Differences in Stator Winding Partial Discharge Activity Between Manufacturers

Greg Stone and Vicki Warren
Iris Power Engineering
1 Westside Drive, Unit 2 Toronto, Ontario, Canada M9C 1B2
gstone@irispower.com, vwarren@irispower.com

Abstract: On-line partial discharge (PD) testing is widely used as a means to assess the condition of the stator winding insulation system in operating motors and generators. Over the past 15 years over 60,000 test results have been collected on thousands of motors and generators with one test method. This data has been statistically analyzed and in over 200 machines, correlated with the known condition of the high voltage insulation as determined by visual inspection of the insulation. As a result, it is now possible to objectively determine if an insulation problem exists by a single on-line measurement. The paper briefly reviews the test method and the PD levels associated with significant insulation deterioration.

The statistical analysis has also produced some surprising results. It seems there is little difference in the PD level distribution between old asphaltic mica insulation, and modern epoxy mica insulation. Of even greater interest, it seems that stator windings made in the past 10 years by 4 of the world's largest 9 manufacturers have higher PD than those made before 1995. This may be due to the higher design stresses used in modern windings.

INTRODUCTION

Over the past 15 years on-line partial discharge (PD) monitoring has become the most widely applied method to determine the condition of the electrical insulation in motor and generator stator windings rated 4 kV or more. Partial discharges (sometimes also known as corona) are small electrical sparks that occur in deteriorated stator winding insulation systems. PD testing detects most (but not all) of the common manufacturing and deterioration problems, including:

- Poor impregnation with epoxy
- Poorly made semiconductive coatings
- Insufficient spacing between coils in the endwinding area (Figure 1)
- Loose coils in the slot (Figure 2)
- Overheating (long term thermal deterioration)
- Winding contamination by moisture, oil, dirt, etc.
- Load cycling problems

Figure 1: The white powder is the result of high PD activity in the endwinding of a large air-cooled generator where the stator bars in different phases were installed too close to one another.

In general, for machines rated 3.3 kV or above, over 50 years of experience with PD testing in motors and generators has shown that years of warning is given of possible winding failure.

There are many methods available to measure the PD activity in operating motors and generators [1,2]. The electrical techniques 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, but today most machines around the world use 80 pF high voltage capacitors to measure the PD.

A particular challenge with PD measurements is encountered in on-line PD measurements when the motor, hydrogenerator or turbo generator is operating normally. Since the machine is connected to the power system, electrical interference (noise) is often present. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, and/or power tool operation. This noise obscures the PD pulses, and may cause the technician to conclude that a stator winding has high levels of PD, when it is actually the noise. The consequence is that a good winding is incorrectly assessed as being defective, meaning that a false alarm is given suggesting that the winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests, and even today, many feel that on-line PD testing is a 'black art' best left to specialists.

Twenty-five years ago, the North American utility industry (via the Canadian Electrical Association and the Amercian Electrci Power Research Institute) sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff with average training [1]. The PD test that was developed emphasized separating PD pulses from electrical noise pulses. Two different sensors were developed. For motors and hydros of any size, as well as turbo generators up to about 200 or 300 MVA, 80 pF capacitors detect the PD, while blocking the high AC voltage. In these machines noise separation methods depend on comparing the time of pulse arrival between a pair of 80 pF capacitive couplers on each phase and/or analyzing the shape of individual pulses from 80 pF. To maximize the signal-to-noise ratio, and thus also to reduce the risk of false indications, the sensors detect the PD at frequencies of 40 MHz and higher.

For very large turbo generators, where there are high levels of electrical noise both from the power system, as well as relatively harmless sparking that may occur in the stator core, a special antenna called the stator slot coupler (SSC) was developed. The SSC separates PD from noise on the basis of pulse shape [1].

These sensors, together with the associated instrumentation (PDA-IV or TGA), have enabled utilities to assess the winding condition with their own staff. Usually the test is done twice per year, and each machine can be tested in about 30 minutes while operating at normal power levels. From the onset of high PD, there is usually at least two years of warning that there is a high risk of stator winding failure [1]. It is estimated that over 50% of all utility generators rated 20 MW or more in North America been permanently equipped with the required PD sensors. Globally, well over 6000 machines have the required PD sensors, and the test is now widely applied in petrochemical and pulp and paper plants.

A large number of test results have been accumulated in a single database with the widespread application of the same on-line test method. To the end of 2003, over 60,000 test results have been accumulated in a single database, 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. The main purpose of this analysis is to help test users determine which motors and generators have failing stator insulation, allowing them to plan appropriate maintenance. However, some interesting results have emerged on the differences in PD activity both as a function of winding age, and machine manufacturer. This paper discusses these findings.

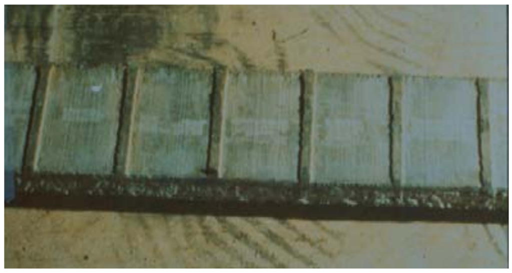

Figure 2: Coil removed for a stator where the coils became loose during operation. The result was that rubbing against the stator core abraded the insulation on the coil sides, and PD ensued.

Partial Discharge Data

As with most PD measurement systems, the number, magnitude and phase position with respect to the 50 or 60 Hz ac cycle are recorded, once PD pulses are separated from the noise pulses. Figure 3 shows a typical plot of the PD from one phase of a motor stator winding. The pulse magnitude is measured in the absolute units of millivolts (mV). From each test, two summary indicators are extracted, representing all the PD pulse data collected. The peak positive and negative PD magnitudes (+Qm and –Qm) represent the highest PD pulses measured in mV with a minimum PD repetition rate of 10 pulses per second. Qm is a reasonable predictor of winding insulation condition. A high Qm measured in a winding compared to a lower Qm in another winding, usually implies that the former winding is more deteriorated.

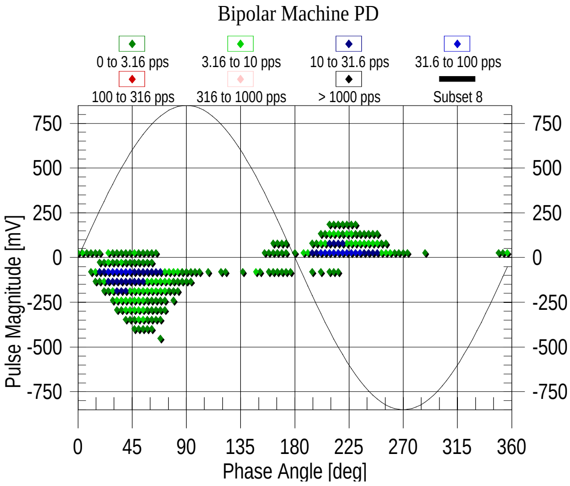

Figure 3: Typical PD data from one phase is plotted with respect to the 60 Hz AC cycle. The vertical scale is the positive and negative PD magnitude in millivolts. The color represents how many discharges are occurring per second at this magnitude and phase position. The higher the PD, the larger is the defect within the insulation. The peak PD magnitude (Qm) for this phase is – 400 mV and +200 mV.

Database to the End of 2003

All test results since approximately 1992 were combined into a single database. This totaled 60,342 tests until the end of 2003. This database contains many repeat tests, sometimes performed over many years. Also, many of the tests were done at different operating conditions. Machine operating conditions can affect the PD activity, and thus add additional variability to the analysis. Therefore the database was carefully reduced such that:

- Only on-line PD readings obtained when the machine was operating at or near full load at normal operating temperature are included
- There is only one test result collected per sensor, thus only the latest reading is extracted
- Tests were discarded where there was reason to believe the measurement was mislabeled.

The result of this culling is that to the end of 2003 there were 4828, 3953, and 2211 statistically independent test results for hydrogenerators, turbo generators and motors, respectively, in the database.

Results

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

- Operating voltage of the stator winding
- Winding age
- Winding manufacturer.

The range in Qm from all the tests for the particular operating voltage was established for each set of the above factors. A cumulative version of the statistical distribution is shown in Table 1. For example, for a 13.8 kV stator in hydrogenerator or pumped storage generator, 25% of tests had a Qm below 38 mV, 50% (the median) of the tests had a Qm below 96 mV, 75% were below 194 mV and 90% of tests yielded a Qm below 392 mV. Thus if a Qm of 500 mV is obtained on an 13.8 kV hydrogenerator, then it is likely that this stator will be deteriorated, since it has PD levels higher than 90% of similar machines. In fact in 220 machines were the stator winding was visually examined after registering a PD level >90% of similar machines, significant stator winding insulation deterioration was always observed.

The effect of a particular factor on Qm was determined by comparing 90 percentile levels between the two data sets composed of, for example, 13.8 kV machines. It was concluded that this factor is important to interpreting results if there was a significant difference in the average and 90% distribution levels of Qm for the two sets.

It is interesting to note from Table 1, that as the rated voltage of a hydrogenerator increases, the 90% level also increases. Clearly results from a 13.8 kV stator should not be confused with those from a 6.9 kV stator.

Table 1: Distribution of Qm for Hydrogenerators with 80 pF Sensors

Open. Volts	6-9 kV	10-12 kV	13-15 kV	16-18 kV
25%	21 mV	42 mV	38 mV	93 mV
50%	38	74	96	213
75%	78	153	194	413
90%	241*	334	392	838

*Variable due to relatively small number of samples

Table 2 illustrates the similar statistical distribution for motors and air-cooled turbo generators where the 80 pF capacitors are installed at the machine terminals (rather than within the stator). Similar tables have also been prepared for hydrogen-cooled machines using either 80 pF capacitors or SSCs as sensors [3]. With these tables, it is now possible for motor and generator owners to determine if the stator winding insulation has a problem with only an initial test. If the PD is higher than that found on 90% of similar machines, then off-line tests and/or a visual inspection would be prudent. Continuous PD monitors would have their alarm levels set to the 90% level.

Table 2: Distribution of Qm for Air-Cooled Stators, 80 pF Sensors on the Terminals

Open. Volts	**2-4 kV**	**6-8 kV**	**10-12 kV**	**13-15 kV**	**>16 kV**
25%	7 mV	17 mV	35 mV	44 mV	37 mV
50%	27	42	88	123	69
75%	100	116	214	246	195
90%	242	247	454	508	615*

*Variable due to strong influence due to a few manufactures

Effect of Winding Age and Manufacturer

An analysis of the statistical distribution of PD for several manufacturers was also performed. Figure 4 shows the results for 13-15 kV air-cooled stators from 11 different OEMs based around the world. Note that the data covers all ages of machines, and all insulation systems made by these manufactures over the years. Clearly there are differences between the manufacturers. For example OEMs D,E,H and J have relatively low PD on average, whereas manufacturer B has relatively high PD for its fleet of machines. The cause of the differences between manufacturers is unknown, but it may be due to different manufacturing processes, electric stress design levels, and assembly methods.

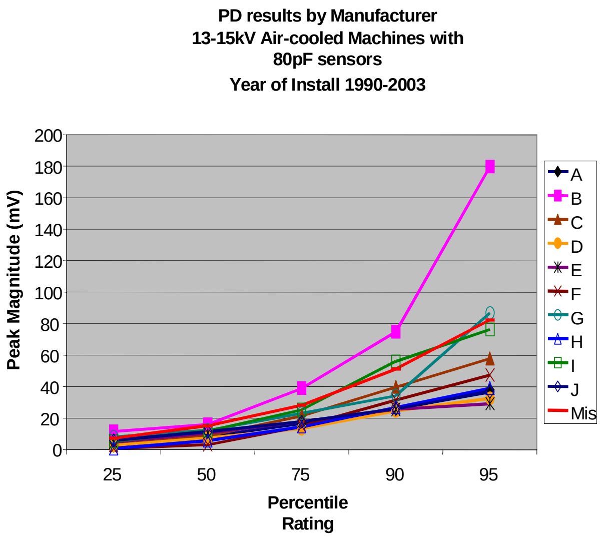

Figure 4: Plot of PD magnitude versus probability of occurrence for 11 major motor and generator manufacturers. Manufacturer B has higher PD than most other manufacturers of 13.8 kV motor and generator stators.

One surprising result from the statistical analysis of the database was the distribution of Qm as a function of winding age. Figure 5 illustrates the PD results in the database from machines that were from one year old to greater than 30 years old. There is no consistent trend – which is surprising since one would normally assume that older windings would be more deteriorated and thus have higher PD levels. Figure 5 implies that both older windings and new windings can have about the same high PD activity. In fact, 4 brands of air-cooled windings manufactured in the past 10 years seem to have higher PD activity than older machines. This may reflect the fact that modern windings tend to operate at higher thermal and electrical stresses than older machines [1,4]. Other explanations for the inconsistent pattern of PD versus winding age may include the observation that manufacturers of machines have a learning curve to climb as they adopt new design and manufacturing techniques, or that machine operators are continuously oscillating between proactive and breakdown maintenance strategies, depending on management policies.

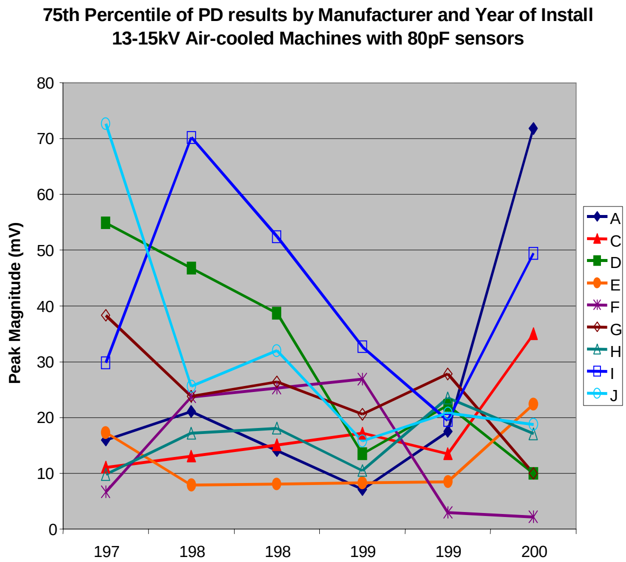

Figure 5: PD activity for 9 motor and generator manufacturers as a function of the year the stator winding was built or rewound. The PD tests were done in 2003. For some manufacturers, the PD activity for machines made in the past 10 years is higher than machines they made more than 10 years ago.

Conclusions

1. With thousands of machines monitored for as long as 25 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. The majority of generators in North America are routinely PD tested on-line.

2. With over 60,000 test results acquired with the same test methods, what constitutes a winding with low, moderate or high PD has been defined. Tables 1 and 2 enable test users to easily identify with some certainty which stators are likely to suffer from groundwall insulation deterioration, with only a single measurement on a machine. Similar tables are available for hydrogen-cooled turbine generators.

3. The practical importance of Tables 1 and 2 is that if one applies PD sensors to a machine, and in the first measurement one obtains a Qm that exceeds the 90 percentile of the relevant Qm distribution, then one should be concerned enough at the PD level to take action such as more frequent testing and/or off-line tests and inspections at the next convenient machine shutdown.

4. Some machines made in the past decade exhibit higher PD activity than machines that are considerably older. Newer machines and rewinds do not necessarily have more reliable insulation.

References

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