tests

Some types of new equipment, because of their physical size, must be assembled at the utility or industrial plant where it will be used. This includes large AIS, almost all GIS, cable circuits once joints and terminations are installed, and most hydro generator stator windings. Thus, the final "factory" test or "commissioning" offline PD test must be conducted at the enduser location ("onsite") to verify the quality of assembly. This is also the case for large liquid-filled power transformers, since often the insulating liquid is added only when the transformer has been delivered to the enduser site.

However, probably the more common reason for performing PD tests at the enduser site is to determine if the electrical insulation is degrading, and maintenance may be required. This requires a baseline test (which could be the commissioning tests mentioned in the previous paragraph), followed by offline tests on the equipment over the years to detect if the PD inception voltage or the extinction voltage is decreasing; or the PD magnitude at a specific test voltage is increasing over time.

The key aspect of onsite/offline tests is that the high-voltage equipment is disconnected from the power system, and a 50/60 Hz high-voltage test supply is brought to site and used to energize the capacitance of the test object. As an alternative to 50/60 Hz voltage, sometimes the high-voltage equipment may be energized using 0.1 Hz AC or an oscillating damped wave voltage. Another alternative consists of a portable variable-frequency resonant test set, where an inductance is made resonant with the test object capacitance. For power transformers, the high-voltage winding is often energized by exciting the low-voltage winding with an external power supply operating at few hundred Hz (Section 15.8). In all cases, the HV test voltage supply must have the kVA capability to raise the voltage of at least one phase of the HV equipment to the test voltage, which often is higher than the rated line-to-ground operating voltage.

The other important requirement is that PD-like interference (also called disturbances) must be minimal to measure PD from the test object alone. With onsite/offline PD testing, the test voltage supply is expected to be interference-free, eliminating an important source of interference. However, onsite PD tests are still susceptible to RF signals coming from any other PD, arcing, or sparking elsewhere in the enduser plant/station. This may greatly increase the false indication rate or reduce the sensitivity to test object PD, compared to factory PD tests. Methods to reduce the influence of such external interference are discussed in Sections 8.4 and 9.3.

1.3.3 Online PD Testing and Continuous Monitoring

In the past few decades, online PD testing, where the high-voltage equipment is self-energized, i.e. energized from the power system, is becoming more popular. The purpose is to detect any aging that has led to an increase in PD activity, and thus a greater risk of HV equipment failure, without having to shut down the HV equipment for an offline test. Since PD is an important indicator of insulation aging or cause of failure for many types of equipment, regular online testing of the PD facilitates condition-based maintenance (CBM), a powerful method for determining when maintenance or replacement is needed.

For online PD testing, most types of PD sensors must be pre-installed during an outage (i.e. the HV equipment is disconnected from the power system) for personnel safety reasons. Online PD testing comes in two flavors: periodic testing with a portable instrument or continuous monitoring with a permanently installed instrument (Section 8.6).

The most difficult aspect of online PD testing is dealing with PD-like interference from the power system, as well as other disturbances from arcing and sparking within the plant or substation. Some of the interference can be exceptionally hard to separate, since it is actually PD or corona from other equipment in the plant or substation, plus the signal levels of such sources can exceed the level of the PD signals in the equipment of interest by several orders of magnitude. An example would be harmless PD occurring on the surface of a transformer ceramic bushing due to rain or snow, or from a sharp protrusion on an adjacent overhead line. If this PD is confused with PD from within the transformer or within the transformer bushing, an asset manager may believe the transformer windings are in trouble, and schedule costly but unnecessary maintenance. As discussed in Chapter 9, there are many hardware- and software-based methods to suppress such disturbances. Many of these are specific for the type of equipment to be tested and are discussed in detail in Chapters 12–16.

1.4 PD Test Standards

As might be suspected in a technology that has been used for more than 100 years, and where the consequences of failure due to PD may result in losses of tens of millions of dollars, there has been considerable effort over the decades to create and revise PD test standards. Perhaps the oldest standard that is directly relevant is the (USA) National Electrical Manufacturers Association (NEMA) Standard 107, "Methods of Measuring Radio Noise" in 1940 [3]. This standard was created to provide a standardized method of measuring the interference from transmission line corona on broadcast radio signals. However, it was also used as an early standardized method for researchers measuring PD in power transformers and bushings [2]. NEMA 107 is revised from time to time and still in current use.

The best-known PD standard is IEC 60270 [4], which has been adopted as a national standard by many countries. This horizontal standard specifies a general-purpose method for offline PD measurement in the low-frequency range (up to about 1 MHz), on any type of test object, and applied either in the factory or for onsite, offline testing. It was developed in the 1960s and published in 1968 (where it was originally called IEC 270) [4]. A few years later, in 1973, a very similar standard was published by the American Society for Testing Materials: ASTM D 1868 [5]. IEEE also produced a similar general-purpose PD test procedure in 1973: IEEE 454, which was subsequently withdrawn, as well as IEEE C37.301, which is IEC 60270 adopted for use in switchgear. All these standards are concerned with the measurement of PD in the 30 kHz to 1 MHz frequency range, using either "narrow band" or "wideband" frequency measurement (Section 6.5.2). The main output of the test is the magnitude of the PD pulses in terms of the apparent charge of each PD pulse. The PD sensor is most often a PD-free coupling capacitor (typically in the range of 100–1000 pF) in parallel with the test object with a detection impedance; or a high-frequency current transformer (HFCT) on the ground side of the test object. These standards also inform how to convert the detected millivolt (mV) signal to apparent charge (picoCoulombs) for capacitive test objects. IEC 60270 is discussed in detail in Chapter 6.

In 2016, the first general-purpose (applicable for all types of apparatus) guidance was published covering electrical PD measurement in the frequency range between 3 and 3000 MHz, that is well