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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.

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

Introduction

(This introduction is not part of IEEE P1434, IEEE Guide to 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 form-wound 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.

Contents

1.	Overview	1
	1.1 Scope	1
	1.2 Purpose	1
	1.3 Limitations	1
2.	References	2
3.	Definitions	3
4.	The nature of PD in machine windings	7
	4.1 Sources of PD	7
	4.2 Forms of PD pulses	8
	4.3 Glow and pseudoglow discharges	8
	4.4 Peak amplitude variation of discharge pulses	9
	4.5 PD under short rise time and repetitive voltage pulses	9
5.	Overview of PD detection methods	9
	5.1 Electrical pulse sensing	10
	5.2 RF radiation sensing	10
	5.3 Power-factor tip-up	11
	5.4 Energy/integrated charge transfer	11
	5.5 Ozone detection	11
	5.6 Acoustic and ultrasonic detection	11
	5.7 Black-out test	11
6.	Electrical pulse and RF radiation sensing systems	12
	6.1 coupling capacitors	13
	6.2 RF current transformers	13
	6.3 Near-field antennae	14
	6.4 Machine frame and other ground circuit sensors	15
7.	Electrical pulse and RIV measuring instruments	15
	7.1 Oscilloscopes	16
	7.2 Spectrum analyzers	16
	7.3 Integrating current detectors	16
	7.4 Quasi-peak pulse meters and RIV meters	16
	7.5 Pulse height analyzers	17
	7.6 Pulse phase analyzers	17
	7.7 Feature extraction analyzers	17
8.	Pulse propagation in windings and calibration issues	17
	8.1 Pulse propagation	17
	8.2 Calibration into apparent charge	18
9.	On-line versus off-line testing	19
	9.1 On-line testing	19
	9.2 Off-line testing	20
	9.3 Quality control testing of individual stator coils/bars or windings	21
10.	Test procedures	22
	10.1 On-line test procedures	22
	10.2 Off-line test procedures for complete windings	24
	10.3 Procedures for pulse-type PD tests on individual coils and bars	27

11. Interpretation of PD test results 28
11.1 Magnitude and polarity of maximum PD pulses 29
11.2 Electromagnetic probe readings 29
11.3 Frequency spectrum analysis 30
11.4 Integrated quantities 30
11.5 Changes in PD magnitude 30
11.6 Pulse height and pulse phase analysis 31
11.7 Feature extraction for identification of noise 31
11.8 Difficulties in objective interpretation of PD data 31

Annex A (informative) 33
Typical PD pulse-phase patterns - examples 33
Feature extraction - examples 33

Annex B (informative) Bibliography 34

Table 1 On-line discharge measurements (typical systems) 45
Table 2 Off-line discharge measurements 51
Table 3 PD measurements on individual coils and bars 54

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

1. Overview

1.1 Scope

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

1.2 Purpose

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

1.3 Limitations

The users of this guide are cautioned that

— Many on-line PD measurements apply only to a small portion of the winding near the sensors.

— Although often more global in their coverage, off-line measurements are not the result of actual operating conditions.

— Different test methods can be expected to yield different results, and absolute limits are difficult to establish.

— Many of the PD measurements are relative in nature, and the effects of the test conditions during measurements can be profound. For direct comparison, it is very important that tests be conducted under similar conditions every time.

— No attempt is made to describe here all known or conceivable systems for measuring PD or all applications of the same.

— Measurement of PD cannot be expected to detect all of the problems to which an insulation system may be prone.

2. References

This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

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

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

IEC 60505 (2004-10), Evaluation and Qualification of Electrical Insulation Systems.[2]

IEC 60270 (2000-12), High-voltage test techniques - Partial Discharge Measurements.

IEC 60270 CORR1 (2001-10), Corrigendum 1 - High-voltage test techniques - Partial Discharge Measurements.

IEC/TS 60034-27 (2006-12), Rotating electrical machines - Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines

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

IEEE Std 4-1995, IEEE Standard Techniques for High Voltage Testing.[3]

IEEE Std 286-2000, IEEE Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation.

IEEE Std 433-2009, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery at Very Low Frequency.

IEEE Std 454-1973 (Reaff 1979), IEEE Recommended Practice for the Detection and Measurement of Partial Discharges (Corona) During Dielectric Tests.[4] (withdrawn)

IEEE Std 510-1983 (Reaff 1992), IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing. (withdrawn)

IEEE Std 943-1986 (Reaff 1992), IEEE Guide for Aging Mechanisms and Diagnostic Procedures in Evaluating Electrical Insulation Systems. (archived)

IEEE P1799, Draft Recommended Practice for Quality Control Testing of External Discharges on Form-Wound Coils, Roebel Bars, Vacuum Impregnated Stator Insulation and Fully Assembled Stator Windings

NEMA Std 107-1987 (Reaff 1993), Methods of Measurement of Radio Influence Voltage (RIV) of High-Voltage Apparatus. (rescinded) [5]

[1] ASTM publications are available from *ASTM International*, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).
[2] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
[3] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).
[4] IEEE Std 454-1973 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).
[6] NEMA Std 107-1987 has been rescinded; however copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 397-7956 (http://global.ihs.com/)

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions*[7] should be consulted for terms not defined in this clause. Other terms related to partial discharge (PD) measurements are defined in ASTM D1868-07.[8]

3.1 apparent charge: The apparent charge (*Q*) of an individual partial discharge (PD) is that charge which, if injected instantaneously between the terminals of the test object, would momentarily change the voltage between its terminals by the same amount as the partial discharge. The apparent charge is expressed in coulombs.

3.2 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.

$$I_t = \frac{Q_1 + Q_2 + \ldots + Q_n}{t_n - t_o} = \frac{\sum_{j=1}^{n} Q_j}{t_n - t_o}$$

where

I_t is average discharge current, A
t_o is starting time, s
t_n is completion time, s
Q_1 Q_2 Q_n are apparent charges transferred in a partial discharge pulse 1 through n, C.

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

3.4 conductive (semiconductive) slot coating: The partially conductive paint or tape layer in intimate contact with the groundwall insulation in the slot portion of the stator core. This coating ensures that there is little voltage between the surface of the coil or bar and the grounded stator core.

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

3.6 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 cathode-ray oscilloscope. The height of the vertical deflection can be related to the discharge magnitude.

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

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

3.9 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.

3.10 dissipation-factor tip-up (∆tanδ): The difference in the dissipation-factor measured at two designated voltages. *See also:* **power-factor tip-up**.

[7] *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/
[8] Information on references can be found in Clause 2.

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

3.12 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 [B5].

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

3.13.1 largest repeatedly occurring PD magnitude (Q_m): <u>The magnitude of the largest pulse with a repetition rate of 10 pulses per second as determined from a pulse height distribution.</u>

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

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

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

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

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

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.

3.18 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.

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

3.20 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.

3.21 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.

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

3.23 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.

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

where

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

3.24 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 frequency range of 10 kHz to 1 MHz, and the results obtained are a function of the bandwidth of the particular detection system.

3.25 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.

3.26 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 100% and 25% of the rated phase-to-ground voltage of the machine. NOTE—See IEEE Std 286-2000.

3.27 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 discharge.

3.28 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 $\geq$100 MHz. Such a pulse discharge may be readily detected at the terminals of the winding or component under by means of conventional pulse detectors, that are generally designed for PD measurements within the frequency band from 10 kHz to several megahertz.

3.29 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.

3.30 pulse phase 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.

3.31 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.

3.32 quadratic rate (D): 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 $(\text{coulombs})^2$ per second. This quantity assigns greater weight to the larger pulses.

$$D = (1/T)[Q_1^2 + Q_2^2 + \dots Q_m^2]$$

3.33 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.

3.34 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.

NOTE—See NEMA Std 107-1987.

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

3.3.5.1 repetitive voltage impulses: impulses that occur when switching of power electronic devices at a carrier or driven frequency

3.36 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 50 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.

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

3.38 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.

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

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

NOTE—See Johnson [B4] and Wilson [B6].

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

3.42 stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond the conductive (semiconductive) 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 conductive (semiconductive) coating to provide electrical contact between them.

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

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

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.

3.43.1 vibration sparking: significant magnetically induced current may flow in the semi-conducting coating of a stator coil or bar if the resistance of the coating is too low. In the presence of vibration the current may be interrupted resulting in sparking and erosion of the groundwall insulation. This may occur at any point between line and neutral.

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.

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 semiconductive 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 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 endwinding elements, and the spacing between components in the endwinding.

PD sites external to the stator winding may occur near improperly installed RTD 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 (Bartnikas and Novak [B3]). 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. Ultrawide-band 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 (Bartnikas and McMahon [B2]). Pseudoglow discharges exhibit features common to both pulseless glow and pulse-type discharges in that, although they exhibit a visually apparent glow, they, in fact, consist of very minute discharge pulses of long rise time, which evade detection by conventional PD detectors as do true pulseless glow-type discharges.

Bridge techniques need to be employed to properly measure and assess the extent of pulseless and pseudoglow discharge activity. Because these discharges are determined by their dissipated energy, the sensitivity of such measurements is low compared with conventional pulse detectors. Pseudoglow discharges represent a transitory state between pulse- and pulseless glow-type discharges. The latter develop under conditions in which cathode emission tends to occur over a large surface area, and the field, because of the greatly dispersed charged particles, is too weak to lead to discharge channel constriction, which constitutes a necessary condition for a pulse-type (spark) discharge to develop. In a pseudoglow discharge, a limited tendency exists to channel constriction, as is substantiated by the existence of the minute pulse, or spark-like breakdowns; i.e., as soon as the discharge pulse current amplitude exceeds a certain value, the spark discharge development is interrupted and extinguished by the current limiting characteristic of the overall circuit. In practice, epoxy surfaces that are exposed to PDs, upon which a sufficient amount of conductive degradation products are permitted to accumulate, for example, in a closed or nonvented cavity, are predisposed to undergo pseudoglow and pulseless glow discharge. However, it is a redeeming feature from the point of view of discharge detectability that in actual insulation systems, it is most uncommon for pseudoglow and pulseless discharges to occur by themselves, because the number and distribution of cavity and gap sizes and their geometries are such that all three types of discharge, namely, pseudoglow, pulseless, and pulse type, tend to occur simultaneously. Thus, in most practical cases, conventional PD pulses detectors detect the presence of PDs, but because of their lack of response to pseudoglow and pulseless discharges, they may not necessarily always measure all the PD activity in a given machine.

4.4 Peak amplitude variation of discharge pulses

For two discharge events of equal amplitude and different rise time, the resulting current pulse having the shorter rise time will be detected as the pulse with a higher apparent amplitude, because the pulse detector response improves with a decrease in rise time of the discharge pulses (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. Some discharges emanating from the surface within the slot are easily identifiable by reason of their inordinately high amplitudes. 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 would 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 voltages 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).

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. Note that in a typical coil, bar, or winding, there may be many hundreds of PD per second; thus, many hundreds of electrical pulses may be detected each second. The voltage pulse can be detected by means of high-voltage capacitors, which are normally connected to the phase terminal or elsewhere in the winding. The capacitor has a high impedance to the power frequency voltage, but appears as a low impedance to the high-frequency PD voltage pulses. Alternatively, a high-frequency current transformer can be installed on the lead that connects the neutral of the machine to the grounding impedance, on the phase leads or in other suitable locations to detect the pulse currents accompanying the PD. The output of the capacitors or the high-frequency current transformer are voltage or current pulses, respectively, which can be measured with an oscilloscope, spectrum analyzer, or pulse height analyzer. Variations of these methods can be used for on-line and off-line tests. Further details on the sensors and the measuring instruments for electrical pulse-sensing methods are provided in Clause 6 and Clause 7, whereas test procedures and interpretation are discussed in Clause 10 and Clause 11.

5.2 RF radiation sensing

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

5.3 Power-factor tip-up

Because each PD is accompanied by acoustic and RF emissions as well as light, it follows that each PD event absorbs a certain amount of energy. The energy dissipated in the PD pulse must therefore be supplied from the source of power frequency voltage, and it can be considered as an increase in the dielectric loss in the stator winding. Thus, an indirect means of measuring the total discharge activity in a coil or winding is to measure the dissipation factor or power factor of the insulation at low voltage (below the PD inception voltage) and at high voltage (where the presence of any PD will increase the dielectric losses). A large power-factor or dissipation-factor tip-up (i.e., the power factor at high voltage minus the power factor at low voltage) may be indicative of severe PD activity in the coil, bar, or winding. However, especially for coils or bars with lower tip-up a correlation between tip-up values and PD activity should not be expected (Gupta and Culbert [B101]). 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 286-2000 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, A and 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 (Dakin [B102]; Dakin and Malinaric [B103]) and application experience (Simons [B104]) 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 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. [B53].

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 Wilson [B54].

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. Alternatively, under conditions of reduced light, ultraviolet detection equipment may be used. In the case of installed windings, 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 coils/bars that are subject to phase-to-phase voltage, or supports associated with the circuit ring bus. 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. In order to locate some discharge sources, it will be necessary to be able to energize one phase at a time with the others grounded. A more complete treatment of this subject will be found in IEEE P1799.

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 6.3.3) and test methods are required to extend the upper frequency limit.

Typical electrical pulse sensors and associated detectors are listed in Table 1 for on-line measurements, Table 2 for off-line measurements on complete windings, and Table 3 for measurements on individual coils and bars. These are intended as examples only. Other systems of sensors and detectors are available that may be equally suitable for particular applications.

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, e.g. 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 in on-line monitoring applications should meet the following requirements:

- Withstand the impulse and 50 Hz or 60 Hz overpotential test voltages of the machine winding over the range of possible operating temperatures.
- Have a PDEV, for pulses >2 pC, higher than the phase-to-phase operating voltage of the machine over the range of possible operating temperatures.
- Have a sufficiently low dielectric loss to ensure that it will be free of signs of thermal runaway over the range of possible operating temperatures.
- 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.
- Meet the physical constraints and electrical clearance requirements of the location in which it is to be installed.

For on-line measurements, the selected capacitors have ranged from existing 0.25 μF surge capacitors to specially installed capacitors 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. 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 (McDermid and Bromley [B30]). 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.

A number of examples of capacitors used as coupling devices can be found in Table 1 through 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.[9] Most of the commercially available CTs are provided with a transfer curve describing its 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.

[9] A transfer impedance of around 5 Ω is recommended. The output impedance is typically 50 Ω.

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 10.1.2.)

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,[10] 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 than 5 MHz was in detecting PD activity. 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 can be determined. This sensor is used for off-line tests with the winding energized at the normal phase-to-neutral voltage, or at lower voltages.

6.3.2 Rotor-mounted scanner PD sensor

The sensors are mounted on the rotor of hydrogenerators for continuous monitoring of PD activity in each stator coil. Four sensors are employed; i.e., one at the top and bottom of adjacent north and south poles. The sensors are synchronously positioned in closest-possible proximity to each coil as it is sequentially subjected to maximum electric stress of positive and negative polarity. The sensors, which are mounted at the centerline of the pole tip, to accommodate reversible machines, consist of a planar electrode oriented to face the coils/bars it scans just outboard of the core edges. Each electrode-coil alignment forms a capacitive divider from coil to rotor causing a portion of any PD voltage signal propagating along a coil to appear on the electrode[11] and in the sensor's circuitry. The PD signals are 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. Few rotor-mounted scanners are still in use.

[10]Named for the Tennessee Valley Authority because of its involvement in the development of the probe, as is reported in Smith [B40].

[11]The electrode size and spacing to the subject coil results in a coupling capacitance of 0.2 pF, with a resulting impedance of 10 kΩ at 100 MHz

6.3.3 Stator slot couplers

The stator slot coupler (SSC) is a two-port stripline 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.

6.3.4 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.

6.3.5 Resistance temperature detectors

Resistance temperature detectors (RTDs) and associated leads have been used to detect PD [B48], [B48a], [B49]. If the PD is detected by means of the leads then the discharge activity cannot be attributed to a particular slot.

6.4 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 an 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 (Blokhintsev et al. [B48]; Aksenov et al. [B52]).

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.

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

[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.

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 technology, with a low-pass filter. In many commercial instruments, the upper cutoff frequency of the filter ranges from about 10 kHz to about 5 MHz. 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

The largest void within the insulation or significant site of slot discharge usually has the largest PD pulses associated with it. Thus, one way to determine the severity of damage involving a coil or winding is the use of a detector that responds primarily to the largest PD pulses. 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.

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 Qm, NQN, Quadratic Rate, etc. (Qm in this case is the value of the largest pulse with a repetition rate of 10 pps.) It is possible to correct for a scale change by converting the density plot to a cumulative plot by integration and redifferentiating 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.

This is in addition to the number and magnitude of the pulses. Thus, the phase-resolved PD data are three dimensional. Different instrument suppliers use different graphical representations to display the data. Each approach has its own merits, but all are just different ways of representing the same information. Such phase-resolved plots enable knowledgable people to confirm that the detected pulses are because of PD rather than because of electrical interference, such as static excitation pulses. In many ways, the pulse phase analysis is the digital summary of the information observed with an oscilloscope (7.1).

7.7 Feature extraction analyzers

In feature extraction analyzers each pulse shape is digitized. The data are displayed in terms of pulse width and bandwidth for the purpose of separating PD pulses internal to the insulation system from external noise sources.

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 IEC 60270 (2000-12), IEEE Std 454-1973, and ASTM D1868-07 specifically exclude, or caution against, the use of apparent charge when dealing with large inductive components, such as stator windings (Heller and Veverka [B9]; Rüdenberg [B17]; Sedding [B18]; Tavner and Jackson [B21]; Kurtz and Lyles [B72]).

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. 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.

Wide-band 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 (Kemp, Gupta, and Stone [B14]; Su, Chang, and Tychsen [B20]; Wilson, Jackson, and Wang [B23]; Wood et al. [B24]).

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 20–30 **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.

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 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 calibration will still only hold for a given machine and a given detection system.

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.

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.

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 pulsewidth. 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.

— *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 (Wilson, Jackson, and Wang [B23])], and an L/C ladder network at lower frequencies.[13] 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).

— If the rotor has been removed, it is possible to provide detailed readings of virtually the entire machine winding, gaining detailed data that are not possible on-line. (More limited PD readings

[13] As defined in *The IEEE Standards Dictionary: Glossary of Terms & Definitions*

can be obtained at each slot of most hydrogenerators with the rotor installed, and similar measurements are made on-line if the hydrogenerator has been equipped with a PD scanner on the rotor.)

— 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, this testing does not occur commonly within the industry at the present time. PD testing can provide an insight into the condition and quality of the coils/bars or complete winding, but there are problems associated with the testing at present.

— *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. 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.

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.

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.

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

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

— Reactive load, in kilovars, 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 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%.

10.1.1 Example of an on-line test procedure for hydrogenerators

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 8–10 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 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 min at minimum load, the PD readings are repeated, together with temperature measurements.

PD measurements are usually made at least 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 (voltage, temperature, load, humidity need to be the same.

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

In the case of on-line measurements, the test voltage supply is the machine. 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 500 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.

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.

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 (Bhimani [B113]) 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 developed for 0.1 Hz testing. Subsequently, work has been done to develop PD test equipment for use with 0.1 Hz test voltages (Miller and Black [B114]).

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 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 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 be observed.*

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. As 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 to 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)]:

$$t_r \leq (0.03/f_2)$$

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 is differentiated by a normalization capacitor with a capacitance of <10% that of the effective capacitance of the winding under test and much more than the stray capacitances. The resultant charge ($Q = CV$) 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:

a) 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.

b) 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

In the case of PD measurements made from a coupling capacitor at the machine terminals, it is common to proceed as follows:

a) Raise the voltage at a rate in accordance with the recommendations of IEEE Std 4-1995, and determine PDIV.

b) Measure the magnitude of the maximum 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 or to higher voltages, as agreed. Some may prefer to determine the pulse height distribution at these same voltages.

c) Follow measurements after the predetermined dwell time at the maximum test voltage. PD measurements are made as the voltage is lowered to the PDEV.

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 to 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 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.) A decision needs to be made as to whether to condition the coil or bar at the test voltage for any period of time before making the measurement.

When the detection circuit outlined in Case 1 of Table 3 is used, the measurements are in the frequency range of 10 kHz to 300 kHz. This detection circuit can be expected to respond to all sources of PD pulses.

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 Quadratric 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.

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 ceramic calibration capacitor 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, may be effective in this application in which 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.

11. Interpretation of PD test results

Interpretation of the test results is the final and sometimes the most important step in making PD measurements (Kurtz and Lyles [B72]; Lyles, Stone, and Kurtz [B74]). 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 endwinding 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.

[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.

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 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.

However, in relative terms, it is possible to make following general remarks:

a) When positive polarity PD pulses, which occur mainly during the negative semicycle 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. 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 condition is more pronounced during on-line tests at high load.

b) When negative polarity pulses, which occur mainly during the positive semicycle of the system voltage waveform, predominate, 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. 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) 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 to locate possible delaminations based on a hollow or clacking sound. 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:

— 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 [B40], 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.

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 frequencies at which various PD sources will predominate.

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 3.17) was developed for use with a PDA, which is applied to on-line measurements on hydrogenerators (Table 1, Case 1). NQN values[15] for various types and conditions of windings in hydrogenerators have been published in Lyles, Stone, and Kurtz [B74].

— *Quadratic rate:* The term "Quadratic Rate" (nQ^2/s) and its weighting are defined in 3.32. 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[16] of this test has established limiting values of nQ^2/s 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 $10^{-9}C^2s^{-1}F^{-1}$, where

C is the charge, in C

s is the time period, in s

F is the capacitance of winding under test, in 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 of winding capacitance. The result is expressed in decibels above $10^{-16}C^2s^{-1}$.

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 $10^{-9}C^2s^{-1}F^{-1}$.

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.

[15]These results apply for the case of 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-H™ instrument, or 850 mV full scale divided into 16 magnitude windows for the PDA-IV™ instrument.
[16]Électricité de France

— *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, 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.

— *Change with gas pressure and type:* In the case of non air-cooled machines, there may be an opportunity to make PD measurements in gas at different pressures. These results can be useful in confirming the sources of PD. Surfaces discharges, especially, will be more prominent at low gas pressure.

— *Change with time (age):* When voltage, temperature, load, humidity, and gas pressure are the same and the magnitude of the PD pulses has increased over a period of time, 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 to determine the possible cause of what may be aging.

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 A.

11.7 Feature extraction for identification of noise

Digitized pulses can be classified according to pulse width and bandwidth. Noise signals usually have different characteristics than PD pulses. Examples of feature extraction will be found in Annex A.

11.8 Difficulties in objective interpretation of PD data

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

11.8.1 Type of insulation system

Acceptable levels of PD activity vary with the type of insulation system. For example, a particular level of PD internal to an insulation system might be acceptable for asphalt-bonded, large flake mica, but hazardous for epoxy-bonded mica paper.

11.8.2 On-line measurements

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 high-frequency range >50 MHz to provide reliable cancellation of noise, 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 <5 MHz 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 Qm) 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 [B62a], what constitutes a high PD reading depends on the voltage class, cooling gas pressure and sensor type.

11.8.3 Off-line measurements

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.

Annex A

(informative)

Typical PD pulse-phase patterns

Examples

Feature extraction

Examples

Annex B

(informative)

Bibliography

NOTE—All bibliography 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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A.6.5 0.1 Hz measurements

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[B114] Miller, R., and Black, I. A., "Partial discharge measurements over the frequency range 0.1 Hz to 50 Hz," *IEEE Transactions on Electrical Insulation*, vol. EI-12, no. 3, pp. 127–135, June 1979.

[B115] Reynolds, P. H., and Manger, H. C., "Field tests of partial discharge in generators at very low frequency," *International Symposium on Generator Insulation Tests*, Toronto, Ontario, Canada, June 1980.**

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A.6.7 Initiation of PD by voltage surges

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A.6.8 Electromagnetic probe

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A.7 Quality control tests on individual stator coils and bars

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[B125] McDermid, W., and Bromley, J. C. "Relationship between partial discharge pulse height analysis and subsequent voltage endurance of stator bars and coils," *IEEE Transactions on Energy Conversion*, vol. 17 no. 4, pp. 721–731, Dec. 1992.

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

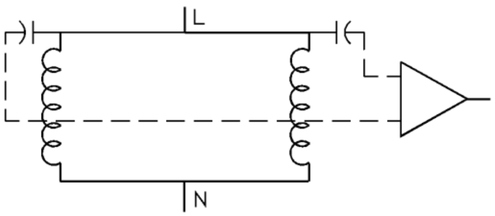
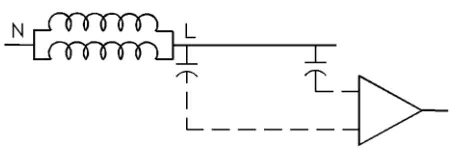
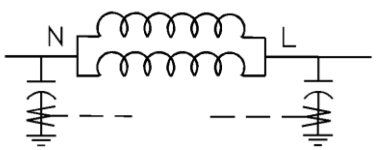
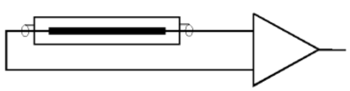
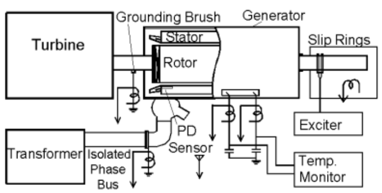
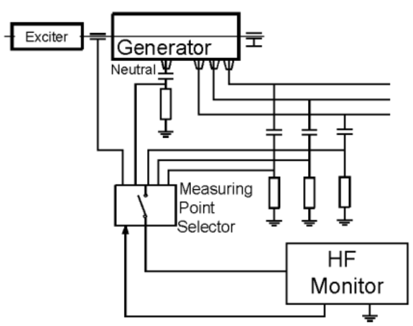
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
1	80 pF coupler terminated in 50 Ω and connected either: -Differentially with a minimum of one coupler near line end of each of two parallel circuits per phase.  - Directional with one coupler per phase at line terminal and a second at least 2 m distant on 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 - 150 MHz (system) or 40 - 350 MHz (system). For lower -3 dB point of around 7 MHz, See [B30] and [B33].	Noise rejection using 40 - 150 MHz instrumentation is achieved by a differential connection of a pair of couplers at the detector input. 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. Completely computerized system.	Serial and parallel ports, USB, Ethernet Differential: H [B28], {B32], [B72], [B74], [B80] Directional: T, S, H [B10], [B30], [B50], [B60], [B62], [B80]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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 - ≥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 [B68]
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 - >1 GHz (sensor) 20 - 800 MHz (detector).	Pulsewidths >20 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 [B46], [B47], [B60], [B62]

Applicability:
H = hydrogenerator
T = thermal generator
S = synchronous condenser
M = motor

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 - 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 [B49], [B48] (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 - 10 MHz	Based on time of arrival of pulses from sensors.		T [B94], [B86]

Applicability:
H = hydrogenerator
T = thermal generator
S = synchronous condenser
M = motor

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

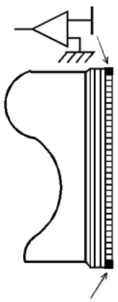
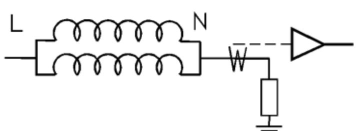
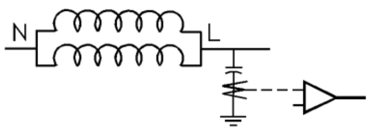
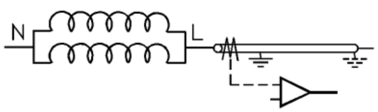
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
6	Capacitive sensor 3-5 cm from coil end arm; sensor at center line of field pole tip on hydrogenerator (1 north and 1 south pole, top and bottom). 	Peak responding, normal: one reading per sensor/slot Analysis mode: readings every 40 μs	20 - 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 [B45]
7	RF CT between generator neutral and grounding transformer. 	Radio noise meter readings in quasi-peak	20 kHz - 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 [B34], [B35], [B37], [B87], [B84]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

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 - 30 MHz (sensor) 20 - 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 - 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 [B6]

Applicability:
H = hydrogenerator
T = thermal generator
S = synchronous condenser
M = motor

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

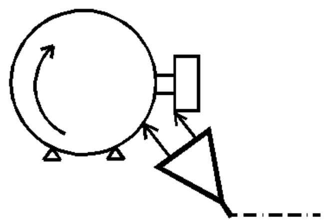
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
10	RF voltage between motor terminal box and adjacent machine frame. Similar approach to generators using first joint in IPB. 	Pulse height analyzer, manual window selection.	1 - 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 [B48], [B52]
11	Ozone monitor whose sensor measures chemical or physical properties of an air sample.	Analog or digital indicator. Calibrated n 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 [B53]
Applicability: H = hydrogenerator T = thermal generator S = synchronous condenser M = motor						

Table 2 - Off-line discharge measurements

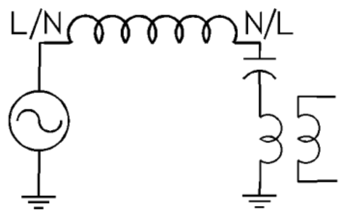
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
1	100 - 10 000 pF coupling capacitor and appropriate inductive matching unit. 	Oscilloscope display, supplemented by indicating meter responding in apparent charge, or sometimes 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 - 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. [B55], [B101], [B104], [B114]
2	10 nF coupling capacitor with matching unit	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 - ≥30 MHz		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).	M, T, S, H [B68]

Table 2 - Off-line discharge measurements (continued)

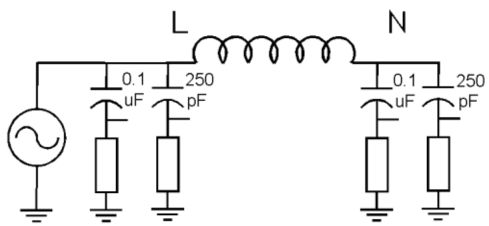
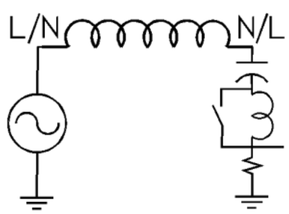
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
3	10 kHz measurement coupler is 0.1 μF or 10 nF 130 kHz measurement coupler is 250 pF  	Indicating meter displaying PD in terms of quadratic rate. The 10 kHz readings are normalized by dividing by the winding capacitance.	500 Hz - 21 kHz And 90 - 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.	[B111], [B109]
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 - 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. [B61]

Table 2 - Off-line discharge measurements (continued)

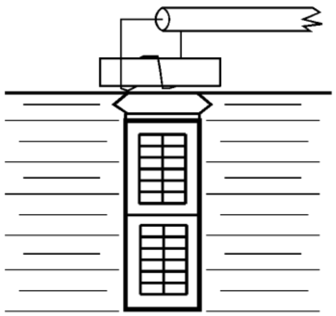
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
5	Electromagnetic probe bridging each slot in turn. 	Peak responding meter scaled in milliamps or quasi-picocoulombs	Probe tuned to 5 MHz	As a result of winding attenuation at 5 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-related 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 hydrogenerator rotor in place.	Indicating meter. [B2], [B39], [B40], [B120]
6	Acoustic probe held at slot under investigation	Indicating meter with arbitrary scale	36 kHz - 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. [B54]

Table 3 - PD measurements on individual coils and bars

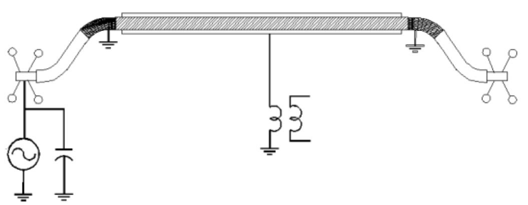
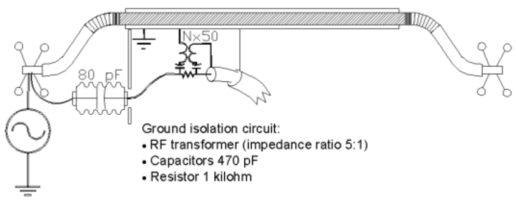
Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
1	100 - 10 000 pF coupling capacitor and appropriate inductive matching unit 	Oscilloscope display, supplemented by indicating meter responding in apparent charge, or sometimes average discharge current or quadratic rate. The amplified pulses may also be monitored using a pulse height analyzer.	10 - 300 kHz sometimes 2 MHz (adjustable)	In accordance with ASTM D1868-07.	Responds to all PD sites: internal, slot surface, end arm.	Most have oscilloscope display. Some also have indicating meter, RS232 interface, parallel & serial ports. [B55], [B101]
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 semi-con adjacent to stress control coating.	Indicating meter displaying PD in terms of quadratic rate.	500 Hz - 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.	[B111]

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

Case	Sensors	Detector/output	Frequency range	Noise rejection	Pros and cons	Data output/ format/ applicability/ bibliography
3	80 pF terminated in 50 Ω at analyzer.  	Pulse height analyzer with pulse-phase capability. Hard disk storage	8 - 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 [B125], [B126], [B128]
4	Acoustic probe	Indicating meter with arbitrary scale	36 - 44 kHz (typical range)		Good for pinpointing sites of high PD activity	Indicating meter and audible tone. [B54]
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.