

IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery

IEEE Power and Energy Society

Sponsored by the
Electric Machinery Committee

and the

IEEE Dielectrics and Electrical Insulation Society

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Abstract: A review of the nature of partial discharge in machine windings, how it can be measured under both off-line and on-line conditions, how it can be measured for individual form wound coils or bars, and the significance and limitations of the measured values are covered in this standard.

Keywords: ac electric machine windings, electrical insulation, form-wound bars, form-wound coils, IEEE 1434™, partial discharge

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Introduction

This introduction is not part of IEEE Std 1434™-2014, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery.

Partial discharge (PD) measurements have been made on the windings of ac electric machinery for over 40 years. The electrical insulation of these windings may be prone to PD activity as a result of internal delaminations and of surface or slot discharge. These kinds of PD activity, when the machine is in normal operation, can result in significant deterioration over a period of time. Experience has indicated that PD measurements can be useful for assessing the condition of complete windings as well as of individual formwound coils and bars.

This guide provides a review of the nature of PD in machine windings, how it can be measured under both off-line and on-line conditions, how it can be measured for individual form-wound coils or bars, and the significance and limitations of the measured values.

IEC 60505 (2004-10)^a defines the various factors that influence the performance of electrical insulation systems. These are the thermal, electrical, environmental, and mechanical stress factors. Stator winding insulation systems of ac electric machinery experience thermal, electrical, mechanical, and environmental stresses during operation. These stresses, individually or in combination, will age the insulation system and may lead to delamination of the groundwall insulation, abrasion of the outer semiconducting (Faraday) shield, loosening of the wedging system, and other potential deterioration mechanisms. Sometimes, as a result of the initial manufacturing process, or because of the subsequent aging, PDs may occur adjacent to the high voltage conductor, in the internal voids of the groundwall, on the outer surface of the coil/bar in the slot, or in the endwinding region. These various PD sites have the potential to cause deterioration to a greater or lesser extent and, in some cases, may ultimately result in an in-service failure. The number, magnitude, and polarity of these PDs can be a direct indication of the condition of the insulation system. However, the trend of these parameters over time is frequently most valuable. Care must be taken that the effects of operating and environmental conditions and test procedures are considered.

^a IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

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1. Overview

1.1 Scope

This guide discusses both on-line and off-line partial discharge (PD) measurements on complete windings of any type, as well as measurements on individual form-wound coils and bars. Measurements selected from those that are outlined may be appropriate for application during the manufacture, installation, operation, and maintenance of windings of ac electric machinery.

1.2 Purpose

The purpose of this guide is to identify test methods that may be useful in the measurement of PD activity involving the electrical insulation systems of ac electric machinery for quality control and to detect winding aging.

1.3 Limitations

The users of this guide are cautioned that:

- Many on-line PD measurements apply only to a small portion of the winding near the sensors.
- Although often more global in their coverage, off-line measurements are not the result of actual operating conditions.
- Different test methods can be expected to yield different results, and absolute limits are difficult to establish.
- Many of the PD measurements are relative in nature, and the effects of the test conditions during measurements can be profound. For direct comparison, it is very important that tests be conducted under similar conditions every time.
- No attempt is made to describe here all known or conceivable systems for measuring PD or all applications of the same.
- Measurement of PD cannot be expected to detect all of the problems to which an insulation system may be prone.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D1868-07, Standard Test Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems.¹

ASTM D2303-97, Standard Test Methods for Liquid-Contaminant, Inclined-Plane Tracking and Erosion of Insulating Materials.

ASTM D3382-07, Standard Test Methods for Measurement of Energy and Integrated Charge Transfer Due to Partial Discharges (Corona) Using Bridge Techniques.

CISPR 16-1-2 ed2.0 (2014-03), Specification for radio disturbance and immunity measuring apparatus and methods — Part 1–2: Radio disturbance and immunity measuring apparatus — Coupling devices for conducted disturbance measurements.²

IEC 60270 (2000-12), High-voltage test techniques — Partial discharge measurements.³

IEC 60270 CORR1 (2001-10), Corrigendum 1 — High-voltage test techniques — Partial discharge measurements.

IEC 60505 (2004-10), Evaluation and qualification of electrical insulation systems.

IEC/TS 61934 (2006-04), Electrical insulation systems — Electrical measurement of partial discharges (PD) under short rise time and repetitive voltage impulses.

IEEE Std C37.20.2™, IEEE Standard for Metal-Clad Switchgear.^{4, 5}

¹ ASTM publications are available from the American Society for Testing and Materials (<http://www.astm.org/>).

² CISPR documents are available from the International Electrotechnical Commission (<http://www.iec.ch/>). They are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

³ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute (<http://www.ansi.org/>).

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IEEE Std 4TM, IEEE Standard Techniques for High Voltage Testing.

IEEE Std 286TM, IEEE Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation.

IEEE Std 433TM, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery at Very Low Frequency.

IEEE Std 510TM-1983, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing. (withdrawn)⁶

IEEE Std 1553TM, IEEE Standard for Voltage-Endurance Testing of Form-Wound Coils and Bars for Hydrogenerators.

IEEE Std 1799TM, IEEE Recommended Practice for Quality Control Testing of External Discharges on Form-Wound Coils, Roebel Bars, Vacuum Impregnated Station Insulation and Fully Assembled Stator Windings.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁷ Other terms related to partial discharge (PD) measurements are defined in ASTM D1868-07.⁸

apparent charge: The apparent charge (Q) of a PD pulse is that charge which, if injected within a very short time between the terminals of the test object in a specified circuit, would give the same reading on the measuring instrument as the PD current pulse itself. The apparent charge is usually expressed in picocoulombs (pC).

average discharge current (I_t): The sum of the absolute magnitudes of the individual discharges during a certain time interval divided by that time interval. When the discharges are measured in coulombs and the time interval in seconds, the calculated current will be in amperes.

$$I_t = \frac{\sum_{t_0}^{t_1} (Q_1 + Q_2 + \cdots + Q_n)}{t_1 - t_0} \quad (1)$$

where

I_t is average discharge current, A

t_0 is starting time, s

t_1 is completion time, s

Q_1, Q_2, Q_n are apparent charges transferred in a partial discharge pulse 1 through n, C.

bandwidth: The range of frequencies within which performance, with respect to some characteristic, falls within specific limits.

⁶ IEEE Std 510-1983 has been withdrawn; however, copies can be obtained from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

⁷ IEEE Standards Dictionary Online subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

⁸ Information on normative references can be found in Clause 2.

contact sparking: Contact sparking comprises two components. One arises due to the cyclic vibration that interrupts the capacitive charging and discharging currents as the external surfaces of the vibrating bars make and break contact with the slot walls. The second effect, which is not included in the definition, is that of electrostatic induced sparking that occurs when two dissimilar materials with different work functions make and break contact.

NOTE—See Bartnikas and Morin [B3].⁹

continuous partial discharges: Discharges that recur at regular intervals, for example, on approximately every cycle of an alternating voltage.

conventional partial discharge detector: The partial discharge (PD) pulses are amplified by a vertical deflection amplifier of an oscilloscope having a bandwidth from approximately 10 kHz to several hundred thousand hertz, and they are displayed on a digital oscilloscope. The height of the vertical deflection can be related to the discharge magnitude.

corona: Visible partial discharges (PDs) in gases adjacent to a conductor.

cross-coupling: Energy appearing in one circuit as a result of coupling from another circuit.

dissipation factor ($\tan\delta$): The tangent of the loss angle δ or the cotangent of the phase angle θ . For values less than 0.1, power factor and dissipation factor are essentially equal.

dissipation-factor tip-up ($\Delta\tan\delta$): The difference in the dissipation-factor measured at two designated voltages. *See also:* **power-factor tip-up**.

electromagnetic radiation: Emission of energy in the form of electromagnetic waves.

high frequency (HF): 3 MHz to 30 MHz.

high-intensity slot discharge: Discharges that recur on a random basis involving a large surface of a coil or bar, separated from the grounded steel core by an air gap. Thus, these discharges involve a substantial amount of energy.

NOTE—See Lonseth and Mulhall [B8].

ionization: The process by which electrons are lost from or transferred to neutral molecules or atoms to form positively or negatively charged particles.

largest repeatedly occurring PD magnitude (Q_m): The magnitude recording by a measuring system which has the pulse train response in accordance with 4.3.3 of IEC 60270, or the magnitude associated with a pulse repetition rate of a specified number of pulses per second, which can be directly inferred from a pulse magnitude distribution. A recommended pulse repetition rate is 10 pulses per second.

low frequency (LF): $30\text{ kHz} \leq f_l \leq 100\text{ kHz}$; $f_2 \leq 500\text{ kHz}$; $100\text{ kHz} \leq \Delta f \leq 400\text{ kHz}$ where f_l and f_2 are the lower and upper limit frequencies and Δf is the bandwidth $f_2 - f_l$. [IEC 60270 wide-band.]

magnetically induced vibration sparking (vibration spark erosion): On non-globally VPI'd machines, significant magnetically induced current may flow in the semi-conducting coating of a stator coil or bar if the resistance of the coating allows sufficient current flow, and the coil or bar is moving in the slot. In the presence of vibration the current may be interrupted, resulting in sparking and erosion of the groundwall insulation. This may occur at any bar or coil between line and neutral.

⁹ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

noise: Unwanted disturbances superimposed on a useful signal that tend to obscure the signal's information content.

normalization: A process by which measurements are compared with a common reference.

normalization capacitor: A capacitor through which charge is injected into a partial discharge (PD) measuring circuit for the purpose of normalizing the measurement.

normalized quantity number (NQN): Originally defined as the normalized area under a straight line fitted to the pulse counts in each magnitude window of a pulse height analysis, in which the pulse counts are expressed as a logarithm of the pulses per second and the pulse magnitude window is a linear scale. The use of the logarithm of the pulse counts in the formula for calculating NQN rather than the use of the actual pulse counts reduces the relative contribution of high repetition rate pulses to the NQN compared with that of low repetition rate pulses. Both the pulse magnitude and repetition rate scales are normalized, and the quantity obtained is divided by the gain of the partial discharge detector. NQN can be represented mathematically as:

$$NQN = \frac{FS}{G \times N} \times \left[\frac{\log_{10} P_1}{2} + \sum_{i=2}^{N-1} \log_{10} P_i + \frac{\log_{10} P_N}{2} \right] \quad (2)$$

where

P_i is number of pulses per second in magnitude window i ,
 N is number of magnitude windows,
 G is gain of the partial discharge detector (arithmetic, not decibels),
 FS is maximum magnitude window in millivolts at unity gain.

Pulses with a high repetition rate have less of a contribution to the NQN than do pulses with a low repetition rate. It should also be noted that even if the normalizing process is followed, the value of NQN for the same partial discharge (PD) activity will vary as a function of the sensitivity of the PD detector and, thus, the width and number of magnitude windows. Therefore, a constant gain needs to be used if various sets of pulse height analysis data are to be compared on the basis of NQN.

off-line testing: Tests that are made with the rotating machine at standstill with the necessary test voltage applied to the winding, or portion thereof, from a separate test supply.

on-line testing: Tests that are made with the rotating machine functioning to transmit and modify force, motion, or electricity.

partial discharge (PD): An electrical discharge that only partially bridges the insulation between conductors. A transient gaseous ionization occurs in an insulation system when the electric stress exceeds a critical value, and this ionization produces partial discharges.

partial discharge extinction voltage (PDEV): The highest voltage at which partial discharges (PDs) above some stated magnitude (which may define the limit of permissible background noise) no longer occur as the applied voltage is gradually decreased from above the inception voltage. PDEV, is expressed as $1/\sqrt{2}$ of the peak of the alternating voltage. Many factors may influence the value of PDEV including the rate at which the voltage is decreased as well as the previous history of the voltage applied to the winding or component thereof. In most cases, PDEV is less than PDIV.

partial discharge inception voltage (PDIV): The lowest voltage at which continuous partial discharges (PDs) above some stated magnitude (which may define the limit of permissible background noise) occur as the applied voltage is increased. PDIV is expressed as $1/\sqrt{2}$ of the peak of the alternating voltage. Many

factors may influence the value of PDIV, including the rate at which the voltage is increased as well as the previous history of the voltage applied to the winding or component thereof.

partial discharge (PD) power loss: The summation of the energies drawn from the test voltage source by individual discharges occurring over a period of time, divided by that time period.

$$P = (1/T) \sum_{i=1}^{i=m} Q_i V_i \quad (3)$$

where

P	is the discharge power, W,
T	is the time period, s,
m	is the number of the final pulse during T ,
Q_i	is the PD magnitude of the i^{th} pulse in terms of the charge transfer measured at the system terminals,
V_i	is the instantaneous value of the applied test voltage in volts at which the i^{th} pulse takes place.

partial discharge (PD) quantity: The magnitude of an individual discharge in an insulation system expressed in terms of the apparent charge transfer (Q) measured at the terminals of the test object expressed in coulombs. In the case of complete windings, such measurements are limited to the low frequency range and the results obtained are a function of the bandwidth of the particular detection system.

power factor (cos θ): The ratio of the power in watts (W) dissipated in a material to the product of the effective sinusoidal voltage (V), and current (I), expressed in volt-amperes. Power factor is the cosine of the phase angle θ between the voltage and the current.

power-factor tip-up: The difference in the power factor of the insulation measured at two designated voltages. In North America, these two voltages are often 25% and 100% of the rated phase-to-ground voltage of the machine as is described in IEEE Std 286.

pseudoglow discharge: A type of partial discharge (PD) characterized by current pulses of relatively small amplitude and, generally, a long rise time. As a result of the upper frequency limitation in their Fourier frequency spectrum, pseudoglow discharges are not readily detected by conventional PD detectors. Pseudoglow discharges are also characterized by a diffused glow that cannot be visually distinguished from that resulting from a true-glow (or pulseless-glow) discharge.

pulse discharge: A type of partial discharge (PD) phenomenon characterized by a spark-type breakdown. The resultant detected pulse discharge has a short rise time, and its frequency spectrum may extend as far as ≥ 100 MHz. Such a pulse discharge may be readily detected at the terminals of the winding or component under by means of LF, HF, VHF, and UHF pulse detectors, that are generally designed for PD measurements within the frequency band from 10 kHz to GHz.

pulse height analysis: The measurement of the number of pulses occurring within a series of magnitude windows over a defined phase period, not exceeding one half-cycle, of the alternating voltage applied to the object under test. Sampling periods of one or more seconds may be involved.

pulse phase analysis (phase resolved PD analysis): A type of pulse height analysis in which there is more than one phase window for each half-cycle of the alternating voltage applied to the object under test.

pulseless-glow discharge: A type of partial discharge (PD) phenomenon characterized by a diffused glow. The overall voltage waveform across a gap space undergoing pulseless-glow discharge does not indicate the presence of any abrupt collapse in voltage, except for the two at the beginning of each half-cycle. Although discharge energy is expended over the pulseless region, a conventional PD detector will give no indication of this, as it will only respond to the two initiating breakdowns in each half-cycle.

quadratic rate: The sum of the squares of the individual discharge magnitudes during a certain time interval divided by that time interval. The quadratic rate is expressed as nQ^2/t , where Q is in coulombs, t is in seconds and n is 1 to m . This quantity assigns greater weight to the larger pulses.

$$nQ^2/t = (1/t) [Q_1^2 + Q_2^2 + \dots Q_m^2] \quad (4)$$

quasi-peak: A quantity, measured with an RC weighting circuit having specified time constant(s), which is a fraction of the peak value of pulses of constant amplitude, the fraction increasing toward unity as the pulse repetition rate is increased.

radio influence voltage (RIV): The radio noise voltage appearing on conductors of electric equipment or circuits, as measured using a radio noise meter as a two-terminal voltmeter in accordance with specified methods as are described in CISPR 16-1-2 ed2.0 (2014-03).

random partial discharges (PDs): Discharges that recur infrequently with a repetition rate of less than one per second.

repetitive voltage impulses: Impulses that occur due to switching of power electronic devices at a carrier or driven frequency.

resistance temperature detector (RTD): A temperature detector that is usually a three-terminal resistor, either 10 Ω copper at 25 $^{\circ}\text{C}$ or 100 Ω platinum at 0 $^{\circ}\text{C}$, whose sensing element is about 25 cm in length, which is encapsulated within an insulating substrate of suitable thermal rating. RTDs are usually installed between top and bottom bars (coil legs) in a given slot. The measuring leads should be positioned such that they do not interfere with the stress control coating.

semiconducting slot coating: A coating, applied on the insulation surface of the slot parts of winding. The semiconducting coating, compound, or tape in which the powder filler or portion of powder filler is a semiconductive material and the electrical surface resistivity of this coating is such that when converted into a semiconducting solid layer, is in the range of 1×10^2 to 5×10^5 ohms per square. This semiconducting slot coating must have uniform tight contacts with the grounded walls of the stator slot. This coating provides minimum voltage between the surface of the coil or bar and the grounded stator core.

signal attenuation: A decrease in signal magnitude from one point to another.

signal reflection: The result of a mismatch in the characteristic (surge) impedances of the signal transmission path in which a portion of the incident signal is reflected in the direction opposite to the incident signal.

signal transmission: The process by which the signal travels in a medium in the same direction as the incident signal.

slot discharges: Discharges that occur between the outer surface of a coil or bar and the grounded core steel.

NOTE—See Johnson [B7], Wilson [B10].

spectrum analysis: Measurement of a signal over a range of frequencies using a detector having a defined bandwidth resolution.

stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond the semiconducting slot coating in high-voltage stator bars and coils. The stress control coating often contains silicon carbide particles that tend to linearize the electric field distribution along the coil or bar end turn. The stress control coating overlaps the semiconducting coating to provide electrical contact between them.

total integrated charge: A quantity derived from pulse height analysis defined as

$$\sum_{x=1}^{x=n} N_x Q_x \quad (5)$$

where

- N is the number of pulses per defined unit of time (e.g., half-cycle or second) in each of x windows, of which there are n in total.
- Q_x is the apparent charge associated with each window, and it is assumed that there is no overlap between windows. This quantity assigns equal weight to all pulse magnitudes.

ultra high frequency (UHF): 300 MHz to 3000 MHz.

very high frequency (VHF): 30 MHz to 300 MHz.

4. The nature of PD in machine windings

4.1 Sources of PD

In most ac electric machines, there are numerous potential sites of PDs. Machine design, materials of construction, manufacturing methods, operating conditions, and maintenance practices can profoundly affect the quantity, location, characteristics, evolution, and the significance of PDs.

One of the most common sources of discharges in a stator is internal discharge which occurs inside small cavities trapped within the groundwall insulation. This activity can be constantly present from the first day of operation until the end of life without reducing the expected life of the machine. It is considered as normal PD activity and it is important to be able to differentiate between this activity and other more deleterious discharges.

Groundwall delaminations and cavities that develop as a result of machine misoperation, thermal aging, bar vibration, and PD erosion may exhibit characteristics that are very different from the characteristics of cavities in new insulation. PD sites may also be present or develop at the interface between the conductor and the groundwall and between the groundwall and the semiconducting treatment on the surfaces of stator winding elements. Other potential sites of PDs may occur within girth cracks, mechanical disruptions of insulation caused by overheating, sites of impact damage, insulation fractures, and abraded areas.

Slot discharge sites may occur as the result of certain semiconducting coating conditions that either are present when the machine is new or develop in operation. These conditions include discontinuities in the semiconducting slot coating, high resistivity values of the coating such that it does not function as intended, porosity, separations, migration defects, and erosion or abrasion defects. Slot discharge sites may also be caused by or extinguished by certain types of chemical contamination. It should be noted that because of the wide variation in stator winding constructions, stator bar vibration may not be indicated by PD activity in some machines.

PD sites may develop at the electrical stress control coating at the slot exit as the result of defects such as electric stress concentrations at the interface between the semiconducting slot coating and the stress control coating, sites of mechanical damage, or shortened stress control coating.

PD sites may be present or develop in the stator endwinding beyond the slot because of chemical contamination, floating metal particles, mechanical damage, relative movement of end-winding elements, and the inadequate spacing between components in the endwinding.

PD sites external to the stator winding may occur near improperly installed RTD or stator slot coupler cables, on phase connection rings because of vibration, mechanical damage, or relative movement; within high-voltage bushings; on surfaces of high-voltage bushings caused by contamination; on phase leads, bus bars, or connection straps, within surge capacitors; and within isolated phase bus duct.

Although there are many potential sources of PD, the user is cautioned that no technology exists today that can uniquely, and unambiguously, take a PD pattern and back-calculate the exact source for each of those defects listed previously. Although some defects produce characteristics and easily identifiable PD patterns, there may be strong overlap among others or multiple contributors. Such situations profoundly complicate accurate interpretation of PD patterns.

4.2 Forms of PD pulses

The form of PD intrinsic to a given discharge site will depend on the gap length or diameter of the cavity, the gas and pressure within, the nature of the surface at the site between where the discharge takes place, and the statistical time lag. The product of the gap separation and the gas pressure establishes the voltage at which the PD occurs, and if the resulting discharge is of the pulse (spark) type, it also determines, in conjunction with the portion of the overall capacitance discharged, the magnitude of the PD pulse. The statistical time lag represents the time necessary for a free electron to appear within the gap (e.g., because of cosmic or natural radiation), which is required to initiate the electron avalanche and breakdown of the gap once the applied voltage across the gap attains a value equal to the breakdown value. If the appearance of the free electron is delayed, the potential across the gap continues to rise sinusoidally until a free electron finally does appear and the breakdown event is initiated at some value of voltage in excess of the nominal breakdown voltage. The difference between the actual breakdown voltage and the nominal breakdown voltage of the gap is a statistically variant quantity and is commonly referred to as the overvoltage across the gap. The larger the overvoltage, the more intense becomes the space charge field developed adjacent to the cathode; this leads to pronounced secondary electron emission at the cathode caused by photon impact, resulting in rapid (fast rise time) pulses having high amplitudes. The larger the overvoltage, the larger the pulse amplitude and the shorter its rise time (see Bartnikas and Novak [B4]). Assuming that all other parameters controlling the discharge process remain invariant, statistical changes in the time lag are reflected in a train of pulses of varying amplitude and separation in time. At large overvoltages, the detected discharge pulse current consists almost entirely of the electron current component, whereas, at zero or low overvoltage, the more protracted discharge current pulses, evince an ion current component tail due to the slower moving ions. VHF and UHF detectors are particularly suited for the measurement of rapid rise-time pulses, though with the slower rise pulses they omit the ionic tail contribution of the pulse. In order to record the total current of a discharge pulse, much lower bandwidth detectors need to be used, which essentially integrate the pulse charge, thereby yielding a measure of the total apparent charge transfer per pulse.

4.3 Glow and pseudoglow discharges

Under certain conditions, the discharge process within the cavities or air gaps may assume a pseudoglow or even a pulseless glow character (see Bartnikas and McMahon [B2]). Pseudoglow discharges exhibit features common to both pulseless glow and pulse-type discharges in that, although they exhibit a visually apparent glow, they, in fact, consist of very minute discharge pulses of long rise time, which evade detection by conventional PD detectors as do true pulseless glow-type discharges.

Bridge techniques need to be employed to properly measure and assess the extent of pulseless and pseudoglow discharge activity. Because these discharges are determined by their dissipated energy, the sensitivity of such measurements is low compared with conventional pulse detectors. Pseudoglow discharges represent a transitory state between pulse and pulseless glow-type discharges. The latter develop under conditions in which cathode emission tends to occur over a large surface area, and the field, because of the greatly dispersed charged particles, is too weak to lead to discharge channel constriction, which

constitutes a necessary condition for a pulse-type (spark) discharge to develop. In a pseudoglow discharge, a limited tendency exists to channel constriction, as is substantiated by the existence of the minute pulse, or spark-like breakdowns; i.e., as soon as the discharge pulse current amplitude exceeds a certain value, the spark discharge development is interrupted and extinguished by the current limiting characteristic of the overall circuit. In practice, epoxy surfaces that are exposed to PDs, upon which a sufficient amount of conductive degradation products are permitted to accumulate, for example, in a closed or nonvented cavity, are predisposed to undergo pseudoglow and pulseless glow discharge. However, it is a redeeming feature from the point of view of discharge detectability that in actual insulation systems, it is most uncommon for pseudoglow and pulseless discharges to occur by themselves, because the number and distribution of cavity and gap sizes and their geometries are such that all three types of discharge, namely, pseudoglow, pulseless, and pulse type, tend to occur simultaneously. Thus, in most practical cases, conventional PD pulses detectors detect the presence of PDs, but because of their lack of response to pseudoglow and pulseless discharges, they may not necessarily always measure all the PD activity in a given machine.

4.4 Peak amplitude variation of discharge pulses

For two discharge events of equal amplitude and different rise time, the resulting current pulse having the shorter rise time will be detected as the pulse with a higher apparent amplitude, because the pulse detector response improves with a decrease in rise time of the discharge pulses (see Bartnikas [B1]). In rotating machines, the principal discharge sites are those occurring within cavity inclusions in the groundwall, surface discharges associated with the slot section of the coil/bar, and discharges involving the end arms. However, the amplitude of the discharge pulses associated with the surface within the slot will generally exhibit a considerable distribution if the coil/bar is loose, because a loose bar within the slot will form an elongated gap approximating a catenary, with the larger magnitude discharges tending to take place at and in close proximity of the center of the catenary. A cyclic variation of the discharge pulse magnitudes would be expected because of cyclic enlargement and contraction of the average slot gap length as a result of the periodic vibration of the loosened bars within the respective slots over each machine rotation period, after degradation of the outer armor. An increase in the discharge pulse amplitude with time in the case of slot discharges could be indicative of an enlargement of the separation between the bars and the slots as the bars become increasingly loosened as a result of gradual mechanical erosion of the outer semiconducting layer and insulation wall because of the vibration caused by the electromagnetic forces. In contradistinction, an increasing number of pulse discharges accompanied by a diminution in their average peak amplitude with time would be suggestive of degradation and eventual carbonization of the thermosetting insulation within the cavities in the bar insulation as well as a possible transition to pseudoglow and pulseless glow discharges.

4.5 PD under short rise time and repetitive voltage impulses

Repetitive voltage impulses of short rise time pose an additional electric stress for the insulation system of ac electric machines. This affects the turn insulation as well as the stress control coatings. See IEC/TS 61934 (2006-04), Cavallini et al. [B183], Cavallini et al. [B184], Espino-Cortes et al. [B185], Tozzi et al. [B188], Tozzi et al. [B189], Wheeler et al. [B190].

4.6 Magnetically induced vibration sparking

Due to the magnetic field in the stator core, surface currents will flow axially along the semiconducting slot coating of a bar or coil. In case the bar vibrates in the slot, these currents may be interrupted at a contact point to the core iron, and the interruption of this current will form an arc to the core. If the resistance of the semi-conductive slot coating allows sufficient current to flow, the resulting arc can damage the groundwall insulation by an erosion process. This so called magnetically induced vibration sparking, which is a

relatively fast deterioration mechanism, may occur at any point of the winding and thus also at lower voltage sites, for example close to the neutral.

4.7 Contact sparking

Contact sparking is defined in Clause 3.

5. Overview of PD detection methods

PDs are accompanied by several physical manifestations: electrical pulses and resulting radio frequency (RF) pulses, acoustic pulses, light, as well as chemical reactions within the cooling gases that are either air or hydrogen. The following subclauses are a summary of how some of these manifestations can be measured as a means of quantifying the PD activity in a stator winding or individual coil or bar.

5.1 Electrical pulse sensing

Because a PD involves a flow of electrons and ions across a small distance in a finite period of time, a small current flows every time the PD occurs. The total current will be governed by the transport of a certain number of picocoulombs of charge. The current flow creates a voltage pulse across the impedance of the insulation system. One of the primary means of detecting PD is to measure the small voltage pulse that accompanies every PD, or the resulting current pulse. These quantities are measured in circuits remote from the PD source. Note that in a typical coil, bar, or winding, there may be many hundreds of PD per second; thus, many hundreds of electrical pulses may be detected each second. The voltage pulse can be detected by means of high-voltage capacitors, which are normally connected to the phase terminal or elsewhere in the winding. The capacitor has a high impedance to the power frequency voltage, but appears as a low impedance to the high-frequency PD voltage pulses. Alternatively, a high-frequency current transformer can be installed on the lead that connects the neutral of the machine to the grounding impedance, on the phase leads or in other suitable locations to detect the pulse currents accompanying the PD. The output of the capacitors or the high-frequency current transformer are voltage or current pulses, respectively, which can be measured with an oscilloscope, spectrum analyzer, or pulse height analyzer. Variations of these methods can be used for on-line and off-line tests. Further details on the sensors and the measuring instruments for electrical pulse-sensing methods are provided in Clause 6 and Clause 7, whereas test procedures and interpretation are discussed in Clause 10 and Clause 11.

5.2 RF radiation sensing

In addition to creating voltage and current pulses within the stator winding, the discharge spark also creates some RF electromagnetic waves that propagate away from the discharge site. The electromagnetic disturbance created by a PD has RF frequencies from 100 kHz to several hundreds of megahertz. AM radios with a suitable antenna can therefore be used to sense that PD activity is occurring. If a directional RF antenna is used, it is sometimes possible to locate the sites of PD activity within the stator winding. Variations of this method can be used for on-line and off-line tests. Further details on the sensors and the measuring instruments for RF radiation sensing methods are provided in Clause 6 and Clause 7, whereas test procedures and interpretation are discussed in Clause 10 and Clause 11.

5.3 Power-factor tip-up

Because each PD is accompanied by acoustic and RF emissions as well as light, it follows that each PD event absorbs a certain amount of energy. The energy dissipated in the PD pulse must therefore be supplied from the source of power frequency voltage, and it can be considered as an increase in the dielectric loss in the stator winding. Thus, an indirect means of measuring the total discharge activity in a coil or winding is to measure the dissipation factor or power factor of the insulation at low voltage (below the PD inception voltage) and at high voltage (where the presence of any PD will increase the dielectric losses). A large power-factor or dissipation-factor tip-up (i.e., the power factor at high voltage minus the power factor at low voltage) may be indicative of severe PD activity in the coil, bar, or winding. However, especially for coils or bars with lower tip-up a correlation between tip-up values and PD activity should not be expected (see James et al. [B138]). Stress control coatings on the end arms of coils or bars can be the cause of increased tip-up, especially for installed windings, in which it is not practical to use guard electrodes. If deterioration is restricted to a small number of coils or bars, it is difficult to detect if power-factor tip-up measurements are restricted to complete circuits. In general, the power-factor tip-up test is less sensitive to PD activity than are the electrical pulse sensing and RF methods described in 5.1 and 5.2. The method can only be applied with the motor or generator out of service. Further information is provided in IEEE Std 286, and Bartnikas and McMahon [B2].

5.4 Energy/integrated charge transfer

An alternate power frequency approach to that described in 5.3 is the measurement of the energy and integrated charge transfer that results from PD activity. These methods, Method A and Method B, are detailed in ASTM D3382-07. In Method A, the power loss attributed to the PD activity is calculated from measurements of capacitance and dissipation factor obtained using a conventional high-voltage capacitance bridge. In Method B, a specialized high-voltage capacitance bridge is used together with an oscilloscope having vertical deflection plates connected in the position of the bridge null detector, whereas the horizontal plates are connected to a high-voltage divider. Below the PD inception voltage, the bridge is balanced such that the oscilloscope displays a horizontal line. Above the PD inception voltage, the oscilloscope display is a parallelogram. The height of the parallelogram represents the sum of the PDs per half-cycle, and the area represents the energy dissipated per cycle by the discharges. This is sometimes referred to as the "Loop Trace Method." Stress control coatings on the end arms of coils or bars can be the source of error in this measurement, especially if it is not possible to use guard electrodes. The test method can only be applied if the motor or generator is not in service. In addition to the details of the test method provided in ASTM D3382-07, a review of its development (see Dakin [B146], Dakin and Malinaric [B147]), and application experience (see Simons [B148]) may be beneficial to potential users. Good correlation with condition has been reported when the test method has been applied to stator coils insulated with thermoplastic materials that are frequently characterized by more dense patterns of PD activity.

5.5 Ozone detection

In air-cooled machines, the presence of discharges on the surface of the coils or bars causes chemical reactions in the adjacent air. One of the byproducts of the chemical reactions is ozone. Ozone is a gas with a characteristic odor. The concentration of the ozone increases if there is substantial surface PD activity. (Internal PD well within the groundwall or adjacent to the copper conductors in form-wound windings will not create measurable ozone.) There are several means of measuring the ozone concentration, including inexpensive chemical tubes and electronic sensors. The concentration of ozone is affected by the temperature and humidity of the environment including that in the machine enclosure and the air flow rate. It may also be related to machine load and power factor. The sampling location is critical. Though it may be possible to detect ozone during off-line testing, it is primarily useful as an on-line monitoring tool. Further information is provided in Cartlidge et al. [B63], and Lépine et al. [B64].

5.6 Acoustic and ultrasonic detection

Each PD creates a small “shock wave” caused by a rapid increase in temperature of the gas in the immediate vicinity of the PD. This small shock wave in turn creates acoustical noise. When many PD pulses are occurring on the surface of the stator coils, a “frying bacon” sound results. The acoustical noise occurs in the frequency range of several hundred hertz to over 150 kHz, with most of the acoustical energy occurring around 40 kHz. Directional microphones can be used to measure the PD sound level, as well as to locate where the surface PD may be occurring. Note that the acoustical noise will not be detected if the PD activity is within the groundwall unless the activity is especially great. The method can also be used in conjunction with fiberglass rods that act as acoustical waveguides and provide electrical isolation between the component being tested and the detector. Further information is provided in Zhu et al. [B68].

5.7 Black-out test

A common means of determining the presence and location of surface discharges is to energize the coil/bar or winding under conditions of complete darkness and conduct a visual inspection from a safe distance. The black-out test is primarily useful for detecting and locating surface discharges that involve the stress control coating, air gaps associated with the end arms of single coils/bars. It can also be used to observe external PD associated with phase-to-phase voltage, or supports associated with the circuit ring bus of VPI'd machine during factory test or on stator models. The black-out test may also be useful for locating girth cracks or slot discharge activity involving individual coils/bars. Some disassembly of the machine may be necessary to facilitate the visual inspection. A 50 Hz or 60 Hz variable voltage supply is desirable for applying the test voltage and safety associated with voltage application and working in complete darkness is an issue. A more complete treatment of this subject will be found in IEEE Std 1799.

5.8 Corona imaging instruments

An alternative to the blackout test to observe the light emitted by external discharges is to use a corona imaging instrument such as an ultraviolet viewer. The advantage of this approach is that it can be performed under normal light conditions which can shorten the test duration and make it easier to locate PD sites. To perform the test under normal or reduced lighting is also safer than performing a high voltage test in complete darkness. Because of this IEEE Std 1799 recommends that the test on a stator assembled at site be made with a corona imaging instrument. The corona imaging instrument can also be used on single bars or coils or for tests on stator models or VPI'd stators.

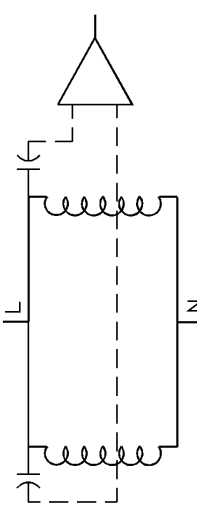
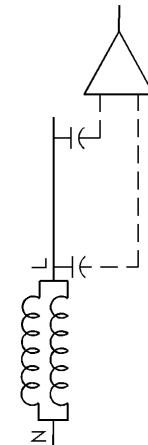
6. Electrical pulse and RF radiation sensing systems

A considerable number of different electrical pulse sensing systems are in use. The machine design and PD activity may define the type of sensors and the installation required.

When a PD event occurs at some location in a winding, the injected charge first flows into the capacitance to ground at the injection site, thereby modifying the local voltage. This voltage change immediately becomes the crest of a wave that propagates in both directions away from the injection site. The nature of the wave at any location away from the injection site depends entirely on the impedance along the path it had to traverse. Because PD pulse rise times may be in the nanosecond range at the injection site, the initial voltage wave has frequencies from the kilohertz to the gigahertz range. However, it should be noted that all components of the test object and the measuring circuit affect the bandwidth of the measurement. The inductance of the sensor's connection to the test object may limit the upper frequency to some tens of megahertz. Specially designed sensors (e.g., see 6.3.2) and test methods are required to extend the upper frequency limit.

Typical electrical pulse sensors and associated detectors are listed in Table 1 for on-line measurements, Table 2 for off-line measurements on complete windings, and Table 3 for measurements on individual coils and bars. These are intended as examples only. Other systems of sensors and detectors are available that may be equally suitable for particular applications. For example an antenna probe having a bandwidth of 100 kHz to 100 MHz is described in Candela and Contin [B33].

Table 1—On-line discharge measurements (typical systems)

Case	Sensors	Detector/ output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
1	80 pF coupler terminated in 50 Ω and connected either: -Differentially with a minimum of one coupler near line end of each of two parallel circuits per phase.  - Directional with one coupler per phase at line terminal and a second at least 2 m distant on isolated phase bus (IPB). (In some cases for cable-connected machines, only the coupler at the line terminal is needed per phase.) 	Pulse height analyzer with pulse-phase capability. Hard disk storage. Pulse height plots in terms of two phase windows or multiphase windows.	40 MHz to 350 MHz (system). For lower -3 dB point of around 7 MHz, see [B35], [B39].	In 40 - 350 MHz instruments, noise rejection is achieved based on time of arrival of pulses from the two couplers. This is especially important for directional couplers. Noise reduction is also achieved by attenuation when differential couplers are installed within a winding.	Differential couplers are sensitive primarily to PD at the line end of the circuits in which they are installed. This is especially true when the couplers are installed within the winding such as at an end cap. Differential coupler connection is usually limited to hydrogenerators because of the need for > 2 m between pairs of couplers. Directional couplers do not attribute PD to a particular stator circuit. Directional couplers are vulnerable to internal noises, such as shaft grounding brushes and back or core sparking, which are prevalent, especially in large turbo alternators, or poor electrical contacts at the machine terminals. Computerized system	Serial and parallel ports, USB, Ethernet Differential: H [B34], [B38], [B99], [B103], [B118] Serial and parallel ports, USB, Ethernet Directional: T, S, H [B14], [B35], [B56], [B74], [B86], [B118]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						