

ADVANCEMENTS IN PARTIAL DISCHARGE ANALYSIS TO DIAGNOSE STATOR WINDING PROBLEMS

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Abstract: On-line partial discharge (PD) testing has been used for over 50 years to assess the condition of motor and generator stator winding insulation systems. In the past decade, advanced hardware and software have enabled superior methods of converting the PD data into practical information about the relative condition of the insulation, as well as determining the root causes of any insulation deterioration. This helps machine owners plan appropriate maintenance.

By performing a statistical analysis of about 19,000 test results in our database, it is clear the type of measuring system, the rated voltage of the stator, as well as if the machine is air or high-pressure gas cooled, has a significant impact on what PD readings may be considered high. Tables are presented which allow, through gross comparisons to similar machines, for a single measurement on a stator to be classed as having high or low PD. In addition, a case study is presented which shows new methods to identify phase-to-phase insulation problems.

INTRODUCTION

The primary purpose of conducting electrical tests and inspections on motor and generator stator windings rated 3.3 kV or more is to identify problems, perform successful repairs, and thus extend the life of the winding. On-line partial discharge testing has been used for decades to help maintenance personnel in this process. Since this test is done without a machine outage, during the test the machine is subjected to normal operating conditions, including mechanical, thermal, chemical, and electrical stresses.

Previous papers have dealt with some aspects of interpreting on-line PD test results [1,2], and a new IEEE Guide is nearing completion that also contains information on interpreting results [3]. This paper discusses recent advances in on-line PD test interpretation. In particular, means of overcoming the limitations imposed by the comparative nature of PD testing are presented. In addition, better ways of identifying PD that may originate in the endwindings or on the circuit ring buses/connections are discussed.

PD TEST SYSTEMS

In order to minimize any ambiguity from varying test methods, the results in this paper are all obtained either using

80pF capacitive couplers that are physically connected to the high voltage lead on either the circuit ring or at the terminals of the motor or generator; or a stator slot coupler (SSC) which are installed in stator slots.

The 80pF capacitors block the 50/60Hz power signal and transmit the high frequency - >40MHz - fast rise-time PD pulse. The test instruments, PDA-IV or TGA, used for all of the results have an input bandwidth of 0.1 to 350MHz and are capable of detecting PD pulses with a rise-time as short as 1ns (typical PD has a rise-time of 1-5ns) [3]. The 80pF capacitive couplers can be installed in two different formats: differential (PDA) and directional (BUS) [4,5]. The differential style (normally used in large hydrogenerators) requires that two couplers be installed at opposite ends of the winding circuit ring. In a differential install, both couplers record machine PD and reject any system noise that arrives simultaneously at the couplers. The directional format (normally used in small hydrogenerators and turbine generators, as well as some motors) requires that the two couplers be installed on the incoming phase bus to the machine terminals, separated by at least 2 meters. In this case, only the coupler near the machine records PD originating in the generator, while the second coupler records system noise.

The SSC is an antenna that is installed adjacent to stator bars operating at high voltage, and thus most subject to PD [5]. Interference is separated from stator winding PD on the basis of pulse shape. The SSC also has the ability to explicitly separate slot and endwinding PD activity, on a pulse-by-pulse basis. This type of sensor is most commonly used in large, hydrogen cooled turbine generators.

INTERPRETING PD MAGNITUDES

Though PD testing has been used satisfactorily for decades, interpretation has often been a difficult task. It is well understood that data taken on the same machine, at the same operating parameters, with the same test setup, are directly comparable. Thus, the most powerful way to interpret the PD data is to trend the activity on the same machine over time. Doubling of the PD every 6 months is an indication that rapid deterioration is occurring [1]. The recurring question has been whether results from different machines, different test setups, and different operating parameters, can be compared with

reasonable assurance. This question is important since PD in inductive equipment cannot be calibrated into an absolute quantity [3,6].

To overcome this problem, 19,000 individual tests were combined into a single database. This data was collected up to the end of 1998. The purpose of this was to statistically analyze what factors, other than insulation system condition, are most important in determining the PD activity [7]. In addition, the analysis was done to determine the statistical range of PD that has been measured from ‘similar’ machines using the same measurement system.

Analysis Process

Unique test records collected from hundreds of operating (on-line) machines were compiled into a single large database. To avoid duplications from a machine, only the latest test results for each machine operating at full load and normal operating temperature were included (about 4500 tests). Since pattern recognition is beyond the scope of this paper, only the four summary variables: +NQN, -NQN (total PD), +Qm, and -Qm (peak PD) were analyzed.

The data was divided by the following criteria: type of sensor installation (PDA or BUS), type of insulation, voltage class, gas coolant, load and temperature.

For analysis it was assumed that each sensor monitors a unique section of the winding and is therefore an independent sample. It was also assumed that the summary variables (Qm and NQN) only reflect true machine PD — the noise cancellation technique of the test setup effectively rejects all of the system noise

Since the purpose of this paper is to establish rough comparisons of PD collected on different machines, and not calibration, these assumptions do not affect the results.

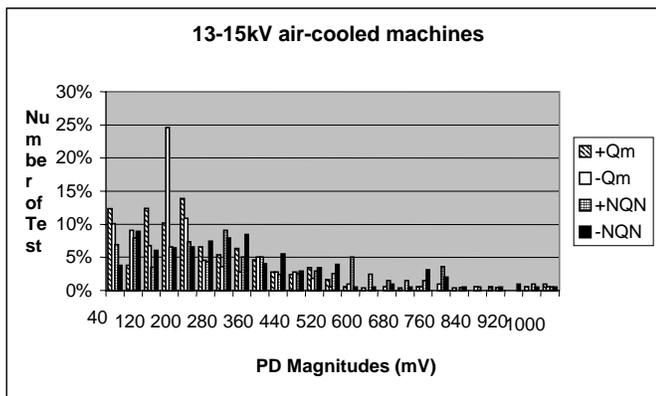


Figure 1 - Probability of occurrence of NQN and Qm levels in air-cooled machines measured with 80 pF couplers.

Table 1 - Distribution of Qm for air-cooled machines using 80 pF capacitive couplers.

Rated V	2-4 kV	6-8 kV	10-12 kV	13-15 kV	16-18 kV	> 19 kV
Avg	89	88	121	168	457	401
Max	2461	1900	3410	3396	3548	3552
25%	2	6	27	9	145	120
50%	15	29	63	79	269	208
75%	57	68	124	180	498	411
90%	120	247	236	362	1024	912

As discussed in [7], an initial analysis showed that:

- air-cooled machines tend to have higher PD than hydrogen cooled machines
- in general, the higher the voltage class of the machine, the higher the PD activity provided the pressure of the gas coolant is constant
- both types of capacitive coupler systems (BUS and PDA) produce similar results
- the type of machine (motor, hydro, turbo), as well as the type of insulation system had little impact on the range of PD levels

Range of PD Levels

For each type of PD sensing system, cooling system and voltage rating, the database was analyzed for the probability of occurrence for each PD magnitude. For example, Figure 1 shows the probability density function of the Qm and NQN PD quantities for air-cooled stator windings rated between 13 and 15 kV, measured with either PDA or BUS type coupling systems. This distribution comes from machines of all ages. Clearly, most machines have low PD activity, and only a few have very high activity.

Table 1 shows the same data in a cumulative fashion. For machines rated between 13 and 15 kV, 25% of the tests have a Qm <9 mV, 50% have a Qm <79 mV, 75% have a Qm <180 mV and 90% have a Qm <362 mV. Thus only 10% of tests for such machines are above about 360 mV. If a single measurement is made on a similar machine, and the PD is 400 mV, then this stator has PD activity greater than about 90% of all similar tests in the database. Clearly such a high reading would warrant further investigation. Similarly, a reading of only 200 mV would not lead to as great a concern about the health of the winding.

Table 1 also shows the cumulative distribution of Qm for stators of other voltage ratings. About 12% of the tests in Table 1 are on turbo generators, 16% are on motors, and 72% of the data are from hydrogenerators.

Table 2 – Distribution of slot Qm in hydrogen-cooled stators using the SSC.

Rated V	13-16kV	17-20kV	21-25kV
Avg	14	11	14
Max	361	243	237
25%	0	0	0
50%	0	0	3
75%	12	7	12
90%	49	33	44

Table 2 shows the range in PD results from SSCs in hydrogen-cooled turbo generators. It is easy to see that the Qm is much lower in hydrogen-cooled machines. A large 22 kV turbo generator that has a Qm in excess of 50 mV has more activity than 90% of similar stators in the database, and thus such a machine needs more testing and/or a visual inspection.

Other tables have been developed and continue to be updated for endwinding PD using SSCs, air-cooled machines measured with SSCs, as well as hydrogen-cooled machines measured with the Bus coupling system. The result of this analysis is that it is possible to objectively determine how significant the PD activity is in any particular winding by grossly comparing its PD levels to those of similar machines.

PHASE-TO-PHASE PD ANALYSIS

Several PD sources may be found in the endwinding part of the winding in a rotating machine. Often the presence of these discharge sources can be related to dust contamination, inadequate spacing, endwinding vibration, poor contact between the semicon and the field-graded area or, as in the case of PD in the groundwall insulation, poor impregnated windings. Although most of the mentioned phenomena give rise to surface discharges, as opposed to discharges internal to the insulation, these phenomena may eventually lead to a phase-to-phase or phase-to-ground failure.

The electrical field distribution within the bulk of the insulation controls partial discharge activity. Since the electrical fields in the endwinding area are phase-to-phase voltage dependent and the electrical fields in the slot area are phase-to-ground voltage, it is possible to distinguish between discharge activity occurring in the slot part and the endwinding part of the winding using Pulse Phase Analysis (PPA). PD interpretation using Pulse Phase Analysis is described thoroughly in [8]. It should be mentioned that discharge activity on the ring bus or between phase leads is also phase-to-phase dependent discharge activity.

Display Method

A PD interpretation tool, AdvancedView, which contains a variety of plots and allows for data manipulation enhances PD interpretation. Specifically, the *Linear Pulse Density* (LPD) plot presents PD pulse magnitude (and pulse repetition rate) as a function of reference phase angle and thus provides a means of Pulse Phase Analysis (PPA). In PPA, the reference voltage usually chosen for a given measurement is the phase-to-ground voltage of the phase subjected to on-line testing. Experience has shown classic PD activity originating in the slot part of the winding to be centered around 45° and 225° with reference to the phase-to-ground voltage. Thus, phase-to-phase dependent discharge activity, such as activity originating from the endwinding area, will be shifted $\pm 30^\circ$ with reference to the phase-to-ground voltage. By creating an LPD plot for each phase of a given machine, with the reference phase-to-ground voltage shifted 120° between phases based on phase rotation, the discharge activity will be presented in the time domain – see Figure 2.

Without entering the area of detailed pattern recognition, it is often possible to distinguish between discharge sources located in the slot area and endwinding area of the winding by detecting at which phase angles the detected discharge is centered.

Case Study

Figure 2 shows a LPD plot for each phase of a 15kV, 165 MVA Turbine Generator with an ABC rotation. The LDP plot for B and C-phases are shifted 120° and 240° with respect to the A-phase reference voltage, showing the discharge activity as it simultaneously occurs in each phase of the stator. The data were acquired at a load of 128MW yielding a winding temperature of 77°C. Figure 2 is an example of Phase-to-Phase dependent discharge activity in the endwinding area. In A-phase, a cluster of negative PD pulses centers at 15° and a cluster of positive pulses at 195° with reference to the A-phase-to-ground reference voltage. Likewise on B-phase, there is a cluster of negative PD pulses at 75° and a cluster of positive PD at 255° with reference to the B-phase-to-ground reference voltage. Each clump is $\pm 30^\circ$ phase-shifted from the classic positions of 45° and 225°. And, in the time domain the clusters in B-phase are perfectly aligned with those detected on A-phase, but opposite in polarity. Furthermore, a minor degree of this activity is capacitively or cross-coupled to C-phase.

The phase position and polarity of the clusters indicate the presence of phase-to-phase dependent discharge activity between adjacent high voltage components of A and B-phases.

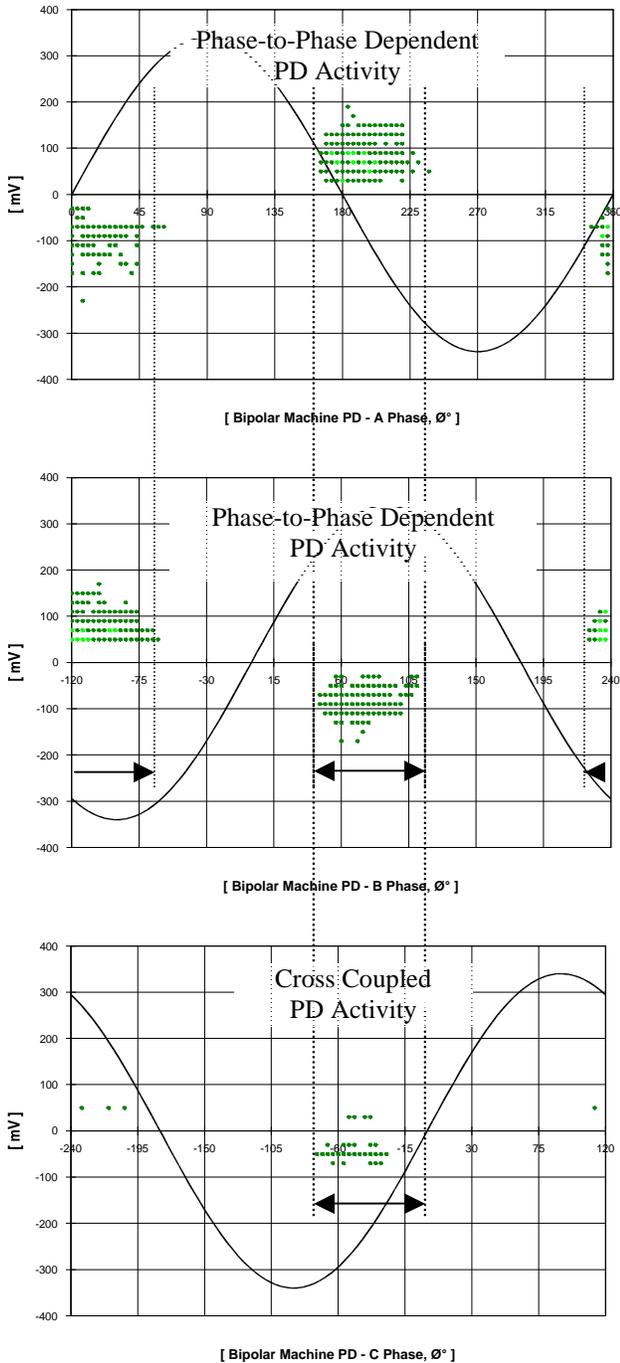


Figure 2 - Phase-to-Phase PD for phases A (top), B (middle) and C (bottom) for an operating generator.

The unit was visually confirmed to have PD in the endwinding between high voltage coils of A and B-phases. There were areas covered with organic residue (“white powder”) due to

discharge activity. This activity may partly have been caused by contamination and partly by insufficient spacing from vibration problems in the endwinding area, due to poorly supported endwindings.

The advantage of pulse phase analysis using phase-shifted LDP plots is evident as it may allow for identification of phase-to-phase voltage dependent PD sources.

CONCLUSION

By comparing the results from a single test to the statistical analysis of a composite of thousands of on-line PD measurements it is possible to determine which stators have significant PD. In addition, by careful analysis of the pulse phase analysis patterns, it is often possible to determine if PD is dependent on phase-to-ground voltage (slot PD) or phase-to-phase voltage (usually endwinding PD).

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