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

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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 above the frequency range specified in IEC 60270. This document recognized the growing application of onsite/offline and online PD testing in high-voltage equipment. The use of higher measurement frequencies usually reduces the risk of false indications due to external electrical interference and often enables the PD sites to be located within the test object. This document, IEC Technical Specification 62478, discusses several types of PD sensors (capacitors, high-frequency current transformers, and antennas), disturbance suppression methods, and PD site location methods [6]. The standard also makes it clear that it is impossible to “calibrate” detected mV signals in terms of apparent charge (pC) in these higher frequency ranges. Chapters 6 and 7 present the differences between conventional IEC 60270 charge-based PD tests and “unconventional” PD measurements at the higher frequency ranges covered in IEC TS 62478.

In addition to the general-purpose PD standards, there are many standards for the measurement of PD for each type of equipment (e.g. power cable, transformers, switchgear, and rotating machines). These more focused standards are important since how to energize the test object, the placement and type of PD sensors, etc., can often be optimized based on the physical structure of the equipment. Also, the interference suppression methods tend to be different for each type of HV equipment and each type of equipment will have its own likely causes of PD. Each cause of PD may have a different phase resolved PD (PRPD) pattern (Section 8.7.3), and thus interpretation tends to be different for each type of equipment. Both IEC and IEEE have developed standards for each type of equipment, as indicated in Chapters 12–16.

1.5 History of PD Measurement

The history of PD testing and the equipment used goes back to the 1910s. One of the first English-language papers was by Prof. Edward Bennett where he used a coupling capacitor to detect PD currents with an oscillograph to measure PD from high-voltage transmission line equipment [7]. The oscillograph is a relatively fast responding electromechanical device like an X–Y chart recorder. The recorded public discussion of this paper shows that PD measurements were being made 15 years beforehand – i.e. 1898! Since this publication there have been many hundreds of papers published on PD measurement methods and technology. There have been over 20,000 papers on PD (and corona) measurements on HV equipment in the IEEE and IEE/IET alone, according to an IEEE Xplore search (Figure 1.1). Clearly this is a prolific field.

When a sampling of these papers is reviewed, there seems to be three eras in the development of PD measuring equipment:

- Radio interference voltage (RIV) methods
- Analog detection up to 1 MHz using oscilloscope displays
- Digital detection and computer-based processing and measurement up to the GHz frequencies

Although the word “era” is used, in fact variations of measurement methods symbolized by each era are still in use today. The following presents a summary of the developments of each era, identifies some key personalities, and some of the companies that first introduced commercial equipment.

1.5.1 RIV Test – The First Era

As mentioned above, this is the first widely applied method to measure PD, although that was not the original purpose of the test. RIV is variously defined as the radio influence voltage or the radio interference voltage. The original purpose of this test was to determine the level of corona

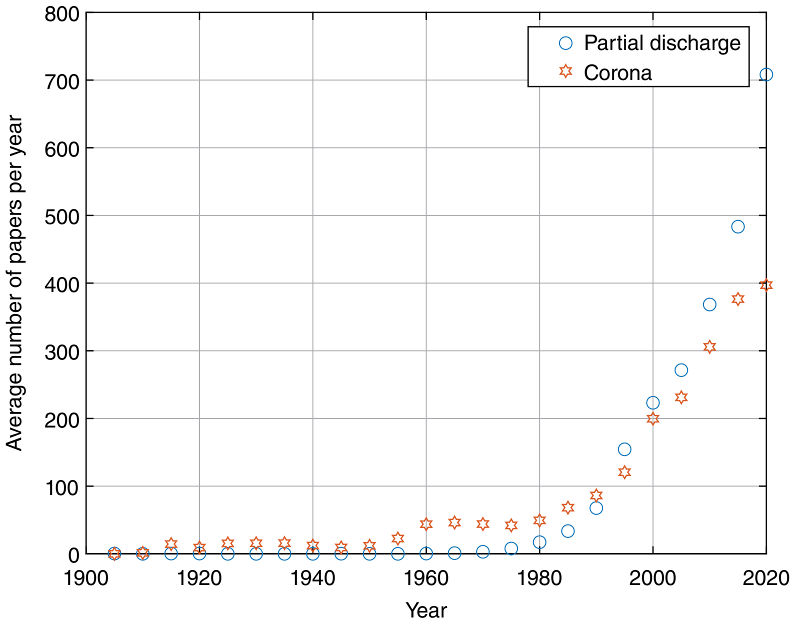

Figure 1.1 Plot of the number of papers on PD and corona vs year of publication in IEEE Xplore.

interference (in microvolts) that an overhead (outdoor) transmission line or its associated (typically glass or porcelain) insulators or transformers (typically, step-down) produces during operation. If the level is too high, complaints from the general public about poor analog radio and analog TV reception could be expected. The PD sensor was either an antenna or some type of coupling capacitor. The signals were measured by a specialized radio receiver (sometimes called a radio noise meter), usually with a center frequency about 1 MHz (i.e. within the normal AM radio broadcast band) with a narrow bandwidth of about 10 kHz. The output of the instrument was a meter that displayed the “quasi peak” – weighted level of the electrical noise produced by the PD activity. In addition, a demodulated signal from the corona could be listened to on a speaker or headphones.

Although early receivers were made by researchers, eventually commercial instruments were made for RIV measurements by Stoddart Aircraft Radio Co. in the United States and Siemens in Europe, among others. The Stoddart noise meters were manufactured beginning in 1944 by founder and IEEE Fellow Richard Stoddart. The use of Stoddart noise meters for PD measurement was a small part of the company’s main business.

Since the noise meters were fundamentally to measure corona from transmission lines, researchers started using RIV methods to detect PD in oil-paper-insulated power cables and oil-filled power transformers. In 1924, Del Mar applied RIV detection to measure the PD in oil-impregnated cables to determine the maximum design electric stress for the insulation [8]. In 1965, two papers described PD measurement in power transformers for factory QA testing using the RIV method [9, 10], also referring to NEMA Standard 107 for the relevant RIV test method. The PD sensor was often the capacitance tap on the transformer bushing, normally used to measure the transformer voltage (Section 15.7.1). Meador suggested a 1000 μV limit at 1 MHz and said the main problem was electrical noise elsewhere in the factory [9]. Dr. Tom Dakin, in his chapter 6 in the Bartnikas/McMahon book on corona [11] suggested that the RIV type of PD test was still the most common type of factory PD test for transformers, up to at least 1979, when the book was written.

Although not widely recognized at the time, Mr. John Johnson of Westinghouse made a critical advance in the late 1940s with the application of PD testing to online insulation condition assessment [12]. We believe these were the first online measurements not intended to measure the radio interference from transmission lines.[1] Initially the PD pulses were detected across a resistor between the stator neutral and ground, using an early oscilloscope to measure the signal.

In the 1980s, Jim Timperley adapted the original RIV method to operating generators, together with Johnson's neutral detection [13]. Instead of measuring the PD level at a fixed frequency or using an oscilloscope, he used a specialized radio receiver that is commonly used for electromagnetic compatibility applications (i.e. measuring the RF signals emitted by electronics, power supplies, etc. to ensure they do not cause other equipment to malfunction). These commercial instruments (which are also close cousins of RF spectrum analyzers) produce a plot of RF signal magnitude (in μV) vs frequency. He initially explored the frequency ranges up to a few MHz, but later expanded the range up to 100 MHz. The PD sensor was usually a high-frequency current transformer (HFCT) mounted on the generator neutral. Timperley preferred to call this version of the RIV test the electromagnetic interference (EMI) test. There are many ways to estimate the peak PD activity, and Timperley uses the definition of quasi-peak in the IEC/CISPR 16-1 Standard. The test is still being performed by a few utilities and service companies today, although some have rebranded EMI testing as electromagnetic signature analysis (EMSA) test.

As presented in Chapter 13, EMI methods have also been applied to both offline and online PD testing of GIS.

1.5.2 Analog PD Detection Using Oscilloscopes – The Second Era

The second era of PD measurement is based on the measurement of PD using analog electronics and displaying the PD on an oscilloscope, so that the PD pulses could be seen with respect to the 50 or 60 Hz AC cycle. That is, it is a time-domain measurement, unlike first era RIV/EMI testing, which is a frequency-domain test. As is seen in Chapter 3, PD occurs in specific regions of the AC cycle depending on its cause and/or location within the insulation system. The modern (at that time) PD instrument depended on the development of better oscilloscopes. The oscilloscope can trace its history back to the development of the cathode-ray tube (CRT) by Nobel-prize winner Dr. K.F. Braun in Germany in 1897. His CRT was used by many researchers in the early 1900s to visualize the voltage and current waveforms of discharges. There were many improvements in CRTs by many researchers over the decades, but it waited until Tektronix invented the Tek 511 oscilloscope in 1946 for oscilloscopes to become externally triggered, calibrated, easy-to-use devices for PD research. The Tek 511 could record signals up to 10 MHz, which corresponds to a 30 ns pulse risetime. This led to the belief that PD pulses had risetimes of several tens of nanoseconds (instead of a few nanoseconds or less as discussed in Chapter 3). It was only logical that specialized oscilloscopes became incorporated into commercial PD instruments.

This era could be said to have started in the 1950s with the work of Dr. George Mole of the British Electrical Research Association (ERA). Mole produced a PD measuring system including a 1 nF

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[1] In a discussion with one of the authors in 1980 or so, Johnson shared an important anecdote: he said they felt they needed to perform online PD testing since Westinghouse, who had recently introduced the Thermalastic™ insulation for stator windings using mica impregnated with the synthetic polyester insulation, was suffering premature failures due to loose coils in the stator slots, leading to surface PD (what Johnson called slot discharge). Offline PD tests were not sensitive to this problem, and online testing was necessary since coil vibration in the slot only occurs when current was flowing though the coils.

Figure 1.2 Recent photograph of a still-working ERA Model 3S, manufactured by Robinson Instruments, probably in the late 1970s. The instrument was first owned and used by the former British utility the CEGB, before being acquired by Iris Power in the 1990s for its museum. The oscilloscope screen shows the typical elliptical trace of a 60 Hz sinewave with PD from a twisted pair of insulated wires superimposed on it. *Source:* Mladen Sasic, Iris Power L.P.

high-voltage PD coupler, a detection impedance using RC or RLC components, a method of synchronizing the PD to the AC cycle, analog filters, and a display based on a CRT [14]. A feature of the display was the use of an ellipse (Lissajous figure) to display the 50 or 60 Hz AC waveform. This allowed a single channel oscilloscope to display both the AC voltage and the PD in a single trace, as well as effectively doubling the sweep time-base compared to a conventional horizontal oscilloscope time-base. That is, the effective sweep speed was 1 ms/division, instead of 2 ms/division with a conventional 50 or 60 Hz sine wave, enabling the very short-duration PD pulses to be more easily seen with respect to the AC cycle. The Mole instrument, and later versions up to the ERA Model 5, were manufactured by Robinson Instruments in England. Figure 1.2 shows a recent photograph of the ERA Model 3, and the AC voltage ellipse on which the detected PD pulses are superimposed. After the commercial success of the early ERA detectors, many companies around the world made similar devices including Biddle Instruments (now part of Megger) and Hipotronics (now part of Hubbell) in the United States and Tettex Instruments (now part of the Haefely/Pfiffner Group) in Switzerland.

This generation of PD detectors worked in IEC 60270 frequency range (that is up to about 1 MHz) and in contrast to RIV methods could display the PD pulses on an oscilloscope screen with selectable “narrowband” or “wideband” frequency ranges. These analog instruments could accommodate a wide variety of coupling capacitors and test object capacitance, usually with different impedance matching units (sometimes referred to as “quadripoles” (see Section 6.3.1)) having different resistance, capacitance, and inductance (if present). The output was both an oscilloscope screen and a meter that recorded the peak (or quasi-peak) PD magnitude. Permanent recordings of the oscilloscope screen were usually made with a camera, usually a Polaroid$^{\text{TM}}$ instant camera, and the magnitudes estimated using a ruler.

The availability of commercial instrumentation in the 1950s that were specifically intended for PD measurement and display led to an explosion in applications to all types of high-voltage equipment. One of the pioneers of this new era was Prof. Frederik Kreuger of Delft University in The Netherlands. His PhD work led to the publication of the first English-language book about PD measurements in 1965 [15]. After a short stint at ASEA in Sweden, for most of his career Kreuger worked for the Dutch cable manufacturer Nederlandse Kabelfabriek. Kreuger, who died in 2015, investigated different PD detection methods and their sensitivity, did research on the best PD detection methods for each type of HV equipment (and especially power cables), developed what is now known as the Kreuger PD bridge to suppress disturbances, and explored how to calibrate the detected signals into apparent charge (pC) [16]. His work led directly to the development of the first international standard for application to PD measurements (IEC 270) in 1968.

Another leading researcher in this era was Dr. Ray Bartnikas. Like Kreuger, Bartnikas began his career with a cable manufacturer (Northern Electric in Canada), before continuing his research into PD measurement at the utility Hydro-Québec's Research Institute (IREQ). Bartnikas investigated optimal methods and limitations for calibrating PD in terms of apparent charge, did research into different forms of PD (including pseudo-glow discharge, Sections 3.5.3 and 4.7), and was key to the effort to develop the first American standard on PD detection, ASTM D1868, in 1973. Bartnikas also edited a book on PD measurement and interpretation, published in 1979, which is still in print [11]. As discussed in Section 1.5.3, Bartnikas, who died in 2022, was also active in the digital era with the development of PD pulse magnitude analyzers.

The research of Kreuger and Bartnikas, together with the commercial availability of relatively portable PD measuring systems, led to the widespread application of PD measurement, both in factories for QA testing of HV equipment, and also in research applications. By the end of the 1960s, virtually every manufacturer of HV equipment, plus every high voltage laboratory, had at least one of these detectors.

Another important personality of this era is Prof. Eberhard Lemke from the Technical University of Dresden, Germany. He also worked for a short time at a power cable manufacturing company, before starting his own company in 1990, Lemke Diagnostics, where he first commercialized the Lemke probe, an RF probe to locate PD sites. The company, which was eventually bought by Doble Engineering, also made IEC 60270-compliant PD instruments. Besides developing his probe, he was very active in researching the physics of PD, PD detection, and PD instrument calibration. He wrote the chapters on PD in a widely read book on high-voltage engineering [17], and chaired a CIGRE committee that prepared a technical brochure on using the 2000 version of IEC 60270, which also has a comprehensive bibliography of English- and German-language papers on the subject [18].

1.5.3 Digitizing, Ultrahigh Frequency, and Post-Processing – The Third Era

The third and current era has had three main technical focuses:

- The transition from analog electronics with an oscilloscope display to digital electronics and digital storage/display of PD data on a computer;
- With the availability of faster digital electronics (and especially analog to digital converters – ADCs), the gradual trend to measure PD at higher frequencies, into the ultrahigh frequency (UHF) range;
- Processing of captured data using digital logic devices (real time) or computer software (post-processing) to separate PD from disturbances and to identify the root cause of any detected PD.

1.5.3.1 Transition to Digital Instruments

Research into digital techniques of measuring PD can be said to have started with Bartnikas and his pulse magnitude analyzer in 1969 [19]. These early digital circuits used discrete transistors to segment the pulse magnitudes into several magnitude bins (or magnitude windows), and then count the number of pulses in each bin over a period of time. As seen in Figure 8.9, the output was a two-dimensional plot of pulse magnitude (horizontal scale) vs a (usually logarithmic) vertical scale of pulse count rate (number of pulses per second per magnitude window). Another important step was taken independently in 1976 by Dr. Andreas Kelen of ASEA in Sweden and Professors Austin and James in the United Kingdom [20, 21]. They combined home-made pulse counting electronics with the digital computers then available to count not only the number of pulses per magnitude window but also the pulses at different parts of the AC cycle. Many such research instruments that could record the number and phase position of the PD pulses were described in the 1980s. In 1988, Bernhard Fruth, Lutz Niemeyer, Marek Florkowski, and Jitka Fuhr of ABB Corporate Research in Switzerland developed a system using the IEC 60270 frequency range called the "PRPDA" – phase-resolved partial-discharge analyzer – probably the first to use the term [22]. The PRPD plot has now become an essentially quasi-standard two-dimensional "color-map" display of the three-dimensional matrix of PD pulse magnitude (vertical or y-axis) vs AC phase position (horizontal or x-axis) vs pulse count rate (the z-axis, represented by changes in pixel color). A concise summary of all this research was published in 1991 by Barry Ward, who chaired an IEEE working group on the subject [23].

One of the first widely used commercial IEC 60270-compliant digital PD instruments was made by Power Diagnostix, which was founded in 1992. It was developed by Dr. Detlev Gross and Dr. Bernhard Fruth, and introduced in 1993. As already mentioned above, Fruth had been an employee of ABB Corporate Research in Switzerland where he researched electrical aging and PD detection in rotating machines, HV cable, bushings, and other insulation materials. Gross had started his own electronics company in 1986 and worked with Fruth to develop what was called the ICM (Insulation Condition Monitor), again employing and further refining and popularizing the PRPD "color-map" plot of PD magnitude vs. 50/60 Hz phase cycle position vs pulse count (again displayed as color). After the Power Diagnostix (now part of Megger) ICM instrument was introduced, many companies, including Hipotronics, Lemke, Omicron, TechImp, Tettex, and many others, introduced similar IEC 60270-compliant instruments using mainly digital technology. Interestingly, Power Diagnostix also introduced an instrument that combined digital time-domain PD measurement with a spectrum analyzer [24]. Prof. Lemke, in a CIGRE brochure, outlined some of the methods used by commercial PD instruments to digitally capture and measure PD in the IEC 60270 frequency range [18]. Since 2000, very few second-era analog PD instruments were being used, due to the convenience and flexibility of digital PD instruments, as well as their ability to share data files with computers for display and data manipulation.

1.5.3.2 VHF and UHF PD Detection

The second focus of this era depended on the development of better oscilloscopes. Tektronix introduced the Tek 465 scope in 1972. Except for the CRT, it was among the first oscilloscopes to use solid-state electronics with a 100 MHz bandwidth. Of special importance for PD measurement was the introduction of a Tek 466 single-shot storage oscilloscope in 1972. The Tek 466 had a 100 MHz bandwidth, so it could clearly display a PD single pulse with a risetime as short as about 4 ns.[2] The development of the analog Tek 7104 oscilloscope in 1978 allowed the PD current pulses to be accurately recorded for the first time, since it had a bandwidth of 1 GHz (corresponding to a 0.3 ns risetime) and its microchannel image intensifier plate made clear photographic recordings of single PD current pulses possible for the first time (Figure 1.3). With each increase in oscilloscope bandwidth up to the 1 GHz range, the risetime of the PD current pulses was found to be shorter

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[2] One of us, who had Dr. Bartnikas as a MASc co-supervisor in 1977, recalls Bartnikas being astonished, when he was told that the measured risetime of the PD current from an electrical tree was less than 4 ns.

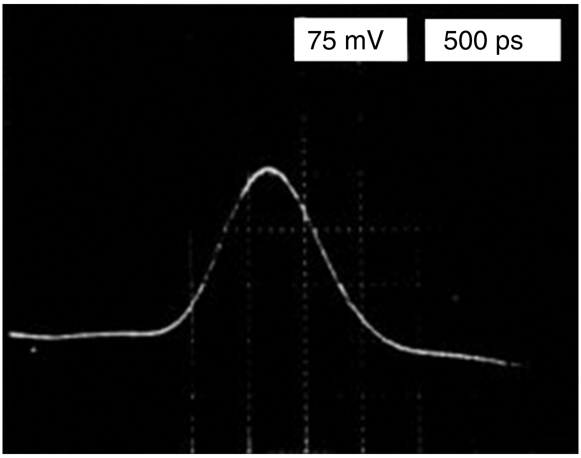

Figure 1.3 Oscilloscope photograph of a single PD current pulse through a 50-Ω resister in series with the test object (an electrical tree growing in epoxy, initiated from a razor blade) measured with a Tektronix 7104 1 GHz analog oscilloscope [25]. The vertical scale is 75 mV/division, and the horizontal scale is 500 ps/division.

than previously believed. The realization that PD created frequencies up to 1000 MHz led many researchers to investigate PD measurement in the VHF (30–300 MHz) and UHF (300–3000 MHz) frequency ranges. As discussed in Chapters 7 and 9, measuring PD in the higher frequency ranges reduced the risk of false indications from the severe electrical interference that is typically found in online PD measurement and directly led to widespread use of online PD measurement in GIS, transformers, and rotating machine stator windings (Chapters 13, 15, and 16).

As mentioned above, the development of 1 GHz oscilloscopes in the 1970s led to a tremendous amount of work on PD pulse shape. In 1982, the theoretical foundation for PD measurement above the IEC 60270 frequency range was presented by Dr. Steven Boggs, who worked for the utility Ontario Hydro in Canada (Boggs continued his research at the University of Connecticut in the United States) [25]. Boggs recognized that what he called ultrawide band (UWB) PD detection with a sensor close to the PD site would have superior ability to suppress interference, especially during online PD measurements. He and his colleagues first applied VHF and UHF detection of PD to GIS and machine stator windings. They recorded the pulse shapes from many test objects and defects. Figure 1.3 shows a single PD pulse from an electrical tree growing in an epoxy. The pulse has a risetime of about 500 ps and a pulse width of 1.5 ns (full width, half maximum). This is probably one of the first images of the true PD current pulse shape. Boggs used various types of capacitors and voltage dividers to achieve several hundred MHz bandwidth in GIS [25]. In 1991, Dr. Brian Hampton and his colleagues at the University of Strathclyde in Scotland published the design of a practical PD sensor for GIS, combined with a continuous UHF PD monitoring system [26]. The sensor was a circular plate installed on the inside surface of GIS maintenance hatch covers (i.e. inside the GIS enclosure); these acted as antennas to pick up the electric field of the PD pulse as it passed through the coaxial waveguide formed by the GIS (Section 13.8.2). Although the PD was detected in the UHF range, they used a demodulator to down-convert the UHF signal so that conventional low-frequency electronics could be used for pulse counting and determining the phase position of the PD.

In the late 1970s, Stone (who later went on to co-found Iris Power, now part of Qualitrol Corp, in 1990) and his colleagues at Ontario Hydro Research started measuring PD in the 30–300 MHz range in operating generators [27]. The advantage of the VHF frequency range is that the high-voltage PD couplers could be much smaller (80 pF) and thus fit within the generator frame; additionally, the time-of-arrival principle could be used to separate stator PD from power system

Figure 1.4 Photograph of the first commercial digital PD instrument that measured PD in the 30–300 MHz range. The PDA-H, introduced in 1986, measured the PD from a pair of permanently-installed 80 pF couplers in each phase of an operating hydro generator. The instrument was controlled by an early PC, which also served as the display device. *Source:* Mladen Sasic, Iris Power L.P.

disturbances using a pair of sensors per phase (Sections 8.4.2 and 16.9). In addition, disturbance suppression based on digital rendering of the pulse shape was possible [28].

From a commercial point of view, the extension of PD instruments to frequencies higher than 1 MHz (in what is now termed an IEC TS 62478-compliant instrument) started in 1986 when FES International (later known as Adwel and now part of Iris Power) introduced an instrument called the PDA-H to measure PD in operating hydro generators in the VHF range (Figure 1.4). In 1991, Iris Power, a spin-off from Ontario Hydro, introduced the PDA-IV, an all-digital instrument working in the VHF range that separated power system disturbances from stator winding PD on a pulse-by-pulse basis and displayed PRPD plots on a built-in LCD display. A year later Iris Power introduced the TGA-S, which worked in the UHF range with a special electromagnetic coupler (called the SSC, for *s*tator-*s*lot *c*oupler, Sections 7.4.5.4 and 16.6.2) that was installed in hydrogen-cooled turbine generators. Another UHF all-digital continuous PD monitor for GIS was introduced by a company based in Scotland called DMS. DMS, now a part of Qualitrol Corp., was founded by John Pearson, Brian Hampton, and Owen Farish of Strathclyde University in 1994, and the PD monitor was based on technology they developed at the university [26]. This was also the world's first commercial continuous online PD monitor. Today there are dozens of companies making VHF and UHF PD instruments, most of which are used for online PD monitoring.

1.5.3.3 Post-Processing of Signals

Another aspect of this era, which was facilitated by digital instruments that are easily interfaced to computers, is the development of tools to aid in the analysis of PD data. In particular, these tools use signal magnitude, phase position, count rate, and applied voltage at the time of the pulse to calculate various indicators of PD activity (quasi-peak magnitude, PD power, PD current, quadratic rate, etc. as outlined in IEC 60270), which are determined after the data has been stored in memory. Perhaps even more importantly, this post-processing can help to separate interference pulses from test object PD pulses and identify the nature of the causes of PD in a test object. This was important since there was a desire, as PD technology spread from the research/high-voltage test labs to HV equipment owners, that PD test users would be able to interpret PRPD patterns without having to be experienced PD researchers.

The first notable contribution in post-processing was made by Dr. Tatsuki Okamoto and Dr. Toshikatsu Tanaka of CRIEPI in Japan in 1986, when they started to apply statistical analysis of the PD patterns with respect to phase angle [29]. A few years later, Prof. Edward Gulski of Delft University in The Netherlands also used statistical methods based on the normal distribution to analyze PRPD patterns [30]. This work was eventually commercialized in a Haefely PD detection system. Prof. Alfredo Contin (University of Trieste) and Prof. Gian Carlo Montanari (University of Bologna) applied statistical analysis to PRPD pattern analysis using the Weibull probability distribution [31]. In all these early examples, the idea was to classify various PRPD patterns to determine the root cause of the PD. Although such techniques are not widely used today, they were the forerunners of other methods that have gained in popularity among PD test users.

In 2004, Prof. Andrea Cavallini and his colleagues at the University of Bologna and the University of Trieste in Italy were probably the first to use nonstatistical post-processing methods to suppress disturbances, as well as to identify different types of PD sources (e.g. differentiate void PD from surface PD). They developed what is known as the time-frequency (T-F) map method [32]. As described in Section 8.9.2, each pulse after A/D conversion was processed into the frequency domain at the same time as an indicator of pulse length was captured. A "map" was created with two axes (time and frequency) with the transformed pulse shape and frequency of each detected pulse. Cavallini discovered that disturbances and different types of PD sources tended to cluster in different regions of the T-F map. The clusters are identified by a skilled observer, or using specialized pattern-recognition algorithms. In many cases, there was a unique PRPD pattern for each cluster, and with experience, the patterns could be associated with different defects or disturbance sources. The technology was first applied to power cables, then spread to other types of HV equipment. This post-processing technology led to the creation by Montanari and his colleagues of a commercial company called TechImp (now part of Altanova/Doble).

Another commercial post-processing method was developed by Dr. Ronald Plath, Caspar Steineke, and Harald Emanuel at MTronix (now part of Omicron). The key feature of this post-processing method is to simultaneously capture the signals from all three phases [33, 34]. The response to an event (a PD pulse or an interference pulse) on all three phases is measured and correlated on a three-dimensional plot of the pulse magnitude in each phase (Section 8.9.3). The "3PARD" plot consists of thousands of pulses. Different types of PD and interference apparently will create clusters in different regions of the diagram. As with the T-F method, clusters are identified, and they usually have a unique PRPD pattern that identifies the nature of the interference or PD sources.

In addition to these post-processing methods, many other signal processing methods have been applied, often using various forms of artificial intelligence or fractal analysis.

1.6 The Future

We have probably entered a fourth era of PD technology. Rather than specific technical advances, the main driver has been the widespread application of continuous online PD monitoring of high-voltage equipment that started as simple research tools 40 years ago. This technology allows HV equipment owners to determine the insulation condition at any time; when PD activity appears or passes certain thresholds (amplitude and/or pulse-count), maintenance engineers are alerted that there has been a change in the insulation condition, and HV equipment maintenance may be prudent. Continuous online PD monitoring commercially started on rotating machines and GIS in the 1990s. Now tens of thousands of machines and thousands of GIS bays are being continuously monitored. A key challenge of continuous monitoring is to extract the useful information from the vast quantities of data collected. As interference separation techniques (needed to avoid false-positive indications) and data reduction methods improve, we expect continuous monitoring to expand not only to other types of HV equipment but also in the number of systems installed. The users of this equipment are not PD researchers, or even experienced high-voltage laboratory staff, but are maintenance engineers or asset managers in generating stations, substations, and industrial plants, who use the input from PD technology as only one aspect of their jobs.

One of the problems holding back further advancement in this technology is the widespread unwillingness of both OEMs and utilities (users) to share detailed information about the data gathered by online monitoring systems vs actual PD defects found in the equipment. This strong tendency toward keeping such information confidential is due, on the one hand, to obvious aspects of competition between the OEMs, but on the other hand, to the general fragmentation and compartmentalization of the power generating and distribution industry; the utilities are reluctant to release any information that may impact their SLAs (service-level agreements) and thus their business models. Without access to this information, it is very difficult to assess the effectiveness of online PDM systems and use that information to improve the technology.

1.7 Roadmap for the Book

This book is primarily intended for technicians, engineers, and scientists whose involvement with PD may be just one part of a wider range of their responsibilities, and who need a better understanding of what they are measuring and how to make and interpret the measurements accurately and effectively.

Chapters 2–4 present a summary of the physics of PD and other associated phenomena. This information may be sufficient for users of PD technology. Researchers, however, should refer to the many references found in Chapters 2–4 for a deeper understanding.

Chapters 5–7 provide some fundamental information of the main ways to detect PD including charge-based “conventional” electrical PD detection (Chapter 6), “unconventional” electromagnetic methods (Chapter 7), as well as a summary of optical, acoustic, and chemical methods. Although the term “unconventional” may imply that electromagnetic methods are less commonly used – in fact the EM methods are far more widely used today than “conventional” methods.

Chapter 8 gives users of PD test equipment some understanding how commercial PD instruments work inside. However, each manufacturer of PD instrumentation will have their own design philosophy and intellectual property that is not shared with equipment users. Thus, readers may only want to review Sections 8.6–8.9, which are important for the interpretation of PD measurements on all types of electrical equipment.

Electrical interference (also known by some as disturbances) have long caused problems during PD measurement. Interference can lead to false-positive indications of insulation problems. Thus, Chapter 9 identifies the main sources of interference and the various methods that have been developed to suppress the influence of interference.

Chapter 10 gives an overview of the basic principles used to interpret PD measurements in all types of electrical equipment. This chapter should be read before reading the interpretation section for each particular type of equipment in Chapters 12–16.

Chapters 11–16 are the heart of the book. Each chapter focuses on a particular type of electrical equipment such as power cables, transformers, etc. Over the decades, PD measurement has tended to be optimized for each type of equipment; specifically the sensors, measurement frequency range, interference suppression methods, and applicable standards are often unique to each type of electrical equipment. Also, each type of equipment tends to have a unique set of insulation issues that give rise to PD. Thus each of these chapters gives an overview of the insulation system for each type of equipment, presents the ways PD can arise due to either manufacturing or aging in service, describes the sensors used and the normal frequency ranges for both offline and online tests, outlines the standards that may be applicable, and gives an overview of interpretation, with reference to the information in Chapter 10. Each chapter presents many case studies.

The two final chapters are on rapidly evolving topics: measurement of PD in DC equipment and measurement of PD during short risetime voltage impulses, as opposed to 50/60 Hz PD measurement discussed in Chapters 6–16.

High-voltage DC systems are increasingly being applied in the transmission systems of electrical grids, especially for overhead and underground/submarine transmission lines. Also, high voltage DC is used in specialized medical and research equipment where PD has been known to occur. Since there is no alternating voltage, and the role of trapped charge (Chapter 3) is more complex, the behavior of PD under direct voltage (DC) is even more stochastic than under AC. The main tool for interpreting PD from test objects using 50/60 Hz excitation, the PRPD plot (covered in Chapter 8), is not relevant under DC conditions, since there is no AC voltage with its inherent positive- and negative-going zero crossings “modulating” the electric field. Chapter 17 introduces practical PD measurement in DC systems, but the field is also rapidly evolving, so references to further reading are presented. In addition, due to the particular behavior of moving particles (a well-known source of PD in GIS) under DC conditions, some specific aspects of PD measurement under DC are also briefly discussed in Chapter 13.

The measurement of PD during voltage impulses is becoming an increasingly important subject with the widespread adoption of power converters and semiconductor-based (e.g. IGBT) switching technologies. The short risetimes of the voltage impulses produced by such power-electronic equipment subjects solid insulation to higher electrical stress and can lead to PD in the converter modules themselves, as well as any connected equipment (power cables, transformers and machine windings, etc.). PD pulse current detection is difficult during voltage impulses, since the voltage impulses are a type of interference that can dominate the PD current pulses. Advancements are made almost daily, so this topic is only briefly discussed in Chapter 18, with many references for further reading.

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* In this book, some common abbreviations will be used to identify publishers. IEEE is the Institute of Electrical and Electronic Engineers, AIEE is the American Institute of Electrical Engineers (a predecessor organization of the IEEE), the IET is the British Institute Engineering and Technology, IEE is the British Institute of Electrical Engineers (a predecessor of the IET), IEC – International Electrotechnical Commission – the worldwide standards organization, CIGRE – Conseil International des Grands Réseaux Electriques – is the Paris-based world-wide organization collaborating on power systems and holding biennial conference, ASTM is the American Society of Testing and Materials.

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