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Identification of Stator Insulation Deterioration Using On-line Partial Discharge Testing

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1. INTRODUCTION

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]. However, questions remain on how to assess stator insulation problems using PD test data. Many users still ask the question, "How do I know if 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.

What is a warning sign for severe stator insulation deterioration? 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), a criterion for acceptable PD levels does not exist for rotating machines due to PD calibration problems [2] [3].

This paper analyses why one cannot rely on an absolute PD magnitude to assess the insulation condition of rotating machines. How to identify stator insulation deterioration effectively and reliably will be discussed and demonstrated by case studies. The paper concludes that trending of PD activity is the reliable way to identify severe insulation deterioration in rotating machines.

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

There are various types of on-line PD testing systems available. 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 alarm for severe stator insulation deterioration based upon the data presentation. The difficulties are caused by the following factors:

- PD calibration problems in rotating machines
- PD location and PD pulse propagation
- PD detector
- PD type
- Differences among machines and among PD measurements

2.1 PD calibration problems in rotating machines

A PD test specification for rotating machines has not been established, although such specifications exist for other high voltage equipment. The reason for this is the lack of an effective calibration technique for PD measurement in rotating machines. 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.

The conventional PD calibration method is not applicable to rotating machines, since

- PD pulses occurring at PD sources cannot be directly measured at local PD sites;
- a complete stator winding cannot be treated as a pure lumped capacitor [4]. 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.

This conventional PD calibration approach is different from what is defined as the PD "calibration" of rotating machines here. The PD "calibration" here means to find the relationship between PD readings obtained at the machine terminals and the actual magnitude of PD occurring at local PD sites within the stator winding [5] [6]. Without such a valid PD "calibration" technique, it is difficult to accurately assess stator insulation condition using the absolute PD magnitude measured at the machine terminals.

2.2 PD location and PD pulse propagation

A PD pulse occurring in the stator winding propagates to the machine terminals through a complex path. The PD pulse can be attenuated particularly in high frequencies and the waveform of the PD pulse can be distorted [7] [8]. However, the PD pulse occurring within the stator winding is actually measured at the machine terminals. The PD pulse measured at the machine terminals has a different magnitude and waveform from the original PD pulse occurring within the stator winding, depending upon the nature of the stator winding.

The PD location in the stator winding also affects the PD magnitude measured at the machine terminals due to the PD propagation and attenuation within the stator winding. A smaller PD magnitude measured at the machine terminals may come from the relatively large PD located far away from the PD sensor, while a larger PD magnitude measured at the machine terminals may come from the relatively small PD located close to the PD sensor.

2.3 PD detectors.

PD detectors (sensors and instruments) used commercially have various frequency bandwidths and centre frequencies. For example, a 500 pF capacitor has a different frequency bandwidth from a 80 pF capacitor, hence the 500 pF has a higher detection sensitivity than the 80 pF capacitor [9]. The current transformers also have a different frequency bandwidth from the capacitive couplers. These PD sensors with various frequency bandwidths produce different PD output values for the same PD event.

Further more, when the PD detector is coupled to the stator winding, the winding frequency spectrum combines with the detector frequency spectrum to form a combined frequency spectrum. 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) [10]. After the PD pulse propagates through the winding and goes into the detector, the original PD pulse has been highly distorted. Consequently, the PD pulse waveform appearing at the output terminal of the detector depends upon both the winding frequency spectrum and the detector frequency spectrum.

2.4 PD types

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

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

The degree of PD threat to the insulation system of rotating machines depends upon the PD type and its location. For example, the same magnitude of PD occurring in the slot (slot discharge) and occurring on the insulation surface (endwinding discharges) results in different degrees of threat to the insulation life. Evaluation of the stator insulation condition by considering only the PD magnitude without considering the PD nature and location is not reliable.

2.5 Differences among machines and among PD measurements

There are considerable differences among rotating machines in design, manufacturing, specification, insulation systems, 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 different lifetime of the insulation.

In addition, there are differences among PD measurements caused by varying operating conditions (e.g. temperature, load, and hydrogen pressure) and varying measurement settings (e.g. instrument types, gain settings). The measurement differences can produce different PD readings for a given PD event.

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

3. A RELIABLE WAY TO IDENTIFY SEVERE STATOR INSULATION DETERIORATION

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

3.1 Neural networks techniques

This approach relies on a great number of reliable PD test data to train the neural networks to get insulation assessment results. Reliability and accuracy of using the approach to assess stator insulation conditions are a major concern. The approach is still under investigation.

3.2 Comparison of PD test data with 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 to be severely deteriorating. If the PD level is within a range of 75% of the low PD readings in the database, the insulation is usually considered as safe. Precautions should be given when using the PD database approach to set alarm levels since it is using the absolute PD magnitude to assess stator insulation conditions.

3.2 Comparison of PD test data with those from similar machines

This comparison gives, in general, a relative condition among rotating machines, i.e. which one is better and which one is worse. However, as previously discussed, due to different PD types and PD locations, 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 assessment results.

3.3 Trend PD data on the same machine.

This approach is usually regarded as the reliable way to diagnose severe insulation deterioration. Insulation degradation is a long-term process. If the insulation system has a stable PD activity (even with a high PD level), insulation failure may not, in general, occur soon. If a significant increase in PD activity within a certain period of time under the same test condition is detected, it indicates a warning sign of severe insulation deterioration and further actions should be taken. A sudden increase in PD activity warrants investigation and is a warning sign of possible insulation failure. The following case studies demonstrate that it is the increase of PD activity rather than an absolute PD magnitude which indicates severe possible insulation failure.

4. CASE STUDIES

Two case studies show how to use trending of PD activity to assess the insulation condition on operating motors and generators. The first case demonstrates that the PD magnitude is not a reliable indicator for possible insulation failure by comparing PD activity of two "sister" motors in a power plant.

4.1 Case 1

Motor A: Motor A is a 6.9 kV, 7000 HP induction motor used for the 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 was installed on the motor after rewinding. One coupler per phase (A1, B1, C1) was installed at the motor terminals. The trending graph of both positive NQN values and negative NQN values is shown in Fig. 1. The trending graph of the maximum PD magnitude is shown in Fig. 2. The NQN (Normalised Quantity Number) value is a measure of total PD activity in one phase of the stator winding.

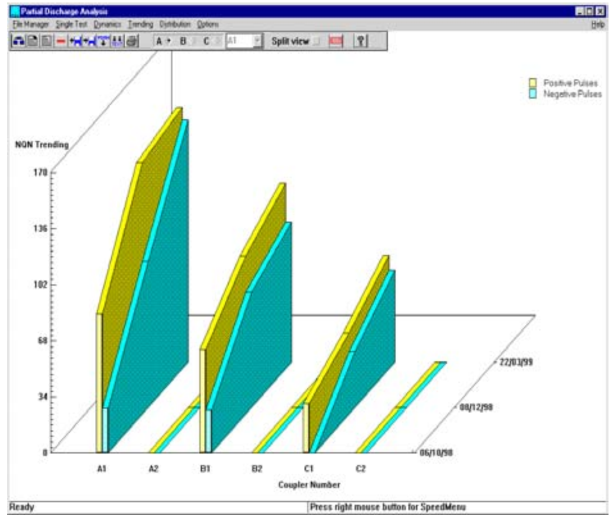

Fig. 1 Trending graph of +NQN and –NQN values of motor A.

In Fig.1, the NQN value in phase C increased more than three times from October 1998 to March 1999. In Fig. 2, 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 in April 1999. The motor was taken out of service and a visual inspection was conducted. The visual inspection confirmed that there was a puncture in the groundwall insulation. The location of the insulation failure was at the interface between the slot portion and the endwinding portion, as shown in Fig. 3. The motor was rewound since the insulation failure.

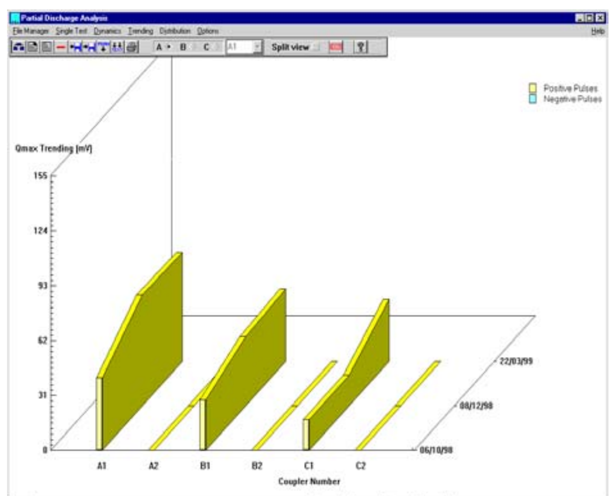

Fig. 2. Trending graph of the positive maximum PD magnitude of motor A.

Fig. 3 Location 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. The trending graphs of the NQN values and of the maximum PD magnitude are shown in Fig. 4 and in Fig. 5. Comparing Figs. 1 and 2 and Fig. 4 and Fig. 5, motor B initially had much higher NQN values and much higher PD magnitudes than motor A. A comparison of the maximum PD magnitude in motor A and motor B is listed in Table 1 and Table 2.

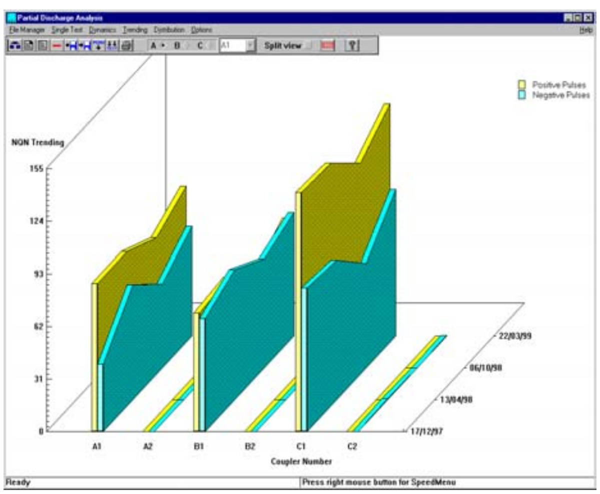

Fig. 4 Trending of +NQN and –NQN values of motor B.

One might expect that the motor with the initially higher PD readings would fail first. It did not actually. Yet motor B with the initially higher PD activity has been operating well while motor A with the initially lower PD activity subsequently failed in service in 1999. This is because the PD activity in motor B was stable, even though it was initially much higher than motor A. 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 increased, i.e. a sign of accelerated insulation deterioration that could lead to insulation failure.

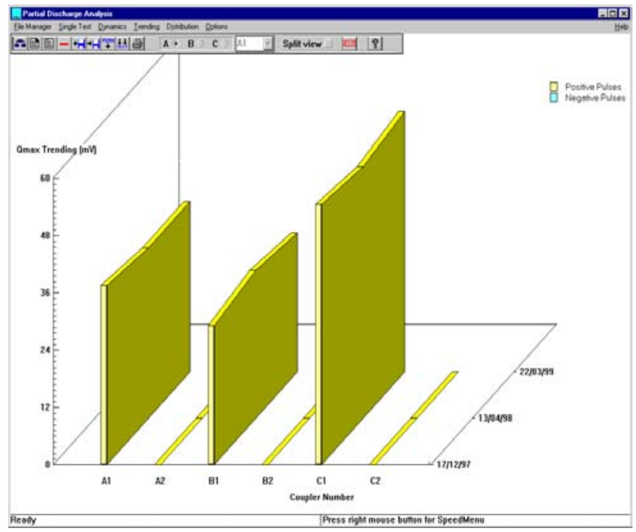

Fig. 5 Trending graph of the positive maximum PD magnitude of motor B.

Table 1 Comparison of the 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 the 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

4.1 Case 2

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 beyond repair. The class B thermoplastic stator insulation, however, did not fail. The opinion of many generator 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.

Extensive off-line tests such as power factor, DC hi-pot, core thermal scans and corona probe tests were performed. The stator winding withstood the hi-pot but showed signs of winding looseness and accelerated winding deterioration in the structural FRF (Frequency response function) test and the power factor test (see test data in Table 3).

Table 3 Power Factor Test Data

Voltage	1985	1989	1993 *	1998
ϕ A				
4kV	0.81	1.17	2.34	2.54
10 kV	1.16	1.82	2.40	3.02
Tip-Up	0.35	0.65	0.56	0.48
ϕ B				
4 kV	0.72	1.27	2.24	2.27
10 kV	1.12	1.84	2.89	2.79
Tip-Up	0.40	0.57	0.65	0.52
ϕ C				
4 kV	0.86	1.17	2.30	2.36
10 kV	1.10	1.74	2.92	2.89
Tip-Up	0.24	0.57	0.62	0.53
* Test data obtained after the generator was overheated.				

After examining the data from the off-line stator insulation tests, the utility decided to install an on-line PD monitoring system for the stator insulation and continue operating the generator with the same stator winding. A PDA system 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. 6 <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 2000 and consistent with the power-factor test data. The PDA reading taken in 2000 is shown in Fig. 6 <1>. There is negative pulse predominance in the curves. This is a sign of internal PD occurring close to the interface between the copper conductor and the groundwall insulation.

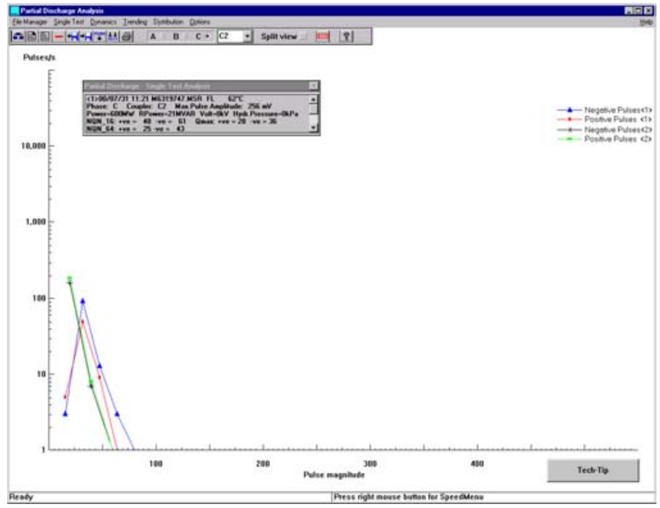

Fig. 6 Comparison of PDA readings taken in 2000 <1> and in 1993 <2>.

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. The avoided cost of the emergency rewind was millions of dollars. This case demonstrates that the threat of machine insulation failure is not great if the PD activity is stable.

5. CONCLUSIONS

An absolute PD testing specification for rotating machines cannot be established due to the lack of a valid PD calibration technique, PD pulse attenuation, difference in frequency bandwidths of PD detectors, PD type and its location, different machine designs, operation, and maintenance. It is not reliable to give a warning of severe stator insulation deterioration based upon an absolute PD magnitude. 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.

Trending of PD activity on the same machine is the reliable approach to identify stator insulation deterioration. A significant increase in PD activity within a certain period of time is a warning sign of possible stator insulation problems. The rate of increase in PD activity is a key factor for the test data analysis.

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