RECENT DEVELOPMENTS IN IEEE AND IEC STANDARDS FOR OFF-LINE AND ON-LINE PARTIAL DISCHARGE TESTING OF MOTOR AND GENERATOR STATOR WINDINGS

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Abstract – Partial discharges (PD) are small electrical sparks that occur in voids within electrical insulation, or on the surface of motor and generator stator winding coils. Offline and online PD testing has become a widely used tool for in-factory quality acceptance and a baseline performance evaluation of new groundwall insulation in stator windings rated 6 kV and above. Many petrochemical plants and refineries perform online PD tests to periodically assess the condition of the stator winding insulation on machines during operation. IEEE and the International Electrotechnical Commission (IEC) have created standards called recommended practices or technical specifications to address offline and online PD measurement using electrical diagnostic equipment, and optical measurement of surface PD. They explain testing objectives and principles, discuss commonly-used methods for measuring PD, and provide guidance for data interpretation.

Users of these standards should identify the PD test method and acceptance criteria, as the standards describe several suitable test procedures, but provide no acceptance criteria. This paper provides an overview and comparison of the standards, and addresses some common questions about offline and online PD tests.

Index Terms: stator winding, insulation, partial discharge, diagnostic testing, standards

I. INTRODUCTION

Partial discharges (PD) are small electrical sparks that can occur in any high voltage insulation system. They indicate that small voids are present somewhere between the high voltage conductor and ground. Most electrical equipment is designed to have no PD during normal operation. This is because the purely organic insulation systems used in power cables, switchgear and transformers deteriorate rapidly when attacked by PD. Motor and generator stator windings rated 6 kV and higher usually exhibit PD in operation, but materials such as mica and glass are PD-resistant and applied to mitigate its effects. However, experience has shown that a significant increase in PD over time may reduce stator winding insulation system operating life.

Elevated PD in new machines may indicate manufacturing problems with impregnation, stress relief coatings or inadequate spacing between coil endwindings or leads to the terminal box. Elevated PD observed in operating machines following an appropriate conditioning period may suggest thermal deterioration, partly conductive contamination of the endwinding, or loose windings in the stator core (in the case of windings made without global vacuum-pressure impregnation). Advanced detection of these issues may allow proactive repairs or rewinding.

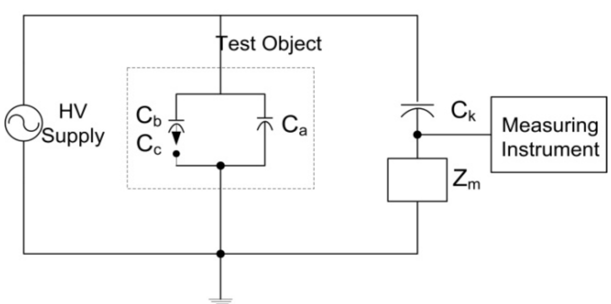
Offline PD testing has been used since the 1930s as an in-factory diagnostic test of new windings. The online test method was first reported in the 1950s [1]. This long experience has recently produced fairly standard test guidelines, but along with that comes a wide variety of test methods developed and used throughout the years. Comparing and contrasting PD testing standards for motors and generators, it should be noted that the general purpose standards such as IEC 60270 and ASTM D1868 cover PD theory and measurement techniques common to all types of electrical equipment. IEEE 1434 is the oldest PD standard written especially for machines, and is compared with the newer IEC 60034-27 and IEC 60034-27-2. Added to this group is the recent publication of IEEE 1799 on blackout testing and surface corona inspection. The paper addresses some common questions about the various standards, especially with respect to PD testing of machines in petrochemical facilities.

II. CONVENTIONAL PD STANDARDS

The oldest general purpose consensus standard for conventional PD testing is ASTM D1868 [2], with its first version published in the 1960s. It then became the foundation of IEC 60270 [3]. Both of these documents are intended for testing equipment that behaves like a capacitive load. They cover only low-frequency (LF) acquisition at < 3 MHz. High voltage capacitive couplers or an impedance in the ground circuit are used to measure the current pulse (mA) associated with each discharge. The PD current is reported as a voltage (mV) across an impedance. The documents do not offer acceptance criteria of PD magnitude or PD extinction voltage (PDEV). Equipment-specific PD standards do address these criteria for test objects other than stator windings.

The magnitude of the detected PD pulse depends on the capacitance of the test object. The higher the capacitance C_a, the more the PD current pulse gets shorted out within the test object, and the lower the current that can flow in the external circuit C_k, where the apparent PD current is detected across an impedance Z_m (Fig. 1). With a capacitive test object (C_a), it is common to transform the PD current or voltage into picoCoulombs (pC), i.e. electrical charge. The rationale for using pC is that it indicates the number of electrons and ions involved in the discharge. The larger the number of electrons, the more the (organic) insulation will be damaged by the electron and ion bombardment, and thus the faster the insulation aging process. In older PD detection systems the integration of the current to yield charge is done in an analog fashion using a low pass filter that works in the low frequency range. It is for this reason that the conventional PD detectors in ASTM D1868 and IEC 60270 are described as low frequency (LF) PD detectors. A PD pulse, which lasts only a few nanoseconds, will be integrated by a low pass filter with an upper cut-off frequency less than 1 MHz. Modern PD detectors will usually digitally integrate the PD current to yield the charge in pC in each pulse. The calibration process involves injecting a known amount of charge (pC) via a pulse generator into the test object and measuring the mA or mV that the calibrating pulse produces on the PD detector output. This gives a ratio between pC and mV.

The PD in individual coils can be calibrated in terms of pC, since a single coil actually behaves like a lumped capacitance between the copper conductor and ground. However, stator windings are not purely capacitive, which means the PD pulses (or the calibration pulses) will respond differently depending on any resonant frequencies that may occur between the winding capacitance and the winding inductance [4].



C_a = coil or winding capacitance
C_b = capacitance in series with void
C_c = capacitance of void where PD occurs
C_k = PD detection capacitance
Z_m = impedance that converts current to voltage

Fig. 1: The voltage signal at the PD detector decreases with increasing capacitance of the coil or winding

IEC 62478 TS "High Voltage Test Techniques - Measurment fo Partial Discharges by Electromagnetic and Accoustic Methods" is being prepared as a companion document covering high-frequency PD measurement in any type of high voltage apparatus. It will address the following acquisition frequency ranges:

- 3 - 30 MHz, high frequency (HF)
- 30 - 300 MHz, very high frequency (VHF)
- 300 - 3000 MHz, ultra high frequency (UHF)

High-frequency acquisition is appropriate for on-line PD testing of electrical equipment. The high signal-to-noise ratio decreases the risk of false positives, and the characteristic output signatures can be correlated to typical locations in the equipment where PD appears.

III. IEEE 1434: ONLINE AND OFFLINE TESTING

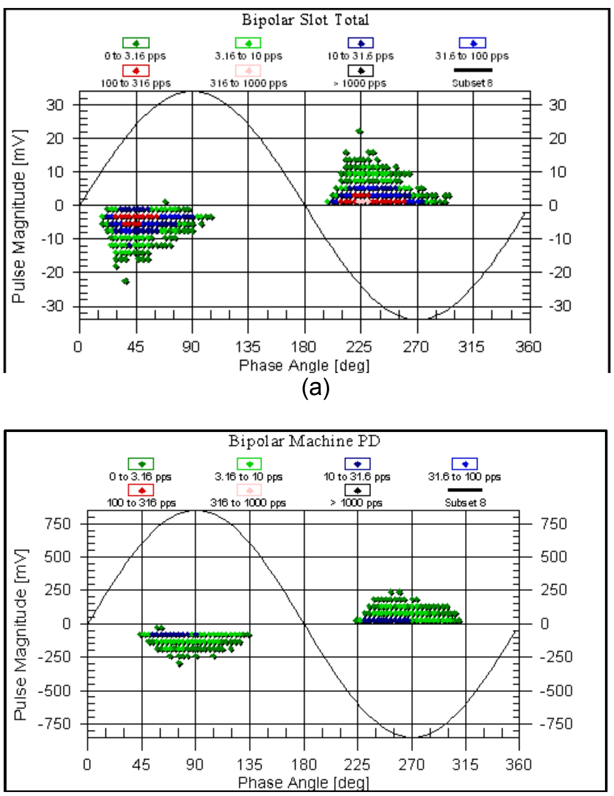
IEEE 1434 [4] was the first consensus guide for offline and online measurement of PD in stator windings, specifically those operating at 50/60 Hz and rated 3.3 kV and above. It describes PD theory in detail, including both low- and high-frequency test methods. There is a compendium of published electrical test methods for conventional PD pulse measurement of stator windings, plus a brief description of optical, acoustic and radio-frequency (RF) detection. It also includes a bibliography with hundreds of related technical papers. However IEEE 1434 does not offer acceptance criteria based on either PD magnitude or extinction voltage. The next revision will likely be available in 2015, and will include some of the following information.

IEEE 1434 presents four methods for offline testing of stator windings based on capacitive couplers for acquisition under several permitted frequency ranges, with both pC and mV as possible measurement units. The variety of options makes it difficult to compare data from different methods. The challenges of calibration by injecting a known pulse and measuring the response of the detector are extensively addressed. The process is called "normalization", to acknowledge that calibration appropriate to lumped capacitances (i.e., sample coils or bars) is not relevant for stator windings due to the winding inductance and resulting resonant frequencies. Four electrical methods are presented measuring the PD on individual coils or bars, again employing different frequency ranges.

Twelve electrical methods for online testing of stator windings are discussed. They include capacitive couplers connected at the machine terminals, RF current transformers (CTs) at the stator winding neutral or on its surge capacitors, and a variety of antennae placed at various locations around the winding. There is an extensive exploration on the merits of different frequency ranges, and those permitted include LF all the way to UHF. Units of PD magnitude may be mV, µV, mA, and dBm.

The opportunity for false indications due to electrical interference (noise) and the zone of coverage for a stator winding are significant considerations when applying an online PD test. Although LF methods are more "searching" (allowing detection of PD from sources farther from the sensor), false positives from noise are more likely. Nearby high current or voltage switching or other unshielded electrical activity can create spurious pulses alongside any actual stator winding PD. This might initiate an unnecessary and costly motor shutdown. Higher frequency detection methods use travelling waves, pulse shape and impedance mismatching to help segregate noise from signal, but there is a trade-off; PD appearing farther from the sensor are more attenuated at higher acquisition frequencies, and so may go undetected.

IEEE 1434 discusses the reliability of capacitive PD sensors, by far the most common type used for on-line testing of machines. The capacitors are connected to the phase terminal, and if they fail, the motor or generator will trip. Originally, IEEE 1434 only required the couplers to have a PDEV above the rated phase-to-phase voltage, when applied phase-to-ground (i.e., to be PD-free at 70% over operating voltage). Based on the latest draft, the next revision of IEEE 1434 will likely harmonize the requirements for capacitive PD sensor reliability with IEC 60034-27-2 [5]. This includes type testing for thermal stability, a PDEV not less than twice rated line-to-ground voltage, and the capacitors must survive 400 hours at 2.17 times the rated phase-to-phase voltage.



(a)

(b)

Fig. 2: Example characteristic PRPD plots of PD magnitude vs. phase angle, for two stator windings, suggesting (a) PD within the stator groundwall insulation, and (b) PD between coils in the endwinding. The color represents the number of PD pulses per second.

IEEE 1434 confines the interpretation discussion to general statements that PD will tend to increase and eventually level off as the insulation ages, and that the manufacturers of rotating machines and PD test instruments should develop a database of results. Upper thresholds for PD will depend on the individual machine, its operating environment, and the characteristics of the PD measurement system. Most systems produce a phase-resolved PD (PRPD) plot of pulse magnitude against the AC cycle (Fig. 2). IEEE 1434 gives examples of characteristic PRPD patterns associated with different stator winding failure processes. Machine operating conditions such as load, winding temperature and ambient humidity influence PD activity in a stator winding. The effect of these operating conditions on PD can also offer clues about its root cause.

IV. IEEE 1799: “BLACKOUT” TESTING

IEEE 1799 [6] is a new recommended practice for the methods that use emitted light to detect PD appearing on stator winding surfaces. It was created in response to reported problems occurring in the endwindings of relatively new machines – specifically, with their stress control coatings and clearances between regions of high voltage. Although this document addresses only surface PD, it does include acceptance criteria, and is therefore more practical to use and interpret than IEEE 1434.

IEEE 1799 is principally employed as a guide to the offline inspection of surface PD as a quality control test for new coils and windings using detected light. For the endwinding inspection of stators, one phase is energized to phase-to-phase voltage (applied phase-to-ground) plus 15% to compensate for temperature. The other two phases are grounded, on the assumption of adjacent line end coils are connected to the phase terminal. This creates phase to phase stress between the coils in the endwinding. Light from any discharges distant from the stator core is then observed – ideally there will be none. Under these test conditions, the stress relief coatings are over-excited, so any visible discharges in these regions are ignored.

After the phase-to-phase inspection, the applied voltage is decreased to phase-to-ground (+15%) to inspect for surface PD on the stress relief coating or at the slot exits. Acceptance is based on whether surface PD is observed on the relevant parts of the winding.

IEEE 1799 describes two methods to detect the light from surface discharges: (1) the human eye, which requires darkness for a “blackout”, “black house” or “lights-out” condition, and (2) ultraviolet (UV) sensitive imaging devices, which may be used in ambient lighting. For the blackout test, the stator is placed in a completely dark enclosure and its winding energized to the required test voltage and inspected for surface PD. After about 15 – 30 minutes in darkness, the human eye becomes sensitive to the very low light emitted by surface PD, and thus an observer can usually determine if and where the activity is appearing. The test is conceptually very simple, but some caveats appear in practice. Setting up in a factory to permit complete darkness may be quite elaborate and time-consuming; observers need to be very close to the energized equipment while both are in darkness; and the perception of PD inception voltage (PDIV) and PDEV may be subjective and poorly repeatable depending on the location and eyesight of the observer [7], although it has been reported that sensitivity to PD light is somewhat independent of the observer [8].

UV imaging devices can distinguish surface PD from normal visible light, permitting inspection without the need for darkness. UV viewers and cameras have become more economical and widely available [7]. IEEE 1799 describes a process to calibrate UV devices against the human eye, because UV imaging devices have different sensitivities.

V. IEC 60034-27-1: OFFLINE PD TESTING

IEC 60034-27 [9] was first published in late 2006 as the first of a two-part series covering PD measurements on motor coils and windings. It is largely based on the offline portion of IEEE 1434, with a few significant exceptions. IEC 60034-27 describes the physics of PD and why it is a useful diagnostic test of stator winding insulation condition. The document applies to both individual coils and offline testing of complete stator windings, and describes two options for PD detection: a capacitor in parallel with the test object (Fig. 1); or an impedance on the ground side of the test object. The recommended systems operate in the low (below a few MHz) frequency range only, using a wideband detector for single coils, bars, and stator windings. For windings, the principle is that LF testing enables PD detection in coils distant from the sensors.

To report PD in pC from tests on individual coils, the calibration procedure described in IEC 60270 is valid. IEC 60034-27 acknowledges that a complete stator winding is not a purely capacitive test object, and for this purpose refers to normalization rather than calibration.

IEC 60034-27 offers no PD acceptance criteria for tests on coils, bars or windings. Like IEEE 1434, the document emphasizes that PD data are comparative only – that it is appropriate to observe the trend in PD behavior of a given winding, or compare a particular coil or winding to a database of PD results from similar coils or windings. Also similarly to IEEE 1434, PD root cause identification is based on analysis of phase-resolved PD plots.

TABLE I
COMPARISON OF IEC AND IEEE STATOR PD STANDARDS

	Standard	
Item	IEEE	IEC
Test Methods		
Offline	4	2
Online	12	5
Surface PD inspection	Yes	No
Frequency Range		
Offline	All	10 kHz – 1 MHz
Online	All	All
Measurement Units		
Offline	pC, mV	pC, mV
Online	All	All
Acceptance Criteria		
Coils	None	None
Stator Windings	None	None

VI. IEC 60034-27-2: ONLINE PD TESTING

The Technical Specification IEC 60034-27-2 [5] was first published in 2012 as the second in a two-part series on PD measurement. It covers online PD testing of stator windings, and is much more restrictive than IEEE 1434 on the allowed detection methods. Permitted sensors include capacitive couplers, RFCTs and microwave antennae, which when taken together total five different measurement systems. Like IEEE 1434, the document includes extensive discussion of the various trade-offs in low frequency versus high frequency instrumentation. In the end, any measurement frequency range is acceptable, which of course makes it difficult to compare data taken by different PD measurement systems. The reliability of capacitive couplers is directly addressed, describing several appropriate type and routine tests for the sensors. The PDEV in particular should be more than twice the rated line-to-ground voltage.

IEC 60034-27-2 offers no PD acceptance criteria for tests on coils, bars or windings, instead providing the usual general statements on interpretation.

Table 1 summarizes the differences between the IEEE and the IEC on-line and off-line test differences.

VII. DISCUSSION

The variety of PD test methods available for coils and stators often raises questions. Many of the most common are addressed here, based on the information in the standards, and the authors' experience.

1. *Does elevated PD indicate impending failure of a winding?* PD is relatively rarely the root cause of failure. Several different stresses impact the winding life, therefore the PD magnitude usually does not determine the rate of deterioration. It is possible for a machine to run for many years with elevated PD, and the activity often levels off or even decreases as the winding nears the end of its life [1,4,5].
2. *Will PD testing find all winding insulation problems?* Online testing will not find metallic debris (such as tools left in the machine) except very near the line end of the winding. Online tests won't find insulation deterioration that is limited to the neutral end of the winding; however, low operating stress means that neutral end coils are at low risk of PD anyway. Offline testing used as a FAT test may be a helpful diagnostic evaluation of the general winding condition. Neither test will detect endwinding vibration, endwinding insulation cracks, or magnetic "termites" within the insulation. PD testing cannot detect problems with rotor winding insulation.
3. *Can PD determine root cause of insulation problems?* For online testing, the effect of winding temperature, load and humidity can provide useful information. If there is a single dominant deterioration process, there will often (but not always) be a unique PRPD pattern. However, if two or more deterioration mechanisms occur simultaneously, then even experts will disagree on the root causes. Despite recent developments in advanced software tools to distinguish mechanisms based on PD patterns alone, ambiguous results are found by independent, blind testing of these tools [1].
4. *Can we specify PD limits for new coils or stator windings?* Yes and no. A purchase specification must identify the test procedure and acceptance criteria. One can include IEEE 1799 for its clear test procedures and acceptance criteria, but this standard is only relevant for surface discharges. For all other measurements, IEC provides a clear procedure, but no acceptance criteria. IEEE has neither a clear procedure nor acceptance criteria. Both the procedure and acceptance criteria should be discussed in detail and agreed upon with the machine manufacturer.

5. *Which is better – offline or online PD testing*? Each has advantages and disadvantages, so they are complementary. Offline testing requires an external AC power supply, energizes all the phase coils to the same voltage (and can therefore detect PD throughout a winding), allows simultaneous energizing of all phases, and generally has a low rate of false positives due to low noise. It is a very useful technique to use for detailed inspections during a shutdown, especially when the results can be compared to a factory- or newly-installed baseline test. Online testing does not require an outage or external power supply, so is almost always simpler and cheaper. Assuming that the detectors are already installed, the online test can be done at any time, and accurately indicates the operating behavior by detecting issues (such as loose coils) that can only be observed during operation.

6. *Should we use LF or HF for PD testing our windings?* It is a trade-off. For offline PD testing, always use LF, particularly if the most searching test for deteriorating coils is needed. In online testing, HF testing will minimize the risk of false positives that may result in a needless shutdown.

7. *How do we determine when maintenance is needed?* If you have measured the offline and/or online PD trend since the machine was built, determine if the PD activity is doubling every 6 months or so. Be aware that PD may become stable or even decrease in older, seriously aged insulation. Also consult with the machine manufacturer or PD system vendor since they may have a database to compare the results with, to determine if the PD is normal or high. PD test results can be compared with visual inspections and other diagnostic tests.

8. If we find high or rapidly increasing PD in our winding, should we shut down the machine? No. PD testing normally gives an early warning of a developing problem. Machines may run for many years with high PD. Watch for a trend, and if possible compare the results to other machines of similar design and operating conditions. Confirm the results through planned outages for inspections and complementary diagnostic tests.

9. Should we PD test our stator windings rated 3.3 kV and 4.1 kV? It depends. For such machines, PD measurements may not provide sufficient notice to plan a turnaround. If the machine fails, the cost of the repair or replacement may be the same as a proactive repair.

VIII. CONCLUSIONS

Theory and techniques for measuring PD in the insulation of high voltage electrical apparatus, in particular of coils and stators for rotating machines, have been in use since the 1960s. There is global industry acknowledgement of the value of PD measurement as both a preliminary quality check of a new insulation system, and a diagnostic test of its health throughout the life of the machine. The many available techniques have been uniquely developed by manufacturers and end users throughout the years.

PD can be measured offline on individual bars and coils, and either offline or online methods may be used for stator windings. IEEE and IEC have recently developed several international guides and recommended practices to draw together the state-of-the-art in PD detection knowledge, and provide guidance on suitable ways to obtain and interpret PD measurements. IEEE and IEC agree on measurement units, frequency ranges for online testing, and the validity of calibration or normalization with respect to the type of test object. However, IEC recognizes roughly half as many test methods in both the offline and online case, is more restrictive about the allowable acquisition frequency for offline tests, and does not have a guide for surface PD inspection.

Due to the wide variety of insulation systems, machine operating conditions, and PD measurement techniques in use, none of the standards from either organization offers acceptance criteria for PD magnitude, inception or extinction voltages. Clearly, further work is needed to develop databases from both online and offline testing, aiming for eventual harmonization and simplification of the standards.

IX. ACKNOWLEDGEMENTS

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XI. VITA

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