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

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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

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

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

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

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 (withdrawn)[6]

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

IEEE Std 1799™, 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.

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

where

I_t is average discharge current, A
t_o 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/).
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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 (tanδ): 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 (Δtanδ): 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 kHz $\leq f_1 \leq$ 100 kHz; $f_2 \leq$ 500 kHz; 100 kHz $\leq \Delta f \leq$ 400 kHz where f_1 and f_2 are the lower and upper limit frequencies and Δf is the bandwidth $f_2 - f_1$. [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.

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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:

$$NQN = \frac{FS}{G\,x\,N} \text{ x } \left[\frac{\log_{10} P_1}{2} + \sum_{i=2}^{N-1} \log_{10} P_i + \frac{\log_{10} P_N}{2} \right] \tag{2}$$

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

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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.

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

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 ith 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 ith 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 (cosθ): 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.

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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.

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

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 °C or 100 Ω platinum at 0 °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 in 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.

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

$$\sum_{x=1}^{x=n} N_x Q_x \tag{5}$$

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.

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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

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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

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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.

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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].

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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.

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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].

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

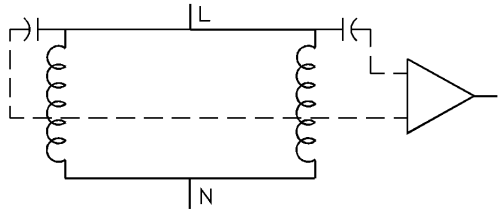
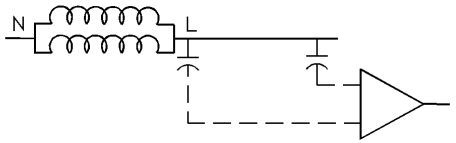
Case	Sensors	Detector/ output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
1	80 pF coupler terminated in 50 Ω and connected either: -Differentially with a minimum of one coupler near line end of each of two parallel circuits per phase.  - Directional 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						

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

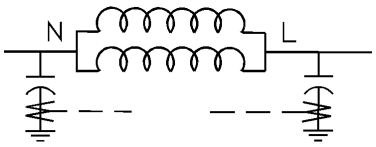
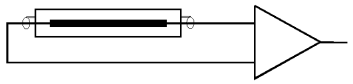
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
2	- 10 nF capacitive coupler with broadband high-frequency current transformer at line terminals. - RFCT with or without 10 nF capacitor between machine neutral and ground. 	Narrow-band and broadband data acquisition in time and frequency domain. Trending of 30 significant characteristic values fingerprints (phase resolved pulse height analysis, histograms, time domain pattern, etc.).	10 kHz to ≥ 30 MHz	- Subtracting signals (two couplers/phase necessary). - Time and frequency windowing. - Automatic interference elimination based on statistical disturbance recognition determines setting of time and frequency windows.	Combination of different measuring methods to increase the interpretation and confidence level. Completely computerized system. Analysis of uninfluenced signals (sampling rate ≥ 40 MB/s without stretcher).	M, T, S, H [B95]
3	Stator slot coupler installed under wedge in existing windings opposite air gap bar closest to line end, or in new windings between air gap bar and back bar, where at least one bar is in a line end position. 	Pulse height analyzer with pulse-phase capability, as in Case 1.	30 MHz to > 1 GHz (sensor) 20 MHz to 800 MHz (detector).	Pulse widths > 6 ns considered to be noise. Can discriminate between pulses traveling from end windings toward slot and vice versa.	Excellent noise immunity. Response limited to one slot. Requires rotor removal for sensor installation. If gas cooled, requires penetration of gas seal.	As for Case 1. T, S [B52], [B53], [B74], [B86]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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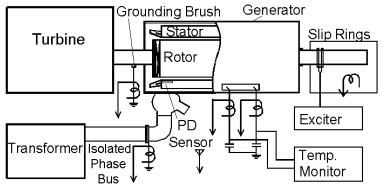
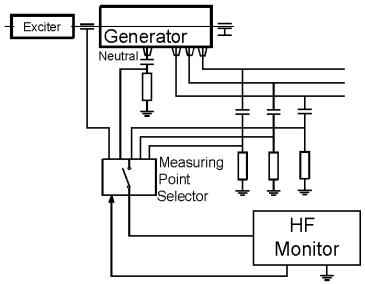
Table 1—On-line discharge measurements (typical systems) (continued)

Case	Sensors	Detector/ output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
4	CT on lead of resistive temperature detector installed in windings between upper coil and bottom coil. Sensors for noise gating located at noise sensors. 	Narrow band data acquisition of pulse height in time domain with multiple sensors. Phase resolved pulse height analysis and histograms.	5 MHz to 60 MHz	Noise rejection algorithm is based on comparison between pulse height of narrow bands with different center frequencies, and comparison between pulse height of different sensors and noise gating.	Simple sensor installation without rotor removal. Sensitivity depends on length of search coil lead.	Byte data addressed by time with condition, sensitivity of each sensor, results of noise rejection. T [B55], [B54] (another version)
5	Surge capacitors grounded through high frequency resistors. Sensors also located at the generator neutral and at the shaft grounding brush. 		30 kHz to 10 MHz	Based on time of arrival of pulses from sensors.		T [B127], [B135]

Applicability:

H = hydrogenerator

T = thermal generator

S = synchronous condenser

M = motor

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

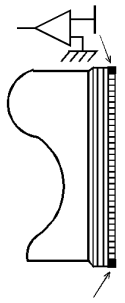
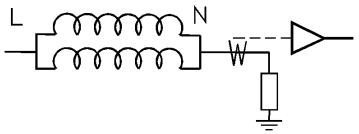
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
6	Capacitive sensor 3 cm to 5 cm from coil end arm; sensor at center line of field pole tip on hydrogenerator (1 north and 1 south pole, top and bottom). 	Peak responding, normal: one reading per sensor/slot Analysis mode: readings every 40 μs	20 MHz to 150 MHz	Noise rejection and slot sensitivity is based on attenuation. Sensitivity ≥100 pC.	PD activity at each slot measured in phase with peak-positive or peak-negative voltage. Multiple readings at each coil location determines statistically significant PD distribution line-neutral. Response limited to max PD pulse.	Hard disk storage. Phone modem access. H [B51]
7	RF CT between generator neutral and grounding transformer. 	Radio noise meter readings in quasi-peak	20 kHz to 50 MHz (typical range; narrow-band measurements)	Noise rejection is based on manual analysis of data across the frequency spectrum.	Requires experienced operator. Does not discriminate between PD occurring on the positive and negative half-cycles of 60 Hz.	Indicating meter or chart recorder T, S, H, M [B40], [B41], [B44], [B125], [B128]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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

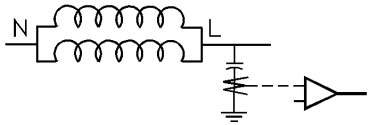
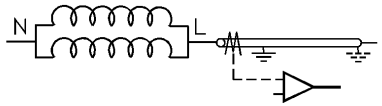
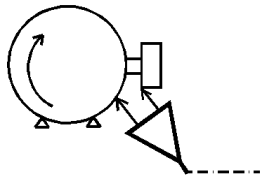
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
8	RF CT on ground lead of surge capacitor applied to motor terminal 	Pulse height analyzer possibly with pulse-phase capability.	100 kHz to 30 MHz (sensor) 20 MHz to 350 MHz (detector)	Relies on there being no noise, or that external noise is attenuated by cables at the frequency of measurement.	Surge capacitors required. Vulnerable to external and internal noise is present.	As for Case 1. M
9	Clamp-on CT applied to cable near motor terminal with no ground on cable sheath at motor side of CT. 	Discharge detector with oscilloscope display.	50 kHz to 300 kHz (system)	Relies on there being no noise.	Single-phase cable sheath must not form shorted turn on RF CT. RF CT may saturate because of 50 Hz or 60 Hz current.	Oscilloscope display or indicating meter. M [B10]
10	RF voltage between motor terminal box and adjacent machine frame. Similar approach to generators using first joint in IPB. 	Pulse height analyzer, manual window selection.	1 MHz to 100 MHz (system)	Relies on sensor being in close proximity to PD source, and on attenuation of noise at the frequency of measurement.	Simple installation. Does not discriminate between PD occurring on the positive and negative half-cycles of 60 Hz. Experienced operator required if applied to generators.	Indicating meter for periodic measurements. PC data logging for continuous measurement. M, T, S, H [B54], [B58]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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

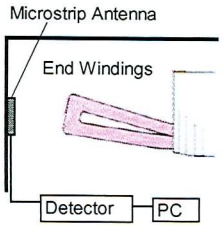
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
11	Ozone monitor whose sensor measures chemical or physical properties of an air sample.	Analog or digital indicator. Calibrated in parts per million.	N/A	N/A	Only detects PD occurring on surface of coils/bars. Not very sensitive in comparison to electrical methods.	Indicating meter for periodic measurements. PC data logging for continuous measurements. M, H [B63]
12	Microstrip antenna installed inside or outside the machine housing 	Narrow band data acquisition. Pulse height analyzer in time domain, phase resolved pulse height analyzer and histogram.	1.8 GHz ±200 MHz	Narrow band characteristic (sensor) Band pass filter (detector)	Simple sensor installation without rotor removal. Micro-strip antenna can detect PD activities over a wide area. Sensors do not cause a failure of stator winding because they are completely insulated from high voltage stator windings. Sensor is preferentially sensitive to PD in the endwinding.	Hard disk storage and PC screen display H, T, S, M [B60], [B61], [B62], [B107]
13	1 nF – 9 nF couplers terminated in 50 Ω have been well used for on-line PD testing. They are installed at line and neutral (optional).	Pulse magnitude and phase resolved graphs	100 kHz to 20 MHz	Filters and modern digital signal processing techniques.	Lower frequency allows detection of PD activity deeper into windings. Noise can be identified by experienced user.	H,T,S,M [B39]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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

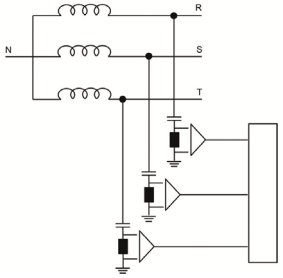
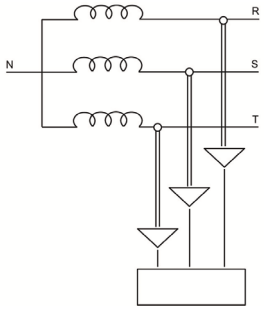
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
14	Capacitive Coupler (80 pF to 10 nF)  HFCT around the conductor  	Pulse energy with pulse-phase capability. Server storage and data post- processing available.	40 kHz to 35 MHz	Digital signal processing of the pulses.	No need for off-line tuning of the noise rejection system. Manual post processing is sometimes required.	Serial, USB, Fiber Optics Capacitive Couplers: H,T,S,M HFCT around the conductor M [B80], [B81], [B82]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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Table 2—Off-line discharge measurements

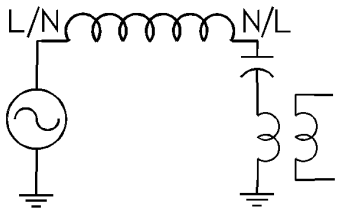
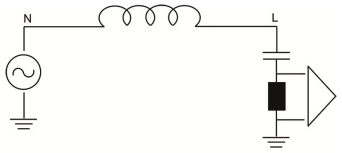
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ bibliography
1	100 pF to 10 000 pF coupling capacitor and appropriate inductive matching unit. 	Oscilloscope display, supplemented by indicating meter responding in apparent charge, or sometimes average discharge current or quadratic rate. The amplified pulses may also be monitored using a pulse height analyzer. Some detectors are designed for use with 0.1 Hz test voltages.	10 kHz to 300 kHz sometimes 2 MHz (adjustable).	Attenuation of PD signals by winding is least at the lower frequency end of the range (e.g., 10 kHz). It may be advisable to measure at both line and neutral ends of each circuit. In one approach, the measurement is limited to the line end, but the normalization pulse is applied at both line and neutral terminals, and the bandwidth of the instrument is adjusted to achieve a similar response.	Response to PD sites in terms of apparent charge varies with the bandwidth of the detection system. Coupling needs to be optimized. Vulnerable to pulse superposition.	Most have oscilloscope display. Some also have indicating meter, RS232 interface, parallel and serial ports. [B69], [B145], [B149], [B160]
2	Capacitive capacitor with matching unit (80 pF to 10 nF) 	Narrow-band and broadband data acquisition in time and frequency domain. Trending of 30 significant characteristic values fingerprints (phase-resolved pulse height analysis, histograms, time domain pattern, …)	10 kHz to ≥30 MHz	Noise rejection is made by digital signal processing of the acquired pulses. Noise can be gated by using other sensors plus synchronized units.	Combination of different measuring methods to increase the interpretation and confidence level. Computerized system. Analysis of uninfluenced signals (sampling rate ≥40 MB/s without stretcher).	USB, Fiber optics [B39], [B80], [B81], [B82], [B95]

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Table 2—Off-line discharge measurements (continued)

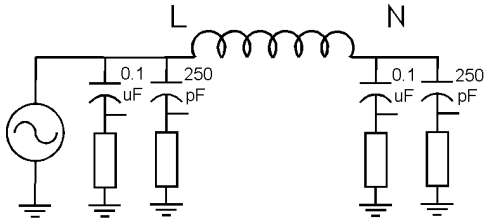
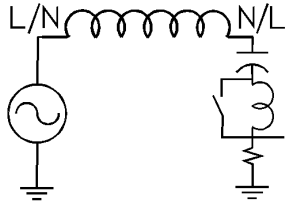
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ bibliography
3	10 kHz measurement coupler is 0.1 μF or 10 nF 130 kHz measurement coupler is 250 pF 	Indicating meter displaying PD in terms of quadratic rate. The 10 kHz readings are normalized by dividing by the winding capacitance.	500 Hz to 21 kHz And 90 kHz to 170 kHz	The 10 kHz measurement responds to PD sources remote from winding terminals. 130 kHz measurement is sensitive to PD near the measured winding terminal.	Although the 10 kHz measurement responds to PD sources remote from the winding terminals, it is vulnerable to superposition errors.	[B155], [B157]
4	1000 pF coupling capacitor terminated in 185 Ω and with variable inductance connected in series to compensate for coupling capacitor below 1 MHz. 	Radio noise meter in quasi-peak.	15 kHz to 30 MHz (possible range of measurement)	As for Case 1. The response of the winding to a given PD site will result in peaks in the response of the narrow-band detector at specific frequencies.	Measurements at a single frequency may be misleading. Does not discriminate between PD occurring on the positive and negative half-cycles of 60 Hz.	Indicating meter or chart recorder. H,T,S,M [B76]

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Table 2—Off-line discharge measurements (continued)

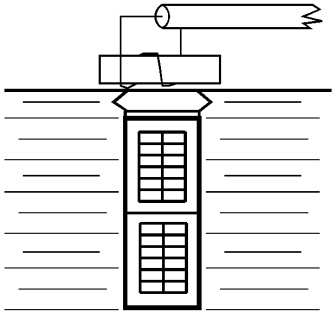
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ bibliography
5	Electromagnetic probe bridging each slot in turn. 	Peak responding meter scaled in milliamps or quasi-picocoulombs	Probe tuned to 5 MHz	As a result of winding attenuation at 5 MHz, a PD site can be located to within one or two slots. User needs to be aware that some PD sites become less active after the test voltage has been applied for a period of time. If detection of phase to phase PD sites is required, an appropriate electric stress needs to be applied to this insulation.	Not always reliable for pinpointing the PD site in a given slot. Does not discriminate between PD occurring on the positive and negative half-cycles of 60 Hz. Can usually test with hydro-generator rotor in place.	Indicating meter. [B2], [B45], [B46], [B166], [B167]
6	Acoustic probe held at slot under investigation.	Indicating meter with arbitrary scale	36 kHz to 44 kHz (typical range)		When used in conjunction with the electromagnetic probe, it is reliable for pinpointing sites of high PD activity, such as slot discharge.	Indicating meter and audible tone. [B67]

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Table 3—PD measurements on individual coils and bars

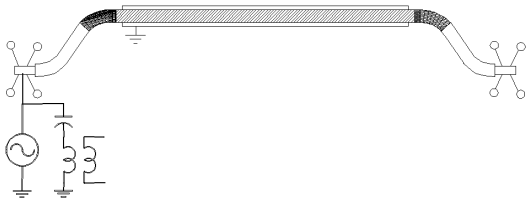
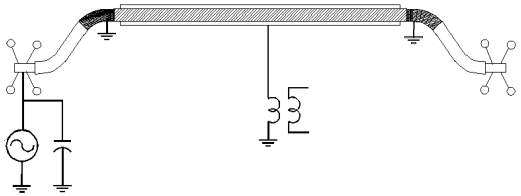
Case	Sensors	Detector/output	Frequency range	Calibration	Pros and cons	Data output/ format/ bibliography
1	1 nF – 2 nF coupling capacitor and appropriate inductive matching unit (quadrapole) 	Oscilloscope display or pulse height/pulse phase analyzer.	100 kHz to 500 kHz as defined in the term *largest repeatedly occurring PD magnitude (Q_m)* in Clause 3.	ASTM D1868 or IEC 60270	Responds to all PD sites: internal, slot surface, end arm.	[B69], [B145]
2	Coupling capacitor is 0.1 μF. Measurements at 10 kHz or 30 kHz.  Optional arrangement showing gap in semi-con coating at ends of dummy slot with externally applied guard bands on semiconducting coating adjacent to stress control coating.	Indicating meter displaying PD in terms of quadratic rate.	500 Hz to 21 kHz for 10 kHz case		Responds to all PD sites unless guard electrodes at ends of slot in which case, response to end arm discharges is reduced.	[B157]

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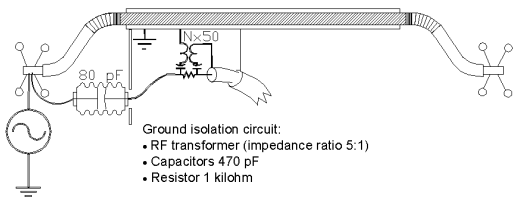
Table 3—PD measurements on individual coils and bars (continued)

Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ bibliography
3	80 pF terminated in 50 Ω at analyzer. 	Pulse height analyzer with pulse-phase capability. Hard disk storage.	8 MHz to 100 MHz (system)	As lead lengths need to be kept to a minimum, a low voltage ceramic capacitor can be attached to the copper within the slot section of a surplus coil or bar. High voltage and ground leads associated with the 80 pF coupler need to be as short as possible and have cross section consistent with high frequency applications.	Good sensitivity to internal PD, but reduced sensitivity to end arm discharges. This may be useful if the application is the detection of internal voids.	Serial and parallel ports, USB, Ethernet [B174], [B175] [B176]
4	Acoustic probe.	Indicating meter with arbitrary scale.	36 kHz to 44 kHz (typical range)		Good for pinpointing sites of high PD activity.	Indicating meter and audible tone. [B67]
5	Electromagnetic probe bridging dummy slot.	Peak responding meter scaled in milliamps or quasi-picocoulombs.	Probe tuned to 5 MHz		Maybe useful for pinpointing the PD site. Does not discriminate between PD occurring on the positive and negative half-cycles of 60 Hz.	Indicating meter.

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6.1 Coupling capacitors

Capacitors are used as coupling devices to pass high frequencies (low reactance at the high PD frequencies) from the point of detection to the input of the measuring equipment. The actual frequency response is a function of both the capacitor and its associated circuit. When terminated directly in 50 Ω the –3 dB point is a function of the coupler capacitance [40 MHz (80 pF), 6.4 MHz (500 pF), 320 kHz (10 nF), etc.]. The capacitor needs to be free of PD activity under the conditions in which it is applied.

A capacitor that is to be used specifically in on-line monitoring applications and installed in close proximity to the stator winding should meet the following minimum requirements:

- Have a PD extinction voltage (PDEV for a specified PD level of 2 pC) greater than two times the phase-to-ground operating voltage, verified by appropriate routine testing.
- Be subjected to a routine power frequency overvoltage test to at least the same voltage as the stator winding.
- Have undergone a voltage endurance type test at least 2.17 times rated line-to-line voltage of the machine and not failed within 400 hours under conditions of room temperature.
- Have a low dissipation factor (≤ 0.5%) that is stable with temperature up to the maximum operating temperature of the stator winding, verified by appropriate type testing.
- Show no signs of deterioration of the above properties after thermal cycling and mechanical vibration representative of operating conditions.
- Have dimensions and mass such that in the installed position, it will not exhibit mechanical resonance, for example, at 100 Hz or 120 Hz and rotational speed frequency. For capacitive couplers installed on motors supplied from variable frequency converters, the installed capacitor should not have resonant frequencies within the ranges of operating speeds and two times the supply frequency. It is also advisable to have margins on these frequencies as they can change with operating conditions.
- Meet the physical constraints and electrical clearance requirements of the location in which it is to be installed.

Refer to Annex B for typical details of type tests and routine tests on coupling capacitors.

For on-line measurements, the selected capacitors have ranged from existing 0.25 μF surge capacitors to capacitors specifically installed for PD measurements that can have values as low as 80 pF. The surge capacitors usually have a paper or film dielectric impregnated with a dielectric liquid. The use of the existing surge capacitors as a coupling device may involve the installation of an RF current transformer on the associated ground lead. Surge capacitors are usually installed in metalclad switchgear or motor terminal boxes and do not operate at as high a temperature as some low value capacitors, which are installed in close proximity to the stator winding. Some low value capacitors have an epoxy-mica dielectric, whereas others have been fabricated from lengths of cross linked polyethylene insulated (XLPE) high-voltage cable. Coupling systems based on the former have exhibited better response to PD pulses (see McDermid and Bromley [B35]). The capacitor selected will depend on a variety of factors, including type of machine, physical constraints, desired bandwidth, and the type of noise reduction scheme that is to be implemented.

For off-line measurements, it is possible to use many of the same capacitors that are applied for on-line measurements. Ceramic capacitors often have good response to PD pulses and may be suitable for use during off-line tests, but they can have increased dielectric losses at temperatures typical of the operating conditions of the machine.

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A number of examples of capacitors used as coupling devices can be found in Table 1, Table 2, and Table 3.

6.2 RF current transformers

RF and other high-frequency current transformers can be effective for monitoring motors, large and small turbine generators, and any other apparatus that may be prone to PD activity. A current transformer (CT) that has a wide-band pulse response can be used to measure high-frequency PD pulses. It is constructed of a ferrite core and is usually encased in a metal housing.[10] Most of the commercially available CTs are provided with a transfer curve describing their frequency response and output signal level. The output signal from an RF CT may be more oscillatory in nature than from other PD sensors if the CT has not been adequately impedance matched.

The CT is usually installed in a low-voltage, ground, or neutral leg of the monitored apparatus. One common location in which to install the RF CT is on the lead from the neutral of a generator to the grounding impedance. In this case, proper clearances must be maintained between the CT housing and the conductor that it surrounds. In some applications, additional insulation is required between the CT housing and the measured conductor. Ensure that a CT installed in this position, with its housing properly grounded, will not experience a flashover when an impulse or a 50 Hz or 60 Hz overpotential test at the full acceptance level is applied to the lead from the neutral of the generator to the grounding impedance. (See also 10.1.4)

CTs are also installed around the ground cable to the surge capacitor, on cables at motor terminals and on connections to ground from cable sheaths. In the case of a CT encircling the primary conductor of a cable, which could be carrying significant 50 Hz or 60 Hz current, there should be an air gap in the magnetic circuit of the CT to prevent saturation.

6.3 Near-field antennae

A variety of sensors are available for both off-line and on-line measurements.

6.3.1 Electromagnetic probe

The electromagnetic, or TVA[11] probe is a proximity sensor that responds to the RF signals radiated by PD within or outside the stator coils. The search coil probe consists of an 1 m insulated rod with a multi-turn coil wound on a ferrite core at one end. A typical coil consists of 15 turns of AWG #14 wire wound on a 10 mm diameter ferrite rod, although some users have employed a lesser number of turns. The ferrite rod is about 50 mm in length. The sensor coil is attached to a coaxial cable for connection to the peak pulse meter. The probe and its connecting cable capacitance form a tuned circuit, which is usually tuned to 5 MHz. Frequencies from 200 kHz to 20 MHz have been evaluated. In some machines, a higher or lower frequency was found to be more sensitive in detecting PD activity than 5 MHz. However, standardization on 5 MHz is recommended to permit comparison of data between machines. The closer the antenna is to the source of PD, the higher the signal output. It is used to identify locations of PD within a high-voltage winding. The magnitude of the signal is displayed in relative terms and may not be useful for specifically quantifying the level of PD. The probe and peak pulse meter cannot distinguish between slot discharge and internal coil PD, and they do not discriminate between positive and negative pulses. However, if the probe is terminated in an oscilloscope instead of the peak pulse meter, the polarity of the pulses and the type of

[10] A transfer impedance of around 5 Ω is recommended. The output impedance is typically 50 Ω.
[11] Named for the Tennessee Valley Authority because of its involvement in the development of the probe, as is reported in Smith [B46].

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discharges can be determined (see Hudon et al. [B168]). This sensor is used for off-line tests with the winding energized at normal phase-to-neutral voltage, or lower voltages.

6.3.2 Stator slot couplers

The stator slot coupler (SSC) is a two-port strip-line antenna. The SSC is an electromagnetic coupler that is sensitive to the electromagnetic energy from PD activity. It is installed in the slots of a stator winding containing coils that are as close as possible to the line end of the winding. They can either be installed directly beneath the wedges or between top and bottom bars in a new or rewound machine.[12] For the SSC installed under the wedge, the sense line is on one side of the substrate, facing the bar or coil, and the ground plane is on the opposite side. The characteristic impedance between the two electrodes is 50 Ω.

Each end of the sense line is connected to a coaxial cable, thus, providing two outputs from each sensor. The SSC has a flat frequency response from 30 MHz to over 1 GHz, for measuring the wavefront of PD pulses that originate under or near the SSC.

6.3.3 Resistance temperature detectors

Resistance temperature detectors (RTDs) and associated leads have been used to detect PD (see Blokhinstev et al. [B54], Itoh et al. [B55], Stone and Campbell [B57]). If the PD is detected by means of the leads then the discharge activity may not be attributed to a particular slot. RTD leads used as a PD sensor would normally be used in conjunction with capacitive or RF PD sensors.

6.4 UHF antennae

Various ultra high frequency (UHF) antennae can be used to detect electromagnetic signals from PD sites. UHF antennae with narrow band characteristics or appropriate cut off frequency need no filters, but antennae with ultra wide band (UWB) characteristics including lower component of voltage impulses are required to have a filtering function to suppress the residual signal inside the acquisition system.

Micro-strip or patch antennae have narrow band characteristics, and it can sensitively detect attenuated PD signals beyond near field (see Kaneda et al. [B60], Muto et al. [B61], Shibuya et al. [B62], Sawada et al. [B107]).

These antennae are primarily sensitive to PD in the end windings of machines.

7. Electrical pulse and RIV measuring instruments

The electrical signals from the various sensors described in Clause 6 can be measured and recorded using a variety of instruments.

Typical electrical pulse detectors and associated sensors are listed in Table 1 for on-line, 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 detectors and sensors are available that may be equally suitable for particular applications.

[12] An SSC is about 50 cm long, 3 mm thick, and is custom made to the slot width. A 25 μm thick copper sense line and a 25 μm ground plane are deposited on an epoxy-glass substrate.

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The following subclauses provide a description of a number of electrical pulse and RIV measuring instruments.

7.1 Oscilloscopes

Signals from virtually every PD sensor can be observed on an oscilloscope that displays the pulse activity in the time domain. The bandwidth of the oscilloscope needs to be equal to or greater than the bandwidth of the PD sensor. In many commercial PD instruments, the oscilloscope is built into the instrument and is the main means of displaying the PD activity. The normal display mode is to use a 2 ms/division sweep speed that enables PD pulses to be displayed with respect to the alternating voltage cycle. Such a display permits skilled users to determine whether the pulses are PD from the insulation system or electrical interference. The relative magnitude of the positive and negative polarity pulses can also be ascertained, which often helps to identify the source of the PD.

7.2 Spectrum analyzers

The spectrum analyzer displays the magnitude of the signals from any of the sensors in Clause 6 as a function of the frequency, that is, in the frequency domain. Because PD pulses at origin are pulses with a duration of a few nanoseconds to a few tens of nanoseconds, the pulses generate Fourier frequencies from virtually dc to well over 100 MHz. The spectrum analyzer measures the intensity of the signal at each observed frequency. The bandwidth of the spectrum analyzer should exceed the bandwidth of the PD sensor. The mixture of inductances and capacitances in complete windings generate a complex transfer function that can create many peaks and valleys in the spectrum analyzer display. Analysis of the display by an experienced person can sometimes reveal the identity and location of the PD within the winding, as well as aid in distinguishing the PD activity from electrical interference. Many spectrum analyzers also have the ability to operate as an oscilloscope, in which the PD pulse at any selectable frequency can be displayed with respect to its position in time on the alternating voltage cycle.

7.3 Integrating current detectors

All electrical PD sensors respond to the PD by outputting a current pulse or a voltage pulse (which is proportional to the current pulse). In many cases, the user is interested in knowing the amount of charge in each PD pulse. Mathematically, the charge is related to the integral of the current signal from the sensor. (As discussed in 11.1, the degree of insulation damage may be related to the charge involved in each PD event.) Thus, many commercial PD instruments integrate the current (or voltage analog) of each PD event to generate a charge response quantified in picocoulombs. The integration is usually accomplished using analog or digital technology, with low-pass or bandpass filters (see Sumereder et al. [B152]). The output of the filter is usually displayed on an oscilloscope, or it is fed to a pulse height analyzer or pulse phase analyzer.

7.4 Quasi-peak pulse meters and RIV meters

Quasi-peak pulse meters and RIV meters are an analog means of being sensitive only to the largest PD pulses rather than to all of the PD pulses. Such instruments incorporate some variation of peak sample and hold circuitry to effectively retain the magnitude of the highest PD pulses detected for a period of tenths of a second to a few seconds. Most of the quasi-peak detectors need a steady stream of pulses to indicate the true peak value. Intermittent pulses may not be registered. A simple analog or digital meter displays the quasi-peak magnitude of the PD pulses in microvolts, milliamps, or picocoulombs.

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7.5 Pulse height analyzers

Owing to the availability of fast digital electronics, pulse height analyzers can now separately measure each of the individual PD pulse events and, thus, determine the number and magnitude of all pulses. The output of the pulse height analyzer is a density plot of PD pulses per unit of time per magnitude window width (i.e., the magnitude resolution) versus the magnitude of the pulses. The pulse height analysis provides a permanent record of an objective indication of the total PD activity. Both the peak pulse magnitude [comparable to a low repetition rate of, say, 10 pulses per second (pps)] and the total PD activity (Clause 3) can be directly inferred from a pulse height analysis. Note that because it is conventional to show the pulse height analysis as a density plot, if the magnitude sensitivity range for the pulse height analyzer is changed, the magnitude window width will change and alter the pulse count for each magnitude window. For example, if the pulse height analyzer has 100 magnitude windows from 1 mV to 100 mV, each magnitude window is 1 mV wide. If the sensitivity is changed from 100 mV to 1000 mV, each magnitude window will be 10 mV wide. All other things being equal more pulses will be counted in the 10 mV wide windows. Thus, changing sensitivity scales will change the pulse height density plot and any derived quantities, such as Q_m, NQN, Quadratic Rate, etc. It is possible to correct for a scale change by converting the density plot to a cumulative plot by integration and re-differentiating the cumulative plot to a common magnitude window width.

7.6 Pulse phase analyzers

A pulse phase analyzer is similar to the pulse height analyzer with the exception that a record is made of the phase position with respect to the alternating voltage at which each PD event occurs.

The pulse magnitude versus pulse repetition rate versus the alternating voltage phase position can be plotted in a three dimensional diagram, sometimes called a phase-resolved plot. Since a three dimensional diagram can be difficult to interpret, many phase-resolved plots are shown in two dimensional form with pulse magnitude on the vertical axis, phase position on the horizontal axis, and pulse repetition rate identified as a color (see Annex C for examples).

Such phase-resolved plots enable knowledgeable people to confirm that the detected pulses are because of PD rather than because of electrical interference, such as static excitation pulses. The phase-resolved plots may also be used to investigate the root cause of any PD (see Annex C). In many ways, the pulse phase analysis is the digital summary of the information observed with an oscilloscope (7.1).

7.7 Time-frequency classification map analyzers

Time-frequency classification map analyzers digitize each pulse shape. The data are displayed in terms of pulse width and bandwidth for the purpose of separating different PD sources from the insulation system and discriminate from external noise sources (see Annex D, Borghetto et al. [B77], Cavallini et al. [B78], Contin et al. [B79]).

7.8 Synchronous three channel/multi-spectral system

The system involves the synchronous processing of PD signals from sensors on three phases in the case of ac electric machines. Multi-spectral PD measurements are based on pulse spectra correlation by applying simultaneously three different band-pass filters (different center frequencies and bandwidth) (see Annex E, Badicu et al. [B80], Koltunowicz et al. [B81], Koltunowicz et al. [B82]).

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8. Pulse propagation in windings and calibration issues

Because pulse propagation and calibration are both frequency dependent, a treatment of one phenomenon without reference to the other is unrealistic. Consequently, the following discussion touches on both subjects. Rotating machines are, at this time, one of the few items of high-voltage equipment that do not have PD specifications. Further, most relevant PD standards, such as IEC 60270 (2000-12), ASTM D1868-07, and IEEE Std 454™-1973 (see [B5]), specifically exclude, or caution against, the use of apparent charge when dealing with large inductive components, such as stator windings (see Heller and Veverka [B13], Rüdenberg [B22], Sedding [B23], Tavner and Jackson [B26], Kurtz and Lyles [B99]).

8.1 Pulse propagation

The response of a particular stator winding to a PD pulse varies depending on the length of the stator core, whether the winding is of the multi-turn coil or single-turn Roebel bar design, the end arm geometry, circuit ring bus layout, and the insulating materials involved. In addition, the PD pulse rise time and its pulse width will be factors in the response of a given detection system applied to a particular winding. The actual PD site and its distance from the detection coupler will have a significant impact on the detected pulse shape and amplitude. As a corollary, the frequency response of the detection system will profoundly influence the characteristics of the signal detected at the terminals of the stator winding.

VHF and UHF pulse response tests on stator windings have shown that a fast rise-time pulse is capacitively coupled through the winding, and that this is followed by a slower electromagnetic traveling wave. In many windings, the fast rise-time, capacitively coupled pulse is subject to rapid attenuation. Generally, the conventional models developed to treat pulse propagation are not applicable at the frequencies (> 100 MHz) implied by this type of coupling. At such high frequencies, stray and interconductor capacitances become increasingly important. These capacitive effects are generally ignored by the low-frequency treatments.

Concerning the slower, electromagnetic traveling wave, the stator winding is treated as a transmission line, with each coil or bar having an associated inductance or capacitance. Depending on the length of each coil or bar and the number in each parallel circuit, every winding will possess a unique set of resonant frequencies. If the pass band of the sensor/detector system coincides with one of these frequencies, the magnitude of the measured PD will be abnormally high (see Kemp et al. [B17], Su et al. [B24], Wilson et al. [B28], Wood et al. [B29]).

Pulse propagation problems are further compounded as the consequence of the overhang region where the coils/bars make the transition from core iron to free space and back to core iron. The surge impedance of a typical stator bar has been found to be in the range of 20 Ω to 30 Ω, whereas in the end arm area, the surge impedance is higher (approximately 300 Ω) but not well defined. Thus, a PD pulse traveling along a stator bar will experience a reflection at the end of the slot, whereas in the end arm area, the transmitted pulse will be further reduced in magnitude because of cross-coupling with other circuits. Cross-coupling can be a source of errors in measurements on the other circuits.

Discharges in the end winding area will generate pulses conducted in the winding to the detection coupler attenuating as they propagate. This activity will also generate an electromagnetic radiated signal at high frequencies that propagates in the air out to the detection coupler. This signal, detected with little attenuation can give PD pulses at the detection point much larger than usual conducted signals. This signal can also give substantial cross-coupling between phase windings and parallel circuits.

The above factors should be considered when selecting an appropriate coupling device. Generally, capacitive couplers and high-frequency current transformers are used for on-line PD tests. PD detection systems operating above 30 MHz can benefit from the attenuation of noise signals and provide for cancellation of noise pulses based on time of arrival. Such a system is sensitive primarily to PD in bars and coils near the coupler. For off-line tests on complete windings, noise levels are generally low, and therefore, it is preferable that such measurements be made at frequencies below 500 kHz to improve the

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response of the detection system to PD sources remote from the terminals. The main disadvantage of PD measurements on windings at these lower frequencies, other than the previously noted resonance problems, is that of pulse superposition, in which anomalously high PD levels may be measured if the pulse repetition rate is comparable to the bandwidth of the detector.

8.2 Calibration into apparent charge

When calibration is carried out, it is usually in terms of apparent charge at the installed sensor location. This may be at one of the winding terminals. When injecting the calibration pulse, all leads should be as short as possible to avoid distortion of the signal because of the lead inductance. Similar precautions should be taken with the connections to any capacitive coupler. Although such a calibration procedure may appear straightforward, a number of difficulties make the procedure more of a scale factor determination (i.e., normalization) than a calibration in the strict sense. The problems associated with attenuation, resonance, and cross-coupling (mutual) have been described previously in 8.1.

These fundamental difficulties are the reason why a true calibration cannot be achieved for stator windings. Consequently, it needs to be emphasized that such a normalization will still only hold for a given machine, a given detection system and if PD occurs close to the calibration point. Discharges occurring some distance away from the calibration point will already have attenuated with propagation and cannot be assumed to be the same as the calibration pulses. In addition, normalization cannot relate to signals propagating radiatively because they involve a completely different propagation mode.

In summary, on completed windings, a completely valid calibration is not possible because of the limitations of the various measuring methods. The results obtained are a function of the winding being tested and the measuring system employed. Consequently, the entire arrangement of the test object, measurement impedance, filter, and amplifier should be considered from a systems perspective. However, differences in the measured PD among similar windings with the passage of time, or under different operating conditions, merit careful consideration.

In off-line PD measurements on a machine with a star connected winding, the observed results (Q_m) may vary significantly depending on whether the measuring system is connected to the phase end **or** the neutral end of one phase of the winding, or phase end **and** neutral end of one phase of the winding, or all three phase ends **or** neutral ends together, or all three phase ends **and** all three neutral ends together. In measurements on one phase of the winding, the observed values for Q_m are generally higher with connection to either phase end **or** neutral end of one phase of the winding, compared to those with connection to phase end **and** neutral end (connected together) of same phase of the winding. Similarly, in measurements of the whole winding (three phases connected together), the observed values for Q_m are generally higher with connection to only three phase ends together **or** only three neutral ends together, compared to those with connection to all three phase ends **and** three neutral ends (all six ends connected together). Also, the observed values for Q_m with connection to one phase of the winding are generally higher as compared to those with connection to the whole winding. The reason for this observed variation is not fully understood. For diagnostic comparison of measured PD values, it is very important to specify how the measuring instrument will be connected to one or more terminals of the winding. For delta connected windings both phase ends would be expected to have a similar insulation condition.

9. On-line versus off-line testing

It is possible to obtain PD test results on properly equipped machines while they are operating (i.e., on-line). Also, testing can be done with machines out of service (i.e., off-line). Depending on the purpose of the test, either method can be used to advantage. It should be noted that there are also disadvantages to both methods.

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The use of off-line testing or visual inspection is strongly recommended to complement the on-line tests in instances in which on-line testing indicates that winding problems are beginning. This off-line testing should be performed at a convenient time during machine outages and should be completed before extensive maintenance or rework is contemplated.

There may be merit in performing PD tests on individual stator coils/bars and completed newly installed windings as a quality control check.

9.1 On-line testing

There are various types of equipment on the market for making measurements that work in a variety of ways. These devices provide the user with the ability to perform tests, on either a periodic or a continuous basis, while the machines are on-line, and thus develop data for trending the PD performance of the machine over its service life. This permits examination of machine condition throughout all factors of influence, including power loading, temperature, and in some cases, humidity.

The major strength of this method is the trending ability. For maintenance reasons, having a tool that can warn of upcoming problems provides the means to plan necessary maintenance around normal outages and, therefore, minimize cost and down time. Testing of this type, in ideal conditions, provides the ability to monitor effects, such as slot discharge, insulation delamination, and end-turn PD.

The state of the art is such that the information obtained may provide a measure of "condition" but should not be considered conclusive in itself. Other observations, inspections, and tests should be performed in addition to verify the findings before extensive maintenance or rework is contemplated. If readings are very low, there is merit in confirming that the sensors and instrumentation are functional.

Obtaining good PD data on windings can be difficult because electrical noise, attenuation, and bandwidth issues can result in measurement problems. These issues can result in misleading readings that may not reflect actual machine conditions.

— *Noise reduction*: Noise reduction is a major issue when performing on-line testing because rotating machines are not operated in an ideal environment for measuring these signals. It is possible to measure signals or discharges generated by other sources, such as attached equipment, radio stations, other airborne noise, commutator noise, etc. Many manufacturers of PD testing equipment take precautions to segregate noise, and most methods are at least partially effective, but few methods, to date, are capable of assuring complete noise elimination.

— *Bandwidth:* The frequency content of a PD pulse is a function of its rise time and pulse width. Each PD source will produce pulses that are characteristic for that site. The frequency is a function of the location and, size of the void, which means that in insulation, as PD progresses, the size of the void will change and, therefore, the associated frequency will also change. As each PD site has an associated frequency, the frequency detection bandwidth of the measuring system (sensor and detector) is an important consideration. PD sites producing signals of frequencies outside the measured bandwidth will be attenuated or not detected at all.

  Many PD measuring systems, because of their internal circuitry or winding coupling methods provide limited bandwidths that can provide only a partial picture of the PD activity that is occurring.

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— *Attenuation/reflection:* Because of the nature of PD pulses, the stator winding should be thought of as a capacitive ladder network at very high frequencies[13] (capacitance to ground predominates), a transmission line at high frequencies[13] [a 2 m long slot corresponds to a half wavelength at 17.2 MHz based on a velocity of propagation of 69 m/μs in machine windings (see Wilson et al. [B28]), and an L/C ladder network at lower frequencies. As pulses travel through the winding, their magnitudes and shapes are distorted by the high-frequency impedance of the winding. The further the pulse travels through the winding, the greater the change in pulse shape. Depending on the frequency response of the detector, pulses of differing lower frequencies and magnitudes may pollute the data or may provide additional data that go undetected.

  Also, as pulses attempt to travel through mismatched impedances (series joints, etc.), there will be attenuation or reflections that will distort the shape of the PD pulses. These effects were discussed in Clause 8.

9.2 Off-line testing

Although off-line testing is more time-consuming and expensive to perform, it can form a good complement to on-line testing if there is concern over trendable machine readings. It is convenient to make the initial offline tests when the machine winding is new. An additional measurement should be considered after one year of service. These measurements will provide a benchmark for future comparison. The major drawbacks of off-line tests are as follows:

— A separate power source sufficient to energize the winding is required.

— The machine has to be taken out of service to perform the measurements, and in some cases, depending on the testing to be performed, partial disassembly may be required.

— Because the machine is not operating, no electro mechanical forces are operating within the machine so that it may not be possible to detect all types of PD (slot discharge/loose winding). In addition, the temperature of the winding will usually be lower.

— All parts of the winding are at high voltage. This may produce additional PD close to the neutral, which does not occur under on-line conditions. There could be a risk of failure when old windings are involved.

— Gas type, pressure, and humidity may differ from the operating condition.

On-line tests may not always correlate to off-line tests as a result of the conditions described in the last three points above.

The off-line test methods have the following advantages:

— Noise sources, other than possibly radiated noise, can be eliminated. This is because all other electrical equipment is isolated from the machine under test, and there are no internal noise sources, such as arcing brushes. The test voltage can be raised to determine PDIV and lowered to determine PDEV.

— By energizing one phase at a time with the others grounded, and then energizing all three phases simultaneously, PD associated with phase-to-phase insulation can be identified.

— Depending on the frequency of the PD sources, it may be possible with certain equipment to locate the source of the PD so that winding repairs can be affected on the exact PD source(s).

[13] Defined in The IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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— If the rotor has been removed, it is possible to provide detailed readings of virtually all slots with a detection antenna, gaining detailed data that are not possible on-line. (More limited PD readings can be obtained at each slot of most hydrogenerators with the rotor installed.)

— During an outage, for off-line PD tests, other measurements can be made and visual inspections can be carried out that may be helpful in identifying the source of the PD.

Bandwidth and attenuation issues are important considerations, as with on-line testing, but with the wide variety of equipment available, it is possible to cover the entire frequency bandwidth by performing tests with more than one type of measurement.

When off-line PD tests are being made at individual slots with an electromagnetic probe, the user should be aware that signals from a single source of PD can be transmitted to other bars/coils in the winding. Thus, it is possible to measure PD from a single source at other slots of the machine.

It then becomes important to understand the winding connection in conjunction with the PD measurements to attempt to understand the transmission/reflection effects. Thus, care should be taken when interpreting measurements of this kind.

9.3 Quality control testing of individual stator coils/bars or windings

Although PD testing is sometimes performed for quality control purposes on individual stator coils/bars or completed windings, and PD testing can provide an insight into the condition and quality of the coils/bars or complete winding, there are still questions associated with the testing and acceptance criteria.

— *Conditioning:* Stator coils/bars when new are not fully cured and have generally not been exposed to voltage for any given time. It is known that under voltage application, the PD within many voids in the stator insulation will become less intense after a period of time. Conditioning issues are discussed in more detail in 10.2.4 and 10.3.

— *Lack of correlation to other tests:* Some work has been done to examine the correlation of PD readings made on new bars to other tests performed on the same samples. At present, there is debate as to whether a correlation exists. Work performed to date shows that in some instances, there appears to be a correlation, and in some other instances, no correlation exists (see McDermid et al. [B176]). The correlation may be affected also by measurement bandwidth, attenuation, and noise considerations.

— *Specifying limits:* Although PD measurements on single bars/coils or installed windings in motors or generators can provide information on the quality of the insulation, many variables involve the testing protocol and specifics of the insulation system that complicate setting limits for quality control purposes. Customers requesting such tests need to be aware of many issues, including coupling and calibration methods, characteristics of instrumentation, test voltage, connection arrangement, test temperature, integrated quantities, and (often novel or proprietary) insulation materials and machine design. Because of variations in PD detection equipment and high-voltage insulation systems, any quality control specification should be developed in concert with the manufacturer of the winding. Some criteria are based on the mean and standard deviation of PD quantities. The overall merits of this type of testing are yet to be proved, but this area is believed to be the source of continued work in the years to come.

— *Quality control for external discharges;* One area where detection of PD is effectively used is for the quality control of external discharges on individual bars/coils, stator models and complete stators. In such cases the detection is made optically during a blackout test or by using a corona imaging instrument. Here a direct line of sight is necessary. More details about this test can be found in IEEE Std 1799.

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10. Test procedures

A well-developed PD test procedure is imperative to obtain useful results.

10.1 On-line test procedures

One of the most important aspects of PD measurements is the recording of machine operating conditions while data are being accumulated. The condition of a machine and its associated electrical system is often critical in future data analysis and determination of PD sources. Available data are those provided by the nameplate and the operating metering/monitoring.

10.1.1 Nameplate data

The following information should be available to those persons analyzing the test data:

- Manufacturer
- Serial number or shop order number
- Rated kilowatts or horsepower
- Rated speed
- Frequency
- Maximum continuous overload rating (e.g., 110%)
- Rated terminal voltage
- Rated line current
- Rated power factor
- Rated gas pressure at maximum kilowatts (e.g., if hydrogen-filled)
- Rated field current and voltage (if synchronous machine)
- Type and rating of exciter for field
- Rated temperature rise of stator winding by RTD
- Date of installation or last stator rewind and by whom
- Stator insulation type (e.g., asphalt-mica, epoxy mica)
- Winding configuration

10.1.2 Operating parameters

The following data in **bold type** needs to be recorded each time a test is made, whereas the remaining information should be available if required by those persons analyzing the data.

- **Load in kilowatts or megawatts**

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- **Reactive load, in kilovars or megavars, and polarity**
- **Stator voltage, line-to-line**
- **Stator current, per phase**
- **Stator RTD temperature, maximum and minimum**
- **Field current and voltage, if available**
- **Gas pressure, if hydrogen filled**
- **Barometric pressure, if air cooled and operating above 1000 m**
- **Humidity and temperature of cooling air, at intake**
- **Operating mode for test: generating, motoring, speed-no-load**
- **Length of time that the load has been constant**
- Number of operating hours
- Number of starts
- Duty: peaking, base load
- Machine vibration level at some reference point, bearing, or turbine headcover

The operation of adjacent machines and equipment should also be noted, particularly if connected to the same high-voltage bus.

Many types of discharge activity are influenced by stator current, stator voltage, winding temperature, operation as motor or generator, gas pressure, and humidity. Isolating those parameters that affect discharge activity is improved when all conditions are accurately listed for each set of data. In order to be able to compare discharge data from one test to the next, it is imperative that the stator voltage be the same within ± 2%.

10.1.3 Example of an on-line test procedure for hydrogenerators and gas turbine generators

For each test, records are made of the stator terminal voltage, field current, megawatts, megavars, and stator RTD temperatures. The measurements often involve the following steps:

- *Load relationship:* Initially, a set of PD readings is taken under conditions of full load, at a stable temperature. Full-temperature stability may require 5 h or 6 h at this load for hydrogenerators equipped with shrouds or air baffles and 8 h to 10 h for units without these features. The load is then reduced to as close to zero as rapidly as possible, and the measurements are repeated, starting with the couplers that showed the most PD activity at full load. The initial and final stator temperature are recorded.
- *Temperature effect:* The largest temperature change will be achieved by selecting a machine that has been shut down for many hours such that it is at room temperature. It is then started, synchronized, and loaded as rapidly as possible to full load followed immediately by a set of PD readings. Once the temperature stabilizes for the full load condition, the PD measurements are repeated.

An alternative method involves selecting a machine that is operating at full load and at a stable temperature. A set of PD readings is taken under these conditions. The load is then reduced to minimum as rapidly as possible, and the PD readings are repeated, beginning with the pair of couplers that is most likely

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to indicate the greatest temperature effect. Temperature measurements are made at the end of this series of measurement. After a period of at least 30 minutes at minimum load, the PD readings are repeated, together with temperature measurements.

Periodic on-line PD measurements are usually made once or twice a year to minimize the deterioration, which may go undetected between tests. Some users prefer spring and autumn when the ambient temperature will be similar, whereas others prefer winter and summer to obtain the maximum difference in temperature. If it is intended to compare the PD data for trending purposes, the operating conditions need to be the same within the following limits:

— Voltage ± 1.5% (e.g., ± 200 V in the case of a rated voltage of 13.8 kV)

— Winding temperature ± 5 ºC

— Load ± 10%

The humidity of the cooling air should be recorded. Surface PD (e.g., end winding) may be reduced at higher relative humidity (see Fenger and Stone [B116]).

10.1.4 Metering, protection, and safety aspects of on-line tests

In the case of on-line measurements, the test voltage supply is the machine and the power system. The permanent metering provides an indication of the operating conditions, and the protective relaying is assumed to be functional.

When the permanent sensing devices are installed in the stator winding or at its terminals, care needs to be taken that there is adequate grounding of the sheaths of the coaxial signal cables for high frequency as well as for the power frequency. This should include adequate power frequency grounding of the cable sheaths at the input to the detection instrumentation. These grounds must never be removed while the machine is in operation.

If the sensor is a capacitive coupler, the center conductor, of the associated coaxial signal cable needs to be grounded through a suitable resistor. For example, for an 80 pF coupler, the associated 50 Ω surge impedance cable is commonly terminated in a 1500 Ω resistor of adequate power rating for grounding purposes. There may also be a need for overvoltage protective devices to be permanently connected between the center conductor of the signal cable and the ground. Such devices must not degrade the shape of the PD pulses.

If the sensor is an RF current transformer, there must be adequate insulation between the sensor and the monitored conductor if the latter normally operates at high voltage or can develop a high voltage. If an RF current transformer is installed on a shielded high-voltage cable, the CT must not infringe on the stress control at the end of the cable. The sheath of this cable should be protected against overvoltages if the grounding of the sheath needs to be altered to accommodate the CT.

If portable sensors are being used for on-line PD measurements, adequate clearances must be maintained from energized and moving parts.

10.2 Off-line test procedures for complete windings

A number of aspects of off-line PD tests differ substantially from on-line measurements. One consideration is the need to disconnect the machine winding from all external buswork and auxiliary equipment, such as the excitation and voltage transformers and surge arresters and capacitors.

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Testing the complete winding at or above the normal line-to-ground operating voltage provides a useful diagnostic method for assessing winding integrity. It is particularly useful if comparison data are available to indicate trends in changes in such quantities as PDIV and PDEV, maximum PD pulse magnitude, and the changes in the maximum PD pulse magnitude as the voltage is raised and lowered. If all three phases are energized simultaneously, there will be no PD because of phase-to-phase electric stress in the end windings. Because of the calibration and pulse propagation issues discussed in Clause 8, it is important that comparisons be made using identical PD sensors and detection instrumentation. Always connect the test circuit in the same way if the intention is to compare test results.

Comparisons may be made as follows, in descending order of usefulness:

a) Comparisons made on the same machine, under similar conditions, over a period of time (typically, at the time of installation and during routine inspections and overhauls).

b) Comparisons among the windings of the three phases on a given machine at the same time.

c) Comparisons with other machine windings of the same rating and design.

d) Data on a large number of machine windings combined with engineering judgment.

Comparison c) and Comparison d) are not limited to off-line measurements.

10.2.1 Test voltage supplies, metering, protection, and safety issues

In the case of off-line measurements, there is a need for a test voltage supply that is capable of energizing the winding in question without overload. Such a test supply is often 50 Hz or 60 Hz; in which case, there will either be a large test transformer that is capable of supplying all of the volt-amperes required to energize the capacitance of the winding or some form of reactive compensation is used either in parallel or in series with the test source. In either case, the test supply should be PD free (e.g., < 10 pC) at the voltage at which it is to be used. Alternatively, a high-voltage low-pass filter can be used to satisfy this requirement.

As an alternative to supplying the substantial volt-amperes to energize the winding at 50 Hz or 60 Hz, very low frequency test equipment was developed (see Bhimani [B159]) that allows the winding to be energized at 0.1 Hz. As a result of work to compare the effect of 60 Hz and 0.1 Hz tests, IEEE Std 433 was first published for 0.1 Hz testing in 1974. Subsequently, work was done to develop PD test equipment for use with 0.1 Hz test voltages (see Miller and Black [B160]).

The waveform of the high voltage applied to the winding should be such that the ratio of the peak-to-peak voltage to root mean square (rms) voltage is equal to $2\sqrt{2}$ within ± 5%. Adjustment of the test voltage is commonly achieved using a variable autotransformer in the 50 Hz or 60 Hz case.

The 50 Hz or 60 Hz test voltage applied to the winding should be measured by means of a voltage transformer or a capacitive or suitable resistive voltage divider connected to a suitable indicating meter. The 0.1 Hz test voltage is measured using a divider. The voltage measuring equipment should be calibrated in terms of peak-to-peak voltage divided by $2\sqrt{2}$.

Test lead connections to the winding need to be securely attached. If a lead should become disconnected during the test, the test will be invalid and the winding will be left with a trapped charge that will be hazardous to personnel.

A suitable contactor and overcurrent relay should be provided that will reliably disconnect the mains supply in the event of a failure or flashover involving any part of the test circuit. This contactor should be supervised by a zero interlock on the variable autotransformer and a deadman switch for a safety watcher. Once electrical and mechanical clearances have been obtained and test connections made, distinctive rope, traffic cones, and signs are commonly used to restrict access to the winding under test. This is especially important in the case of large machines that may have many possible ways for personnel to come into

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contact with the winding. One person must have the responsibility for deciding when the test voltage is to be applied, and there must be consistent verbal and visual signals that everyone understands. At the completion of the test, a visible ground of adequate ampacity must be applied to the terminals of the windings or individual coils/bars before contact is made by personnel. Some of these issues are addressed in more detail in IEEE Std 510-1983. *Applicable corporate and regulatory safety requirements must also be met.*

In the case of the electromagnetic probe test, the person positioning the probe at the stator slots may be close to the winding under test. *Extreme caution must be observed if it is necessary for personnel to be close to an energized winding during an off-line test.* Some users require the use of rubber gloves by the person positioning the probe. If the indicating meter is attached to the probe, it must be adequately grounded. It is not advisable to make measurements of this type, with a person holding the probe, unless the end connections of the coils/bars are fully insulated. In the case of measurements with an acoustic or ultrasonic probe, some of the same issues must be taken into consideration. Some commercially available acoustic, or ultrasonic sensors are assembled within a fiberglass, reinforced plastic tube that provides some electrical isolation.

10.2.2 Test connections to the winding

The connections between the test voltage supply and the winding under test should be kept as short as possible, and high-voltage leads should be of sufficient diameter to not produce PD during the test. A measurement with the test specimen disconnected will determine whether the test supply is PD free. If the machine winding being tested has bushings, these surfaces should be clean and dry.

As the test voltages normally do not approach the hipot level, it is acceptable to connect the test voltage supply to either the line or to the neutral terminal of the winding under test, without shorting these two terminals together. Where the PD measurements are being made by means of a high-voltage coupling capacitor, this capacitor may be connected to the line terminal of the winding, and in one approach, the voltage supply may be connected to the neutral terminal, thus, allowing the winding to help attenuate any noise signals from the mains. The test can be repeated with the opposite connection to determine whether there is a difference between the PD activity near the line and near the neutral. In some cases, there may still be a need for a high frequency filter for the mains connection to the test supply to eliminate electrical noise from the power system.

A decision that often needs to be made is whether to test each circuit or each phase separately with all other circuits grounded. This has the effect of applying some electric stress to the phase-to-phase insulation. This may be important in the case of windings that have close phase-to-phase spacing in the endwinding area, or in the case of machines in which the endwindings have been subjected to contaminants. A second test with all circuits energized may assist in determining which PD is related to the phase-to-phase electric stress.

Some users of the electromagnetic probe test prefer to energize the entire stator winding simultaneously so that they can measure at each slot in a sequential manner.

10.2.3 Response checks on detection systems

When PD measurements are made, it is common to normalize the measuring system in terms of apparent charge at the winding terminal, to which the coupling capacitor is attached. This involves using a pulse of known voltage magnitude, having a rise time t_r (10% to 90% of peak value) that bears the following relationship to the upper frequency limit f_2 of the measuring system [IEC 60270 (2000-12)]:

$$t_r \leq (0.03/f_2) \tag{6}$$

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Independent of f_2, t_r shall be less than 60 ns. For unipolar repetitive pulses, the decay time of the voltage pulses should be large compared with the rise time or $1/f_1$ where f_1 is the lower frequency limit of the measuring system. A range of 100 μs to 1000 μs will usually be suitable. For bipolar pulse injection, the magnitude of the pulse needs to be quasi-stable for the time interval between consecutive pulses, and this time interval should be significantly longer than is the resolution time of the measuring system. The rise time of both voltage steps shall be equal.

The voltage pulse (V) is differentiated by a normalization capacitor with a capacitance (C_c) of < 10% that of the effective capacitance of the winding under test and much more than the stray capacitances. The resultant charge ($Q = C_cV$) is applied between the high-voltage terminal of the coupling capacitor and ground, as is shown in Figure 1 of ASTM D1868-07. It has been previously pointed out that the response of this detection system to actual PD in the machine winding is very much a function of the bandwidth of the system and the location of the PD site in the winding. However, such response checks are important for demonstrating that a particular detection system is responding in a repeatable fashion.

In the case of electromagnetic probe measurements with the peak pulse meter at 5 MHz, it is also important to demonstrate that the response of the detection system is unchanged from one occasion to the next. Two approaches have been used as follows:

1) A number of turns of wire are wound on a "U" shaped ferrite core, and a pulse of known magnitude is applied to this winding through a differentiating capacitor. The magnetic circuit is completed by the ferrite loop stick of the electromagnetic probe, which is attached to the peak pulse meter.
2) A pulse of known magnitude is applied through a differentiating capacitor at the input of the peak pulse meter, with the electromagnetic probe attached.

10.2.4 Application of test voltages

The PD measurements may be made one phase (or circuit) at a time with all other circuits grounded. Alternatively all phases may be energized simultaneously so as to exclude the phase-to-phase insulation.

In the case of PD measurements made from a coupling capacitor at the machine terminal, it is common to proceed according to Method A or Method B:

Method A:

a) Raise the voltage at a rate in accordance with the recommendations of IEEE Std 4, and determine PDIV.
b) Condition the winding for 1 minute at a minimum of 65% of 1000 V plus twice the rated phase-to-phase voltage of the machine (2E + 1).
c) Measure the magnitude of the PD pulses as the voltage is lowered from the conditioning level. The voltage of PD measurement may include a voltage higher than rated phase-to-phase voltage, the rated phase-to-phase voltage, and the rated phase-to-ground voltage. A detector having an oscilloscopic display can be used for the PD measurement. Some may prefer to determine the pulse height distribution or phase resolved signature at the same voltages.
d) Determine PDEV.

Method B:

a) Condition the winding for a minimum of 5 minutes or up to 15 minutes with the maximum voltage that will be used for the partial discharge measurements. This could be the rated phase-to-ground voltage of the winding, or the rated phase-to-phase voltage. Following the conditioning lower the voltage to zero and commence the partial discharge measurements.

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b) Raise the voltage at a rate in accordance with the recommendations of IEEE Std 4, and determine PDIV.

c) Measure the magnitude of the PD pulses at the inception level (e.g., with a detector having an oscilloscopic display), and record any changes in these magnitudes as the voltage is increased up to the rated phase-to-ground voltage, the rated phase-to-phase voltage and to higher voltages, as agreed. Some may prefer to determine the pulse height distribution or phase resolved signature at these same voltages.

d) Determine PDEV.

In the case of electromagnetic probe tests, it is common to make the measurements at the rated phase-to ground voltage of the machine. However, if relatively high PD readings are obtained, measurements may be made at lower voltages to determine the expected PD activity at operating voltage for particular coils/bars in the winding.

Some users of the electromagnetic probe test prefer to condition the winding at the selected test voltage for a period of time up to 1 hour before making any measurements. Especially in the case of some thermoplastic windings, this may result in a substantial reduction in PD activity. Others do not observe a conditioning period but record the sequence in which the measurements were made.

10.2.5 Time intervals between routine tests

Appropriate time intervals between routine off-line PD tests will vary depending on the following factors:

— Opportunity to test.

— Experience with the particular insulation system.

— Duty to which the machine is exposed (peaking/base load).

— Whether on-line PD tests are made.

Measurements should be made often enough so that significant deterioration will be detected before major damage has occurred.

10.3 Procedures for pulse-type PD tests on individual coils and bars

Many of the requirements for pulse-type PD tests on individual coils and bars are similar to those for PD tests on complete windings. A dummy slot made from two continuous, metallic electrodes should be provided, having the same length as the real slot, and should be attached to the sides of the bar by means of clamps. The stress control coating on the end arms of the coil/bar needs to be fully functional, and any guard electrodes applied during power-factor tip-up tests should be disconnected and removed. (It is not adequate to simply disconnect the guard electrodes and allow them to “float” electrostatically.)

PD measurements can be made using a coupling capacitor at the terminal of the coil or bar as suggested in Table 3. It is common to proceed according to Method A or Method B:

Method A:

a) Raise the voltage at a rate in accordance with the recommendations of IEEE Std 4, and determine PDIV.

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b) Condition the coil or bar for 1 minute at a minimum of 1000 V plus twice the rated phase-to-phase voltage of the machine (2E + 1).

c) Measure the magnitude of the PD pulses as the voltage is lowered from the conditioning level. The voltage of PD measurement may include a voltage higher than rated phase-to-phase voltage, the rated phase-to-phase voltage, and the rated phase-to-ground voltage. A detector having an oscilloscopic display can be used for the PD measurement. Some may prefer to determine the pulse height distribution or phase resolved signature at the same voltages.

d) Determine PDEV.

Method B:

a) Condition the coil or bar for about 5 minutes with the maximum voltage that will be used for the partial discharge measurements. This could be the rated phase-to-ground voltage of the winding, the rated phase-to-phase voltage, or a higher voltage. Following the conditioning lower the voltage to zero and commence the partial discharge measurements.

b) Raise the voltage at a rate in accordance with the recommendations of IEEE Std 4, and determine PDIV.

c) Measure the magnitude of the PD pulses at the inception level (e.g., with a detector having an oscilloscopic display), and record any changes in these magnitudes as the voltage is increased up to the rated phase-to-ground voltage, the rated phase-to-phase voltage and to higher voltages, as agreed. Some may prefer to determine the pulse height distribution or phase resolved signature at these same voltages.

d) Determine PDEV.

When the detection circuit outlined in Case 1 of Table 3 is used, the measurements are in the frequency range of 100 kHz to 500 kHz. This detection circuit can be expected to respond to all sources of PD pulses. Direct comparisons can be made in the values of PDIV, PDEV and Q_m. For individual stator coils and bars measured in the above indicated frequency range the magnitude of the PD should be reported in apparent charge (pC) according to the procedure in IEC 60270 or ASTM D1868.

Some employ the detection circuit described in Case 3 of Table 3. This involves measurements at frequencies above 8 MHz to obtain a detection system with reduced sensitivity to external discharges involving the coatings of the stator coil or bar, but acceptable response to the discharges in internal voids and delaminations. In order to obtain repeatable results, it is vital that the high-frequency grounding be referenced to the dummy slot using short connections.[14] Response checks are made possible by the use of a coil or bar with a small calibration capacitor with low inductance attached to the copper in the slot section, as close as possible to the measuring terminal. In the case of coils, there is a significant difference in response between having the terminals shorted or unshorted. For these tests, it is common to measure at the rated phase-to-ground voltage. Alternatively, higher voltages have been used because sometimes this reveals internal discharge activity that is not apparent at normal operating voltage.

If it is determined that a particular coil, or bar has significant PD, it may be desirable to attempt to pinpoint the site(s). A black-out test, or use of a corona imaging instrument, may be effective in this application when the PD involves the external coatings of the coil or bar. If this is not successful, the use, with appropriate safety precautions, of the electromagnetic probe, a capacitive probe, or an ultrasonic probe may reveal the location of the PD activity.

[14] A small 80 pF epoxy-mica coupling capacitor facilitates the physical optimization of the test circuit, and when terminated in 50 Ω, it provides the desired bandwidth.

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11. Interpretation of PD test results

Interpretation of the test results is the final and sometimes the most important step in making PD measurements (see Kurtz and Lyles [B99], Lyles et al. [B103]). It is necessary to decide whether there are indications of a defect and if so, what is the probable nature of this condition. If a defect is apparent, it is appropriate to determine what supplementary tests and inspections should be made before planning corrective action.

Because the results of PD measurements using electrical detection techniques are most readily quantified, the interpretation of these results will be discussed here.

For ac electric machinery, the following three types of PD activity are of interest:

a) Discharges in voids or delaminations within the insulation, including those adjacent to the high voltage conductor.

b) Discharges occurring between the surface of the coil/bar and the stator core, commonly known as slot discharge, which may involve looseness of coils/bars.

c) Discharges in the end-winding area and circuit ring bus.

It is important to be able to differentiate between these sources of PD to properly assess the condition of any machine winding. It needs to be kept in mind that some PD activity can be expected from machine windings and from coils and bars.

The results of PD measurements can be summarized in a number of forms, depending on the particular measuring technique selected. Factors to be considered when analyzing these results are as follows.

11.1 Magnitude and polarity of maximum PD pulses

It is difficult to define appropriate maximum allowable PD levels because this is frequently a characteristic of the particular insulation system and the external coatings. In the case of measurements at the terminals, which are frequently in terms of millivolts at the detector input, or apparent charge in picocoulombs, the detection system bandwidth and attenuation characteristics of complete windings have a profound effect on the PD magnitudes that are measured. However, by establishing records of many tests on particular insulation systems and winding configurations, by means of a common detection system, unusually high PD magnitudes can be identified. Other tests and inspections are then required to establish the significance of these PD levels. Statistical distributions of Q_m have been published (see Bélec [B84], Stone and Warren [B112], Maughan [B104]), that are relevant for 80 pF sensors on the stator terminals with instrumentation in the VHF range that can be used for comparison purposes.

However, in relative terms, it is possible to make the following general remarks for off-line tests and on-line tests except where the dominant PD is occurring phase-to-phase in the end winding:

a) When positive polarity PD pulses (i.e., pulses mainly in the negative semi-cycle of the system voltage waveform) predominate, in magnitude, the source of the PD likely involves the external semiconducting coating on the slot section or the stress control coating of the coil/bar (see Stone et al. [B110]). In the case of air-cooled machines, such discharges may be accompanied by the production of ozone. If the stator coils or bars become loose in the slot, the positive polarity PD pulses can be expected to have at least twice the magnitude and ten times the repetition rate of the negative polarity pulses. This is not always the case for repetition rate (see Hudon et al. [B93]). The condition is more pronounced during on-line tests at high load.

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b) When negative polarity pulses (i.e., pulses mainly in the positive semi-cycle of the system voltage waveform) predominate, in magnitude the source of the PD can be expected to be at or near the copper strands, and may indicate an incomplete bond between the insulation and the copper. (see Stone and Warren [B112]). In the case of multi-turn coils, there may be an inadequate bond between the turn insulation and the groundwall.

When the condition described in list item b), above, is found involving individual coils and bars, a simple follow-up check is a "tap test" along the slot section of the coil/bar using a large coin or other metallic object to locate possible delaminations based on a hollow or clacking sound. An acoustical sensor has also been used in this application (see Zhu et al. [B68]). It may also be useful to repeat the PD test, varying the clamping pressure of the dummy slot, and record any changes in PD activity.

11.2 Electromagnetic probe readings

Measurement of PD at individual slots using the electromagnetic probe, tuned to 5 MHz, and the peak pulse meter results in readings in terms of "milliamps peak pulse." (Other similar peak pulse meters are scaled in "quasi-picocoulombs.") These readings are not greatly affected by the winding configuration, but they do reflect the particular insulation system and the condition of surface coatings and end arms. Although the comparison of results from similar machines is frequently the best way of establishing appropriate limiting values, some users have found by experience that the condition of coils/bars should be questioned when the peak pulse readings in "milliamps peak pulse" at operating voltage exceed the following values for service aged windings:

— Asphalt mica: 100 mA

— Polyester mica: 30 mA

— Epoxy mica: 20 mA

In the case of polyester-mica and epoxy-mica insulation systems, readings in excess of these limits frequently are caused by slot discharge, for which corrective measures are available. However, cases have also been reported involving polyester- and epoxy-bonded systems in which readings in excess of the above limits have been as a result of internal delamination. These limits apply to ferrite probes and peak pulse meters that have been constructed as described in Smith [B46], and where the ferrite probe is held in contact with the stator core, across the slot in which the coil or bar in question is installed. This probe can be used in conjunction with an acquisition system allowing for phase resolved representation as reported in Hudon et al. [B168]. This may enhance the source recognition capability. High probe readings (in excess of those above) can be investigated to establish the PDEV and establish from the winding diagram if these slots have bars/coils that could potentially discharge in service.

The number of probe readings per slot varies with the type and condition of the machine. In the case of hydrogenerators with the rotor in place some users make a single probe reading at one end of the slot. For machines where the rotor has been removed and the slot length is < 2 m, readings at the two ends and mid-slot may be sufficient. Other users have found it useful to scan the entire length of each slot with the probe and to record the maximum readings in four of five sections. With a sufficiently small probe this is often possible with the rotor in place.

11.3 Frequency spectrum analysis

Through measurements over a range of frequencies using a narrow-band radio noise meter, or a spectrum analyzer, it is possible to identify noise sources and some PD sources as a result of their characteristic frequencies. Knowing the lengths of the stator slot and the coil/bar end arms, it is possible to predict the

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frequencies at which various PD sources will predominate. Some examples of characteristic frequency ranges have been published (see Hudon and Bélec [B92]).

11.4 Integrated quantities

The use of integrated quantities is an attempt to represent all PD pulses per unit of time by a single number, sometimes with less weight being assigned to the pulses with a high repetition rate (Clause 3).

— NQN: The NQN (defined, together with weighting and limitations, in Clause 3) was developed for use with a PDA, which is applied to on-line measurements on hydro-generators (Table 1, Case 1). NQN values[15] for various types and conditions of windings in hydro-generators have been published in Lyles et al. [B103]; however, the usefulness of these values is in doubt.

11.5 Changes in PD magnitude

In the case of on-line measurements, changes in PD magnitude with respect to operating parameters or time can assist in identifying the source of PD and its relative severity. Some new windings may require several months of operation before stable "benchmark" readings are possible because of the continued cure of resin and slot contact effects.

— *Change with load:* When temperature and voltage are held constant, a change in the magnitude of the positive polarity pulses between light load and full load is indicative of a loose winding. Such signs merit early investigation because erosion of thermosetting groundwall insulation caused by the combination of slot discharge and electromechanically induced vibration can be rapid.

— *Change with temperature:* When load and voltage are held constant, a change in the magnitude of PD pulses, as the temperature increases or decreases, is usually indicative of discharges internal to the insulation. This is sometimes a sign of delamination between layers of tape. In this case, the positive and negative polarity PD pulses will be similar in magnitude and repetition rate, or possibly, the negative polarity pulses will predominate. Changes in temperature can also affect PD associated with the stress control coatings and slot PD (see Hudon et al. [B93]), but in this case, the positive polarity pulses predominate.

— *Change with humidity:* The humidity of the surrounding air (or gas) will have an effect on the magnitude and repetition rate of discharges involving the external surfaces. Higher PD has been attributed to the surfaces of the end arms at times when the humidity is low (see Fenger and Stone [B116]).

— *Change with gas pressure and type:* In the case of hydrogen-cooled machines, there may be an opportunity to make PD measurements in a different gas or at different pressures within guidelines of the OEM. These results can be useful in confirming the sources of PD. Surfaces discharges, especially, will be more prominent at low gas pressure. If the magnitude and PD pattern shape remains essentially the same at both pressures the source is not likely to be from the stator winding (i.e., inside the hydrogen seal). On the other hand, if the PD magnitudes increase with decreased hydrogen pressure, then the source is likely from the stator winding (see Sedding et al. [B9]).

— *Change with time (age):* When voltage, temperature, load, humidity, and gas pressure are the same and the magnitude of the PD pulses has increased with time the insulation is aging (delamination, abrasion, contamination, or tracking). Doubling of the Q_m in 6 months to 12 months may indicate

[15] These results apply for 80 pF couplers installed at the interface between the circuit ring bus and the line end coil/bar, and with a gain of 2 for the PDA-HTM instrument which is no longer manufactured, or 850 mV full scale divided into 16 magnitude windows for the PDA-IVTM instrument.

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rapid aging–insulation condition change, and further measurements are desirable to determine whether the PD is related to load or to temperature. If neither is the case, the characteristics outlined in 11.1 should be reviewed and the stator winding should be checked visually in detail or other diagnostic tests made to determine the possible cause. It should be pointed out that degradation will cause a modification of the insulation surface condition, but also of the metallic surface of the core in case of slot PD due to the oxidation by ozone. Such changes can have a significant impact on the PD activity as was reported in Lévesque [B100]. A stabilization or decline in Q_m may be the result of improved contact with the core, charge deposition in internal voids, etc. In some cases Q_m may be high in new windings and decline during the first several months of operation.

11.6 Pulse height and pulse phase analysis

Pulse height analysis allows the user of the test to record the number of pulses that fall within certain defined magnitude windows. In pulse phase analysis, the pulse height analysis, is carried out separately in a substantial number of phase windows over the alternating voltage cycle. This combination of features may greatly assist in identifying the conditions that are described in 11.1 and 11.5. Examples of PD patterns that have been associated with specific defects will be found in Annex C.

11.7 Time-frequency classification map

Digitized pulses can be classified according to pulse width and bandwidth. Noise signals usually have different characteristics than PD pulses. Examples of the time-frequency classification map will be found in Annex D.

11.8 Synchronous three channel/multi-spectral system

Multi-spectral PD measurements are based on pulse correlation by applying simultaneously three different band-pass filters (different center frequencies and bandwidth). Examples will be found in Annex E.

11.9 Difficulties in objective interpretation of PD data

Some of the difficulties encountered in the interpretation of PD measurements on ac electric machinery are as follows. There is some risk in relying solely upon pattern recognition without inspection and other confirming diagnostics.

11.9.1 Type of insulation system

PD activity varies with the type of insulation system. For example, a particular level of PD internal to an insulation system might be high (e.g., asphalt-bonded, large flake mica), but not indicative of impending failure, whereas in general for epoxy-bonded mica paper lower PD levels may be expected.

11.9.2 On-line measurements

The following are some difficulties related to on-line measurements encountered in the interpretation of PD measurements on ac electric machinery.

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a) When no means is provided for reliably eliminating noise, an experienced person is required to operate the test equipment and to distinguish between PD and noise.

b) In cases in which the measuring system works in a frequency range > 50 MHz (both UHF antennae and capacitive sensors) the PD measurement may be restricted to a small portion of the winding immediately adjacent to the sensor. In these cases, the test may be of a sampling nature, and thus, such sensors should be installed close to expected PD sources, usually close to the high-voltage end of the winding.

c) In cases in which the measuring system works in a low-frequency range < 500 kHz to provide a reliable overall view of the complete winding, corresponding adaptive noise cancellation has to be applied.

d) Attempts to rank test data using numerical techniques such as NQN need to be restricted to similar windings in which the couplers are installed in the same locations. In addition, ranking by NQN needs to be restricted to the use of only one sensitivity range of the detector that always has magnitude windows of the same width and number, unless appropriate mathematical corrections have been made for range changes.

e) In general, when PD on windings is measured at frequencies less than 50 MHz, as discussed in Clause 8, it is usually difficult to rank the severity of the PD activity (for example, Q_m) with a single measurement of the PD. Thus the condition of the winding must be determined based on the trend over time of the winding, or the PD measurement should only be compared to nearly identical windings to determine relative severity. However, some experience has shown that when PD is measured in the VHF or UHF frequency range, the winding behaves more like a surge impedance, and ranking of severity from a single measurement may be possible. For example, in Stone and Warren [B112], what constitutes a high PD reading depends on the voltage class, cooling gas pressure and sensor type.

11.9.3 Off-line measurements

The following are some difficulties related to off-line measurements encountered in the interpretation of PD measurements on ac electric machinery.

a) PD results in apparent charge at the terminals of windings can only be compared for identical winding designs and where the PD measuring system bandwidth is the same.

b) Electromagnetic probe readings do not distinguish between positive- and negative-polarity PD pulses, and thus, the PD cannot be attributed to slot discharge or internal delaminations without carrying out other tests.

c) Electromagnetic probe measurements may not reliably pinpoint the source of the PD.

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Annex A

(informative)

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NOTE—All items followed by a double asterisk (**) are available from the CEATI International Inc., 1010 Sherbrooke St. West, Suite 2500, Montréal, Québec, Canada H3A 2R7.

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Annex B

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Coupling capacitor type tests and routine tests

B.1 Introduction

PD sensors of the coupling capacitor type, specifically intended for on-line PD measurements, are usually installed in close proximity to the stator windings of generators and motors. If these capacitors fail, the motor or generator will trip with a consequent loss of production. Thus capacitive PD sensors need to be made especially reliable. Before coupling capacitors are installed on a motor or generator, the vendor should ensure a low risk of failure using both type tests (performed on at least one coupling capacitor) as well as routine tests (performed on every coupling capacitor that is installed on a machine).

B.2 Type tests

Type tests are performed on one or more typical examples of coupling capacitors after they are first manufactured, or after any significant change (such as change in dielectric materials or dimensions).

B.2.1 Voltage endurance

A voltage endurance test will be performed on at least one design of coupling capacitor to ensure that it will not degrade due to PD activity. The voltage endurance test will be performed at 2.17 times the rated phase to phase voltage of the coupler, and the coupler shall not fail in less than 400 hours in accordance with IEEE Std 1553 Schedule A. The coupler will be tested between 20 ºC and 30 ºC, since this temperature tends to produce the highest PD.

B.2.2 Tracking resistance

Since capacitive couplers may be subjected to partly conductive contamination, the insulating materials used on the surface of the couplers shall be tested for their ability to withstand electrical tracking. The ASTM D2303 inclined plane test method shall be used to evaluate tracking resistance. As per IEEE Std C37.20.2, the minimum average time to failure of five samples will be 300 minutes.

B.2.3 Direct voltage withstand test

A direct voltage will be applied to a typical coupling capacitor according to the method in IEEE Std 4. The applied voltage will be the 1.3 times the minimum acceptable direct-voltage withstand for switchgear of equivalent phase to phase voltage rating (E) according to IEEE Std C37.20.2. The 1.3 factor provides a safety margin.

B.2.4 Lightning impulse test

A 1.2 × 50 microsecond lightning impulse voltage will be applied to a typical coupling capacitor according to the method in IEEE Std 4. The applied voltage will be the 1.3 times the minimum acceptable lightning

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impulse withstand voltage for switchgear of equivalent phase to phase voltage rating (E) according to IEEE Std C37.20.2. The 1.3 factor provides a safety margin.

B.2.5 Dissipation factor

The dissipation factor, measured according to IEEE Std 4, will be performed as a function of coupling capacitor temperature. The test will be performed while the coupling capacitor is in an oven that is gradually raised from room temperature in 10 ºC steps until the stated maximum operating temperature of the coupling capacitor (typically 100 ºC or less). The duration at each temperature step is 30 minutes to allow temperature stabilization. The dissipation factor at any temperature will be stable and less than 0.5%.

B.2.6 Thermal cycling

To ensure that different components within the coupling capacitor do not crack due to extremes of temperature, one coupling capacitor shall be subjected to five thermal cycles between –30 ºC and the specified maximum operating temperature of the coupling capacitor. The capacitor will be held at the low and high temperatures for 30 minutes each cycle. There will be no change in the PDEV and dissipation factor between before and after the five thermal cycles. The thermal cycling test can also be used as a quality control test on a sampling basis, to ensure that all the materials are as specified.

B.3 Routine tests

Every coupling capacitor will be subject to the following tests shown in B.3.1, B.3.2, and B.3.3, as a minimum:

B.3.1 Capacitance and dissipation factor

Each capacitor will be subjected to a low voltage capacitance and dissipation factor test at 20 ºC to 30 ºC. The dissipation factor should be below 0.5%. The capacitance should be the normal specified capacitance, ± 5%.

B.3.2 PDEV test

Each capacitor shall be subjected to a partial discharge extinction voltage test at 20 ºC to 30 ºC, using the method in ASTM D1868 or IEC 60270. The coupling capacitor shall have a PDEV that exceeds twice the rated phase to ground rms voltage, with a minimum sensitivity of 2 pC.

B.3.3 Alternating voltage withstand test

Each coupling capacitor shall be tested with 50 Hz or 60 Hz alternating voltage to twice the rated phase to phase voltage plus 1 kV [i.e., (2E +1) kV] for 1 minute. For example, a capacitor rated 15 kVac, would receive an alternating voltage hipot test of 31 kV, rms.

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Annex C

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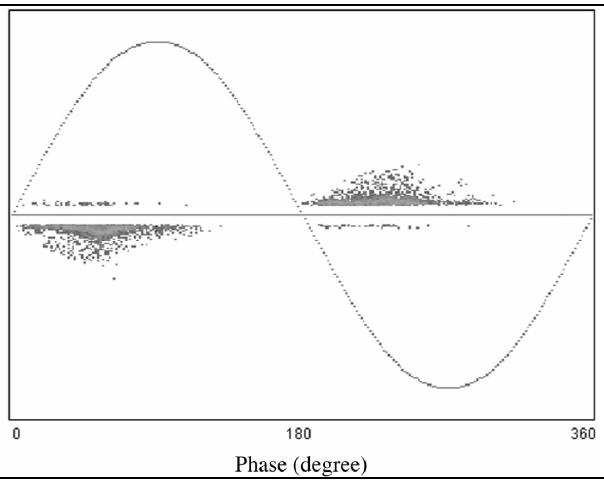
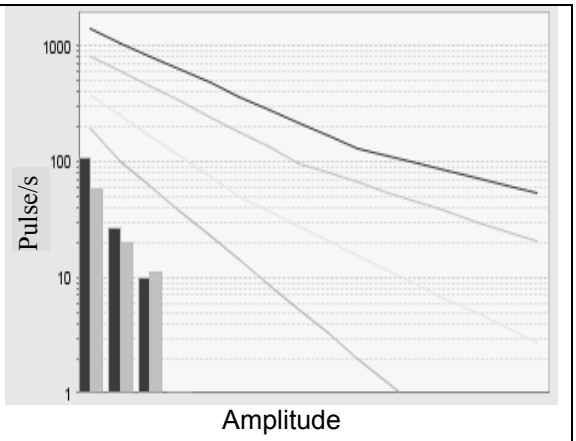
Typical PD pulse-phase patterns (examples)

C.1 Introduction

This annex presents examples of characteristic pulse-phase (phase-resolved) patterns and compares them with their 2D (rate as a function of amplitude) equivalent. In the 3D representation, pulse amplitude is plotted against the voltage phase angle. The third dimension is related to the pulse repetition rate and is given by gray scale shading. In both type of representation, discharge amplitude usually goes down with magnitude. The examples are for 13.8 kV stator bars insulated with resin-rich epoxy mica tape and equipped with a stress control coating on the end arms immediately adjacent to the slot. On actual machines in service when several sources of PD are present, it is never clear if the recorded pattern comes from the suspected source.



PD+ ≈ PD-, Amplitude: low to intermediate, rounded shape similar in each half cycle



PD+ ≈ PD-, Amplitude: low to intermediate

Figure C.1—Internal discharges

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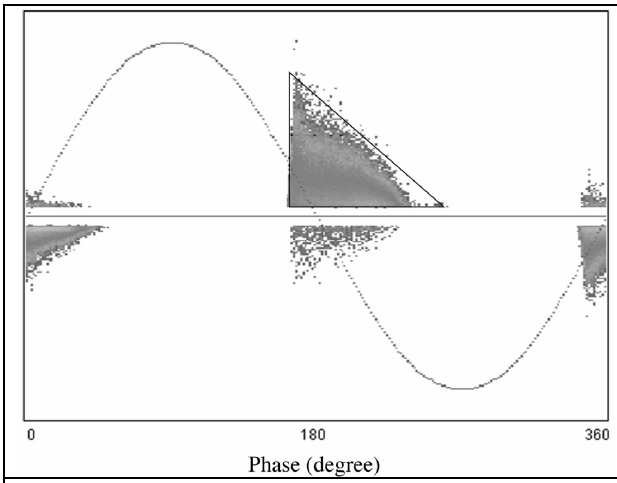	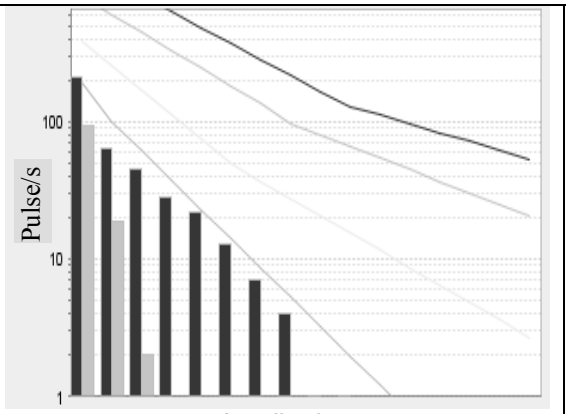
PD+ > PD-, The characteristic triangular shape during negative half cycle is indicative of slot discharges. Amplitude: intermediate	PD+ > PD-, 2D signature similar to external PD at the stress control coating, Amplitude: intermediate

Figure C.2—Slot discharges

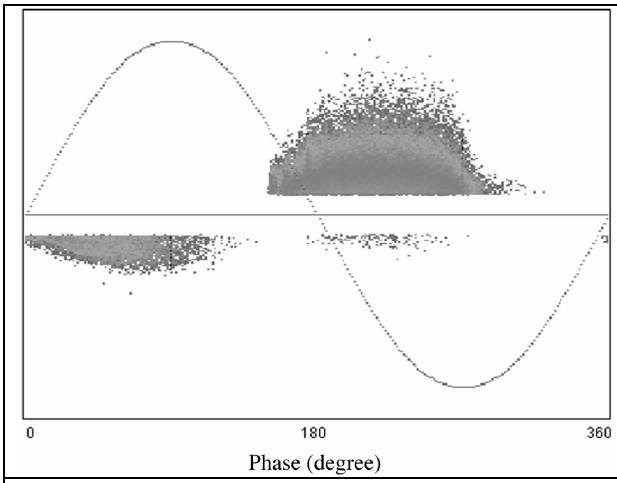	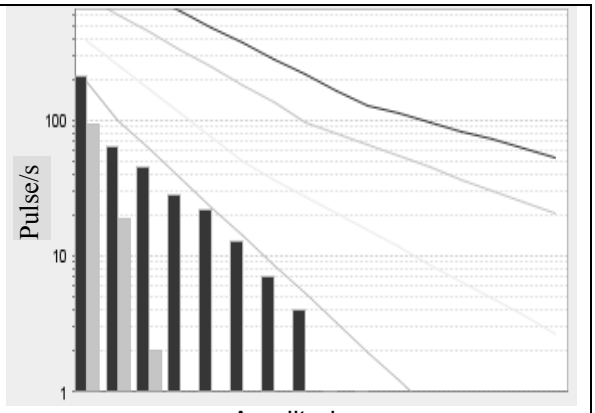
PD+ > PD-, the asymmetry in favor of discharge during the negative half cycle is generally more rounded than slot PD. Amplitude: intermediate to high	PD+ > PD-, 2D signature similar to slot PD, Amplitude: intermediate to high

Figure C.3—External PD at the stress control coating

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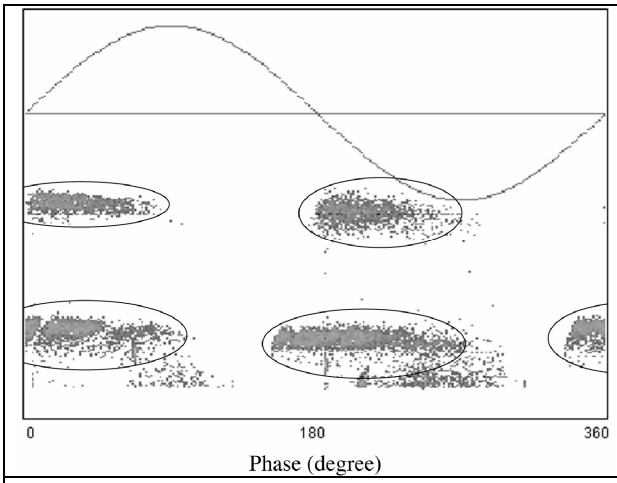	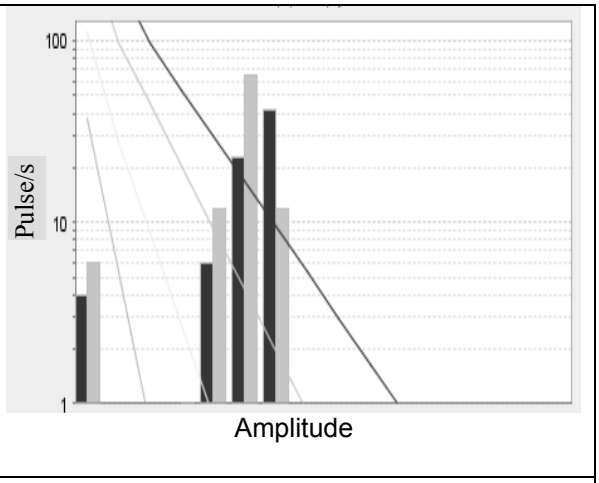
Generally, forms horizontal clouds. Amplitudes : average to high	PD + ≈ PD- (not always), non uniform decrease of rate vs amplitude, presence of hump at higher amplitudes. Amplitudes : average to high

Figure C.4—Gap discharges

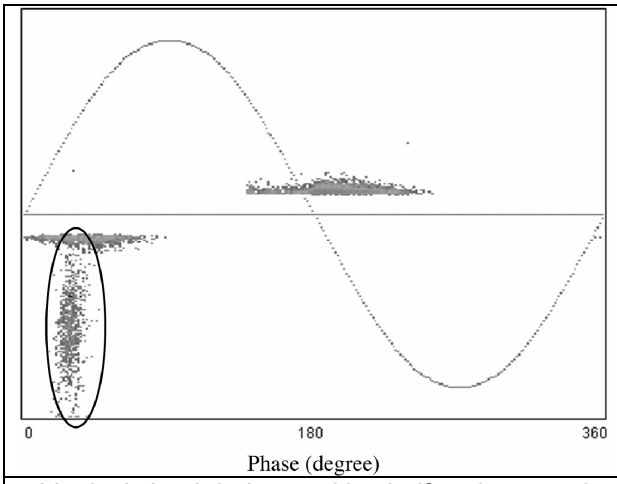	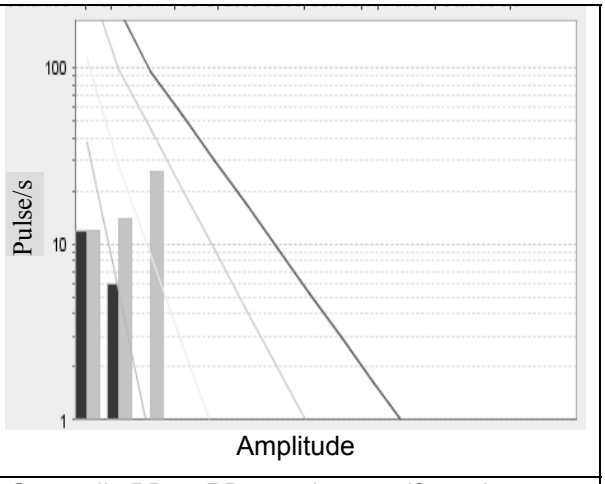
Vertical cloud during positive half cycle around 30 degrees to 40 degrees (some times also seen in both half cycles). Amplitude: very high.	Generally PD- > PD+, and non uniform decrease with amplitude. May be mistaken with Gap discharges. Amplitude: high

Figure C.5—Surface tracking

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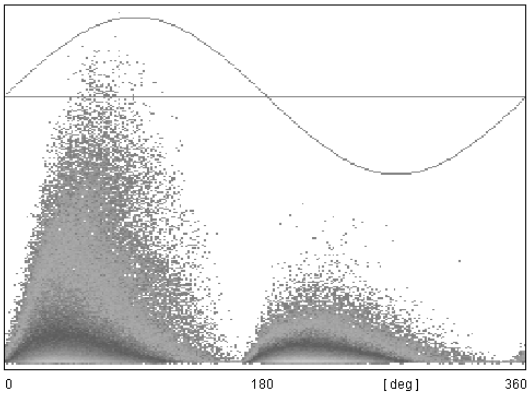	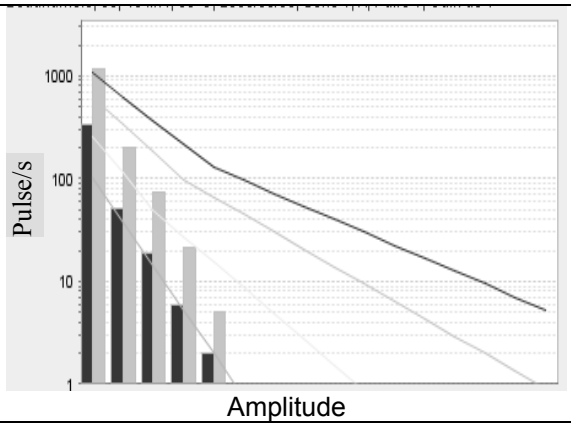
PD- > PD+, number of discharges usually low, with a larger rounded hump during the positive half cycle. Amplitude: low to intermediate	PD- > PD+, uniform decrease of rate vs amplitude. Amplitude: low to intermediate

Figure C.6—Delamination

Further information on this subject will be found in Hudon and Bélec [B92].

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Annex D

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Typical time-frequency classification map

D.1 Typical time-frequency classification map

Figure D.1 illustrates a typical time-frequency classification map.

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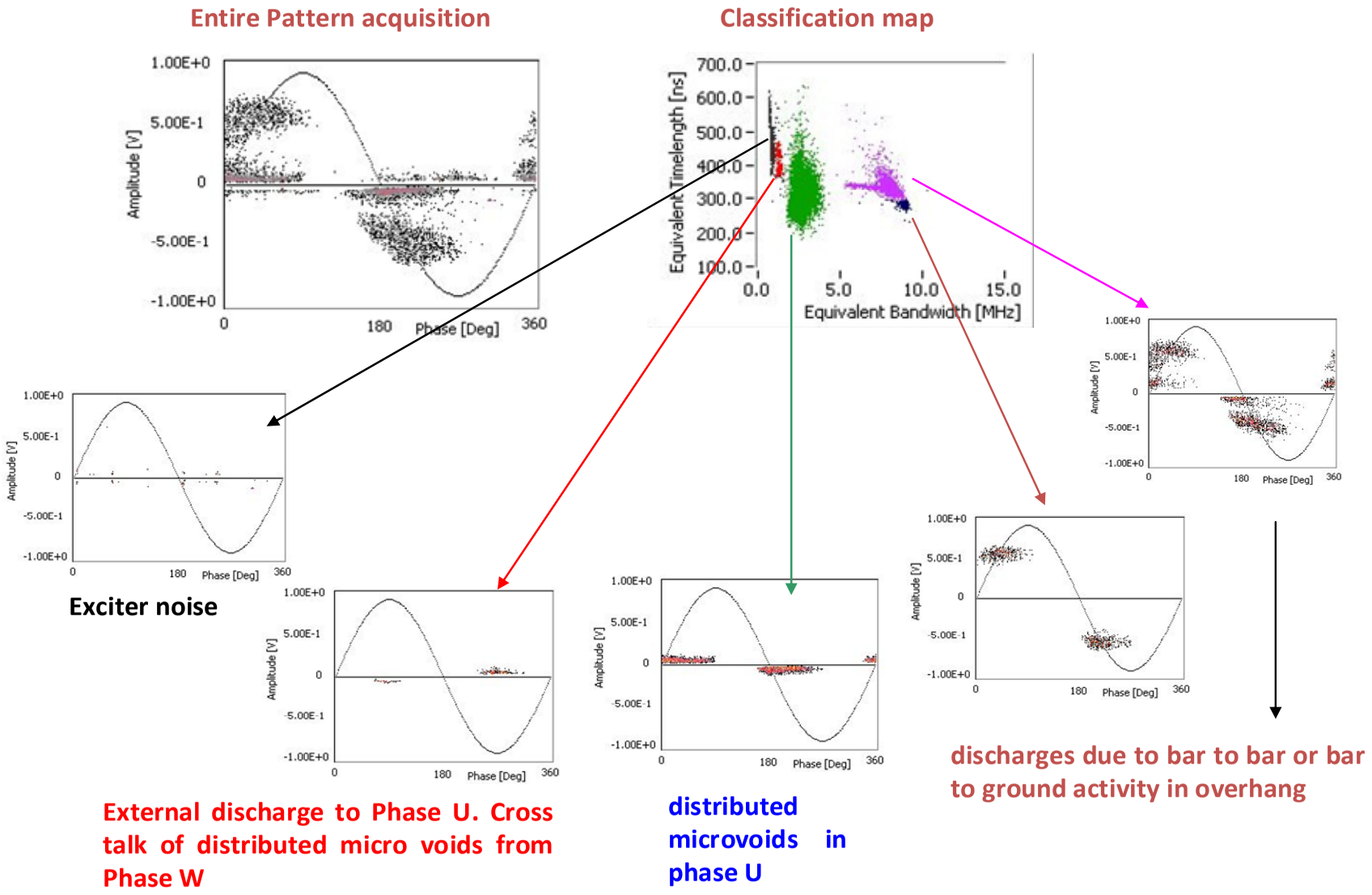

Figure D.1—Typical time-frequency classification map

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Annex E

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Synchronous three channel multi-spectral analyzer

E.1 Synchronous three channel multi-spectral analyzer

Figure E.1 illustrates a typical multi-spectral classification map (three channels).

Figure E.2 illustrates a typical multi-spectral classification map (single channel).

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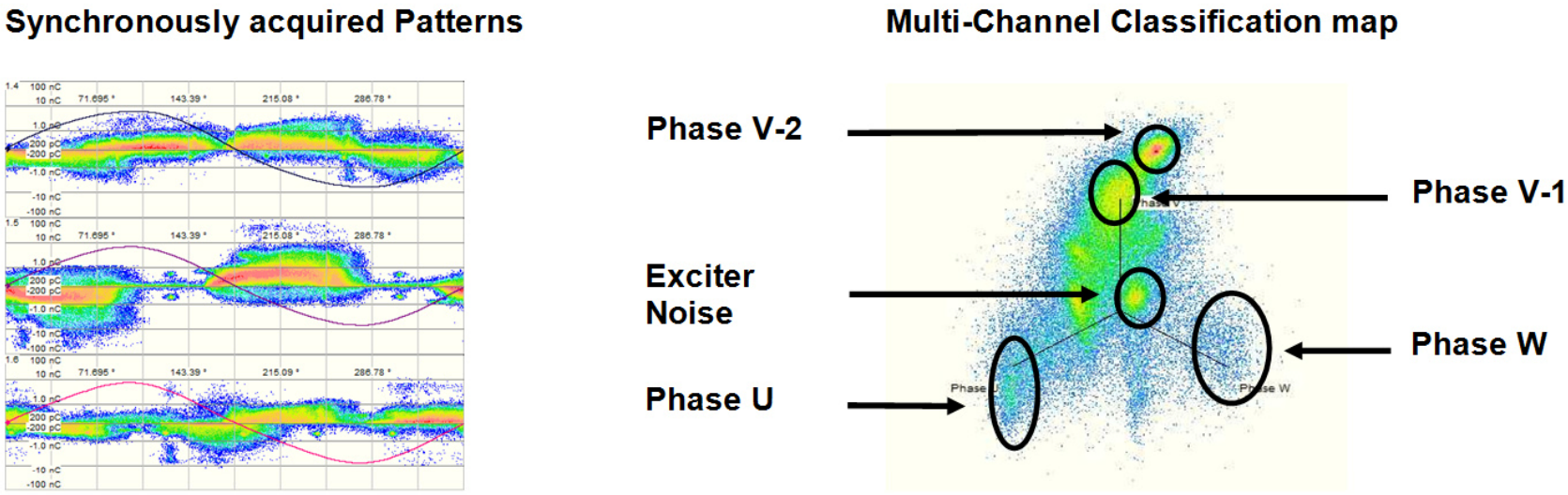

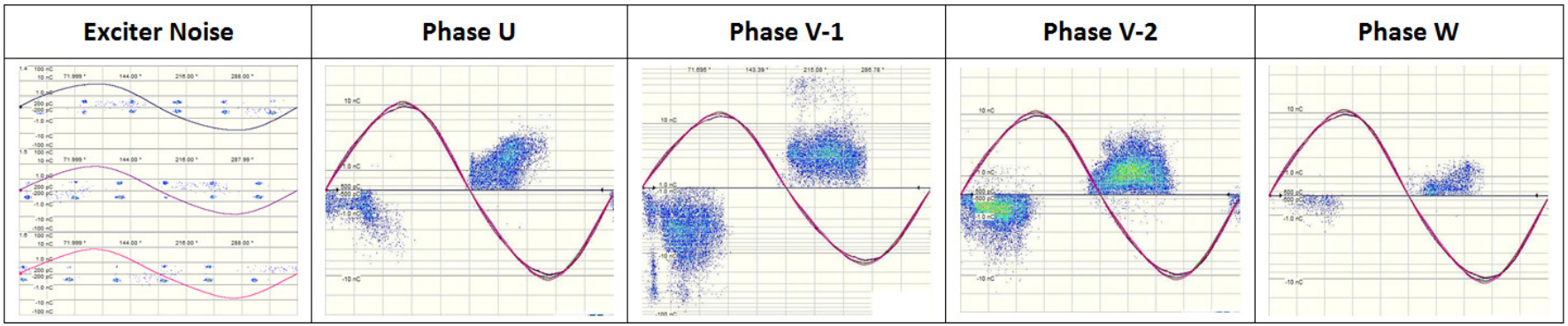

Figure E.1—Typical multi-spectral classification map (three channels)

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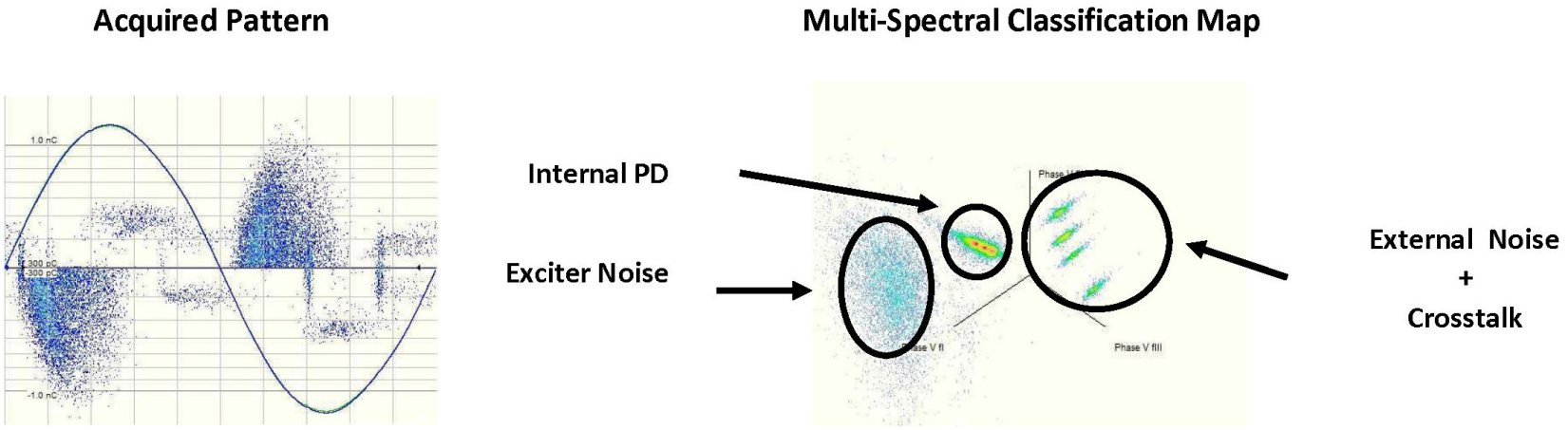

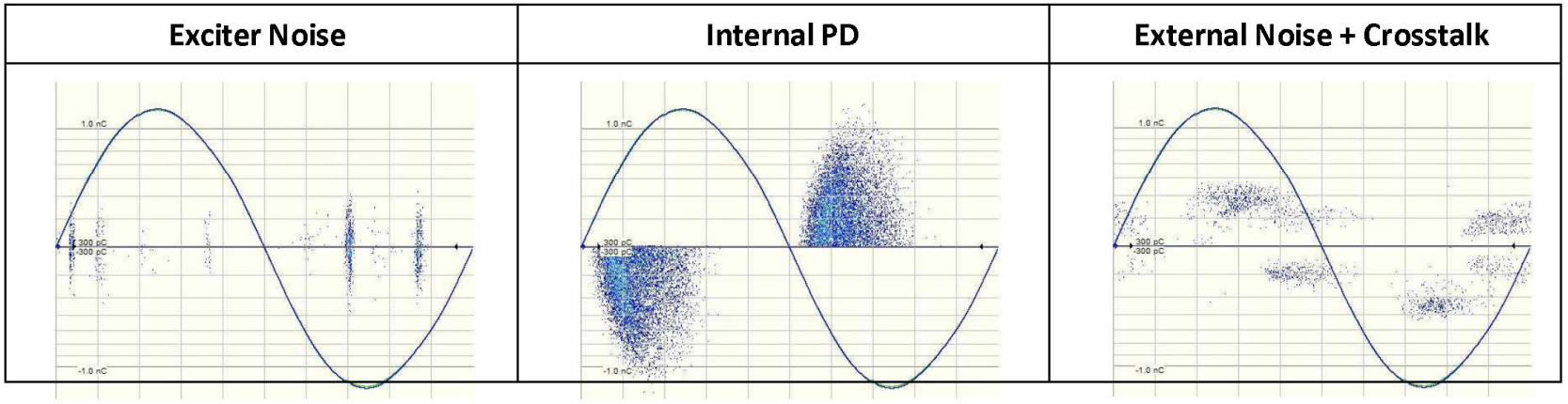

Figure E.2—Typical multi-spectral classification map (single channel)

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Annex F

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Electrical pulse and RF radiation sensing systems in limited use

The following sensing systems have been used in the past but are in limited use today:

F.1 Rotor-mounted scanner PD sensor

The sensors can be mounted on the rotor of hydro-generators for continuous monitoring of PD activity in each stator coil. The PD signals must be transmitted off-rotor and correlated with slot position. Although the PD magnitude is quantifiable, the principal purpose is to statistically locate PD activity within the stator winding structure. *Although no longer manufactured, a number of rotor-mounted scanners are still in use.*

F.2 Capacitive probes

Capacitive probes are usually custom-designed sensors that consist of a single plate, usually brass, which is connected to a length of coaxial cable. The PD signal is electrostatically coupled to the sensor. The high voltage conductor forms the second plate of the capacitor. The actual value of the capacitor depends on the dimensions of the single plate and the degree of coupling to the component being measured. It is only used to make spot measurements on a coil or a lead. The component being measured has to be energized, and the sensor is scanned over the component to measure its PD. The frequency response depends on the sensor capacitance and the input impedance of the instrumentation, which is coupled to the sensor.

F.3 Machine frame and other ground circuit sensors

PD currents may flow on the inner surface of the machine frame. A machine frame sensor consists of a point probe that measures the voltage drop across a known distance between parts of the frame or between the frame and the bus duct housing. In the latter case, the sensor may require a blocking capacitor to avoid undesired 50 Hz or 60 Hz current flow between the machine frame and the housing of the bus duct. The typical sensor involves two magnetically held point probes that are attached to the frame. The two points are spaced at a controlled distance for all measurements, typically, with a 150 mm distance between them. Each point is connected into a differential amplifier that conditions the measured signal. The impedance of the sensor is very low, and it has a broad bandwidth. Measurements are made at high frequency to reduce the effect of noise (see Blokhintsev [B54], Aksenov et al. [B58]).

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Annex G

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Interpretive methods in limited use

The following interpretive method has been used in the past but is in limited use today:

G.1 Quadratic rate

The term *quadratic rate* (nQ^2/t), an integrated quantity, and its weighting are defined in Clause 3. Two measurements are made on a machine winding. The first is at 10 kHz using coupling capacitors of 0.1 μF (or sometimes 0.01 μF) and is sensitive to PD sites throughout the winding. The major user[19] of this test has established limiting values of nQ^2/t that are a function of the rated voltage of the machine. The unit of measurement is normalized by dividing by the winding capacitance and is expressed in decibels above $10^{-9}Q^2t^{-1}C_t^{-1}$, where

Q is the charge, in coulombs (C)

t is the time period, in seconds (s)

C_t is the capacitance of winding under test, in Farads (F)

A second measurement is made at 130 kHz using 250 pF coupling capacitors at the line end and the neutral end of the winding to obtain an indication as to the location of the major PD sources in the winding. As the PD measured is considered to be near the coupling capacitor, the measured quantity is not normalized by dividing by winding capacitance. The result is expressed in decibels above $10^{-16}Q^2t^{-1}$.

For individual coils and bars, the measurement is made at 10 kHz (or 30 kHz) using an 0.1 μF coupling capacitor. The quadratic rate is expressed in decibels above $10^{-9}Q^2t^{-1}C_t^{-1}$.

When the detection circuit outlined in Case 2 of Table 3 is used, the measurements are typically at 10 kHz or 30 kHz. This detection circuit can be expected to respond to all sources of PD pulses. The results are in terms of quadratic rate, which is an integrated quantity. Sometimes a gap is left in the conducting (semiconducting) coating near either end of the slot section to allow guard electrodes to be applied (see Case 2 of Table 3). This reduces the response to PD involving the end arms.

[19] Électricité de France

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