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Comparison of Low Frequency and High Frequency PD Measurements on Rotating Machine Stator Windings

G.C.Stone
Iris Power-Qualitrol
Toronto, Canada
gstone@qualitrolcorp.com

H.G. Sedding
Iris Power-Qualitrol
Toronto, Canada
hsedding@qualitrolcorp.com

C. Chan
Iris Power-Qualitrol
Toronto, Canada
cchan@qualitrolcorp.com

C. Wendel
Iris Power-Qualitrol
Brugg, Switzerland
cwendel@qualitrolcorp.com

***Abstract*— Partial discharge (PD) testing has been used for over 60 years primarily as a method to detect aging of the stator winding insulation in motors and generators rated 6 kV and above. More recently it has also been used by some machine manufacturers as a means of assuring the quality of the insulation. The PD measuring systems in use work either in the low frequency regime (less than about 1 MHz) or in the very high frequency (30-300 MHz) range. By reference to several international standards, published work as well as some experiments described here, the advantages and disadvantages of the two approaches are reviewed. In most circumstances it is now clear that off-line PD tests should be done in the low frequency range. For on-line tests, either frequency range can be used, but with different advantages.**

Keywords— partial discharge, measurement frequency, stator winding, electrical insulation

I. INTRODUCTION

Partial discharges (PD) occur in a wide variety of high voltage electrical apparatus such as transformers, gas insulated switchgear, power cables and rotating machines. Unlike power cables, switchgear and transformers, off-line factory PD testing has been relatively rarely applied as a quality assurance (QA) test for new coils or windings. Only in the past 10-15 years has there been some limited interest in using it as a QA test for stator windings [1-3]. More commonly, machine owners have been using off-line and on-line PD testing to assess the condition of the stator winding insulation in order to determine if maintenance is needed. Problems such as loose coils in the stator slots, contamination leading to electrical tracking and thermal aging of the insulation are easily detected [1,4,5].

There are many different types of PD testing equipment that have been used for coils and stator windings. Most use a capacitor to detect the PD pulse currents in the presence of the 50/60 Hz high voltage. The instrumentation to measure the PD current pulses most commonly includes an analog to digital converter that determines the number, magnitude and phase position (with respect to the 50/60 Hz ac cycle) of the PD. However almost every brand of PD detector works in a different part of the frequency spectrum. Since each partial discharge pulse is the result of a brief flow of electrons lasting only a few nanoseconds at atmospheric pressure, by the Fourier transform, frequencies from 0 Hz up to several hundred MHz are created by each discharge. Thus PD can be detected in a very wide range of frequencies. This paper is a review of how the frequency range affects the detection of PD in individual coils and stator windings.

II. STANDARDS FOR PD DETECTION

The most common standard referred to for PD measurement is IEC 60270 [6]. This document describes the test circuits for measuring PD, and describes the process for calibrating the detected mV magnitude of the PD pulse into apparent picoCoulombs (pC). PicoCoulombs, a unit of charge, is traditionally used for PD measurement since the damage to **organic** insulation by the discharge will be related to the number of electrons in the discharge, i.e. the charge. Since the groundwall insulation in high voltage stator windings partly consists of inorganic mica, this assumption may not be valid [7]. IEC 60270 normally assumes that a capacitor detects the PD, and that the test object is also predominantly capacitive, which is not true for stator windings. IEC 60270 also suggests the measurement frequency be anywhere in the range from 50 kHz to 1 MHz. Any frequency can be used in that range, although it does categorize two sub-classes of detector:

- narrow band detection in the 9-30 kHz range with a center frequency anywhere between 50 kHz and 1 MHz
- wide band detection in the 100 kHz to 900 kHz range.

PD detection above 1 MHz is not covered by this standard.

In 2016, IEC 62478 was published [8]. It is a complementary document to IEC 60270, and it covers the frequency range above the 60270 range. In particular, it defines the following ranges:

- Low frequency, LF -below 3 MHz (i.e. approximately the frequency range in IEC 60270)
- High frequency, HF – 3 to 30 MHz

- Very high frequency, VHF – 30 to 300 MHz
- Ultra high frequency, UHF – 300 to 3000 MHz.

In addition to detection of the PD by capacitors, this new document indicates the PD can be measured by high frequency current transformers (HFCTs) and different types of UHF antennae. Clause 4.3.6 of IEC 62478 makes clear that above the LF range, a direct calibration into pC is not feasible, as has been pointed out in the past [7,9]. Instead a "sensitivity check" is performed by comparing a conventional LF PD test (measured in pC) with a test in the HF, VHF or UHF range (measured in mV or dbm). IEC 62478 identifies several practical schemes for measuring PD above the LF range on switchgear, transformers and stator windings.

A. Off-Line Testing of Stator Coils and Windings

IEC 60270 and IEC 62478 are standards that apply to any type of high voltage equipment. IEEE 1434 describes PD testing of stator windings in particular. IEC has also prepared two documents specifically for the stator windings and coils in motors and generators. IEC 60034-27-1 discusses the off-line PD testing of coils and complete stator windings [1]. The document suggests that for both coils and complete windings, the PD test be done in the IEC 60270 frequency range (i.e. below 1 MHz) and with a wideband detector (to minimize PD pulse superposition effects).

Stator bars and coils are mainly capacitive in nature. Thus the LF range will enable the PD to be measured in pC in tests on stator coils and bars. Theoretically this implies the same PD level in pC should be measured on a coil or bar, independent of the specific frequency range and manufacturer of the PD detector. In practice there may be as much as a three times difference in the PD magnitude in pC on the same test object [2, 10], presumably due to different frequency ranges and detector impedances, even though they are all in the LF wideband range. As discussed later, different LF instruments also calculate the peak PD magnitude in different ways.

IEC 60034-27-1 does indicate that it is best to measure the PD in off-line tests on a complete stator winding in the wideband LF range. This is because in an off-line test, all the coils are energized to the test voltage, and thus any coil in the stator can have PD. Due to the inductive – capacitive nature of the stator winding, if a PD pulse occurs, for example at the neutral end of the winding, and the PD sensor is located at the phase-end of the winding, the PD pulse is likely to be attenuated and distorted as it propagates from the neutral end to the PD sensor's location [11]. The higher the detection frequency, the greater is the attenuation effect [1]. Thus PD detection in the LF range normally produces less attenuation, and one is more likely to detect PD far from the PD sensor.

B. On-Line PD Testing of Complete Windings

IEEE 1434 and IEC 60034-27-2 discuss on-line PD measurement in motors and generators, that is, during normal operation of the machine. These documents identify the different types of sensors that can be used for on-line PD detection (capacitors of different capacitances, HFCTs, and UHF antennae such as SSCs). There are also an extensive discussions on the need for sensor reliability, since if a PD detection capacitor fails, it will cause a forced machine outage. However, unlike for off-line testing it is noted that any frequency range (LF, HF, VHF and UHF) can be used, and has been used, for on-line testing. From 1950 to 1980, only LF wideband PD detection was employed, typically with a 1 nF capacitor on each phase or an HFCT at the winding neutral. However, the signals measured not only contained stator winding PD, but also high frequency electrical signals from noise and disturbance sources – such as transmission line corona, sparking electrical contacts, slip ring sparking, variable speed drive invertor switching noise, etc. This made the extraction of the stator winding PD from the electrical interference difficult. Usually only experts with several years of experience could make reliable diagnosis [12]. As a result, since the 1980s, various researchers have explored performing on-line PD measurements at higher frequencies (not only in machines, but also in gas-insulated switchgear, cables and transformers).

The advantage of PD detection at the higher frequencies was that better methods of suppressing noise and disturbance were possible [4, 8]. For example, the time of flight method of separating stator PD from power system noise can be implemented if two sensors are installed per phase on the bus between the power system and the machine (Figure 1 in IEC 60034-27-2) [4,5]. In addition, researchers have noted that the shape of the pulse is different between stator PD and most types of power system noise. This has enabled noise and PD separation on the basis of time domain pulse shape analysis [4,5] or using a software-based technique called time-frequency mapping [13]. These methods require the pulse arrival time to be measured with a time-domain accuracy of several nanoseconds, and/or the pulse shape be recorded in the VHF range. If the signals were acquired in the LF range, the relative time of pulse arrival from two sensors cannot be distinguished, nor can the true pulse shape. Another method uses UHF antennae within the generator. In the UHF range it is almost impossible for noise signals outside of the machine to penetrate within the frame, compared to LF or even VHF noise signals. Thus UHF sensors seem to provide the greatest amount of noise immunity [4,8,14].

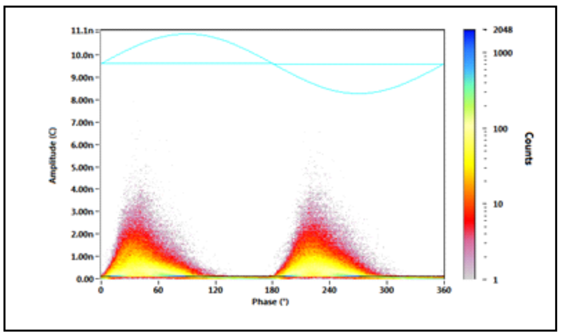
The limitation of on-line VHF and UHF PD detection is that PD originating in the stator winding physically far from the PD sensor is usually more strongly attenuated than PD close to the sensor. Thus all the relevant IEEE and IEC standards caution users that PD remote from the PD sensors may not be detected in the VHF and UHF ranges. Reference 11 suggests that the VHF methods may detect PD in only 10-15% of the winding, although this may have less impact in on-line tests since the coil/bar voltage is lower away from the line-end of the winding. Thus it is important to install any sensors as close as possible to the coils/bars operating at the highest voltages which are most likely to have PD, rather than near bars or coils operating at lower voltages.

III. COMPARSION OF PD MEASURED IN DIFFERENT FREQUENCY RANGES

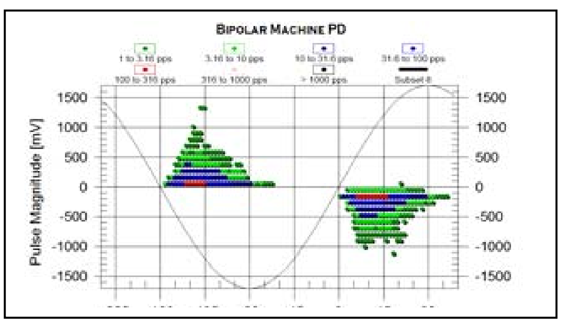
To illustrate the differences between PD detectors using different frequency ranges, off-line PD was measured on 2 stators, with the PD measured at about the same time using different frequency ranges.

A. LF vs VHF Off-line PD on Motor Stator

Off-line PD tests were performed using LF and VHF PD detectors on a 13.2 kV, 6000 HP motor stator winding. The LF test was performed with a PDTech DeltaMaxx analyzer using a 1000 pF PD detection capacitor. It operated in the wideband mode in frequency range 40 – 800 kHz. C phase had the highest activity and is shown in Fig. 1. Fig 1a shows the phase resolved PD (PRPD) pattern obtained after stabilization at 8 kV (just above rated line to ground voltage). Fig 1b shows the VHF PRPD plot measured on the same phase of the stator winding at the same voltage using an 80 pF PD sensor and an Iris Power TGA-B instrument. The PD detection frequency range is 40 -350 MHz.



(a)

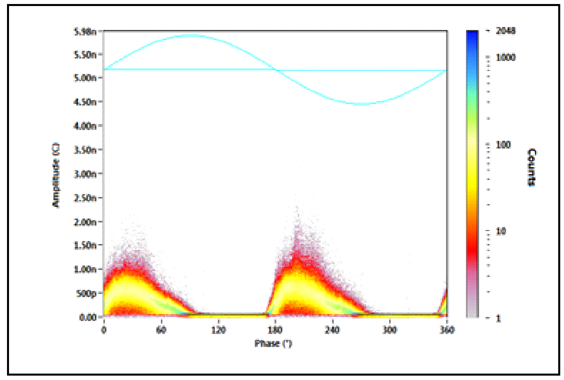


(b)

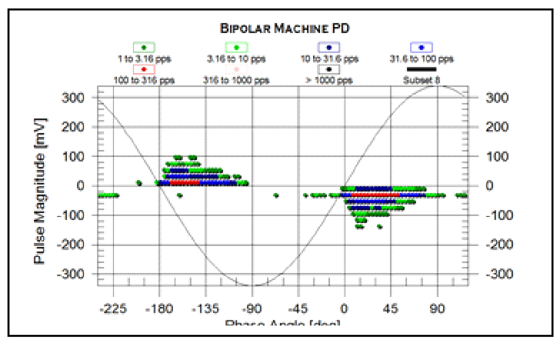
Fig.1. Off-line PD test on a stator winding measured in the LF (a) and VHF (b) frequency ranges. The vertical scale is the apparent pulse magnitude in either nC or mV. The horizontal scale is the phase angle of the 60 Hz AC cycle. The colour of the dots represents the number of PD pulses per second. Note that the VHF PRPD plot shows the polarity of the PD pulses. In the LF PRPD plot the pulse polarity is suppressed, but can be inferred from its position on the AC cycle.

The peak PD magnitude (Qm) for the VHF measurement (calculated using the definition for digital instruments in IEC 60034-27-1) is +816 mV and -912 mV. This Qm is the magnitude at a PD pulse repetition rate of 10 pulses per second (pps). The LF PD instrument calculated Qm to be 2.5 nC, using the same 10 pps definition. Note however some LF instruments calculate the peak PD magnitude using a method based on an analog definition of the largest repetitive magnitude in a train of pulses, as defined in IEC 60270. Note that visual inspection revealed the insulation to be very delaminated

C phase of this stator winding has a ratio of 2.7 pC/mV between the LF and the VHF detectors. However, note the cautions in IEC 60034-27-1 and several papers [1-3, 7-10] that different brands of PD instruments are likely to give much different pC levels even under the same test conditions. The PRPD patterns and the relationship between positive and negative PD is essentially the same between LF and VHF.



(a)



(b)

Fig. 2. LF (a) and VHF (b) off-line PD test on a 200 MVA generator stator

Fig. 2b shows the PRPD plot measured in the VHF range on C phase under the same test conditions as for the LF test. It shows the same PRPD pattern as for the LF test. The Qm (calculated at 10 pps) is +106 mV and -121 mV. Thus the ratio between the LF test in pC and the VHF test in mV is 9.1 pC/mV, which is substantially different than the ratio measured on the motor.

B. LF vs. VHF Off-Line PD in a Turbine Generator Stator

The stator winding of an 18 kV, 200 MVA hydrogen-cooled generator was also given an off-line PD test using both LF and HF instruments described above. The tests were done at about 9.7 kV, a little below the rated line to ground voltage, in atmospheric pressure air. Fig 2a shows the PRPD plot from Phase C, which had the highest activity. The plot shows classic internal groundwall activity (see IEC 60034-27-1 for PRPD plots associated with each type of PD source), with approximately equal positive and negative PD activity. A Qm of 1.1 nC was measured.

IV. ADVANTAGES OF LF AND VHF PD DETECTION

Off-line tests on both coils/bars and complete stator windings should normally be performed in the LF range, even though Figures 1 and 2 show the PRPD patterns are essentially the same as for VHF patterns. For coil/bar tests this will allow the PD to be scientifically quantified in terms of apparent charge (pC). For windings, the LF range maximizes sensitivity to PD in more of the coils/bars in the winding.

The choice between LF and VHF (or UHF) is more difficult for on-line testing. The basic advantages of the LF test for off-line testing, as described in IEC standards [4,8], include:

- Greater sensitivity to PD occurring in coils that are further away (in space or in the circuit) from the PD sensor. This advantage is perhaps less important than for off-line tests, since the coil/bar voltage decreases linearly through the circuit from the phase terminal to the neutral end of the winding. As the voltage deceases so does the PD magnitude and the number of defects that produce PD. In practice, in side by side on-line PD testing, we have never seen a LF test detect a verified (by visual inspection) stator winding insulation problem that a VHF test did not detect.
- The same instrumentation used for off-line tests can be used for on-line testing, reducing instrumentation costs.
- Usually only a single sensor per phase (3 per machine) is needed for LF testing.

In contrast, the VHF and UHF tests have different advantages:

- There is greater immunity to noise and disturbances from the power system with VHF and UHF methods, which lowers the risk of false indications of stator winding problems. Also this implies that less expertise is needed to perform and interpret PD results, since there is a lower risk the stator PD is obscured by the noise. This results in a lower marginal test cost. Continuous PD monitoring is also less likely to give false indications.
- With some of the VHF methods and all of the UHF methods, it is possible to locate with more certainty where the PD is occurring within the winding.
- Most capacitive PD sensors in VHF methods can meet the sensor reliability requirements stipulated in IEC 60034-27-2, thus reducing the risk that a PD sensor may fail the machine
- Peer-reviewed databases containing hundreds of thousands of test results have been summarized in tables of "high" and "low" PD. These severity levels have been confirmed by visual inspections on many hundreds of machines [15].

It is clear that both the LF and VHF ranges can detect severe PD in a winding. The LF method tends to be preferred by OEMs and test service providers who have the expertise to separate the PD from the noise, and judge the severity based on experience with similar machines. Owners of machines tend to use the VHF and UHF methods since utility staff can perform the test and do a basic interpretation with relatively little training and experience.

V. CONCLUSION

Side by side off-line PD tests have shown that PD can be detected in the 40-800 kHz (LF) range as well as the 40-350 MHz (VHF) range. The standards suggest that the LF range is used for off-line PD tests on coils and windings. However, the choice of LF vs VHF testing is not so clear for on-line PD testing of motors and generators. LF may detect more PD in the winding, but at the cost of a much greater risk of false indications when compared to VHF testing.

REFERENCES

[1] IEC TS 60034-27-1, "Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines", 2018

[2] A. Petit, "Comparison of PD amplitudes of stator bars taken with different instruments", Proc IEEE Electrical Insulation Conference, June 2015, pp 255-261.

[3] M.J. da Silva, et al, "On the Variability of PD Results Among Expert Independent Laboratories", Proc IEEE Electrical Insulation Conference, June 2016, pp194-197

[4] IEC TS 60034-27-2 "On-line partial discharge measurements on the stator winding insulation of rotating electrical machines", 2012.

[5] G.C. Stone, V. Warren, "Objective Methods to Interpret Partial-Discharge Data on Rotating-Machine Stator Windings" IEEE Transactions on Industry Applications. Vol.42, No.1, January/February 2006, pp 195-200.

[6] 60270, "High Voltage Test Techniques. Partial Discharge Measurements.", 2015

[7] G. C. Stone, "Calibration of PD Measurements for Motor and Generator Windings--Why It Can't Be Done," IEEE Electrical Insulation Magazine, 9-12, January 1998.

[8] IEC 62478, "High Voltage Test Techniques – Measurement of Partial Discharges by Electromagnetic and acoustic Methods", 2016

[9] I. Kemp et al, "Calibration Difficulties Associated with PD Detectors in Rotating Machines", Proc IEEE Electrical Insulation Conference, October 1987.

[10] S. Ul Haq et al, "Comparative Study of IEC 60270 Compliant Instruments for PD Pattern Acquisition", IEEE PCIC, Sept 2016.

[11] M. Henriksen et al, "Propagation of PD and Noise Pulses in Turbine Generators", IEEE Trans EC, Sept 1986, pp161-166.

[12] G.C. Stone, "A Perspective on Online Partial Discharge Monitoring for Assessment of the Condition of Rotating Machine Stator Winding Insulation", IEEE Electrical Insulation Magazine, Sept 2012, pp 8-12.

[13] A. Cavallini et al, "Advanced PD Infer3ence in On-Field Measurements. Part 1: Noise Rejection", IEEE Trans DEI, April 2003, pp 216-224.

[14] G.C. Stone et al, "Relative ability of UHF antenna and VHF capacitor methods to detect partial discharge in turbine generator stator windings", IEEE Trans DEI, Dec 2015, pp 3069-3078.

[15] H.G. Sedding, et al, "Progress In Interpreting On-Line Partial Discharge Test Results From Motor And Generator Stator Windings", Paper A1 – 202, CIGRE, 2016.