How to Identify Stator Insulation Problems Using On-line Partial Discharge Analysis

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ABSTRACT

On-line partial discharge (PD) testing of the stator winding of hydro generators, turbine generators, and large motors has been performed for half a century. However, questions remain on how to best use PD data to identify stator insulation problems. This paper analyses why one cannot rely on an absolute PD magnitude to assess the insulation condition of rotating machines. Some of the factors which affect the diagnosis of stator insulation problems include the following:

- **PD calibration problems in rotating machines**
- **Bandwidth of the PD detector**
- **PD types and locations**
- **Differences among machines and PD measurements**

The paper describes how these factors influence the assessment of stator insulation condition. PD trend analysis is recommended as the best way to identify machine insulation problems and is well demonstrated by some case studies. Precautions in using a PD database to assess the likelihood of insulation failures are given. The paper concludes that a significant increase in PD activity within a certain period of time is a sign of severe insulation deterioration.

1. INTRODUCTION

As competition increases in the electric power generation market, utilities and other power producers are facing increasing pressure to reduce the amount and cost of maintenance and testing efforts yet increase the availability of the power generation equipment. Consequently many power generators are moving away from OEM maintenance schedules due to their conservative nature and instead are now striving to do the right maintenance on the right equipment at the right time.

A vital step in the maintenance strategy of power generators is to “close the loop” on their stator testing and maintenance efforts, as shown in Fig. 1. They need to ensure that their efforts do not stop at purchasing suitable test equipment. The power producers must then use the instruments to acquire data, analyze the data to turn it into useful information, use the information to make operation and maintenance decisions, take action based upon those decisions and then repeat the process to determine the effectiveness of their efforts.

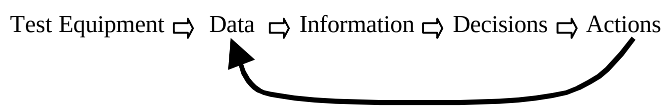

Fig. 1 Closing the loop on diagnosing insulation condition.

On-line partial discharge (PD) testing has been used to provide useful information to diagnose and monitor the integrity of stator winding insulation of large generators and motors for half a century [1]. A number of on-line PD instruments and measurement systems for rotating machines are now available. Some individuals and companies have reported good success in interpreting PD data and taking action on rotating machines [2]. However, questions remain on how to assess stator insulation problems using PD test data.

While on-line PD testing is widely used today for condition-based maintenance of rotating machines, many users still ask the question, “How do I know when my machine has a problem?” Does a rotating machine with higher PD readings fail more quickly than one with lower PD readings? Can one use an absolute PD magnitude to turn on a red light for stator insulation deterioration? These questions are critical to successful use of on-line PD testing technology.

Naturally, one expects that a criterion of an absolute PD magnitude exists for evaluating stator winding insulation condition. Unfortunately, unlike many other types of high voltage equipment (such as cables and switchgear), a criterion for acceptable PD does not exist for rotating machines due to PD calibration problems.

This paper describes why an absolute PD criterion cannot be established for rotating machines. How to identify stator insulation deterioration effectively and reliably will be discussed and demonstrated with some case studies.

2. WHAT INFLUENCES ASSESSEMENT OF STATOR INSULATION CONDITION BASED UPON PD MAGNITUDES?

The first step in the diagnostic procedure is to obtain PD data. There are various types of on-line PD testing systems available. Several PD instruments have been developed that are good at detecting the PD and rejecting noise [3] [4] [5] [6] [7] [8]. Common types of PD data presentation are pulse height analysis graphs, phase resolved graphs, normalised quantity numbers (NQNs), polar graphs, etc. However, there are difficulties in setting an alarming threshold based upon the data presentation. The difficulties are caused by the following factors:

- **PD calibration problems in rotating machines**

A PD test specification for rotating machines has not been established, although such specifications exist in most of high voltage equipment [9]. The reason for this is the lack of an effective calibration technique for PD measurement in rotating machines. Since PD pulses occurring at PD sources cannot be directly measured at PD sites, a calibration of PD measurement at machine terminals is required. The "calibration" is to establish a scale relationship between readings of a PD measurement system at the machine terminals and the actual magnitude of PD occurring at PD sites within the stator winding.

The conventional PD calibration approach, as stated in IEC 270 and ASTM D1868, is to inject a pulse with a known amount of charge into the machine terminal and to determine the magnitude of the response produced by the PD measurement system in response to the injected pulse. The calibration pulse with a voltage V is injected into the winding via a calibration capacitor C. The injected charge is $Q = CV$. Then, a scale relationship between the injected charge Q and readings of the PD measurement system can be established. This conventional PD calibration approach is not what is defined for PD "calibration" of rotating machines in the above paragraph.

The conventional PD calibration method is not applicable to rotating machines, since a complete stator winding cannot be treated as a pure lumped capacitor. The stator winding actually is a complex circuit network with distributed inductance, capacitance and resistance. The simple relationship $Q = CV$ cannot be applied to rotating machines.

When a PD pulse propagates through the stator winding, the stator winding can attenuate the PD pulse particularly in high frequencies and cause resonance of the PD pulse [10] [11] [12]. The PD pulse actually occurring within the stator winding is measured and calibrated at the machine terminals. Therefore, the PD pulse measured at the machine terminals may have a different magnitude and waveform than the original PD pulse occurring within the stator winding, depending on the nature of the stator winding [13]. Therefore, it is difficult to accurately assess stator insulation condition using the PD magnitude measured at the machine terminals.

- **PD detectors.**

PD detectors having various frequency bandwidths and centre frequencies are commercially used. These PD detectors may produce different PD output values for the same PD event. Further more, when the PD detector is coupled to the stator winding, a frequency spectrum combining the winding frequency spectrum and the detector frequency spectrum is produced. The combined frequency spectrum can either increase the PD magnitude (when the detector is within the peak values of the winding frequency spectrum) or decrease the PD magnitude (when the detector is within the valley values of the winding frequency spectrum) [14]. After the PD pulse propagates through the winding and goes into the detector, the original PD pulse has been distorted. The PD pulse appearing at the output terminal of the detector depends upon both the winding frequency spectrum and the detector frequency spectrum.

- **PD types and PD locations**

PD occurs at various locations in the stator winding and in various types. For example, PD occurs

- at the interface between the winding and the slot (slot discharges);
- within groundwall insulation;
- at the interface between copper conductors and groundwall insulation;
- in the endwinding region.

The degree of threat to the insulation system of rotating machines depends upon the PD type and location. The same PD magnitude with different PD types and locations in the stator winding may result in different degrees of threat to the lifetime of the insulation system. For example, the same magnitude of PD occurring within the internal insulation (groundwall discharges) and on the insulation surface (phase-to-phase discharges) results in different degrees of damage to the insulation system. Hence, evaluation of stator winding insulation by considering only the PD magnitude without considering the nature and locations of PD is not reliable.

- **Differences among machines and PD measurements.**

There are considerable differences among rotating machines in specification, manufacturing, QA and acceptance testing, installation, operation, maintenance, environment, etc. Even for the same manufacturer and the same type of rotating machines, differences in installation, operation, and maintenance may cause different degrees of insulation degradation and result in varying PD levels. In addition, there are differences among measurements caused by varying operating conditions (e.g. temperature, load, and humidity) and varying measurement settings (e.g. instrument types, gain settings). Therefore, a direct comparison of PD readings among different rotating machines is difficult.

In summary, all of the above factors can influence the absolute PD readings. Therefore, it is not reliable to give a warning of insulation failures based upon the absolute PD magnitude.

3. HOW TO IDENTIFY STATOR INSULATION DETERIORATION

Several approaches have been used to assess insulation condition of rotating machines. For example,

- neural networks/pattern recognition technique has been applied to recognise PD problems[15];

- compare PD test data to a PD database;

  This approach sets an alarm level by comparing the detected PD readings to PD data in a database. For example, if the PD level is within a range of 10% of the highest PD readings in the database, the insulation may be considered bad. If the PD level is within a range of 75% of the low PD readings in the database, the insulation is usually regarded as good. One should be cautious when using this PD database approach to set alarm levels since it uses the absolute PD magnitude to assess the condition of stator winding insulation.

- compare PD test data with similar machines in the same plant;

  This comparison gives a relative condition among rotating machines (i.e. which one is better and which one is worse). However, as previously discussed, due to differences among machines, even those with identical design made by the same OEM, and in the same operating and measurement parameters, this method may not always produce reliable results.

- compare PD test data with previous readings on same machine.

  Since the major strength of on-line PD testing is the trending ability [16], this approach is usually regarded as the best way to diagnose insulation problems using on-line PD data. If a significant increase in PD activity within a certain period of time is detected, further actions should be taken. As a general rule of thumb, PD activity doubling in six months or less is often a sign of severe insulation deterioration.

Once machine problems have been identified, the next question is what action should be taken. If the machine under test is in good condition, no action would be taken. Although nothing is done, consciously doing nothing is different from ignorantly doing nothing. Consciously doing nothing means that you know the machine condition and confidently chose not to take action rather than just doing nothing out of ignorance and hoping for the best. If the machine under test is in bad condition, one should take further testing and inspection to corroborate whatever type and degree of insulation deterioration indicated by PD test data. For example,

- power factor tip-up tests for internal delamination;
- wedge tightness/visual inspection for slot discharge or bar looseness;
- visual inspection for endwinding discharge.

4. CASE STUDIES

The following case studies demonstrate trending of PD activity in assessing the insulation condition on operating machines. The first case compares PD readings of two "sister" motors in a power plant.

Motor A: Motor A is a 6.9 kV, 7000 HP induction motor used for induced draft fan in a power plant. Motor A had Duraguard, class F insulation in its stator winding and was rewound in 1994. An on-line PD monitoring system from ADWEL International was installed on the motor after rewinding. The trending graphs of the NQN values and of the maximum PD magnitude are shown in Figs. 2 and 3. The NQN (Normalised Quantity Number) value is a measure of total PD activity in the stator winding.

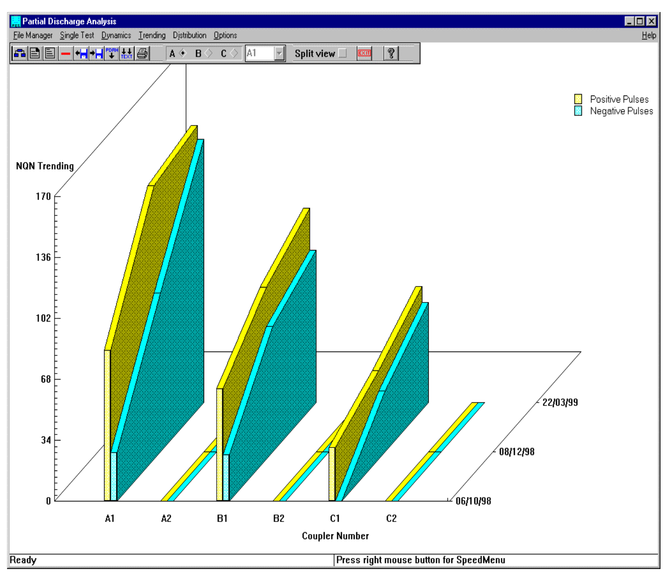

Fig. 2 Trending of + NQN and –NQN values of motor A.

In Fig.2 above, the NQN value in phase C increased more than three times from October 1998 to March 1999. In Fig. 3 below, the maximum PD magnitude in phase C increased more than two times over the same period of time. This motor failed in service during start-up due to insulation breakdown. The motor was taken out service and a visual inspection was conducted. The visual inspection confirmed that there was a puncture in the groundwall insulation leading to the insulation failure. The location of the insulation failure is at the interface between the slot portion and the endwinding portion, as shown in Fig. 4. The motor has been rewound since the insulation failure.

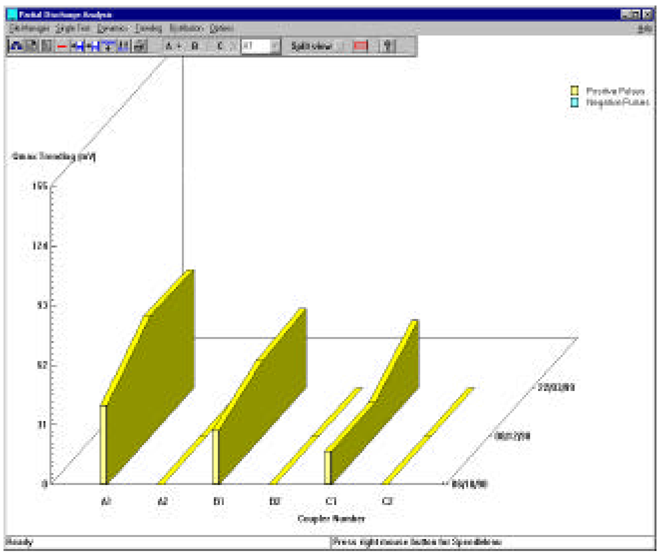

Fig. 3 Trending graph of the positive maximum PD magnitude of motor A.

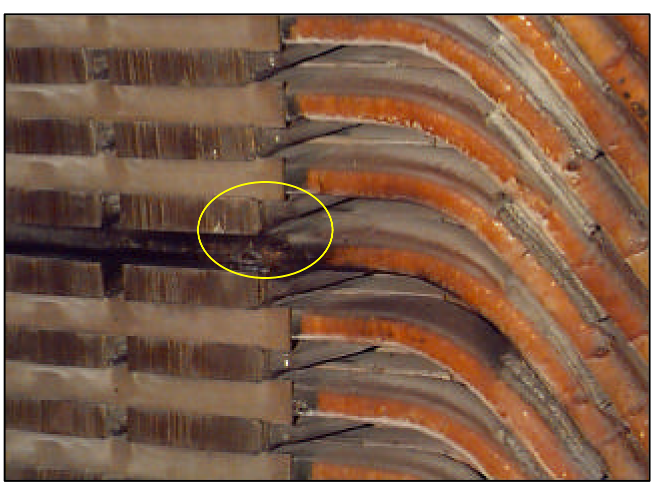

Fig. 4 Visual inspection of the insulation failure.

Motor B: Motor B is an identical "sister" motor operating at the same site. Motor B was equipped with the same on-line PD monitoring system in 1994. The trending graphs of the NQN values and of the maximum PD magnitude are shown in Fig. 5 and in Fig. 6. Comparing Figs. 2 and 3 and Figs. 5 and 6, motor B had higher NQN values and higher PD magnitudes than motor A. Yet motor B with the higher PD activity has been operating well while motor A with the lower initial PD activity subsequently failed in service.

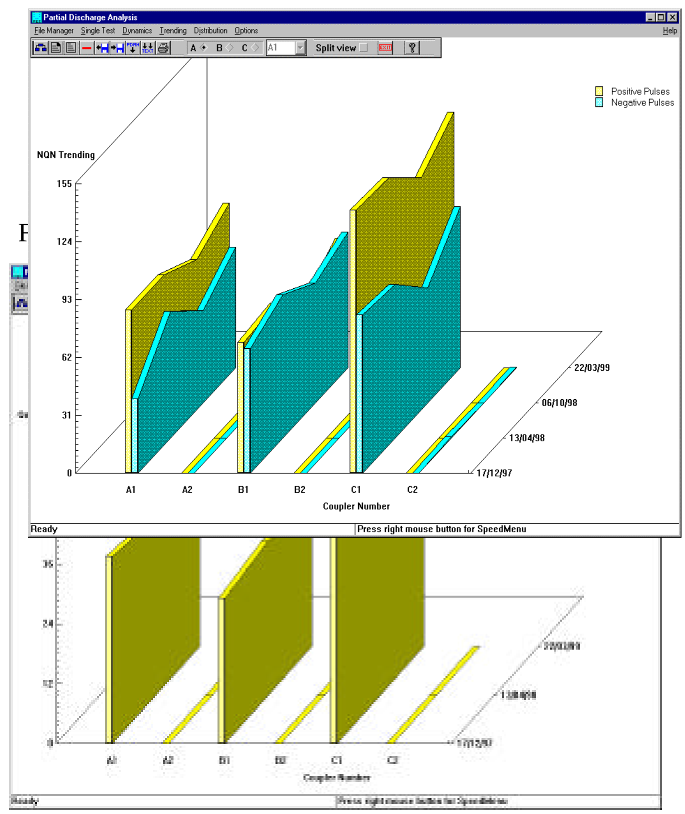

Fig. 6 Trending graph of the positive maximum PD magnitude of motor B.

A comparison of the maximum PD magnitude in motor A and motor B is listed in Table 1 and Table 2. One might expect that the motor with the higher PD readings would fail first. It did not actually. This is because the PD activity in this motor was stable, even though it was relatively higher than the other motor. Stable PD activity over time indicates that insulation deterioration has not progressed much. A significant increase in PD activity within a certain period of time indicates that the rate of insulation deterioration is accelerated (i.e. a sign of the rapid progress of insulation deterioration that could lead to insulation failures).

Table 1 Comparison of positive maximum PD magnitude of motor A and motor B

Test Date	Oct. 1998	Dec. 1998	March 1999
Motor A	20	36	48
Motor B	62	56	65

Table 2 Comparison of negative maximum PD magnitude of motor A and motor B

Test Date	Oct. 1998	Dec. 1998	March 1999
Motor A	0	26	30
Motor B	45	38	48

The second case involves a 730 MW, 20 kV steam turbine generator. During a start-up in 1993 the generator was extremely overheated due to a failure of the automatic hydrogen cooling system. The stator winding temperature reached 165 C° before the cooling failure was discovered and the generator was immediately shut down. The wedges, filler blocks and bracing ties of both the stator and rotor were melted or burned black beyond repair. The class B thermoplastic stator insulation, however, did not fail. The opinion of many experts at the time was that, if restarted, the stator winding would most likely fail and should be rewound immediately. The confidence to continue running the generator was lost.

After examining the data from the off-line stator insulation tests, the utility decided to install an on-line condition-monitoring system for the stator insulation and continue operating the generator with the same stator winding. A PDA system from ADWEL International was installed during the re-wedge outage in 1993 to enable future monitoring of the partial discharge activity in the stator winding.

The utility successfully restarted the generator and began closely monitoring the on-line PDA readings to detect any signs of severe insulation degradation. The first on-line PDA readings were taken in July 1993, as shown in Fig. 7 <2>. The PD levels were not alarmingly high. This suggests that the insulation system was still in good shape, even though the generator had been overheated. The confidence to continue running the generator was re-established. The utility has performed periodic PDA testing on the generator to monitor any progress of insulation deterioration since 1993. The PDA trend was steady from 1993 to 1999 and consistent with the power-factor test data. A recent PDA reading taken in August 1999 is shown in Fig. 7 <1>. There is negative pulse predominance in the curves. This is a sign of internal PD occurring closer to the interface between the copper conductor and the groundwall insulation.

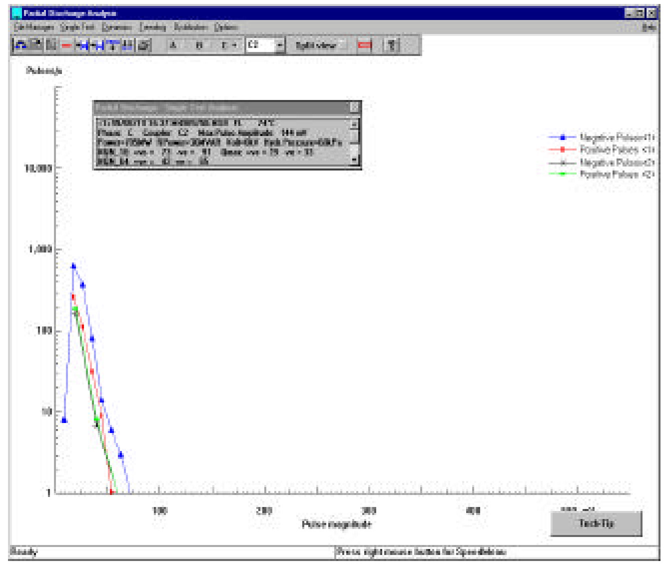

Fig. 7 Comparison of PDA readings taken in 1999 <1> and in 1993 <2>.

The low PD activity initially detected by the PDA system supported the utility's decision to continue operating the generator with the overheated stator winding. Consistent PDA readings from 1993 to date have given the utility confidence to keep running the unit and to maximize its lifetime. The avoided cost of the emergency rewind was millions of dollars. This case demonstrates that insulation deterioration has not progress much if the PD trend is stable, that is, the threat of machine insulation failure is not great.

5. CONCLUSIONS

An absolute PD testing specification for rotating machines cannot be established due to the lack of a valid PD calibration technique. It is not reliable to give a warning of severe stator insulation deterioration based upon an absolute PD magnitude. Therefore, one should be cautious when using a PD database to set alarm levels, since this approach is based upon an absolute PD value. It may be useful to compare PD readings of a rotating machine with those identical to it in a PD database to determine relative stator insulation condition among similar types of rotating machines.

The trending of PD activity is the best approach to identify severe stator insulation deterioration. A significant increase in PD activity within a certain period of time is a sign of severe stator insulation deterioration. The rate of increase in PD activity is a key factor to determine if a warning should be given.

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