Differences Between Partial Discharge Tests on Air-Cooled and Hydrogen-Cooled Rotating Machines

H. G. Sedding[1*], M. Sasic[1], V. Warren[1] and G.C. Stone[2]
[1] Qualitrol-Iris Power (Canada)
[2] Stone Dielectrics (Canada)
*hsedding@qualitrolcorp.com

Abstract **–** Partial discharge (PD) testing, both off- and on-line, is widely used by manufacturers and end users of high voltage generators and motors to assess the insulation condition of the stator winding to aid maintenance planning. The widespread use of this technology lead to the development of standards such as IEEE 1434, IEC 60034-27-1 and IEC 60034-27-2 that provide guidance on uniform methods of measurement and data interpretation.

This paper examines some aspects of applying on-line and off-line PD testing on air-cooled and hydrogen-cooled rotating machines.

- Using a database of more than 700,000 measurements, describe the differences between on-line PD data recorded on air-cooled and hydrogen-cooled generators and the consequences for interpretation of the PD behaviour.
- The PD database comprises measurements obtained using VHF and UHF detection methods, thus the effects of PD coupling method are discussed.
- Correlation, or lack thereof, between the results of on- and off-line PD testing

Keywords: partial discharge, rotating machine, stator winding, hydrogen, database

I. INTRODUCTION

Partial discharge (PD) can be both a cause and/or a symptom of many types of stator winding insulation system deterioration mechanisms in motors and generators rated 3300 V and above More particularly, on-line PD measurement has been able to determine if the electrical insulation is deteriorating due to loose coils in the slots resulting in insulation abrasion; thermal deterioration or load cycling leading to insulation delamination; and electrical tracking caused by partly conductive contamination of the endwindings [1-7]. On-line PD testing is also able to determine if manufacturing or installation problems, such as poor impregnation with epoxy, or coils being too close together in the endwinding, are severe enough to shorten the winding life.

Many methods are available to measure PD activity in operating machines. The electrical techniques all rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. A good overview of all the different means for detecting PD in machines is presented in IEEE 1434 [8]. This document also provides the framework to enable reliable on-line PD measurements to be made, as does IEC 60034-27-2 [9].

A significant challenge with PD measurements performed in normal motor or generator operation is that electrical interference (noise) often is present [8, 9, 10]. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, power tool operation, and electrostatic precipitator discharging. This noise obscures the PD pulses and may cause the unwary technician to assume that a stator winding has high levels of PD, when in fact the high levels are caused by the noise. The consequence is that a good winding is incorrectly assessed as being defective – that is a false alarm is given that a winding is deteriorated, when it is not. Such false alarms reduce the credibility of on-line PD tests.

Consequently, over the last few decades, robust and objective noise separation methods based on comparing the time of pulse arrival between a pair of capacitive couplers and/or analyzing the shape of individual pulses [4, 6] have been developed. To maximize the signal-to-noise ratio, and thus also to reduce the risk of false indications, the sensors detect the PD at frequencies 40 MHz and higher [8]. The resulting test methods achieved their goal and have enabled utilities to assess the winding condition with their own staff. Around the world, over 17,000 machines have the required sensors permanently installed.

With the widespread application of the same on-line test methods, a tremendous number of test results have been accumulated in a single database. To the end of 2020, over 700,000 test results have accumulated over the past 25 years using portable test instruments, and simple statistical analysis has been applied to the database in order to extract information that can help test users to better interpret PD results. The best means to determine if a winding is significantly deteriorated remains monitoring the trend in PD activity over time. Unfortunately, the PD magnitudes are not only affected by the degree of insulation deterioration, but the machine operating voltage, coolant gas pressure, etc, may also affect results.

II. STATISTICAL PD DATABASE

Analysis of the database identified a number of key factors that were observed to influence the PD results, including:

- Sensor installation
- Voltage class
- Hydrogen pressure

The range in Qm from all the tests for the particular operating voltage was established for each set of the above factors. A

TABLE I. DISTRIBUTION OF QM (MV) FOR AIR-COOLED, 80 PF SENSORS ON THE TERMINALS (TGA)

	Operating Voltage (kV)					
Cumulative Probability (%)	**2-5 kV**	**6-9 kV**	**10-12 kV**	**13-15 kV**	**16-18 kV**	**> 19 kV**
25%	8	28	41	55	41	42
50%	22	75	89	124	72	85
75%	65	177	196	265	157	165
90%	243	353	385	529	310	504
95%	391	553	638	778	579	750

sample of the statistical distribution is shown in Table I. The percentage values displayed in the left hand column in Tables II through V, represent the cumulative probability. Thus, if a Qm of 500 mV is obtained on a 13.8 kV generator, then it is likely that this stator will be deteriorated, since it has PD magnitudes higher than 90% of similar machines. In fact, in over two hundred cases where a machine was visually examined after registering a PD level >90% of similar machines, significant stator winding insulation deterioration was observed [11].

Partial discharge is a gas discharge process thus, it is extremely dependent, not only on the geometry of the gas gap, but also the gaseous medium. Thus, PD magnitudes from air-cooled machines are typically higher than machines cooled with hydrogen at elevated pressure. Therefore, it is not advisable to compare the results from machines using different gas mediums. Most of the hydrogen-cooled machines have high rated loads and may suffer from problems such as core iron arcing which may cause difficulties in separating the high frequency noise associated with this phenomenon from that of PD. Partial discharge or noise activity at the machine terminals, outside the hydrogen environment, can make stator winding insulation condition difficult to interpret. This difficulty was the principal reason for the development of stator slot couplers (SSC) that have been discussed at length in other publications [6].

Comparing Table II to Table I shows that the Qm values for gas-cooled machines are generally lower than for the air-cooled machines for the same nominal voltage rating. This is especially observable at higher pressures, where 75% of the tests for all operating voltages operated above 207 kPag are below 110 mV and 90% generally below ~250 mV, less than half of that observed on the air-cooled machines.

Table III illustrates the similar statistical distribution for hydrogen-cooled turbogenerators where SSCs are installed. Since these machines are operating in a hydrogen environment, the overall slot PD is quite low. In particular, the PD magnitude at the 90% level is significantly lower for hydrogen-cooled machines than for their air-cooled counterparts. It should be observed that though the majority of the machines have slot Qm values less than ~30 mV, there are a few with levels higher than 60-200 mV. These machines should be subjected to further tests and inspections. The statistical values for endwinding (EW) PD are also available but not shown here. Comparison of the Qm values between these Tables clearly shows the profound effect of the gas environment and pressure as well as the type of sensor employed.

Though it is always recommended to trend the results for one machine over time and thus monitor the rate of degradation of the stator winding, it is also possible to compare results from similar machines. Tables I through III may be used to ascertain whether a machine warrants further tests and inspections or is operating within reasonable limits. Concerns should only be raised if the PD levels on a specific machine are above the 90th percentile (High).

TABLE II. DISTRIBUTION OF QM (MV) FOR HYDROGEN-COOLED MACHINES WITH DIRECTIONAL CAPACITIVE COUPLERS (TGA)

	Operating Voltage (kV)									
	13-15 kV			**16-18 kV**				**19 kV and higher**		
H_2 pressure (kPag)	***76-138***	***145-207***	***Over 207***	***76-138***	***145-207***	***214-345***	***Over 345***	***145-207***	***214-345***	***Over 345***
< 25th	33	20	16	17	34	24	9	43	23	9
< 50th	91	46	43	81	86	43	18	89	55	28
< 75th	189	94	81	146	333	85	38	163	108	77
< 90th	438	198	198	268	791	194	141	203	161	548
< 95th	756	393	485	389	976	307	322	239	206	951

TABLE III. DISTRIBUTION OF QM (MV) FOR GAS-COOLED STATORS USING SSC SENSORS – SLOT PD

	Operating Voltage (kV)										
	13-15 kV			16-18 kV			19-22 kV			23-27kV	
H_2 pressure (kPag)	***76-138***	***145-207***	***Over 207***	***75-207***	***214-345***	***Over 345***	***75-207***	***214-345***	***Over 345***	***214-345***	***Over 345***
< 25th	0	0	0	0	0	0	1	0	0	0	0
< 50th	9	0	9	0	5	2	9	7	3	8	3
< 75th	31	14	17	13	15	10	23	19	11	31	9
< 90th	48	66	32	58	22	24	97	41	25	66	18
< 95th	60	92	47	90	34	32	229	57	39	100	29

III. PARTIAL DISCHARGE IN HYDORGEN-COOLED GENERATORS

Most hydrogen-cooled turbine generators (which in the 1950s tended to be turbine generators rated more than 100 MVA, but now may be rated over 500 MVA) use hydrogen at elevated pressure (typically 200-400 kPag), since a high pressure gas is much more effective at cooling the rotor winding than atmospheric pressure hydrogen. As is well known from Paschen's law, above a very low pressure, as the pressure of a gas increases, the electrical stress needed to cause electrical breakdown of a gas increases [12]. The breakdown stress at 100 kPa (that is, 0 kPag) of hydrogen is close to that of air, at about 3 kV/mm. At 300 kPa (200 kPag), the electrical breakdown stress is about 7 kV/mm. Thus, when all other things are equal, fewer voids within the groundwall insulation or defects on the surface of the insulation are likely to have sufficient stress to cause breakdown, and result in PD. Therefore, a stator winding at elevated hydrogen pressure is likely to exhibit fewer PD pulses per second. In addition, unlike air-cooled machines where surface PD may result in the generation of ozone and, consequently, nitric acid, PD in hydrogen does not create a corrosive gas that can accelerate the deterioration of the insulation, including rubber gaskets, and metallic structure of the generator. However, if the voids attain the breakdown threshold stress for the gas pressure, then PD can occur [13]. A further factor to consider is that due to the absence of oxygen in hydrogen-cooled machines, thermal ageing will be reduced.

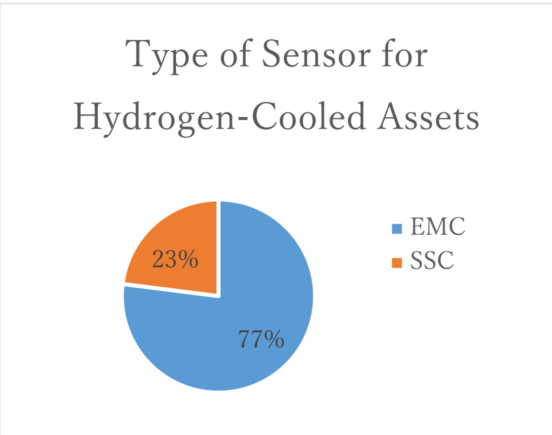

Figure 1. Percentage of results in database per sensor type

Over 4500 on-line PD tests from over 1200 hydrogen-cooled machines were analyzed. The PD was detected by one of two methods: 80 pF capacitive PD sensors also known as epoxy-mica capacitors (EMCs) or an alternative method used UHF antennae-type PD sensors installed in the stator slot (called the stator slot coupler or SSC). Figure 1 illustrates the percentage of measurements derived from each type of sensor in the analysis. Inspection of Figure 1 shows that the majority of PD measurements were derived from EMCs. This predominance is the result of the requirement that SSCs can only be installed with the rotor removed. Over the years, such outages have become less common due to the desire of end users to minimize such outages and the widespread use of robotic inspection methods.

A. *EMC Sensors*

As shown in Figure 2 and Figure 3, EMCs can be used to detect PD activity in hydrogen-cooled machines; however, because these sensors are located outside of the generator housing at the machine terminals the results may be influenced by any arcing occurring at the machine's terminals. In some cases, this requires a manual examination of the results to determine whether the PD is originating within the stator winding or from another source, such as the bushings, PT's or CT's at the terminals. And since the latter activity would be occurring in air where levels greater than 200mV are normal, then the much lower magnitude PD from within the hydrogen environment of the stator winding may be obscured. As such, there are limitations to the application of the statistical results from the database to hydrogen-cooled machines using EMCs, and in these cases, it is important to determine whether the results are influenced by external sources. This issue is explored in detail elsewhere [15].

B. *SSC Sensors*

Since SSC sensors are located within the hydrogen environment, the probability of detection of activity from sources external to the winding is low. Therefore, it can be assumed that the majority of the pulses detected by the SSCs are from internal sources originating within or on the surface of the stator winding, such as shown in Figure 2 and Figure 4

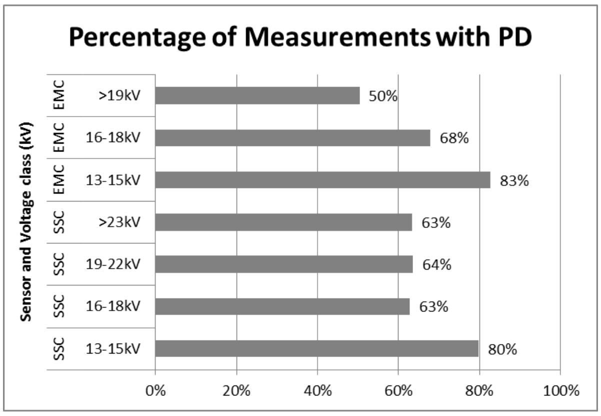

Figure 2. Percentage of results in database per sensor type

C. *Assets with PD*

For each type of sensor and rated voltage class, the percentage of measurements with discernible PD was determined. "Discernible" is defined as detectable PD with a pulse count rate that exceeds 10pps so that a peak magnitude (Qm) could be calculated. Figure 2 shows that for each category over 50% of the measurements had discernible PD. As shown in Figure 3 in most cases, the PD pattern exhibits a classic pattern indicative of PD originating within the stator winding insulation, i.e., the PD clusters are centred around the 45° and 225° phase positions with no evidence of polarity predominance.

Figure 3 and Figure 4 show classic phase-resolved PD patterns obtained from the same hydrogen-cooled generator with the same operating conditions derived from SSCs (Figure 3) and EMCs (Figure 4). Since the patterns in these figures are almost textbook examples of PD patterns, clearly PD does occur in hydrogen-cooled machines. Also, the pulse patterns are similar, regardless of sensor, indicating the same deterioration mechanism is likely operative.

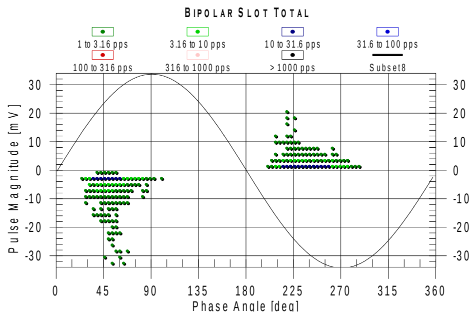

Figure 3. Phase-resolved PD plot using antenna sensors (SSCs) on a generator operating at 18 kV, 167 MW and 300 kPag

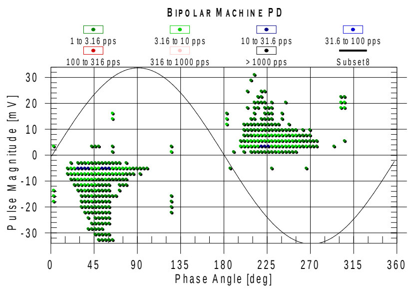

Figure 4. Phase-resolved PD plots using 80 pF capacitive sensors (EMCs) on the same generator as Figure 3 with identical operating conditions.

The horizontal scale is the phase angle of the power frequency. The vertical scale is the PD magnitude in mV. The color of the dots represents the PD pulse repetition rate.

IV. Correlation between PD behaviour and hydrogen pressure

In off-line tests when the stator is tested in air at atmospheric pressure, the PD magnitudes in voids within the groundwall or defects on the surface seem to have much higher magnitudes than when the winding is tested in high pressure hydrogen [16][17]. The reasons for this reduction in magnitude are not clear (at least to the authors), since in principle, an increase in the stress is needed to cause breakdown in a high-pressure gas void and, thus, should increase the energy stored in the void prior to breakdown, increasing the PD magnitude. It is obvious that surface PD would be influenced by the hydrogen pressure, but it has also been established that the gas pressure within a groundwall void is essentially the same as hydrogen pressure within the generator [18].

Figure 5 shows that the PD magnitude from phase-to-phase activity during normal service is affected by the hydrogen pressure. This data is from a single generator. Specifically, an increase in hydrogen pressure decreases the PD magnitude. This confirms the results from off-line test data in [16][17].

To evaluate this further, PD detected using SSCs for two voltage classes, 16-18kV and 19-23kV, were analyzed macroscopically using the data from hundreds of generators. Since the sensor separates data into endwinding and slot activity, these were analyzed separately. As shown in Figure 6 and Figure 7 below, there appears to be a slight correlation between PD classified as endwinding and hydrogen pressure. This may be due to the additional energy required to generate an arc at the higher hydrogen pressure. The lack of correlation shown with the SSC Slot activity is puzzling, in view of investigations [18] that demonstrated the gas pressure in the voids in the solid insulation almost instantaneously reach equilibrium with the surface pressure and requires further investigation [Figure 8 and Figure 9].

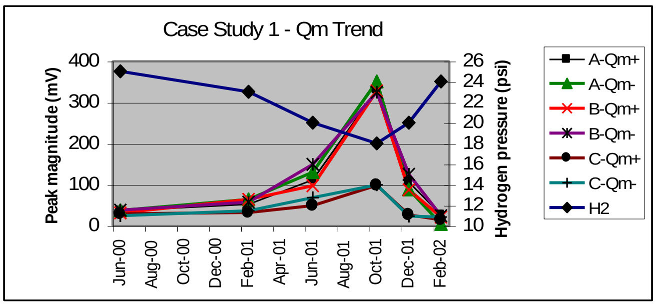

Figure 5. Effect of hydrogen pressure on peak PD magnitude in an operating 60 MVA, 13.8 kV hydrogen-cooled turbine generator with known phase-to-phase discharge activity.

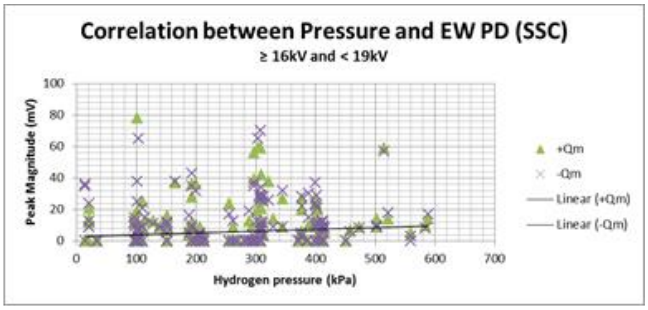

Figure 6. SSC Endwinding Activity (≥ 16kV and < 19kV)

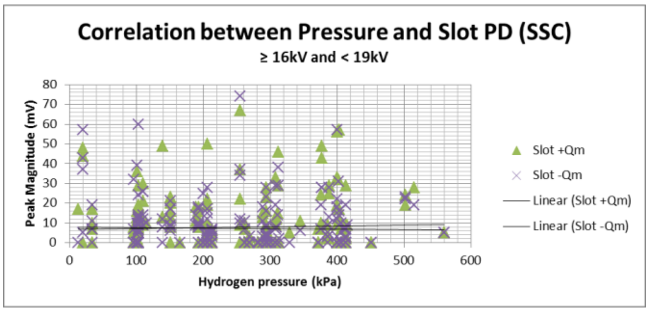

Figure 7. SSC Endwinding Activity (≥ 19kV and < 23kV)

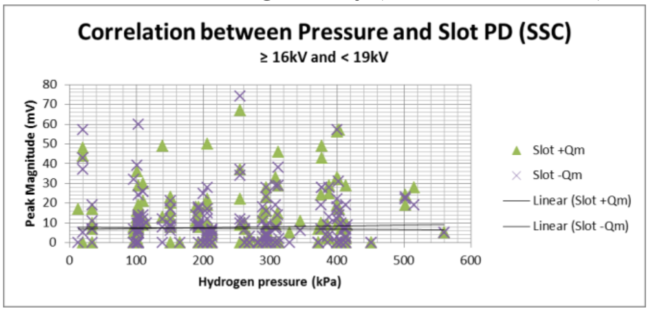

Figure 8. SSC Slot Activity (≥ 16kV and < 19kV)

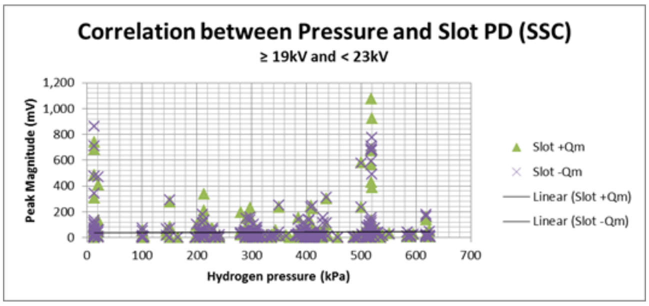

Figure 9. SSC Slot Activity (≥ 19kV and < 23kV)

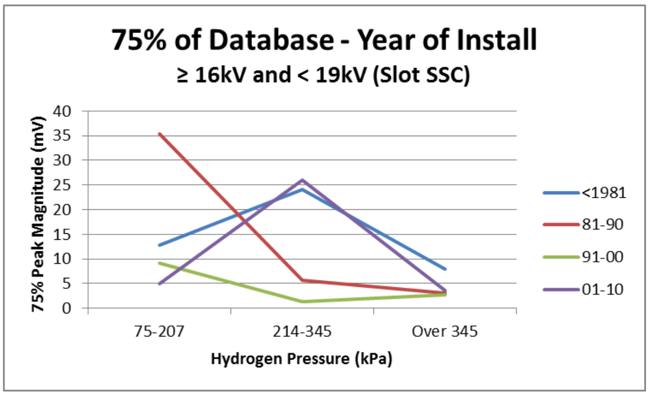

Figure 10. SSC Slot – 75% ranking in the database for 16kV-19kV assets based on year of winding installation

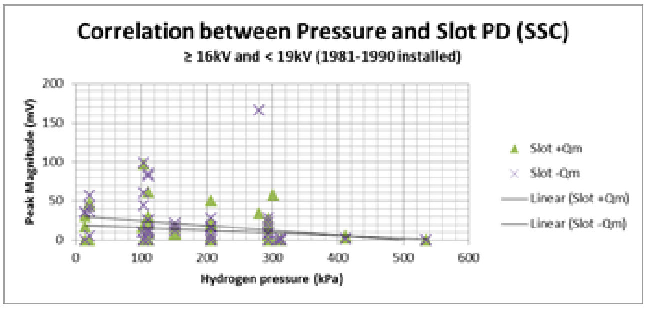

Figure 11. SSC Slot -- PD correlation with Pressure for 1981-1990 installations (≥16kV-19kV)

As shown in Figure 10 there appears to be an inverse correlation between PD and pressure for windings installed before 1981, but for the newer windings there is no obvious correlation.

Further examination of the 16kV-19kV results clearly shows the *inverse correlation* for those windings installed between 1981-1990. [Figure 11] And for those windings installed from 1991-2000 and 2000-2010, as shown in Figure 12 and Figure 13, respectively, there is a *direct correlation*. There is no obvious reason for the difference, but perhaps the materials or deterioration in the older windings leads to an *inverse correlation*, whereas, the newer windings exhibit more of the expected *direct correlation* between PD magnitudes and hydrogen pressure when all other conditions
are equal.

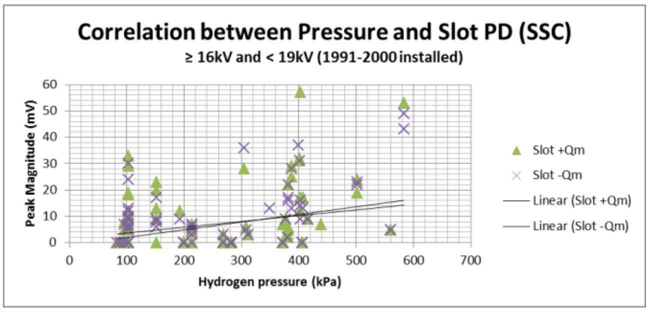

Figure 12. SSC Slot -- PD correlation with Pressure for 1991-2000 installations (≥16kV-19kV)

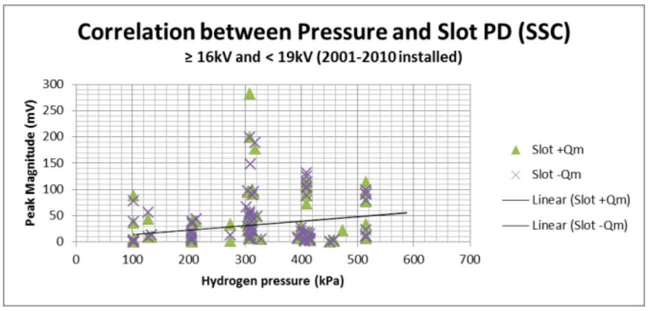

Figure 13. . SSC Slot -- PD correlation with Pressure for 2001-2010 installations (16kV-19kV)

V. Correlating on- and off-line PD tests

Often, in cases where high PD sources are identified from on-line measurements, off-line PD testing is employed during an outage to confirm and/or locate the presence of PD-related deterioration or defects. In many cases, a direct correlation between the results of these two variants of PD testing is not found. This observation is not surprising because of the temperature and voltage distribution differences, and the absence of mechanical forces when the machine is off-line. For example, an off-line PD test may produce a pessimistic result because the entire winding, or individual phase, is energized to the same high potential and thus coils or bars at, or close to, the neutral point may contribute to the PD result whereas in operation, the electrical stress at these locations would be insufficient to result in discharge. Similarly, interpreting the results of an off-line PD test on a hydrogen-cooled machine, usually conducted in air at atmospheric pressure, presents challenges when comparing with on-line measurements obtained with the stator winding operating in a pressurized hydrogen environment. In cases, where the on-line PD test results indicate high PD magnitudes associated with internal void discharge, an off-line test employing a locative tool such as a corona probe cab used to identify the source. Alternatively, or in conjunction, visual inspection of the winding is often the best means of identifying defects. Of course, such tests or inspections normally require that the generator be disassembled.

VI. Conclusions

Partial discharge does occur in hydrogen-cooled stator windings. Such PD has been detected using both 80 pF capacitive sensors and SSC sensors (UHF antennae) installed in the stator slots. PD data collected from over 1000 hydrogen-cooled machines, correlated with the visual inspection of the stator windings, has enabled the establishment of approximate levels of peak PD magnitude at which further investigation of the winding would be prudent. There is some evidence that there is an inverse correlation between PD and hydrogen pressure in older windings, perhaps due to delamination or a characteristic of older insulation materials. For newer windings, a direct correlation is more likely, but not definitive. Because of this correlation, it is essential that both voltage and hydrogen pressure be considered when comparing results against the statistical database.

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