2019 Electrical Insulation Conference (EIC), Calgary, Alberta, Canada, 16-19 June 2019

Investigation of Partial Discharge Activity and Insulation Life of a Large Hydro Generator

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***Abstract*—Partial discharge (PD) is a well-known indicator of an aging insulation system, so trending the PD activity is suggested as a tool to prevent insulation failures by targeted interventions. This paper presents a case study in which on-line PD measurements showed a significant increase over several years and triggered an investigation and repair plan. Off-line site tests confirmed the concerns and helped in locating and replacing the most vulnerable bars. Laboratory tests on the service-aged bars also provided valuable information about the root cause and insulation condition of the winding.**

Keywords—stator winding, partial discharge, insulation life, delamination, dissection analysis

I. Background

PD activity had been one of the major concerns of a 16 kV, 480 MW hydro-generator. Only two years after installation of this generator in 1984, signs of PD activity appeared in the overlap area of the semi-conductive and stress-grading coatings of higher-voltage bars. Repairs performed by the manufacturer by re-applying the semi-conductive and stress-grading coatings improved the conditions temporarily. However, as it is well-known [1], these repairs are normally effective only for the short term and periodic repairs are required to keep this phenomenon under control. The latest repairs on semi-conductive/grading overlap were performed in 2014 with negligible impact on the overall PD readings of the generator.

Since 1994, PD activity of the stator winding is monitored by means of four PD couplers per phase. Each phase has eight parallel circuits and the existing couplers monitor only half the winding. Nevertheless, periodic and more recently, continuous PD monitoring, has been an effective tool in evaluating the stator winding condition. Fig. 1 shows the PD activity of the generator in the form of the largest repeatedly occurring PD magnitude with repetition rate of 10 pulse per second, commonly known as Q_m [2]. The graph shows the maximum and the average Q_m for positive and negative pulses recorded by the total of 12 PD couplers. The graph shows that the PD activity has been fairly stable until 2006 with a maximum Q_m of 500 mV for a specific circuit and the average for all couplers of under 150 mV. From 2007, the maximum Q_m shows unstable behavior which is followed by a significant increase in beginning in 2013.

In addition, the last two measurements in 2017 show an inverse PD temperature/load effect. During a full load hot measurement at 485 MW and a stator winding temperature of 72°C, the maximum recorded Q_m was +1618/-1460 mV. With a load change down to 358 MW and stator winding temperature of 55°C, the Q_m increased to +2695/-3500 mV. Additional investigation of PD behavior using phase resolved PD (PRPD) patterns at different loads and temperatures suggested that the winding may have delamination and/or debonding. Delamination was considered likely given the winding design (i.e. 3 m core stack height) and the fact that this generator had been used as a peaking unit and been subjected to thermal cycling for over 30 years.

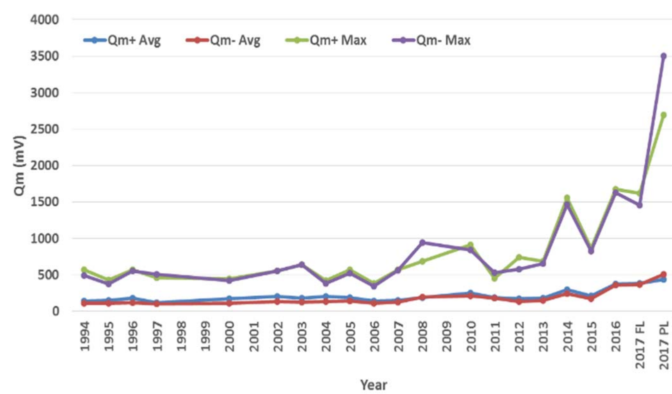

Fig. 1. Trend of PD activity of the generator. The data was taken at full load hot, except the last datapoint that was taken at partial load and a lower temperature.

The continuous on-line monitoring system recorded PD activity exceeding 4000 mV, which was significantly above the published limits of concerns for the highest activity of hydro generators in the 16–18 kV voltage class [3]. On-line PD test results indicated that the maximum PD activity on all circuits with PD couplers had been less than 500 mV except for circuit T1A1 that had the maximum recorded PD on the winding. See Fig. 2 for historical PD readings of phase A couplers.

The high levels of PD and the rapidly increasing trend prompted an investigation plan to determine the root cause and to evaluate its impact on the insulation life of the winding. The investigation included site tests to confirm the on-line PD test results and to identify and replace bars with the highest PD readings. It also included extensive laboratory testing on the bars removed from the generator in order to determine the root cause of the high PD readings and to evaluate the insulation life.

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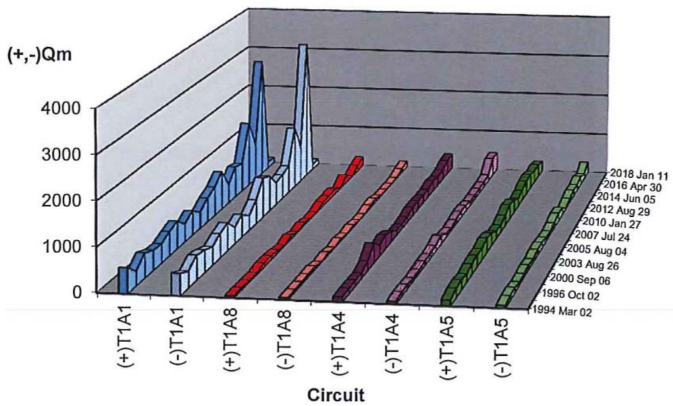

Fig. 2. Maximum PD activity trend of phase A circuits

II. Site Tests

On-line PD test results indicated that circuit T1A1 had extremely high PD activity. Off-line tests were performed to validate the on-line test results, and included off-line PD measurement on the circuits that had PD couplers and using a corona (TVA) probe to screen the slots for PD activity. Both tests were performed while the winding was energized from an external power source at 9.2 kVac, 60 Hz that was equivalent to the phase-to-ground in-service voltage. In addition to verifying the on-line and off-line PD test results, the corona probe test was especially useful in evaluating the condition of the circuits that did not have PD couplers. Based on a combination of the off-line PD and corona probe test results, six front bars were selected for removal and laboratory investigation. Table I shows the test results for the selected bars.

TABLE I. Test Results for Selected Bars

Bar	*Circuit/ Bar Voltage*	*On-line PD (mV)*	*Off-line PD (mV)*	*Corona Probe (mA)*
615	A1/9.0 kV	+2722/-3333	+1156/-1315	120
225	A4/9.0 kV	+428/-637	+396/-555	88
343	A6/8.3 kV	No PD Coupler	No PD Coupler	105
017	B1/9.0 kV	+132/-119	+292/-413	89
622	B1/8.7 kV	+132/-119	+292/-413	80
563	B8/9.0 kV	+268/-243	+218/-282	34

III. Laboratory Tests

The six removed bars were sent to the laboratory along with two spare bars for additional tests. One spare front bar (spare-F) and one spare back bar (spare-B) were selected for the test program. The following tests were performed on the bars:

A. Visual Inspection and Tap Test

Visually, the bars all appeared adequate along the slot section with no evidence of partial discharge activity.

Tap tests were conducted to determine the quality of bar construction and to locate possible delamination or voids in the insulation system. All the bars removed from the generator showed audible symptoms of delamination or major voids. The suspect areas were as small as 25 mm long and as large as 1.37 m long, such as on bar 343. Overall, it was apparent that delamination was a major phenomenon with the service-aged bars. The spare bars did not show any symptoms related to delamination or major voids.

B. Corona Inception and Extinction Voltage (CIV & CEV)

The bars were tested for corona inception and extinction voltage. The voltage was increased from zero in a gradual manner until the first signs of PD activity appeared. Considering the background noise levels in the lab, the lowest voltage that triggered PD activity of 10±2 pC was considered as the corona inception voltage (CIV). The voltage then was increased to a slightly higher level before gradual reduction. The corona extinction voltage (CEV) was recorded as a voltage that PD activity reduced to less than 10 pC. Table II shows the CIV and CEV values for each bar. All service-aged bars except one had very low CIV ranging from 2 to 3 kV. Bar 615 which had highest PD and corona probe test results, showed comparable CIV to the spare bars with sudden increase at this voltage.

TABLE II. Corona Inception and Extinction Voltages for Service-Aged and Spare Bars

Bar	*Circuit / Bar Voltage*	*CIV (kV)*	*CEV (kV)*
615	A1/9.0 kV	4.6	2.5
225	A4/9.0 kV	2.0	1.6
343	A6/8.3 kV	2.7	2.1
017	B1/9.0 kV	2.8	2.2
622	B1/8.7 kV	2.8	1.6
563	B8/9.0 kV	3.0	1.5
Spare-F	-	5.0	4.2
Spare-B	-	5.8	5.1

C. Partial Discharge Test

PD activity of the bars was measured at 10 kVac after 5 minutes of conditioning at this voltage. PD activity was measured using 80 and 1000 pF capacitive couplers. Table III shows the Q_m measured with each coupler.

Bar 343 showed the highest PD activity among the bars. The PRPD graph for this bar showed that the type of PD was not classic and that different types of PD were occurring simultaneously. This bar also had a low CIV and also visual corona activity, which together with possible internal PD, resulted in a complex phase resolved graph. Bar 615 also showed high PD activity with both couplers. Unlike bar 343, bar 615 showed classic internal PD activity, especially with the 1000 pF coupler. Fig. 3 shows the PRPD graph for bar 615 as an example. Bar 622 showed fairly high PD activity as well. With the 1000 pF coupler, it showed signs of internal PD with some noise that could be related to the visible corona that was observed in the slot section where the semi-conducting paint was damaged. Spare-F bar showed higher PD compared to Spare-B bar and it is believed that the difference was partly due to the damaged stress grading area of this bar. Other bars showed medium to low PD activity.

TABLE III. QM MEASURED WITH 80 AND 1000 PF COUPLERS

Bar	80 pF Coupler		1000 pF Coupler	
	Qm+	*Qm–*	*Qm+*	*Qm–*
615	1785	1786	1716	1709
225	84	76	84	97
343	2766	2362	>3000	>3000
017	110	111	173	220
622	1147	1430	626	583
563	333	338	129	150
Spare-F	96	121	211	94
Spare-B	29	21	11	10

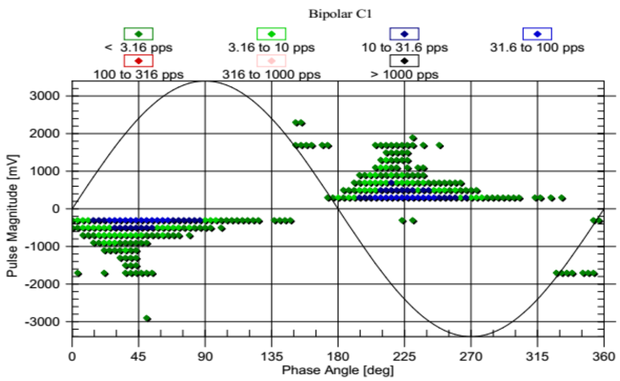

Fig. 3. PD Activity of bar 615 at 10 kV, measured with 1000 pF coupler

D. Dissipation Factor and Capacitance

Dissipation factor (DF) and capacitance were measured over a range of voltages between 2 and 16 kV with 2 kV steps. Fig. 4 shows the DF for all the bars. Fig. 5 shows the DF tip-up in two voltage ranges. Tip-up between 2 kV and 10 kV could be considered as representative of the losses that are created by the electrical stresses at operating conditions. The DF between 10 and 16 kV represents losses that are triggered at higher than operating voltages. The comparison between these two DF tip-up values could be useful in estimating the extent of the larger voids/delamination that are triggered only at voltages higher than operating voltage. The change in capacitance value, ΔC, between two test voltages could also be an indirect indication of voids and delamination. Therefore, comparing the DF, tip-up, and ΔC, along with the PD patterns, could give an indication of voids/delamination and associated losses at different voltage levels.

Fig. 4 shows that the bars have fairly comparable DF at voltages up to 8 kV, however the rate of increase in loss changes for different bars at higher voltages. Bars 615, 343, and 563 are three bars with fairly high dissipation factor tip-up, and ΔC (Fig. 5 and 6). This is believed to be a sign of major voids or delamination within the insulation. Spare-F bar and Spare-B bar show the lowest tip-up, and ΔC in both voltage ranges. This was expected and agrees with their low PD activity.

E. Voltage Endurance (VE) Test

In order to evaluate the remaining insulation life, service-aged bars 225, 17, and 622 and bar spare-B were subjected to a voltage endurance (VE) test. The test was performed in accordance with the IEEE 1553 Schedule A test regime (i.e. 34.7 kV test voltage and the minimum time-to-failure of 400 hours). The test temperature was kept constant at 90°C, which was the highest recorded operating temperature of the winding. All bars passed the VE test without failure.

F. AC Breakdown Test

After completion of the VE test, three bars (225, 622, and spare-B) were subjected to a dielectric breakdown test. An initial test voltage of 33 kV (i.e. 2E+1) was applied for one minute. The voltage was then increased by steps of 3 kV, with a 1 minute hold time (excluding the rise time) at each voltage level until breakdown. The breakdown voltage and the total elapsed time were recorded for each bar. During the test, the bar arms were submerged in insulating oil to prevent flashover in the grading area. Bars 225 and spare-B broke down at 69 kV and bar 622 at 51 kV.

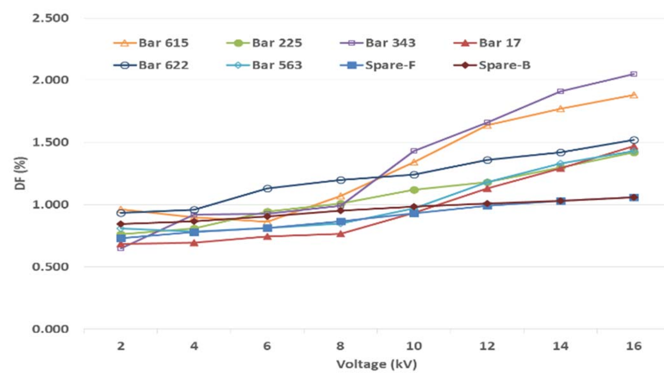

Fig. 4. Dissipation factor between 2 and 16 kV

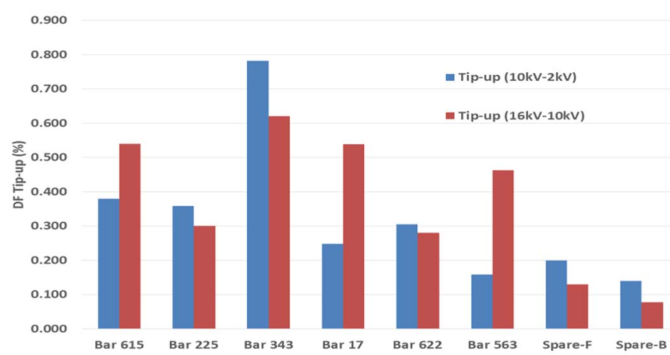

Fig. 5. Dissipation factor tip-up between 10-2 and 16-10 kV

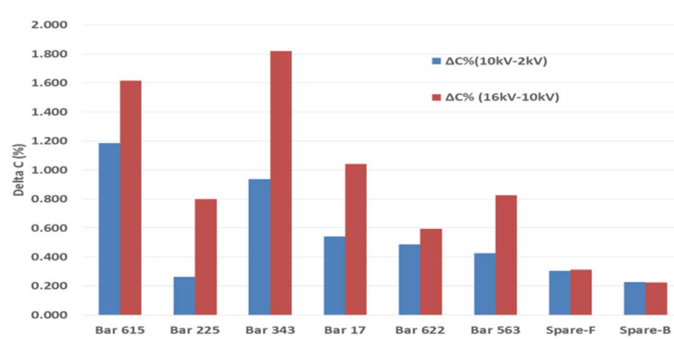

Fig. 6. ΔC between 10-2 and 16-10 kV

G. Dissection Analysis

Dissection analysis was performed on all bars in two stages. Bars 615, 343, 563, and spare-F were dissected after the initial diagnostic tests. The second stage was after completion of the VE and breakdown tests: bar 17 was dissected after the VE test, and the remaining bars (225, 622, and spare-B) were dissected after the breakdown test. A combination of the peeling method and microscopic examination of thin slices was used for evaluation. The insulation system included tape with large-flake mica splittings.

Fig. 7 shows signs of severe PD in the bar 615 innermost layers of insulation. This bar showed the highest on-line and off-line PD and corona probe readings. Fig. 8 shows debonding for the same bar. For the service-aged bars, the peeling method showed a very weak bond between the copper and insulation. Bonding in the bulk of the insulation was found to be fairly strong and the taping was consistent with minor folds and waves.

Fig. 9 shows the significant PD signs within the innermost layers of insulation for bar 225. The location of PD was consistent with the other bars, however the intensity was much higher in this bar due to the accelerated aging test (i.e. VE test) and the AC breakdown test. Despite the higher intensity, the PD activity was found to be contained within debonded area and not extended to the outer layers.

Fig. 7. Signs of severe PD in bar 615 within the innermost layers of insulation

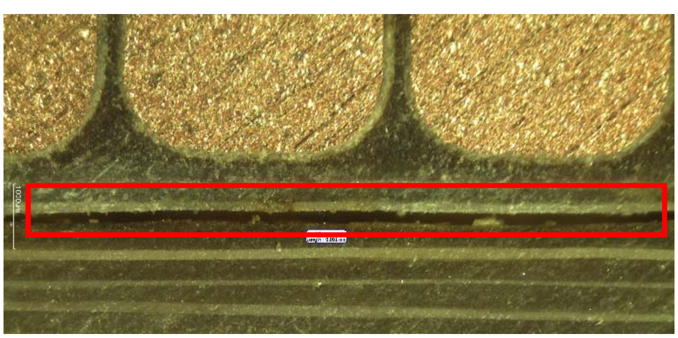

Fig. 8. Debonding of the insulation and copper in bar 615

Fig. 9. Bar 225 survived the VE test despite the severe PD activity

IV. Summary and Conclusions

Laboratory test results were consistent with the findings from the on-line PD and off-line PD tests. The bars removed from the circuits with the highest PD and corona probe readings also showed higher PD, DF, tip-up, and ΔC results in the lab tests. Dissection of three service-aged bars confirmed the earlier conclusions of debonding/delaminations. Peeling method dissection confirmed that high intensity PD had been occuring within the innermost layers of insulation of bar 615. Despite the high PD activity, it seemed that the large mica splittings of the mica-tape insulation and high-quality taping had blocked the PD from progressing into the outer layers of insulation. After suceessful completion of VE testing, dissection analysis of the remaining three service-aged bars confirmed that the insulation was capable of withstanding the high-intensity PD within the large voids created by debonding. The AC breakdown test also confirmed that the dielectric strength of the ground-wall insulation was still acceptable.

After the bars were replaced, corona probe, off-line and on-line PD measurements showed significant PD reduction. After repairs, the T1A1 circuit Qm magnitude reduced to +113/-94 mV. Prior to bar replacement, this circuit had PD activity with a Qm of as high as 4125 mV. On-line PD monitoring proved valuable in detecting the high PD activity, helped in planning for targeted tests and investigations, and reduced the urgency for larger intervention in this and the sister generators.

References

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