Advances in Interpreting On-Line Partial Discharge Test Results on Stator Windings

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Abstract

On-line partial discharge (PD) testing has been used for decades to help maintenance personnel detect rotating machine stator winding insulation problems at an early stage and thus optimally plan any required maintenance. Specifically, the test can find loose, overheated, and contaminated windings, well before these problems lead to failure. The test has also found use in determining the effectiveness of any repair work.

The widespread application of on-line PD testing has enabled the accumulation over the past 20 years of a database with, currently, approximately 700,000 test results. This proposed contribution presents the basics of on-line data collection, including the implementation of noise rejection algorithms and possible methods in improvements in interpreting test results. One case study describing application of on-line partial discharge testing on a hydro generator will be presented.

1. Introduction

Partial discharges can be both a cause and/or a symptom of many types of stator winding insulation system deterioration mechanisms in motors and generators rated 3300 V and above. Thus it is not surprising that the on-line measurement of partial discharges has been used to assess the need for maintenance in stator windings since 1951 [1]. More particularly, on-line PD measurement has been able to determine if the electrical insulation is deteriorating due to loose coils in the slots resulting in insulation abrasion; thermal deterioration or load cycling leading to insulation delamination; and electrical tracking caused by partly conductive contamination of the endwindings [1-7]. On-line PD testing is also able to determine if manufacturing or installation problems, such as poor impregnation with epoxy, or coils being too close together in the endwinding, are severe enough to shorten the winding life.

Many methods are available to measure the PD activity in operating machines. The electrical techniques all rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. The earliest methods measured the PD pulse currents by means of a high frequency current transformer at the neutral point [1, 2]. Shortly thereafter, high voltage capacitors connected to the phase terminals were used to detect the PD pulses [3-5]. Capacitor sizes ranged from 80 pF to over 1000 pF. More recently, RF antennae are also used to detect PD in operating machines [6, 7]. A good overview of all the different means for detecting PD in machines is presented in IEEE 1434 [8]. This document also provides the framework to enable reliable on-line PD measurements to be made, as does IEC 60034-27-2 [9].

A particular challenge with PD measurements performed in normal motor or generator operation is that electrical interference (noise) often is present [8, 9, 10]. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, power tool operation, and electrostatic precipitator discharging. This noise obscures the PD pulses, and may cause the unwary technician to assume that a stator winding has high levels of PD, when in fact the high levels are caused by the noise. The consequence is that a good winding is incorrectly assessed as being defective – that is a false alarm is given that a winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests, and even today, many feel on-line PD testing is more art than science and best left to specialists.

Beginning 25 years ago, the Canadian utility industry sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff with only a few days training. The tests that were developed, now known generically as the PDA test (for hydrogenerators) and TGA test (for turbine generators and motors) emphasized separating PD pulses from electrical noise pulses. The noise separation methods depend on comparing the time of pulse arrival between a pair of capacitive couplers and/or analyzing the shape of individual pulses [4, 6]. To maximize the signal-to-noise ratio, and thus also to reduce the risk of false indications, the sensors detect the PD at frequencies 40 MHz and higher [8]. The resulting test methods achieved their goal and have enabled utilities to assess the winding condition with their own staff. As a result, it is estimated that over 50% of all utility generators rated 20 MW or more in the USA and Canada have now been equipped with the required sensors. Around the world, over 15,000 machines have the required sensors permanently installed.

With the widespread application of the same on-line test methods, a tremendous number of test results have been accumulated in a single database. To the end of 2019, over 685,000 test results have accumulated over the past 25 years using portable test instruments, and simple statistical analysis has been applied to the database in order to extract information that can help test users to better interpret PD results. This paper updates a previous

contribution from 2002 [11] that introduced this concept. The best means to determine if a winding is significantly deteriorated remains monitoring the trend in PD activity over time. Unfortunately, the PD magnitudes are not only affected by the degree of insulation deterioration, but the machine operating voltage, coolant gas pressure, etc, may also affect results. With the availability of on-line PD monitoring systems that continuously measure the PD on a motor or generator, while simultaneously acquiring machine operating data, a better appreciation of the effect of operating conditions on PD activity has been obtained. Thus, this paper also presents the ranges in operating condition that enable the measurement of valid trends of PD activity.

2. PD Database

2.1. Data presentation

All the data presented here is obtained using either 80 pF capacitive couplers (installed within the stator winding or on the machine terminals) or stator slot couplers (SSCs), which are antennae installed under the wedges in stator slots containing phase end bars [4, 6]. As with most PD measurement systems, the number, magnitude and phase position with respect to the 50/60 Hz ac cycle are recorded, once PD pulses are separated from the noise pulses. The pulse magnitude is measured in the absolute units of millivolts, rather than picoCoulombs, due to the difficulty in calibrating into pC caused by the inductive-capacitive nature of a complete stator winding [8].

Two types of plots are generated for each partial discharge test. The first type of plot is two-dimensional (2-D), where the number of partial discharges per second versus PD magnitude is displayed. The greater the number of pulses per second, the more widespread is the deterioration in the winding. The higher the PD magnitude, the more severe is the deterioration. An example is shown in Figure 1. The second type of plot (Figure 2) is a three-dimensional phase resolved PD (PRPD) plot, where the PD magnitude (vertical scale) and PD pulse repetition rate (colour coded to proportional to pulse density) versus the ac phase angle (horizontal scale) are displayed. Experience has indicated that such pulse phase analysis can be used to identify if multiple deterioration mechanisms are occurring, and the mechanisms responsible.
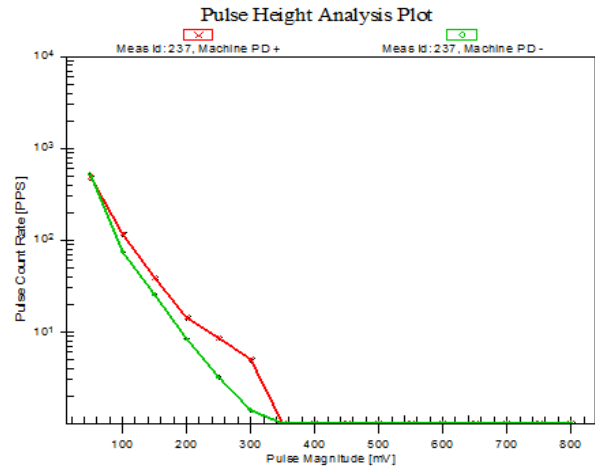

Figure 1 - 2-D plot showing the number of partial discharges per second versus PD magnitude
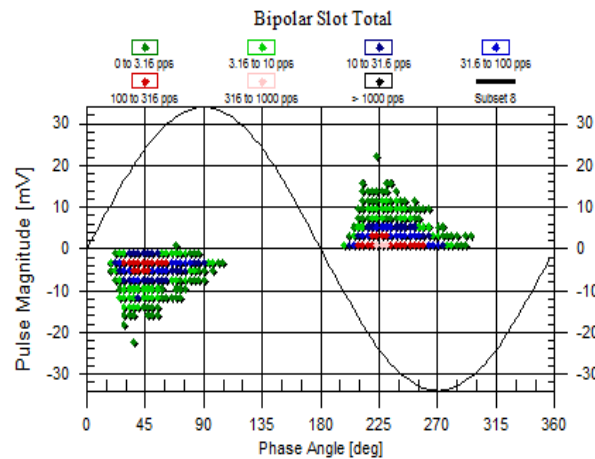

Figure 2 - 3-D phase resolved PD plot showing the PD magnitude (vertical scale) and PD pulse repetition rate (colour coded to proportional to pulse density) versus the ac phase angle (horizontal scale)

The 2-D and 3-D plots are unwieldy for making comparisons amongst the machines. The PDA or TGA summarizes each plot with two quantities: the peak PD magnitude (Qm) and the total PD activity (NQN). The Qm is defined to be the magnitude corresponding to a PD repetition rate of 10 pulses per second [9]. Qm relates to how severe the deterioration is in the worst spot of the winding, while the NQN is proportional to the total amount of deterioration and is similar to the power factor tip-up. Since the Qm scalar quantity is more indicative of how close the winding is to failure, the peak magnitude (Qm) will be used throughout this paper for comparisons.

It has been noted that Qm is a reasonable predictor of winding insulation condition [11]. That is, a high Qm, measured in a winding compared to a lower Qm in another winding, usually implies that the former winding is more deteriorated. Initially, this was a surprise since the mV readings were not calibrated for winding load. We now believe that the Qm readings reported here, that

are measured at frequencies above 40 MHz, may be somewhat absolute because the pulses are measured as traveling waves, and all oscillations after the first peak in a single PD event are disregarded. Since the surge impedance of a coil in a slot is roughly the same for all sizes and types of machines, the very wide band measurement of the first peak in a PD pulse does not 'see' the entire capacitive and inductive load of the stator winding, thus leaving the measurement free of the effects of LC oscillations and reflections.

2.2 Database to the end of 2019

After the accumulation of all available test data through 2019 with over 685,000 records from tests using portable instruments only, a database was carefully compiled using the following selection criteria:
- only on-line tests obtained during normal operation
- only one test result per sensor
- the most recent test at Full Load and Hot stator winding temperature (FLH)
- any test with questionable results was discarded

Once these criteria were applied, about 20,000 statistically independent test results from over 8,000 machines were analyzed.

Table I shows the breakdown of the results that were retained once non-FLH and repeat tests were discarded.

Table I - Number of FLH Tests by Machine Type

Motors	32%
Hydrogenerators	24%
Turbine generators	44%

2.3 Statistical analysis

The database was analyzed to determine the effect on Qm of several different factors, including:

- Sensor installation
- Voltage class
- Hydrogen pressure

The range in Qm from all the tests for the particular operating voltage was established for each set of the above factors. A sample of the statistical distribution is shown in Table I. The percentage values displayed in the left hand column in Tables II and III, represent the cumulative probability. For example, for 13-15 kV stators in turbine generators or motors, 25% of tests had a Qm below 51 mV, 50% (the median) had a Qm below 115 mV, 75% were below 235 mV and 90% of tests yielded a Qm below 430 mV. Thus, if a Qm of 500 mV

is obtained on a 13.8 kV generator, then it is likely that this stator will be deteriorated, since it has PD magnitudes higher than 90% of similar machines. In fact, in over two hundred cases where a machine was visually examined after registering a PD level >90% of similar machines, significant stator winding insulation deterioration was observed [12].

Table II - Distribution of Qm (mV) for Air-Cooled Machines, 80 pF Sensors on the Terminals (TGA)

Cumulative Probability	Operating Voltage (kV)				
	6-9 kV	10-12 kV	13-15 kV	16-18 kV	> 19 kV
25%	25	35	51	39	40
50%	67	85	115	80	96
75%	145	196	235	207	225
90%	331	415	430	313	566
95%	507	670	619	486	842

A PDA installation in a hydrogenerator uses the same 80 pF sensors and these are typically installed within one metre of the junction between the incoming phase bus and the first coil/bar in the circuit. A sensor at this location will be extremely sensitive to any pulses originating within the coil/bar since the magnitude of the pulse will be amplified when it reaches the impedance mismatch between the bus and the coil/bar. Thus, it may be reasonable to assume the PD magnitudes obtained with couplers at this location will be higher than when the couplers are located outside the machine housing typical of directional (TGA) installations. However, when comparing the TGA results, Table II, to the PDA results, Table III, though there are some minor variances, there is little significant difference between the statistical summaries for windings rated less than 19 kV. Thus, it is safe to say that for a 13.8 kV winding, regardless of installation type, the PD levels should be less than ~250 mV and those machines with PD higher than 500 mV need further investigation.

Table III - Distribution of Qm (mV) for Air-Cooled Machines, 80 pF Sensors Installed within the Machine Housing (PDA)

Cumulative Probability	Operating Voltage (kV)				
	6-9 kV	10-12 kV	13-15 kV	16-18 kV	>19 kV
25%	10	38	38	39	52
50%	25	72	97	131	146
75%	51	132	202	338	380
90%	149	289	387	625	837
95%	285	452	580	856	1094

Partial discharge is a gas discharge process, thus, it is extremely dependent, not only on the geometry of the gas gap, but also the gaseous medium. Thus, PD magnitudes from air-cooled machines are typically higher than

machines cooled with hydrogen at elevated pressure. Therefore, it is not advisable to compare the results from machines using different gas mediums. Most hydrogenerators (PDA installations) are air-cooled, thus all of the tests for gas-cooled machines with capacitors were obtained using a TGA instrument and sensors at the machine terminals. Most of the hydrogen-cooled machines have high rated loads and may suffer from problems such as core iron arcing which may cause difficulties in separating the high frequency noise associated with this phenomenon from that of PD. Partial discharge or noise activity at the machine terminals, outside the hydrogen environment, can make stator winding insulation condition difficult to interpret. This difficulty was the principal reason for the development of stator slot couplers (SSC) that have been discussed at length in other publications [6]. Results obtained with these types of sensors on hydrogen-cooled machines are beyond the scope of this contribution.

Though it is always recommended to trend the results for one machine over time and thus monitor the rate of degradation of the stator winding, it is also possible to compare results from similar machines. This statement is made on the basis of employing the sensors and test techniques described in this paper. Tables II and III may be used to ascertain whether a machine warrants further tests and inspections or is operating within reasonable limits. Concerns should only be raised if the PD levels on a specific machine are above the 90th percentile (High). In all cases, this means increasing the frequency of PD testing to determine the rate of deterioration and when possible, conduct specialized tests, inspections and repairs as required. In mica-based insulation systems, PD is a symptom of a failure mechanism; action should be based on the severity of the failure mechanism detected by the PD, not the PD results. PD levels exceeding threshold alarms are warnings for further investigation to determine the cause of the high PD; however, be aware that PD levels can fluctuate with ambient and operating conditions. Maintenance should be based on the cause of the PD, not the overall levels. Continuous PD monitors should have their alarm levels set to the 75% or 90% level.

The time of winding failure is normally the result of a deteriorated winding being subjected to an extreme stress such as a lightning strike, out-of-phase synchronization, excessive starts, or system imbalance. As these are unpredictable, it is impossible to forecast when a failure will occur. However, by monitoring the PD characteristics of a stator winding, it is often possible to determine which machines are more susceptible to failure, and therefore which require maintenance.

3. Case Study

In 1995, cable type 80pF partial discharge sensors supplied from FES International (now IRIS) were installed at the Solhom power plant, Generator 2.

Generator is rated 125 MVA, 14.7 kV, 300 rpm. After the first PD test in more than 20 years, performed in November 2018, high PD levels, in comparison to IRIS severity database [13], were measured on the two phases. The PD levels were among the top 10% of the highest measured levels on machines with stator windings in this voltage class. The analysis of phase resolved plots indicated that phase to phase discharge is the most likely cause of elevated PD levels. This required action to avoid further damage and possible insulation breakdown. Using PD results and generator stator winding diagram it was possible to focus on the specific area of stator and a short 2 hour shutdown was sufficient to visually locate the problem, Figure 3.
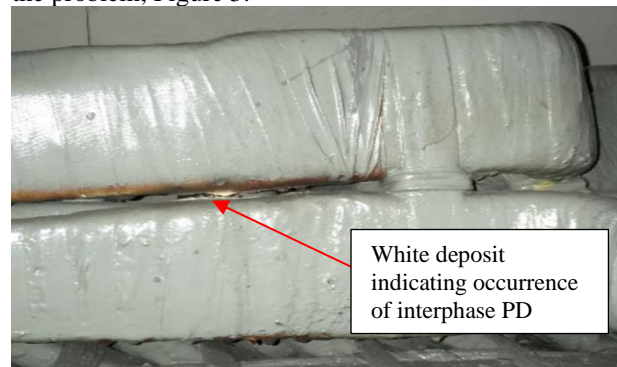

White deposit indicating occurrence of interphase PD

Figure 3 – Evidence of partial discharge between two phases

At the first opportunity (summer 2019) the corrective action was undertaken to eliminate this problem. After that, on-line PD tests were performed under the same operating conditions and results compared to the first test, done in November 2018, Figure 4.
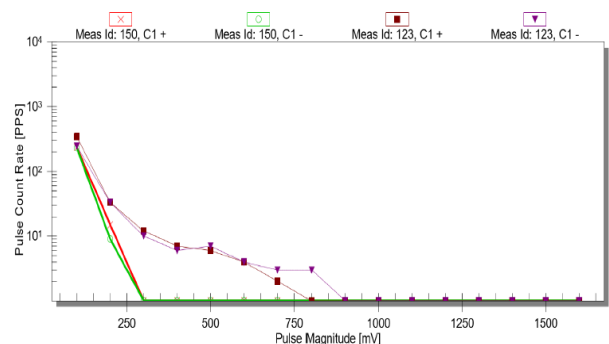

Figure 4 – Comparison of PD pulse amplitudes before (brown/violet) and after repair test (red/green)

The 2019 test results indicated significant reduction in amplitude of PD pulses, conforming the effectiveness of repair.

4. Conclusions

1. With many thousands of machines monitored, some for as long as 30 years with the same method, on-line partial discharge testing has become a recognized, proven tool to help maintenance engineers identify which stator windings need off-line testing, inspections and/or repairs.

2. With over 685.000 test results acquired with the same test methods, what constitutes a winding with low, moderate or high PD has been defined. Tables such as Table II and III enable test users to easily identify with some certainty which machines are likely to suffer from stator groundwall insulation deterioration, with only a single measurement on a machine.

3. The trend in PD over time is still the most reliable way to identify which machines need maintenance. However, since the PD activity is not only affected by deterioration, but also by operating load, voltage, temperature, gas pressure and humidity, these factors must be similar from test to test. Ensuring that these factors are the same when tests are done over the years, will enable the maintenance engineer to detect deteriorating stator insulation at the earliest possible time.

5. References

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