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Generator Maintenance: Using PD Measurements to Identify Stator Winding Insulation Problems

Canadian provincial utility BC Hydro uses on-line partial discharge measurements to identify winding insulation problems in the stators at its hydro facilities. Several decades of experience show that this type of measurement is an efficient tool for assessing insulation condition.

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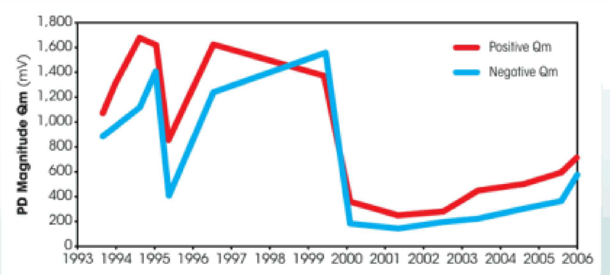
Partial discharge (PD) measurement is used to detect small sparks that occur on the insulation system of a generator's stator winding. These sparks may occur within the groundwall insulation, between the winding surface and core, or at the end-turn surface of the stator winding. These electrical sparks can damage the insulation material and may eventually cause insulation failure.

BC Hydro has used generator winding on-line PD monitoring for more than 20 years on machines with a voltage rating of 13.8 kilovolts (kV) and above. The utility has 70 generators this size, and 45 hydro generators are equipped with PD monitoring systems. As a result of this monitoring, PD occurring in the slot portion between the semi-conductive layer and core, at the end-turn of the stress control grading areas, and within the groundwall insulation has been identified.

Three recent stator replacement projects have been completed in BC Hydro facilities. This work includes some of the stators experiencing high PD problems that were identified using PD monitoring.

PD activity can be affected by many factors, including the location and geometry of the voids in the insulation that cause PD, as well as the load and winding temperatures. Interpretation of PD results can be challenging, often relying on the knowledge of an expert.1,2,3 The following case studies will help explain how to use PD measurements to identify stator winding insulation problems, as well as the benefits of PD measurements.

FIGURE 1 PD Magnitude Trend



Partial discharge (PD) activity on Unit 4 at the Peace Canyon generating station increased from 1993 to 1995. Conductive room temperature vulcanized rubber was injected in 1995, which temporarily decreased PD activity. In 1999, 13 bars were replaced on this unit.

How BC Hydro measures PD

Many methods are available to measure PD activity in operating machines. BC Hydro uses 80 to 100 pF coupling capacitors, which are connected to the end caps of the winding, taps of the winding circuits, or circuit ring buses. Each pair of couplers is differentially connected to the line end of the winding, with a minimum of two and a maximum of eight couplers per phase. At the low voltage end of the coupler, a surge arrestor protects the coupler from failure. PD measurements are performed using PDA IV test equipment from Iris Power LP.

Typical on-line PD measurement is performed annually on each machine at the rated load and with the stator winding temperature stabilized. For 16 machines, a continuous on-line PD monitoring instrument supplied by Iris is installed. This instrument continuously collects PD data while the machine operates - which results in many data points per day - and calculates the average, maximum, and minimum daily or monthly values. It also can perform an individual measurement at any time.

Result interpretation considers five aspects:

- PD pattern plot, which shows the pulse per second (pps) versus the PD magnitude;

- PD pulse polarity predominance, where the PD magnitude of one polarity is greater than the other;

- Pulse phase analysis, where the PD pulse distribution is analyzed with respect to the reference alternating current voltage phase angle;

- Temperature and load effects on PD activity; and

- Trend PD magnitudes of each coupler.

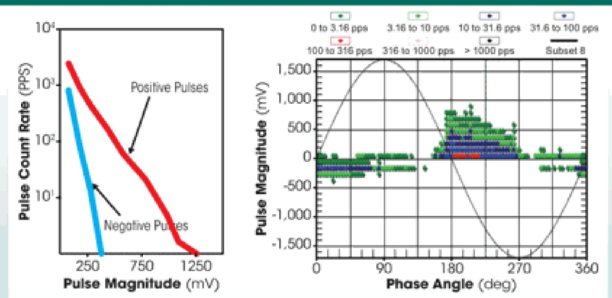
Case studies

The following four case studies provide examples of the types of PD activity occurring, with the PD evidence observed during visual inspections. For all four case studies, the stator winding insulation is Class 135 (B) epoxy mica.

Slot discharge at Peace Canyon

The 700-MW Peace Canyon Generating Station contains four 184 megavolt-ampere (MVa), 13.8-kV air-cooled generators that were installed in 1980. After 12 years of operation, ozone levels of 180 to 500 parts per billion (ppb) were measured inside the generator enclosure.4 In 1993, 12 couplers were installed on each stator winding. Since then, PD measurements have been performed annually under rated load with steady winding temperature conditions.

FIGURE 2 PHA and PPA Plots



The results of pulse height analysis (PHA) and pulse phase analysis (PPA) for Unit 4 at Peace Canyon are considered to be indicative of slot discharge. This includes the positive polarity predominance in the PHA graph and the distribution of positive pulses at 180 degrees.

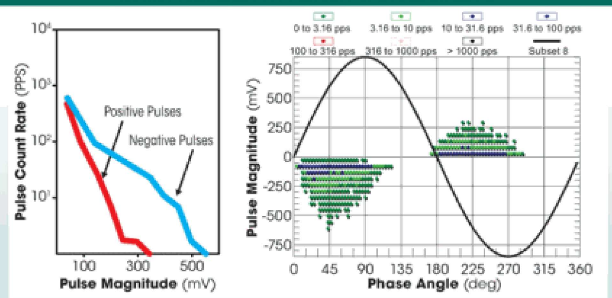
PD test data for all four units has been trended. Figure 1 illustrates a typical PD magnitude trend of circuit T9B in the Unit 4 generator. From 1993 to 1995, PD activity was increasing. In April 1995, injection of conductive room temperature vulcanized rubber into the slot portion of the high-voltage bars temporarily reduced this PD activity. However, PD increased the following year, quickly reaching the level seen before this repair attempt.

In November 1999, a line to ground fault occurred on a back bar while the unit was in service. This fault was determined to be caused by a metallic object left in the machine during construction in 1980. The faulted bar was replaced, along with the 12 front bars that had to be removed to access this bar. Three of the 13 bars replaced are the second, third, and fourth bars from the line lead end of circuit T9B. The PD level decreased radically on this circuit. However, it increased slowly over the following years.

In comparison to other generators in BC Hydro's database, the windings from these four machines have high PD. The PD magnitude was 1,000 to 1,500 millivolts (mV); for a normal machine it is about 100 mV. Typical PD patterns for these units are illustrated in a pulse height analysis (PHA) plot (see left side of Figure 2), which shows the PD pps versus the PD positive and negative pulse magnitude, and pulse phase analysis (PPA) plot (see right side of Figure 2), which shows the PD pulse distribution with respect to the reference phase angle of 60 Hertz (Hz) phase-ground voltage. The PHA plot shows a positive polarity predominance and linear decrease in pulse density with the increase in pulse magnitude. The PPA plot shows the PD pulse distribution was centered at 0 degrees for negative pulses and 180 degrees for positive pulses. This type of PD pattern is considered indicative of slot discharge.1

Unit 4 was removed from service in 2006. An inspection was conducted, and 12 front and nine back bars were removed for investigation. These were either the first or second bar from the line end of the three phases. In the slot portion of the bars, a significant amount of semiconductive coating and side packing had been eroded by PD activity.

FIGURE 3 PHA and PPA Patterns of Groundwall PD



The winding on Unit 10 at G.M. Shrum has one of the higher PD readings among the ten units in this station. Results from the PHA plot (at left) and the PPA plot (at right) suggest the PD source was in the groundwall insulation and that the voids may be close to the copper conductor, which was a result of debonding thermal deterioration.

This type of PD damage was observed on both sides of all front and back bars (with and without side packing), but the damage was more severe on the side with side packing than on the side without. Also, the damage to the top and bottom ends was more severe than that to the middle portion of the bar.

Four stators were replaced at Peace Canyon. High PD was one of the reasons.

Slot discharge at G.M. Shrum

Unit 4 at the 2,730-MW G.M. Shrum Generating Station is rated at 239 MVa, 13.8 kV, and is air cooled. The stator was removed from service in 2008 after experiencing many problems over its 39 years of operation, including high PD activity on the stator winding. The winding was equipped with one capacitive coupler per circuit, for a total of six couplers per phase. On-line PD measurement was performed annually, and PD data had been trended over the previous 15 years. PD pulse magnitudes for phase A indicated that the high PD occurred on some circuits and the PD magnitudes were unstable. The trends for phase B and C are similar to phase A. The PD pulse intensity was about 700 mV. The PD patterns observed were similar to those in Figure 2.

Eight front and three back bars were removed for detailed inspection before this stator disposal. These bars were either the first or second bar from the line lead end of A, B, and C phase.

Severe slot discharge damage was observed on seven bars. These bars were in the circuits with high PD readings. The remaining removed bars were in reasonably fair condition. The semiconductive armour tapes were eroded by the PD activity between the bar surface and core and bleached by ozone. Over time, the armour tape was completely eroded away and the mica tape was exposed. The mica tape had degraded and become brittle. This stator has been replaced, but the PD problem was not the main reason.

This slot portion of the bars for Unit 4 at Peace Canyon shows erosion of a significant amount of semiconductive coating and side packing. This erosion was caused by PD activity that occurred between the bar surface and slot.

Groundwall discharge at G.M. Shrum

The generator for Unit 10 at G.M. Shrum is rated at 316 MVa, 13.8 kV, air cooled, and is about 31 years old. The winding insulation has six capacitive couplers per phase. The PD data has been trended over more than 15 years.

This winding has one of the higher PD readings among the ten units in this station. Figure 3 shows a typical PD pattern of this winding. In the PHA plot, the PD density shows negative polarity predominance and a linear decrease with pulse magnitude increase. In the PPA plot, the PD pulses are centered at phase angles of 45 degrees for negative pulses and 225 degrees, for positive pulses. The PD clouds had close to symmetrical triangular distribution. The PD magnitude in this winding also has negative temperature-dependent characteristics; PD readings obtained at the machine operation in no load and winding temperature low conditions are two or three times higher than that in full load and winding temperature high conditions. There is no notable PD evidence at the end-turn of the winding, and ozone level is low inside the generator enclosure.

These characteristics suggested the PD source was in the groundwall insulation and that the voids may be close to the copper conductor, which was a result of debonding thermal deterioration. This type of insulation problem is difficult to repair, and this unit is still in service.

Stress control grading area discharge at Mica Creek

The four air cooled generators at 1,740-MW Mica Creek were rated at 457 MVa, 16 kV. The winding insulation was manufactured in the mid-1970s. These windings were subjected to severe discharge in the grading paint area. The top and bottom ends of the bars showed white powder and grading paint damage due to PD. These bars were at high potential.

On Unit 4 at the G.M. Shrum station, the semiconductive armour tapes were eroded by the PD activity between the bar surface and core and bleached by ozone (photo at left). Over time, the armour tape was completely eroded away and the mica tape was exposed (photo at right).

The PD characteristics of the winding showed no polarity predominance between the positive and negative PD pulses. There was a linear decrease in pulse density with increase in pulse magnitude, and the PD clouds were triangular shaped and centered at 0 degrees and 180 degrees in the negative and positive cycles, respectively. The PD pulse intensity was about 500 mV.

The stators have been replaced in all four units. The last stator, of Unit 1, was removed from service in 2009, and seven front bars and one back bar were removed for investigation. These bars were either the first or second bar from the line leads and experienced severe end-turn PD activities when the machine operated. There was no obvious PD damage at the slot portion of the bars. One removed bar was dissected in three locations, one at the middle and two at the grading paint area. Results indicated that the groudwall insulation was in fair condition.

Characteristics of PD activity

Based on the experience of PD result interpretation for BC Hydro generators and in correlation with visual inspection, each type of PD activity has identifying characteristics (see Table 1).

PD Activity	PD Pattern Shape	Polarity Predominance	Temperature Effect	Pulse Distribution
Groundwall	Symmetrical triangle	None or negative	Negative	Centered at 45° for negative pulses and 225° for positive pulses
Slot	Near symmetrical triangle	Positive	Positive	Centered at 0° for negative pulses and 180° to 210° for positive pulses
Stress Control Grading Area	Triangle	None	Positive	Ranged from 0° to 75° for negative pulses and 180° to 255° for positive pulses
Inadequate Space	Cloud shaped or non-classic	Random	No predictable	Random between 0° or 90° for negative pulses and 180° or 270° for positive pulses

Different types of PD activity can have similar PD patterns. A temperature-dependent PD measurement may assist in identifying the source of the activity. For example, if the voids are within the groundwall insulation, the size of the voids usually decreases with the increase in stator winding temperature. Therefore, the PD readings reduce with the increase in winding temperature increase, so there is a negative temperature effect.

In some cases, the PD cloud distribution has a phase-to-phase voltage-dependent characteristic. This type of PD activity usually occurs at the end-turn of the winding and can be identified using A, B, C phase pulse phase analysis graphs.

Conclusions and lessons learned

More than 20 years of experience show that stator winding insulation problems can be identified through analysis of PD pattern, polarity predominance, pulse phase distribution, temperature dependence, and trends, in correlation with ozone measurement and visual inspection.

PD testing is a cost-efficient method of monitoring stator winding insulation condition, as accurate measurements can be made while the generator is operating. Trending PD data over time allows for the planning of corrective intervention when it is most cost-efficient. In addition, it is important to establish a baseline PD trend when a winding is new.

To continue increasing the knowledge of PD interpretation, laboratory and practical studies should be continued and PD measurements, trends, and analysis results from various companies should be compiled.

Notes

1. Hudon, C., and M. Belec, "Partial Discharge Signal Interpretation for Generator Diagnostics," *IEEE Transactions on Dielectrics and Electrical Insulation*, Volume 12, No. 2, April 2005, pages 297-319.

2. Li, S., and J. Chow, "Partial Discharge Measurements on Generator Stator Winding Case Studies," *IEEE Electrical Insulation Magazine*, Volume 23, No. 3, pages 5-15.

3. Stone, G.C., and V. Warren, "Effect of Manufacturer, Winding Age and Insulation Type on Stator Winding Partial Discharge Levels," *IEEE Electrical Insulation Magazine*, Volume 20, No. 5, pages 13-17.

4. Belec, M., and S. Li, "Investigation and Diagnosis of a 184 MVA Air-Cooled Generator Heavily Affected by Slot Partial Discharge Activity," Electrical Insulation Conference (EIC), IEEE, Piscataway, N.J., 2007.

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