Trends in stator winding partial discharge in air-cooled generators

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On-line partial discharge testing has become a recognized and proven tool to help maintenance engineers determine which stator windings require off-line testing, and/or repairs. The author reviews progress in this field, and demonstrates how past experience has made it possible to make a number of predictions with confidence concerning the condition of stator windings.

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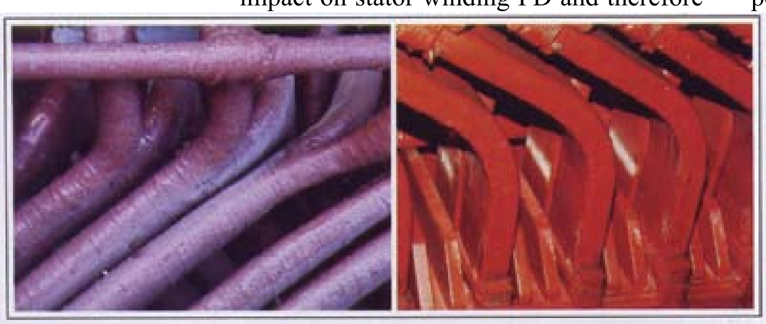
Since its inception as a diagnostic test in rotating machines, partial discharge (PD) testing has been used to assess the condition of the stator winding insulation in hydro generators rated at 3 kV and above. The preferred test is carried out on-line, as no machine shutdown is required and the stresses acting on the winding are those that occur in service. Historically, the trend in activity in older windings has been one of a gradual rise after many years of relatively stable discharge levels.

In the past few years there have been reports that modem air-cooled stator windings are suffering from premature deterioration of the insulation. Although individual reports have been presented as case studies these are too few to provide any statistical basis for a detailed analysis. This has resulted in claims that the situation is normal, and does not merit concern.

The availability of a large database of PD data collected from more than 2000 air-cooled machines allows for an objective investigation of any change in the rates of deterioration. Factors such as machine voltage class, manufacturer, machine type, insulation type and age of the stator winding can all be examined, to determine their impact on stator winding PD and therefore the potential effect on winding life.

The white powder is a result of high PD activity in the endwinding (left) and at the interface between stress control materials (right) of large air-cooled generators. In one case, the stator bars in different phases were installed too close to one another, in the other, the 'connection' between materials has failed.



A coil removed from an 80 MVA hydro generator stator, where the coils became loose during operation. The result was that rubbing against the stator core abraded the insulation on the coil sides between the core vents, and PD ensued.

From this analysis it is apparent that there arc differences between manufacturers, particularly in the most common voltage range of 13-15 kV, and that there has been a noteworthy pattern of increased discharge activity from some manufacturers over the past ten years. The assumption from this more objective analysis is that the higher design and operational stresses imposed on stator windings in the past decade may be resulting in more rapid deterioration of insulation systems. Thus, operators need to be aware of the impact of the design temperature and voltage stress limits when purchasing windings, and their ultimate impact on prospective winding life.

Background

Over the past 15 years, on-line partial discharge (PD) monitoring has become one of the most widely applied methods to determine electrical insulation condition in machine stator windings rated at 3 kV or more. Partial discharges (sometimes referred to as corona) can be defined as small electrical sparks which occur in deteriorated stator winding insulation systems. PD testing detects most, but not all, common manufacturing and deterioration problems, such as:

- poor impregnation with epoxy;
- poorly manufactured semi-conductive coatings;
- insufficient spacing between coiling in the endwinding area (Fig. 1);
- loose coils in the slot (Fig. 2);
- overheating (long-term thermal deterioration);
- winding contamination (by moisture, oil, dirt, and so on); and,
- insulation problems caused by load cycling.

By and large, more than 50 years of experience with PD testing in motors and generators (rated 3 kV or above) indicates that possible winding failure can be detected some years in advance.

There are many methods available to measure the PD activity in operating motors and generators [Stone, *et. al,* 2004']. Electrical methods rely on monitoring the current or voltage pulse created whenever a partial discharge occurs. Early practices measured PD pulse currents using a high frequency current transformer at the neutral point. However, at present, 80 pF high voltage capacitors are used when measuring PD in most motors and generators.

On-line PD measurements (measurements taken during normal machine operation) can be somewhat challenging; as the machine is connected to the power system, electrical interference (noise) is often present. Corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, and/or power tool operation, are all sources of electrical interference. Such interference obfuscates PD pulses. Consequently, a technician may conclude that a stator winding has high levels of PD, when, in fact, it is noise. This can result in a good winding being incorrectly assessed as being defective. In effect, a false alarm is given, suggesting that a winding is bad, when it is not. False alarms such as this reduce the credibility of on-line PD testing, and, at present, many still feel that PD testing during normal machine operation is best left to specialists.

Twenty-five years ago, the North American utility industry (via Canadian Electricity Association and the Electric 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 [Stone, *et. al,* 2004']. The on-line PD test that was developed emphasizes PD pulse and electrical noise pulse separation. By comparing the pulse arrival time between a pair of 80 pF capacitive couplers on each phase, and/or by analysing the shape of individual pulses from these sensors, noise and PD pulses can be separated. The sensors detect the PD at frequencies of 40 MHz and higher, in an effort to maximize the signal-to-noise ratio, thus reducing the risk of false indications.

This on-line PD testing method has enabled utilities to use plant staff to evaluate winding condition. Accordingly, at present in North America, it is estimated that considerably more than 50 per cent of utility generators rated 20 MVA or above have been permanently equipped with the necessary PD sensors; worldwide, more than 6000 machines have the required sensors.

Partial discharge data

With the widespread application of the same on-line test method, numerous test results have been accumulated in a single database. By the end of 2005, the database consisted of more than 80 000 results, all of which can be accessed to extract information to help test users interpret PD results better. The database was carefully condensed so that:

- only the most recent on-line PD readings obtained when the motor or generator was operating at or near full load, at normal operating temperatures, are included;
- there is only one test result collected per sensor; and,
- any results from off-line tests and investigation were discarded.

A simple statistical analysis was applied to the database to provide information to assist test users in determining which machines have failing stator insulation, allowing plant personnel to plan suitable maintenance. Even so, some interesting results have been recorded on the variance in PD activity as a result of winding age and machine manufacturer.

Standard for most PD measurement systems, the number, magnitude and phase position of discharge activity with respect to the 50/60 Hz AC cycle are recorded; however, with this particular test, PD pulses are separated from the noise pulses before the data are recorded. Fig. 1 shows a typical plot of the PD recorded from one phase of a generator stator wind ing. Note that the pulse magnitude as displayed is using the unit of millivolts (mV).

Two summary indicators are extracted from each valid test; these represent all the collected PD pulse data. The peak positive and negative PD magnitudes (+Qm and -Qm) denote 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. Increased winding deterioration usually correlates to the winding with a higher Qm, when compared with another winding with a lower Qm.

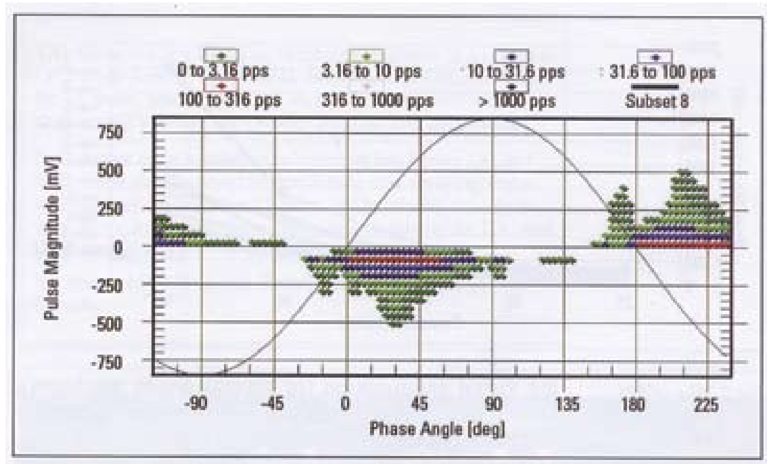


Fig. 1 Typical PD data from one phase is plotted with respect to the 50/60 Hz AC cycle. The vertical scale is the positive and negative PD in millivolts. The colour represents how many discharge are occurring per second at this magnitude and phase position. The higher the PD, the larger is the defect within the insulation. The PD magnitude (Qm) for this phase is about 500 mVfor both positive and negative activity.

Table 1: Distribution of Qm for hydro generators with 80 pF sensors

Operating Volts (%)	6-9 kV	10-12 kV	13-15 kV	16-18 kV
25	4 mV	38 mV	34 mV	62 mV
50	30	78	94	162
75	56	163	195	357
90	210*	376	383	798

* Variable because of a relatively small number of samples

Table 2: Distribution of Qm for air-cooled stators, 80 pF sensors on the terminals

Operating Volts (%)	2-4 kV	6-8 kV	10-12 kV	13-15 kV	16-18 kV*
25	7 mV	16 mV	28 mV	39 mV	47 mV
50	24	49	74	98	98
75	86	129	177	226	210
90	274	276	401	461	540

* Variable because of the strong influence of a few manufacturers

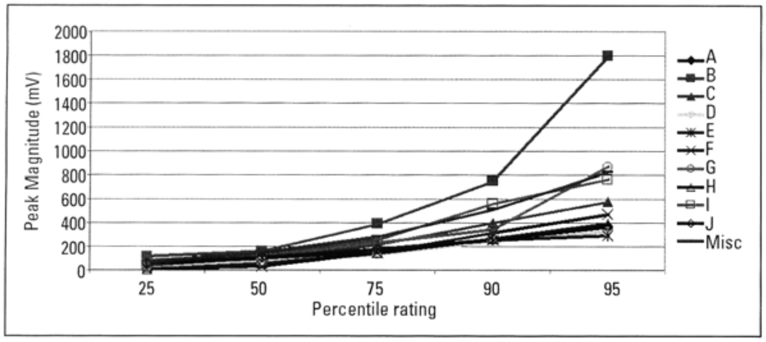


Fig.2.Plot of PD magnitude versus probability of occurrence for ten major motor and generator manufactures. Manufacturer B has higher PD than most other manufacturers of 13-15 kV motor and generator stators.

Analysis of PD database

The database was analysed to determine how Qm is affected by several factors, including:

- sensor installation;
- winding age; and,
- winding manufacturer.

For each factor, the range in Qm from all the tests for the particular operating voltage was established. Table 1 gives a sample of the statistical distribution. For example, for 13-15 kV stators in hydro generators or pumped-storage units, 25 per cent of tests had a Qm of less than 34 mV, 50 per cent (the median) had a Qm of less than 94 mV, 75 per cent were below 195 mV, and 90 per cent of the tests yielded a Qm of less than 383 mV. Hence, if a Qm of 500 mV is obtained on a 13.8 kV hydro generator, it is likely that stator winding deterioration has occurred, since it has PD results higher than 90 per cent of similar machines. Indeed, significant insulation deterioration was observed during visual examination (of several dozen machines), after registering a PD level >90 per cent of similar machines [Maughan, 20062]. Of particular interest is Table 1: note, as the rated voltage of a winding increases, the 90 per cent (or alarm) level increases as well. Clearly, results from a 13.8 kV stator should not be confused with those from a 6.9 kV stator.

Table 2 shows a similar distribution for motors and air-cooled hydro and turbo generators of less than 18 kV, where the 80 pF capacitors are installed at the machine terminal (rather than within the stator). Data collected from hydrogen-cooled machines and those with other types of PD sensors have generated similar Tables.

These tables, together with initial testing, allow machine owners to assess whether or not the stator winding insulation is defective. If PD results prove to be greater than that found on 90 per cent of similar machines, then off-line and/or visual inspection are greatly encouraged. Note, continuous PD monitors should have their alarm levels calibrated to the 90 percent level.

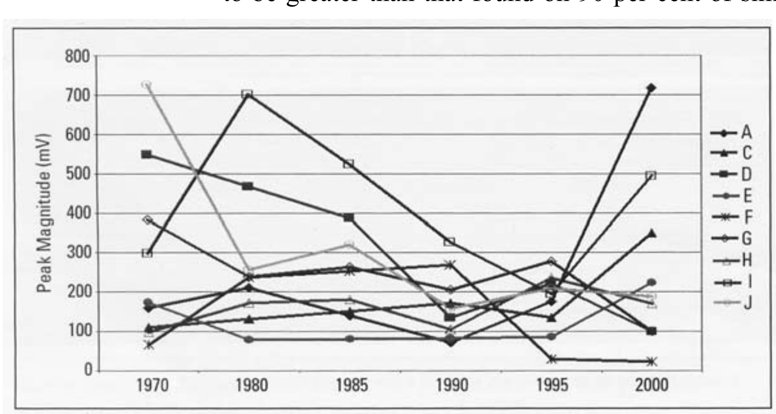


Fig. 3. PD activity for nine motor and generator manufacturers as a function of the year the stator winding was built or rewound. The PD tests were done in 2003. For some manufacturers, the PD activity for machines made in the past 10 years is higher than machines they made more than 10 years ago.

Effect of winding age and manufacturer

An analysis was also carried out on the statistical distribution of PD for several manufacturers. Fig. 2 shows the results for 13-15 kV air-cooled stators from ten original equipment manufacturers (OEMs) in different parts of the world. The data include all machine ages, as well as all insulation systems manufactured by these OEMs, spanning several years. Undoubtedly, there are differences between the manufacturers. For example, OEMs E, H and J have, on average, relatively low PD, whereas manufacturer B has relatively high PD for its large number of machines. The source of iliese discrepancies is unknown, but different manufacturing processes, electric stress design levels, and assembly methods, may contribute. At present no study has been carried out which that relates these results to long-term stator winding reliability.

Of particular interest was a surprising result from the statistical analysis of the database: the distribution of Qm as a function of winding age. Fig. 3 shows the PD results of the 75th percentile from machines that ranged in age from 5 to 30+ years. There is no consistent trend, which is surprising as it would normally be assumed that older windings would have deteriorated more, and therefore have greater PD levels. However, based on Fig. 3, it can be inferred that both old and new windings can have similar high PD activity. In fact, four brands of air-cooled windings manufactured in the past 10 years seem to have higher PD than older machines by the same manufacturer. This may reflect the fact that modem windings tend to operate at higher thermal and electrical stresses than older machines [Griffith, *et. al,* 20003].

There are other conclusions for the inconsistent pattern of PD versus winding age: OEMs have a learning curve to climb as they implement new design and manufacturing techniques; or, machine operators are continuously alternating between proactive and breakdown maintenance strategies, determined by management policies.

Maintenance implications

Based on the discussion above, what are the maintenance implications of these findings? First it is important to realize that the advances in insulation design and materials do not necessarily translate into any improvements or extensions of reliable, trouble-free operation for extended periods. While such performance should be achievable, the improvements in materials coupled with the need for competitive pricing has resulted in design and installation with little margin for error. Pressures to increase voltage stresses (reduced insulation build), temperatures (less copper), reduced inactive copper (lower end winding height) have resulted in the potential to accelerate aging greatly. Margins for error are almost non-existent, and when some parameter has been compromised or miscalculated, then reliable operation and long life are jeopardized. Thus, there are many instances where newly rewound machines have shown much poorer performance and reliability than the lifetime performance of the windings they replaced.

One means available to the plant/owner operator to help reduce the chances of premature end of life is through the specification and procurement process.

By being aware of potential problem areas, it is possible to require a vendor to demonstrate good winding design and manufacture contractually. This can be achieved through built-in tests and checkpoints in the process, and thereby reduce the chances of acquiring a winding from a supplier that will have less than expected life and performance. Such tests and reviews of similar designs will provide a means to evaluate different suppliers on equal grounds and serve as a means to identify and eliminate the poor ones.

Another factor which should not be overlooked in relation to maintenance is the need to monitor the winding regularly. While in older windings, excess margins in design, as well as materials were more forgiving of marginal installation, today's windings demand close monitoring and, when indicated, inspection to provide many years of life. As demonstrated above, this can be achieved without taking the winding out of service through the collection and analysis of on-line data such as partial discharge activity. This is most crucial during the first year or so of operation, when early signs of impending problems can be used to formulate an appropriate maintenance strategy to forestall early failure. It is particularly important to detect any tendency for winding movement, which is most prone to occur in the initial operation of any modem winding. It can also reveal possible deficiencies in insulation consolidation and its ability to operate at the designed temperatures. As we have seen here, the use of on-line partial discharge activity can provide that information based on historical data and the findings derived from that, and through direct comparison with other results, provide an immediate assessment of relative condition.

Conclusions

Thousands of machines have been monitored for as long as 25 years, using the same method. As a result, on-line partial discharge testing has become a recognized and proven tool to help maintenance engineers ascertain which stator windings require off-line testing, inspection, and/or repair.

Using the same test methods, more than 80 000 test results have been obtained. Consequently, what constitutes a winding with low (<50 per cent), moderate (50-75 per cent) or high (>90 per cent) PD has been determined. Tables 1 and 2 allow test users to identify easily (with only a single measurement on a machine), with some certainty, which stators are likely to suffer from groundwall insulation deterioration.

The practicality of Tables 1 and 2 enable users to determine whether or not further action should be taken. If a machine has been equipped with PD sensors and in the first measurement a Qm that exceeds the 90th percentile of the relevant Qm distribution is obtained, then further action is encouraged. This can include more frequent testing and/or off-line tests, and inspection at the next convenient machine shutdown.

Some machines manufactured in the past decade show signs of higher PD activity than machines which are much older. Thus, new machines and rewinds do not necessarily have more reliable insulation. Diligence in specifications, production tests and installation practices are necessary to maintain winding reliability and longevity. ◊

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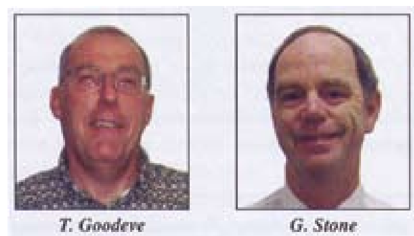
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