PARTIAL DISCHARGE TESTING: A PROGRESS REPORT

HYDROGEN-COOLED WINDINGS

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1 ABSTRACT

It has long been known that comparing the partial discharge results obtained from a single machine is a valuable tool enabling companies to observe the gradual deterioration of a machine stator winding and thus plan appropriate maintenance for the machine [1]. In 1998, at the annual Iris Rotating Machines Conference (IRMC), a paper was presented that compared thousands of partial discharge (PD) test results to establish the criteria for comparing results from different machines and the expected PD levels [2]. At subsequent annual Iris conferences, using similar analytical procedures, papers were presented that supported and expanded upon the previous criteria [6 - 20].

In the past few decades, trending of PD results has provided plant maintenance personnel with advanced notice as problems develop within their stator winding insulation. Though prediction of failure is never exact, increases in PD activity over time have been shown to indicate advancing damage to the stator winding that could lead to premature failure. Turbine generators in nuclear, coal, oil and some gas-fired power plants are normally rated above a few hundred megawatts and tend to be hydrogen-cooled (and above 500 MW or so, both direct-water and hydrogen-cooled). One of the features of hydrogen cooling is the suppression of partial discharge (PD) activity by the hydrogen gas at high pressure. Because of this, there has been some controversy about the effectiveness of on-line PD testing to detect insulation problems in hydrogen-cooled machines; this paper will present a statistical summary of on-line PD measured on hydrogen-cooled turbine generators, together with some specific case studies.

Disclaimer: The analyses contained within make the assumption that the operating gas pressures are correctly entered into the database at the time of the test.

Calibration of on-line PD test results is impractical [3]; therefore, only results obtained using the same method of data collection and noise separation techniques are compared. For this paper, all the data were obtained with a PDA-IV, TGA, Trac or Guard test instrument. Data collected through 2015 was used; and, as in past papers, it is standardized for frequency bandwidth and pruned to include only the most recent full-load-hot (FLH) results collected for each sensor on operating machines. All questionable data or data from off-line testing or unusual machine conditions was excluded, leaving over 20,000 statistically independent new results collected from about 6,000 machines. The Appendix presents the statistical summary of the latest data to enable Trac, Guard, TGA, and PDA-IV test users to compare on a gross level their test results to those of similar machines.

2 INTRODUCTION

2.1 PD - A COMPARISON TEST

Partial discharges (PD) are small electrical sparks that occur when voids exist within or on the surface of high voltage insulation of stator windings in motors and generators. These PD pulses can occur because of the manufacturing/installation processes, thermal deterioration, winding contamination or stator bar movement during operation. As the insulation degrades, the number and magnitude of PD pulses will increase. Although the magnitude of the PD pulses cannot be directly related to the remaining life of the winding, the doubling of PD pulse magnitudes approximately every 6 months has been used as a “rule of thumb” to indicate rapid deterioration is occurring. If the rate of PD pulse activity increases rapidly, or the PD levels are high compared to other similar machines, this is an indicator that visual inspections and/or other testing methods are needed to confirm the insulation condition [4]. Furthermore, if the PD magnitudes by the same test method from several identical windings are compared, the windings exhibiting higher PD activity are generally closer to failure [1]. This paper examines the validity of this approximation.

2.2 PREVIOUS PAPERS

The conclusion of previous papers was that when comparing PD data results from different machines, the following parameters must remain constant:

- Test instrument bandwidth and noise separation techniques [2]
- Type of sensors [2, 5, 12, 15]
- Operating voltage of the machines [2, 11, 12, 19]
- Operating gas coolant of the machines – PD is pressure dependent [2, 8, 12]
- PD levels appear to be influenced by the quality of design, manufacturing, and installation, and not solely operating hours or operating condition [6, 7, 10, 13, 14, 16, 20]
- Impact of ambient conditions [18]

Not as significant are:

- Type of insulation system [6, 9, 12]
- Machine type [2,5,6,11]
- Winding type [2,5,6,11]

Differences in operating loads and temperatures could also affect the results, but these were dependent on the condition of the stator winding and therefore, would only be applicable when comparing the PD results obtained from a single machine, not when comparing results from different machines.

3 COLLECTION OF DATA

3.1 PD TEST METHOD

During normal machine operation, an instrument called the PDA-IV or TGA is temporarily connected to the previously installed sensors in each phase. The sensor blocks the power frequency voltage, and passes the high frequency voltage pulse accompanying partial discharge. To avoid any confusion with electrical noise from power tool operation, corona from the switchgear, RF sources, etc., the PDA-IV or TGA separates PD from system noise on the basis of time-of-arrival and pulse characteristics, and measures the number, magnitude and ac phase position of the PD pulses.

3.2 DATA PRESENTATION

Two types of plots are generated for each partial discharge test. The first type of plot is two-dimensional (2-D), where the number of partial discharges per second versus PD magnitude is displayed. The greater the number of pulses per second, the more widespread is the deterioration in the winding. The higher the PD magnitude, the more severe is the deterioration. The second type of plot is three-dimensional (3-D), where the quantity (vertical scale) and magnitude (scale coming out of the page) of the PD versus the ac phase angle (horizontal scale) are displayed. Experience has indicated that such pulse phase analysis can be used to identify if multiple deterioration mechanisms are occurring, and what the mechanisms are.

The 2-D and 3-D plots are unwieldy for making comparisons amongst the machines. The PDA-IV or TGA summarizes each plot with two quantities: the peak PD magnitude (Qm) and the total PD activity (NQN). The Qm is defined to be the magnitude corresponding to a PD repetition rate of 10 pulses per second. Qm relates to how severe the deterioration is in the worst spot of the winding, while the NQN is proportional to the total amount of deterioration and is similar to the power factor tip-up. Since the Qm scalar quantity is more indicative of how close the winding is to failure, the peak magnitude (Qm) will be used throughout this paper for comparisons.

3.3 2015 DATABASE

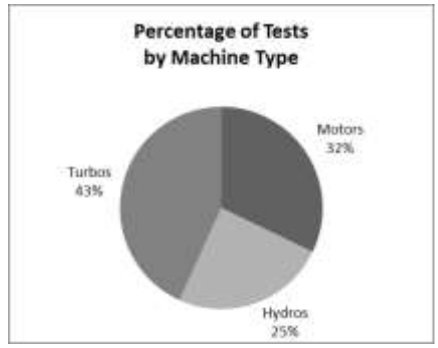
After the accumulation of all available test data through 2015 with over 550,000 records from tests using portable instruments only, a database was carefully compiled using the following selection criteria:

- only on-line tests obtained during normal operation
- only one test result per sensor
- the most recent test at Full Load and Hot stator winding temperature (FLH)
- any test with questionable results was discarded

Once these criteria were applied, about 20,000 statistically independent test results from about 6,000 assets were analyzed.

The following tables show the breakdown of the results that were retained once non-FLH and repeat tests were discarded.

Number of FLH Tests by Machine Type	
Motors	32%
Hydros	25%
Turbos	43%



The appendix shows the updated statistical distribution of peak PD magnitudes for various voltage classes and sensor types.

3.4 STATISTICAL ANALYSIS

The database was analyzed to determine the effect on Qm of several different factors, 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 sample of the statistical distribution is shown in Table 1. For example, for 13-15 kV stators in turbine generators or motors, 25% of tests had a Qm below 54 mV, 50% (the median) had a Qm below 120 mV, 75% were below 261 mV and 90% of tests yielded a Qm below 520 mV. Thus if a Qm of 500mV is obtained on a 13.8 kV motor or turbine generator, then it is likely that this stator will be deteriorated, since it has PD results 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 [22].

Table 1. Distribution of Qm for Air-Cooled Stators, 80 pF Sensors on the Terminals

Oper kV	2-5kV	6-9kV	10-12kV	13-15kV	16-18kV	> 19kV
25%	9	25	45	54	38	63
50%	21	66	98	120	76	101
75%	63	158	210	261	162	231
90%	214	336	412	520	329	626
95%	363	521	643	770	570	935

Table 2 illustrates the similar statistical distribution for hydrogen-cooled turbo generators where stator slot couplers (SSC) capacitors are installed. For these, both the operating voltage and gas pressure influence the results. Similar tables have also been prepared for air and hydrogen-cooled machines with other types of PD sensors and can be found in the appendix of this paper.

Table 2. Distribution of Qm for Gas-Cooled Stators using SSC sensors – Slot PD

Oper V	13-15kV			16-18kV			19-22kV			23-26kV	
H2 (kPa)	**76-138**	**145-207**	**Over 207**	**75-207**	**214-345**	**Over 345**	**75-207**	**214-345**	**Over 345**	**214-345**	**Over 345**
H2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
25%	0	0	0	0	0	0	1	0	0	0	0
50%	9	1	7	0	6	2	8	7	5	8	3
75%	31	13	16	13	13	11	23	21	12	31	8
90%	48	63	31	58	21	24	95	46	25	66	17
95%	60	92	47	90	27	34	225	69	38	100	27

With these tables, it is now possible, with only an initial test for motor and generator owners, to determine if the stator winding insulation has a problem. If the PD is higher than that found on 90% of similar machines, then off-line tests and/or a visual inspection would be prudent. Continuous PD monitors should have their alarm levels set to the 75% for 4kV rated and below and the 90% level for above 4kV rated assets.

4 HYDROGEN-COOLED ASSETS

4.1 BACKGROUND

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 a high pressure (typically 200-400 kPag or about 29-58 psi-g), 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 [21]. 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 high hydrogen pressure is likely to exhibit fewer PD pulses per second, that is, an *inverse correlation*. In addition, unlike air-cooled machines where the PD creates corrosive gases (ozone and nitric acid); PD in hydrogen does not create a corrosive gas that can accelerate the deterioration of the insulation and metallic structure of the generators. However, as long as voids do attain the breakdown threshold stress for the gas pressure, then PD can occur. [29]

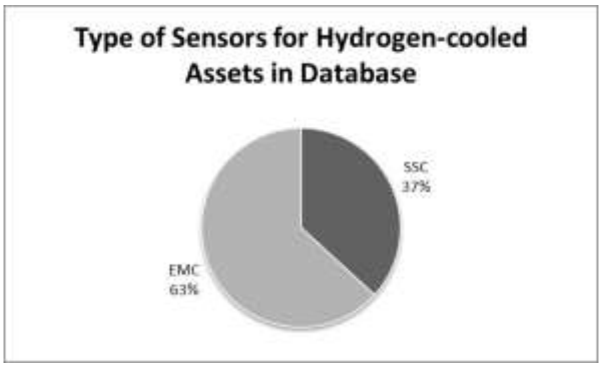


Figure 1. Percentage of results in database per type of sensor

4.2 IS THERE PD IN HYDROGEN?

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 (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]

4.2.1 EMCs

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. Be advised that the results in the database also include results that may be skewed by the presence of external activity.

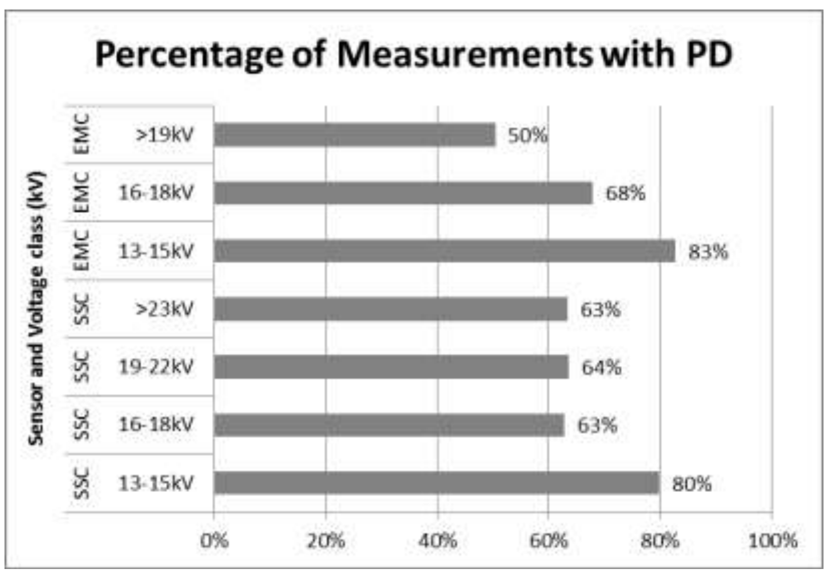


Figure 2. Percentages of measurements with discernible PD

4.2.2 SSC Sensors

Since SSC sensors are located within the hydrogen environment, there is minimal, if any, detection of activity from sources external to the winding. Therefore, it can be assumed that all 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.

4.2.3 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. For all of the assets with EMC sensors, 94% had discernible PD, while 83% of the assets with SSC sensors had 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.

Figure 3 and Figure 4 show classic phase-resolved PD patterns obtained from two hydrogen-cooled generators. Since the patterns in these figures are almost textbook examples of PD patterns, clearly PD does occur in hydrogen-cooled machines.

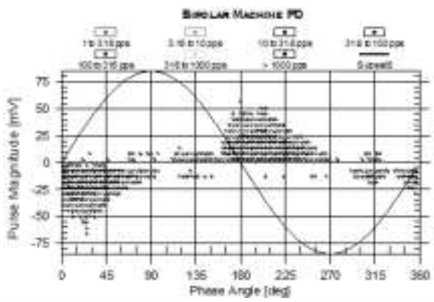


Figure 3. Phase-resolved PD plots for 3 phases using 80 pF capacitive sensors (EMCs) on a generator operating at 18 kV, 117 MW and 200 kPag.

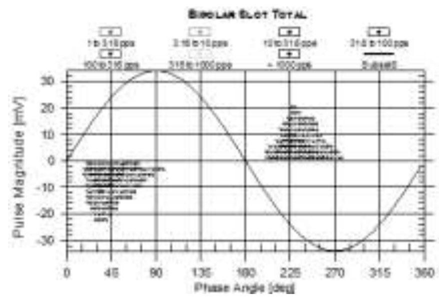


Figure 4. PD plots using antennae sensors (SSCs) from a generator operating at 24 kV, 467 MW and 410 kPag

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.

4.3 IS THERE A CORRELATION BETWEEN PD AND 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, or an *inverse correlation* [23][24]. 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, or a *direct correlation*. 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 [25].

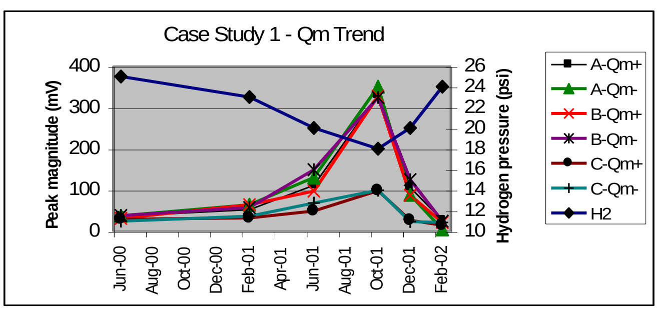


Figure 5. Effect of hydrogen pressure on peak PD magnitude in an operating 60 MVA, 13.8 kV hydrogen-cooled turbine generator with known phase-to-phase discharge activity.

Figure 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 [23][24].

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 *direct 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 and requires further investigation [Figure 8 and Figure 9].

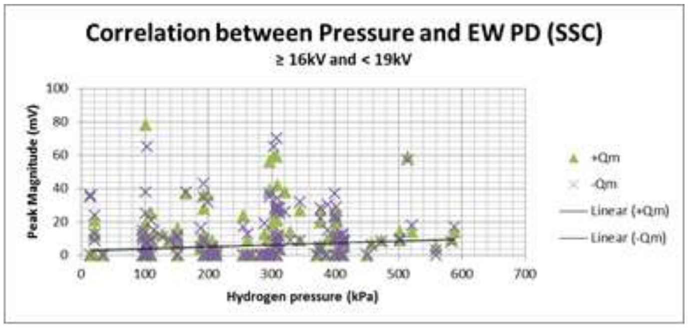


Figure 6. SSC Endwinding Activity (≥ 16kV and < 19kV)

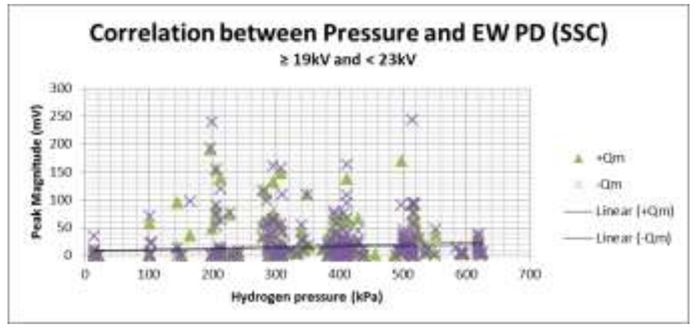


Figure 7. SSC Endwinding Activity (≥ 19kV and < 23kV)

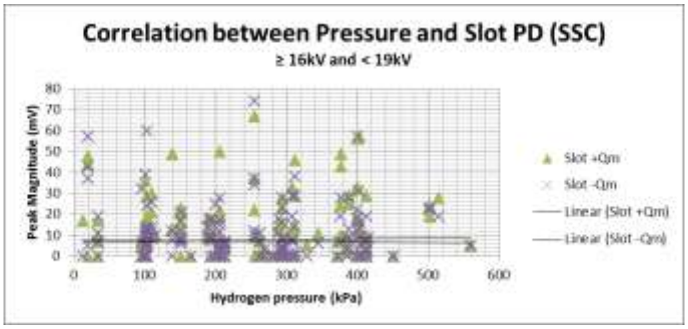


Figure 8. SSC Slot Activity (≥ 16kV and < 19kV)

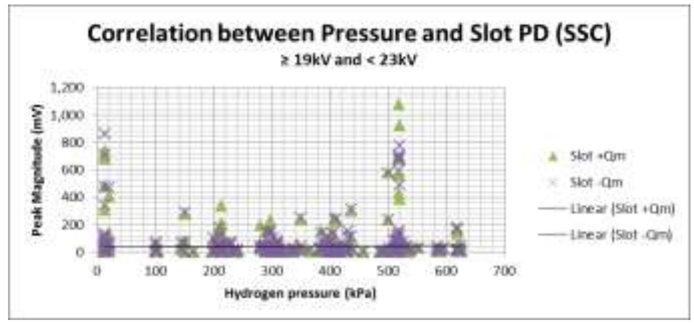


Figure 9. SSC Slot Activity (≥ 19kV and < 23kV)

4.3.1 Is this correlation impacted by Age of Winding?

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.

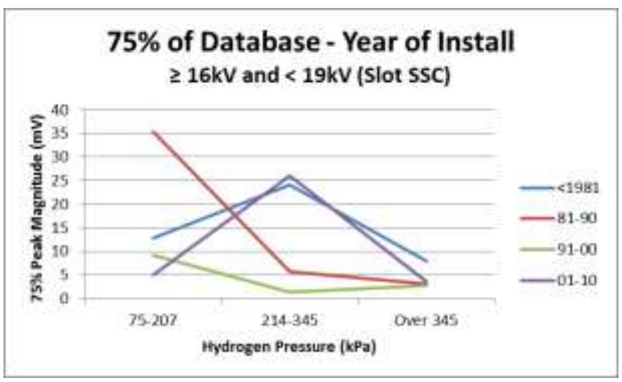


Figure 10. SSC Slot – 75% ranking in the database for 16kV-19kV assets based on year of winding installation

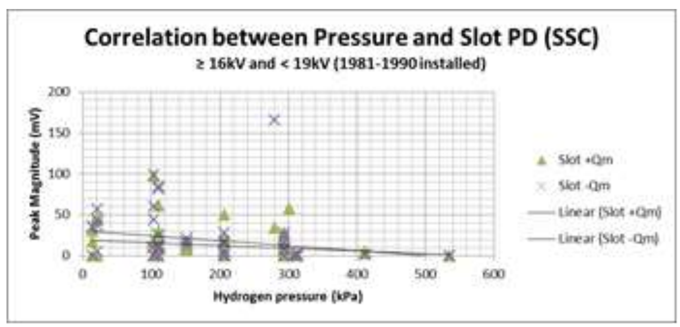


Figure 11. SSC Slot -- PD correlation with Pressure for 1981-1990 installations (≥16kV-19kV)

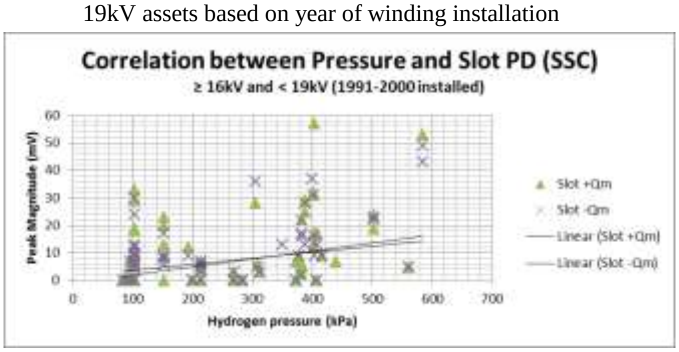


Figure 12. SSC Slot -- PD correlation with Pressure for 1991-2000 installations (≥16kV-19kV)

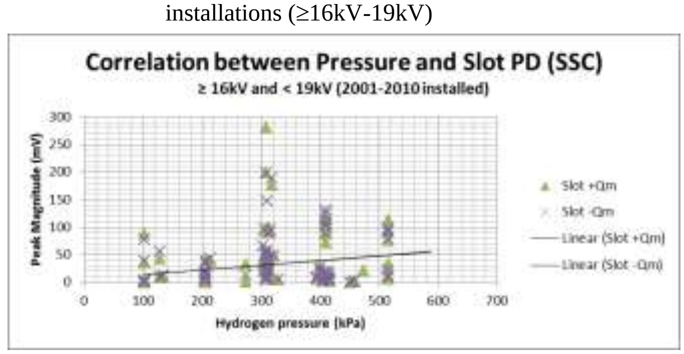


Figure 13. SSC Slot -- PD correlation with Pressure for 2001-2010 installations (≥16kV-19kV)

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.

4.3.2 Is this correlation impacted by Winding Manufacturer?

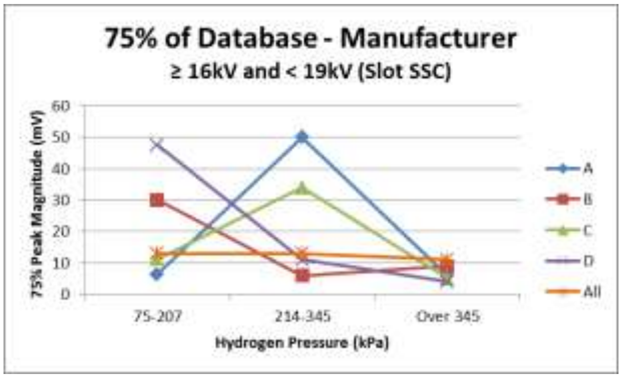


Figure 14 SSC Slot – 75% ranking in the database for 16kV-19kV assets based on year of winding installation

As shown in Figure 14, there appears to be an *inverse correlation* between PD and pressure for windings by two manufacturers (B and D), but for the others there is no obvious correlation.

For the B and D manufacturers, it should be noted that the majority of their windings with results in the database were installed prior to 1990, which may explain the reason for the *inverse correlation* as shown in Figure 15.

For the other two manufacturers, A and C, a large portion of their windings were installed in or after 1990, which suggests the more erratic correlation may be due to differences in materials or age. Note the direction correlation exhibited in Figure 16.

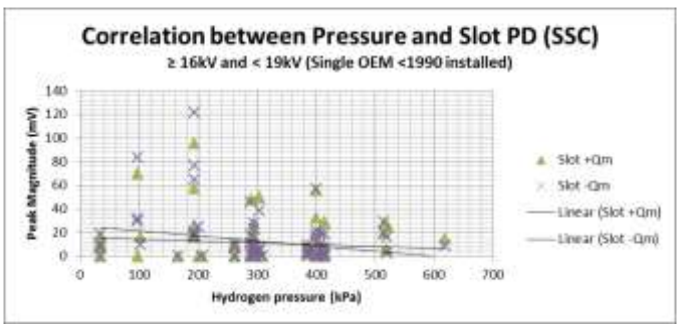


Figure 15. SSC Slot -- PD correlation with Pressure for Manufacturer D for windings installed < 1990 (≥16kV-19kV)

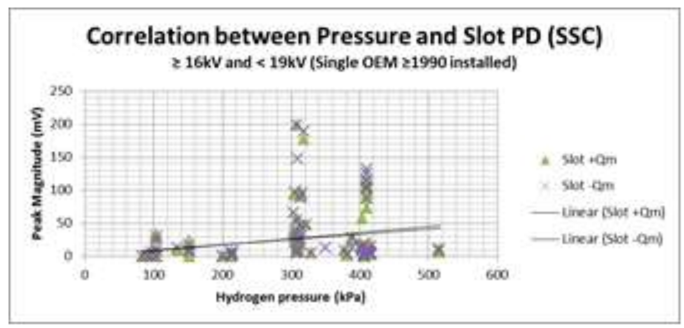


Figure 16. SSC Slot -- PD correlation with Pressure for Manufacturer C for windings installed ≥1990 (≥16kV-19kV)

5 CONCLUSION

PD does in fact occur in hydrogen-cooled stator windings. This 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.

Though it is always recommended that you 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. If the test instrument is a TGA, PDA-IV, Trac or Guard and the sensors are either 80pF capacitors, or stator slot couplers, then the tables contained within the appendix can be used to ascertain whether a machine warrants further tests and inspections or is operating within reasonable limits. Yellow flags should only be raised if the PD levels on a specific machine are above the 90th percentile (High). In all cases, raising the flag means increasing the frequency of PD testing to determine the rate of deterioration and when possible, conduct specialized tests, inspections and repairs as required. In mica-based insulation systems, PD is a symptom of a failure mechanism;

action should be based on the severity of the failure mechanism detected by the PD, not the PD results. PD levels exceeding threshold alarms are warnings for further investigation to determine the cause of the high PD; however, be aware that PD levels can fluctuate with ambient and operating conditions. Maintenance should be based on the cause of the PD, not the overall levels. Continuous PD monitors should have their alarm levels set to the 75% or 90% level.

The time of winding failure is normally the result of a deteriorated winding being subjected to an extreme stress such as a lightning strike, out-of-phase synchronization, excessive starts, or system imbalance. As these are unpredictable, it is impossible to forecast when a failure will occur. However, by monitoring the PD characteristics of a stator winding, it is often possible to determine which machines are more susceptible to failure, and therefore which require maintenance.

6 REFERENCES

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7 APPENDIX – DATA ANALYSIS OF RESULTS THRU 2015

The following summarizes the analysis of the PD levels, given by Qm number, for all data collected with Iris equipment up to the end of the year 2015 with over 550,000 results. Since it has been well established that it is ambiguous to compare PD results obtained using different types of sensors [3], data analysis requires separation of the database based on sensor type. The two basic types of sensors used in the data collection are: 80pF capacitors (cable-type and epoxy-mica type) and stator slot couplers (SSC). Furthermore, data will be separated based on gas cooling pressure and operating voltages.

7.1 CAPACITORS – (AIR-COOLED MACHINES)

The most widely employed sensors are the 80pF couplers used on motors, hydro-generators, and small turbine generators. There are two methods of sensor installation for the capacitive couplers, the directional (TGA) and the differential (PDA) methods.

7.1.1 Directional Method (TGA)

The directional method is used primarily on motors and small turbine generators and occasionally on small hydro-generators.

Qm values for air-cooled machines with directional capacitive couplers (TGA)

Rated kV	2-5	6-9	10-12	13-15	16-18	> 19[1]	
25%	9	25	45	54	38	63	25% of the results have Qm levels below this value
50%	21	66	98	120	76	101	50% of the results have Qm levels below this value
75%	63	158	210	261	162	231	75% of the results have Qm levels below this value
90%	214	336	412	520	329	626	90% of the results have Qm levels below this value
95%	363	521	643	770	570	935	95% of the results have Qm levels below this value

As shown here, the majority, 75%, of the results obtained with the directional mode installation (BUS) of capacitive couplers are below 210mV for machines rated less than 12kV, 261mV for machines rated 13-15kV, 162mV for 16-18kV, and 231mV for those >19kV.

Additionally, there is at least a doubling of the Qm levels between the 75% and the 90%, which supports the definition of *rapid deterioration* as doubling over a twelve-month interval [28]. There are a few machines with PD much higher than the 90th percentile with Qm levels >500-935mV. These machines are suspected to have significant deterioration.

7.1.2 Differential Method (PDA)

The differential method is used primarily on large hydro-generators having an internal circuit ring bus.

There are two major differences in the directional and differential installations: one is the method of time-of-arrival noise separation and the second is the actual location of the couplers. Since both time-of-arrival noise separation techniques work similarly, this difference should have little impact to the test results.

However, the difference in the sensor locations can greatly affect the results. A differential (PDA) installation in a larger hydro-generator uses sensors normally placed within one meter of the junction between the incoming phase bus and the first coil/bar in the circuit. A sensor at this location will be extremely sensitive to any pulses originating within the coil/bar since the magnitude of the pulse will be amplified when it reaches the impedance mismatch between the bus and the coil/bar. Thus, it is reasonable to assume the results obtained with the couplers at this location will be higher than when the couplers are located outside the machine housing typical of directional (TGA-BUS) installations. However, when comparing the directional (TGA) results to the differential (PDA) results, though there are some minor variances, there is little significant difference between

[1] Fluctuations from previous years due to a large influence by one or more manufacturers

the statistical summaries for windings rated less than 16kV. Thus, it is safe to say that for a 13.8kV winding, regardless of installation type, the PD levels should be less than ~250mV and those machines with PD higher than 500mV need further investigation.

Qm values for air-cooled machines with differential capacitive couplers (PDA)

Rated V	**6-9kV**	**10-12kV**	**13-15kV**	**16-18kV**	**> 19kV**	
25%	12	20	34	23	90	25% of the results have Qm levels below this value
50%	33	50	88	81	176	50% of the results have Qm levels below this value
75%	66	112	190	222	659	75% of the results have Qm levels below this value
90%	172	240	364	557	857	90% of the results have Qm levels below this value
95%	315	385	530	729	993	95% of the results have Qm levels below this value

7.2 CAPACITORS – (GAS-COOLED) (TGA)

Since the occurrence of PD is extremely dependent on the electrical breakdown point of the gas medium, PD results from air-cooled machines are typically higher than machines cooled with either hydrogen or pressure carbon dioxide. Therefore, it is not advisable to compare the results from machines using different gas mediums. Since most hydro-generators (PDA installations) are air-cooled, all of the tests for gas-cooled machines with capacitors were obtained using a TGA instrument and directional sensor installation. Most of the hydrogen-cooled machines have high rated loads and frequently suffer from problems with the core iron arcing. PD or noise activity at the machine terminals, outside the hydrogen environment, can make stator winding insulation condition difficult to interpret. As a result, stator slot couplers (SSC) are the recommended sensors in these applications to avoid misdiagnosis resulting from the capacitive sensor detecting core-iron problems in addition to stator winding problems.

Qm values for non air-cooled machines with directional capacitive couplers (TGA)

Rated V	**13-15kV[2]**				**16-18kV**				**> 19kV**		
H2 (kPa)	**76-138**	**145-207**	**214-345**	**Over 345**	**76-138**	**145-207**	**214-345**	**Over 345**	**145-207**	**214-345**	**Over 345**
H2 (psig)	**11-20**	**21-30**	**31-50**	**>=51**	**11-20**	**21-30**	**31-50**	**>=51**	**21-30**	**31-50**	**>=51**
25%	28	21	16	27	17	33	21	9	43	22	10
50%	75	50	34	80	80	72	40	21	94	49	27
75%	157	98	67	197	146	379[3]	97	47	172	90	60[2]
90%	346	183	179	600	268	905[3]	191	272	217	154	398[2]
95%	830	293	419	965	389	976	354	350	246	224	987

As expected, the PD results for gas-cooled machines are much lower than for the air-cooled machines. This is especially observable at higher pressures, where 75% of the tests for all operating voltages operated above 31psig are below 200mV and 90% generally below ~250mV, less than half of that observed on the air-cooled machines (Section 7.1.1). At the lower operating pressures, the PD levels are generally much higher, with a few machines having extremely high PD of Qm levels >600mV, which would require more tests and investigation.

[2] Fluctuations from previous years due to a large influence by one or more manufacturers
[3] Fluctuations from previous years due to a small sampling size

7.3 STATOR SLOT COUPLERS (SSC) – (GAS-COOLED)

Qm values for non air-cooled machines with SSC sensors- Slot PD

Rated V	13-15kV			16-18kV			19-22kV			23-26kV	
H2 (kPa)	**76-138**	**145-207**	**Over 207**	**75-207**	**214-345**	**Over 345**	**75-207**	**214-345**	**Over 345**	**214-345**	**Over 345**
H2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
25%	0	0	0	0	0	0	1	0	0	0	0
50%	9	1	7	0	6	2	8	7	5	8	3
75%	31	13	16	13	13	11	23	21	12	31	8
90%	48	63	31	58	21	24	95	46	25	66	17
95%	60	92	47	90	27	34	225	69	38	100	27

The preferred sensor for turbine generators rated higher than 100MVA is a stator slot coupler (SSC). The sensor is placed within the slot of the highest voltage bar either directly beneath the wedge or between the top and bottom bars in the slot. There is little difference in the results obtained from the two installations [2]. Since these machines are operating in a hydrogen environment, the overall slot PD is quite low relative to the air-cooled windings. It should be observed that though the majority of the machines have slot Qm values less than ~30mV, there are a few with levels higher than 60-200mV. These should be subjected to further tests and inspections. The SSC is a high frequency antenna that detects the pulses and through pulse analysis, the TGA is capable of discriminating between pulses originating in the high voltage insulation and those from core-iron arcing or external sources. Furthermore, the SSC/TGA test setup can identify whether the PD originates in the slot or in the endwinding [15]. The endwinding PD is slightly lower than the slot PD, with 90% of all the tests less than ~15mV. There are, however, a few machines with Qm levels higher than 25mV, and these machines require additional attention.

Qm values for non air-cooled machines with SSC sensors- Endwinding PD

Rated V	13-15kV			16-18kV			19-22kV			23-26kV	
H2 (kPa)	**76-138**	**145-207**	**Over 207**	**75-207**	**214-345**	**Over 345**	**75-207**	**214-345**	**Over 345**	**214-345**	**Over 345**
H2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
25%	0	0	0	0	0	0	0	0	0	0	0
50%	0	0	0	0	0	0	0	0	0	0	0
75%	0	0	2	0	4	2	1	2	5	0	2
90%	20	9	7	14	11	16[4]	9	11	16	3	6
95%	34	19	20	20	18	32	28	19	28	8	18[4]

7.4 STATOR SLOT COUPLER – (AIR-COOLED)

Qm values for air-cooled machines with SSC sensors

Slot PD		
Rated V	**13-15kV**	**16-24kV**
25%	0	1
50%	15	3
75%	38	13
90%	84	75
95%	120	123

Endwinding PD		
Rated V	**13-15kV**	**16-24kV**
25%	0	0
50%	0	1
75%	9	2
90%	38	9
95%	60	22

There are a few air-cooled machines being monitored with stator slot couplers. As previously described, because of the differences in the electrical breakdown points of the gas mediums, it is not recommended to compare results from air-cooled machines to those from gas-cooled ones. It is not surprising that the PD levels for the air-cooled machines with SSCs are generally higher than the gas-cooled ones. The majority of these machines have slot Qm levels less than ~38mV, but there are a few with extraordinarily high slot PD, >90mV, that would require further investigation.

[4] Fluctuations from previous years due to small sampling size