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Summary of Recent Advances in On-Line PD Interpretation in Stators

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PARTIAL DISCHARGE TESTING: A PROGRESS REPORT

STATISTICAL EVALUATION OF PD DATA

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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 [4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

In order to evaluate the industry trends of PD magnitudes, this paper introduces a unique approach to evaluating PD activity when using stator slot couplers (SSCs). This approach using prime summary numbers provides an improved tool when trending the development of problems for machines typically rated 100MW or higher where the presence of core-iron arcing could influence the PD test results. Only data collected through 2007 was used; and, as before, 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 almost 13,000 statistically independent results.

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 either a PDA-IV or TGA test instrument. 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.

INTRODUCTION

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 indicates 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].

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]
- Operating voltage of the machines [2,11, 12]
- 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]

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.

COLLECTION OF DATA

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 bases of time-of-arrival and pulse characteristics, and measures the number, magnitude and ac phase position of the PD pulses.

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.

2007 Database

After the accumulation of all available test data through to 2007 with over 140,000 records, 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

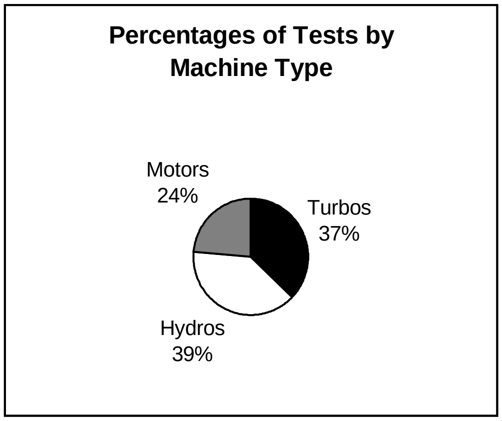
Once these criteria were applied, about 13,000 statistically independent test results were analyzed.

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	24%
Hydros	39%
Turbos	37%

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



Statistical Analysis

The database was analyzed to determine the effect on Qm of several different factors, including:

- Sensor installation
- Voltage class

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 hydrogenerators or pump-storage units, 25% of tests had a Qm below 34 mV, 50% (the median) had a Qm below 92 mV, 75% were below 191 mV and 90% of tests yielded a Qm below 371 mV. Thus if a Qm of 400 mV is obtained on an 13.8 kV hydrogenerator, 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.

Table 1. Distribution of Qm for Hydrogenerators with 80 pF Sensors

Rated V	6-9kV	10-12kV[1]	13-15kV	16-18kV	> 19kV
25%	14	20	34	39	77
50%	35	49	92	109	142
75%	88	99	191	260	311
90%	262	208	371	576	801
95%	472	354	551	770	928

Table 2 illustrates the similar statistical distribution for motors and air-cooled turbo generators where the 80pF capacitors are installed at the machine terminals (rather than within the stator as in Table 1). Similar tables have also been prepared for hydrogen-cooled machines and those with other types of PD sensors and can be found in the appendix of this paper.

Table 2. Distribution of Qm for Air-Cooled Stators, 80 pF Sensors on the Terminals

Oper. Volts	2-5kV	6-9kV	10-12kV	13-15kV	16-18kV	> 19kV
25%	8	26	29	53	44	25
50%	25	70	74	122	77	80
75%	67	152	181	245	160	162
90%	235	273	382	477	285	469
95%	487	375	563	771	394	784

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 90% level.

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[1] Fluctuations from previous years due to a low number of samples

USING PRIME SUMMARY NUMBERS FOR SSCS

Background

On many large (>100MW) high-speed turbo generators there are PD-like pulses that occur because of core iron arcing. It is impossible to discriminate between these pulses and true (insulation) PD using external capacitive coupler, so it is recommended that an antennae type sensor be used. This antennae sensor, or stator slot coupler, is comprised of an electrode structure printed on an epoxy-glass laminate [Figure 1].

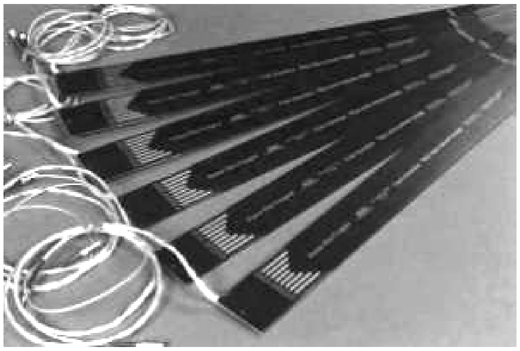


Figure 1. Stator Slot Couplers (SSCs)

The SSC is placed in the slot embedded either between the top and bottom coils or directly underneath the wedge as shown in Figure 2. Like the capacitive couplers, the SSC blocks the low frequency pulses but detects the high frequency PD-like pulses. However, since no electrical connection is made to the winding, the SSC is only sensitive to PD occurring within the slot containing the sensor. Though this limits the amount of coverage for the sensor, it does guarantee that only PD from the slot, not the core, will be detected.

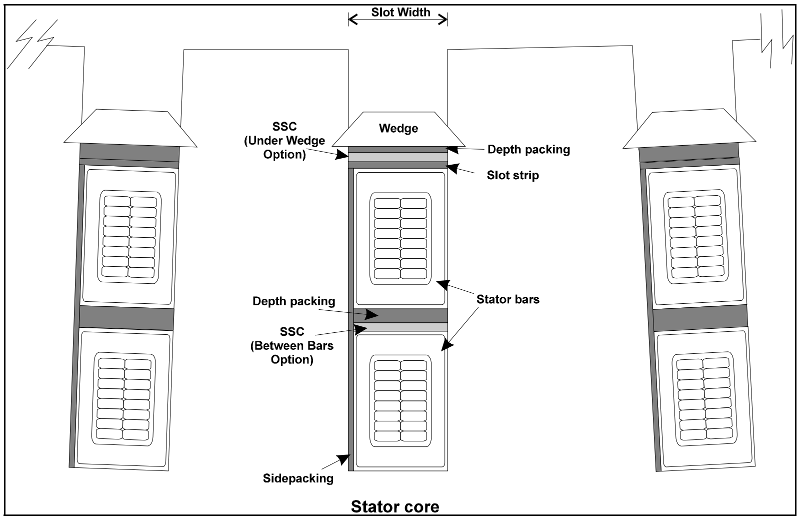


Figure 2. Location of SSCs

Figure 3. Installed SSCs

Standard PD Interpretation

It is important to remember that the bar semicon (conductive coating) is in fact transparent (i.e. it has an effective high resistance) at high frequencies, or more correctly, the skin depth is so big at high frequencies, that the electromagnetic field from the PD penetrates the bar semicon and interacts with the SSC. The semicon is only conductive at 50/60 Hz, which prevents the SCC from seeing high voltage. So from a high frequency point of view, the ground plane of the SSC is the ground plane for traveling waves. But from a 50/60 Hz point of view, the bar semicon is the ground plane.

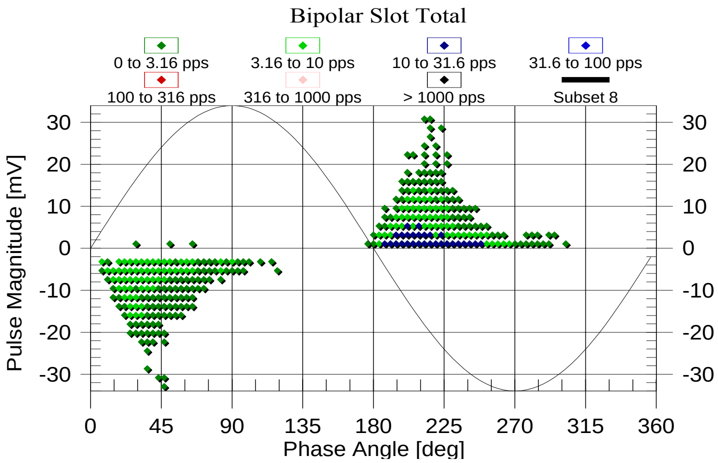


Figure 4. Classic PD Activity

In most of the cases the PD pulses occur due to the voltage difference between the core (ground) and the conductor. With classic PD, negative pulses occur from 0º - 90º of the AC cycle, centered on 45º (Figure 4). Positive PD occurs between 180º - 270º of the AC cycle,

These relationships are only valid if the PD sensor is in parallel with the stator winding. In this situation, PD in a void within a coil creates a current pulse which (*say*) travels up to the high voltage phase terminal, passes through the sensor (80pF) and the 50 Ω load within the instrument, and onto ground (Figure 5 and Figure 6). centered on 225º.

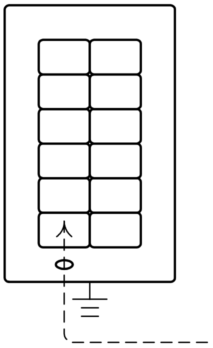


Figure 5.

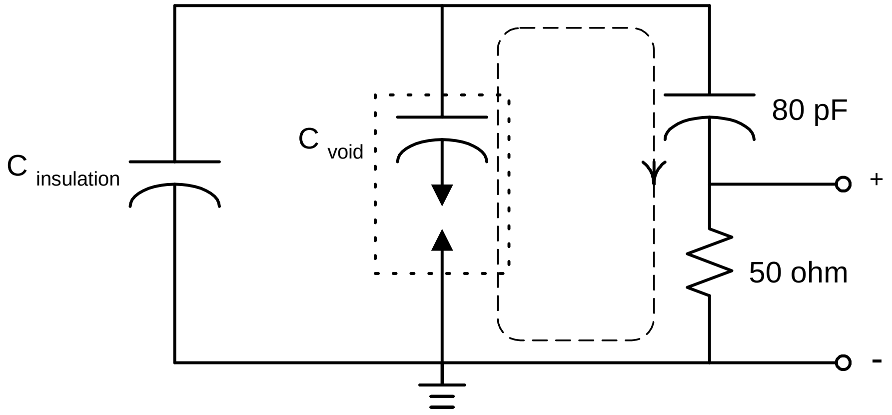


Figure 6.

(The PD current is assumed to flow up to the high voltage conductor)

To complete the current loop (current must flow in a closed loop according to Kirchoff's current law), the current pulse flows through the ground back to the discharge site (where it capacitively couples to the void). If we take the convention that a current into a resistor is positive in polarity, then a positive voltage is measured with respect to ground in Figure 6 with the current flow as shown. Therefore, when the PD current detected is in *parallel* with the PD site, the measured pulse through the sensor is 180° out-of-phase with the original pulse "through" the void, and the PD will be negative during the positive portion of the cycle. For SSCs, this usually applies to sources of PD away from the sensor in the slot or the endwinding. This is also the pattern observed when capacitive couplers are used as the sensing device.

PD Interpretation with Prime Summary Numbers

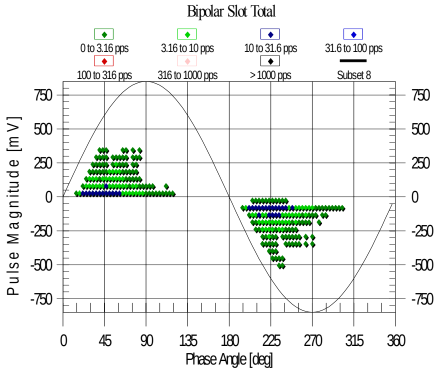


Figure 7. Reverse Classic PD

In addition to classic PD patterns, when PD is detected with an SSC, it is often observed that if the PD is under the SSC (Figure 7), that the reverse polarity of classic PD pattern is measured.

In parallel with the capacitance of the coil is the capacitance of the transformer winding or other stray capacitances to ground (Figure 8). In this case, a PD in the coil creates a current loop that flows to the high voltage terminal, through the stray capacitance to ground, through the ground and up through the PD sensors (50 Ω resistor) back to the PD site (Figure 8).

Since the current flow is now up into the 50Ω resistor from the groundside, it is in phase with the current through the void. Thus when the PD current detected is in *series* with the PD site, a positive current will be detected during the positive portion of the AC cycle (Figure 8). The polarity is reversed from the classic pattern.

We believe this occurs because if the PD is under the SSC sense line, then current flow will be from the sense line to the 50Ω resistor in the TGA-S instrument, and back to ground. Thus, instead of the PD being detected in parallel, PD under the SSC sensor is in series and explains why PD may have a revered polarity in SSC plots (Figure 7).

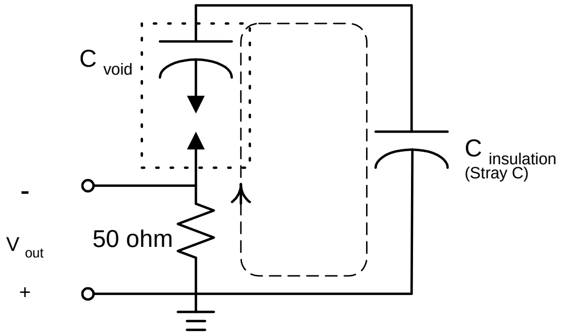


Figure 8.

Prime Summary Numbers

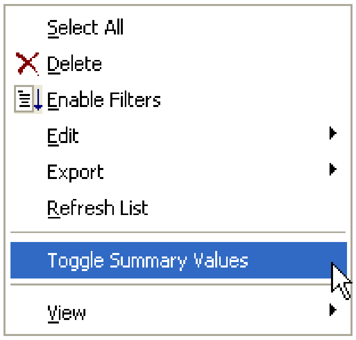
Because of the possibility of the reversal in polarity of Classic PD when using SSCs, Iris has introduced a different set of summary numbers, called the Prime summary numbers: +Qm’, -Qm’, +NQN’, and –NQN’. These prime numbers are calculated using a similar algorithm to the normal numbers with the exception of the polarity evaluation. Thus, the –Qm’ will include all of the pulses that occur during the positive AC cycle (first quadrant) regardless of the pulse polarity and the +Qm’ will include all of the pulses during the negative AC cycle (third quadrant) regardless of pulse polarity. Similar adjustments are made for the NQN’ values.

These prime summary numbers consider both PD pulses that originate in parallel and in series with the SSC, and therefore provide the customer a better solution to monitor their stator winding for developing problems.

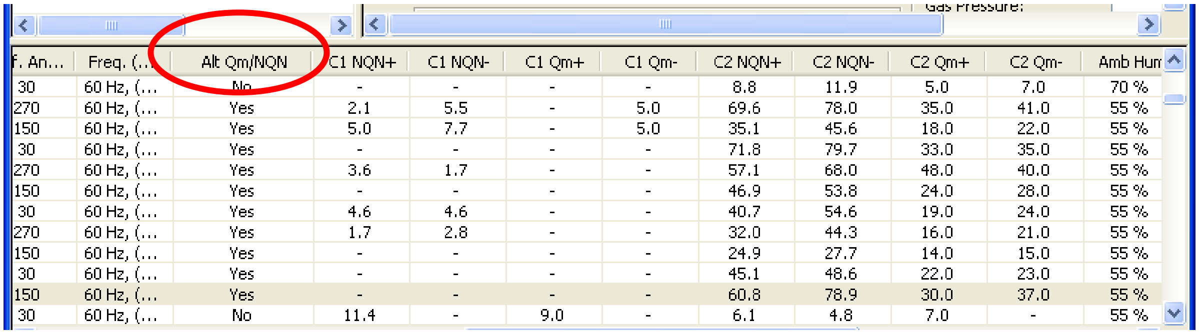
Software Options

PDLitePro, the Iris software used to collect PD data makes it easy for you to switch between the standard and prime summary values.

You can Toggle between the summary variables using the traditional and Alternate (Prime) to in PDLitePro using the right-click option in the Measurements Window.



You can observe on the Measurements window in PDLitePro whether the Alternate (Prime) numbers are being displayed.



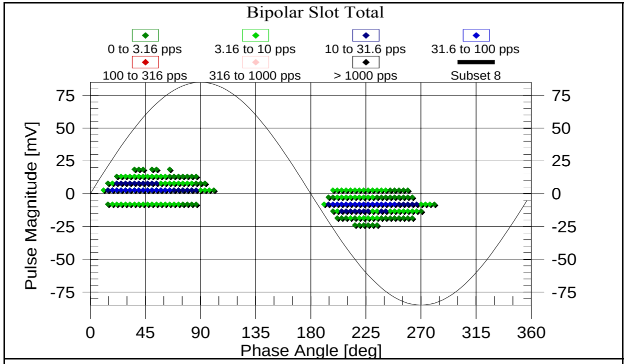
f. An…	Freq. (…	Alt Qm/NQN	C1 NQN+	C1 NQN-	C1 Qm+	C1 Qm-	C2 NQN+	C2 NQN-	C2 Qm+	C2 Qm-	Amb Hu
30	60 Hz, (…	No	-	-	-	-	8.8	11.9	5.0	7.0	70 %
270	60 Hz, (…	Yes	2.1	5.5	-	5.0	69.6	78.0	35.0	41.0	55 %
150	60 Hz, (…	Yes	5.0	7.7	-	5.0	35.1	45.6	18.0	22.0	55 %
30	60 Hz, (…	Yes	-	-	-	-	71.8	79.7	33.0	35.0	55 %
270	60 Hz, (…	Yes	3.6	1.7	-	-	57.1	68.0	48.0	40.0	55 %
150	60 Hz, (…	Yes	-	-	-	-	46.9	53.8	24.0	28.0	55 %
30	60 Hz, (…	Yes	4.6	4.6	-	-	40.7	54.6	19.0	24.0	55 %
270	60 Hz, (…	Yes	1.7	2.8	-	-	32.0	44.3	16.0	21.0	55 %
150	60 Hz, (…	Yes	-	-	-	-	24.9	27.7	14.0	15.0	55 %
30	60 Hz, (…	Yes	-	-	-	-	45.1	48.6	22.0	23.0	55 %
150	60 Hz, (…	Yes	-	-	-	-	60.8	78.9	30.0	37.0	55 %
30	60 Hz, (…	No	11.4	-	9.0	-	6.1	4.8	7.0	-	55 %

Prime Number Evaluation

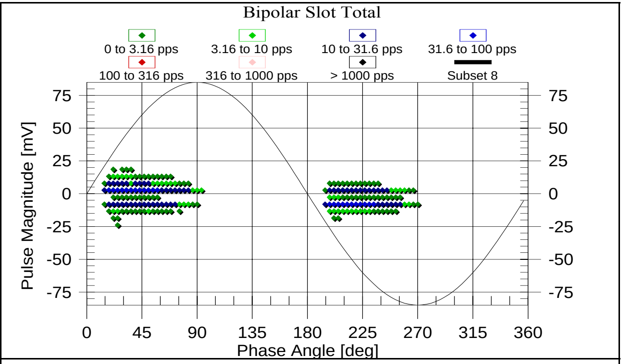
In order to evaluate the effect of changing to prime numbers, all SSC data received in 2008 was evaluated. Of the SSCs evaluated, the following patterns were observed:

- For the Endwinding Sensor Qm value, the average change was 6
- For the Slot Sensor Qm value, the average change was 14

The following plots are examples of data from on asset where the Prime Numbers have a large influence.



Maximum Qm changed from 10 (standard) to 45 (prime)



Maximum Qm changed from 22 (standard) to 32 (prime)

Since the change in Qm values will affect the Iris statistical database, a comparison from how the database would look when using standard values to prime values for the 2008 SSC data evaluated is shown below. Note that these charts are only samples. In 2010, the updated database will be officially released.

Table 1. Comparison of Standard to Prime

Rated V	**13-15kV (standard)**				***13-15kV (prime)***		
H2 (psi)	**11-20**	**21-30**	**> 30**		***11-20***	***21-30***	***> 30***
Avg	59	34	46		*71*	*56*	*71*
25%	14	0	12		*20*	*11*	*22*
50%	27	14	26		*35*	*39*	*37*
75%	50	41	43		*59*	*78*	*54*
90%	93	77	105		*118*	*107*	*160*
95%	189	116	145		*285*	*149*	*222*

Rated V	**19-23kV (standard)**				***19-23kV (prime)***		
H2 (psi)	**11-30**	**31-50**	**>50**		***11-30***	***31-50***	***>50***
Avg	32	11	13		*66*	*13*	*14*
25%	0	5	4		*5*	*5*	*5*
50%	1	7	12		*38*	*9*	*11*
75%	39	13	20		*87*	*17*	*20*
90%	90	22	28		*120*	*32*	*29*
95%	135	32	35		*276*	*42*	*34*

CONCLUSION

By observation, it is apparent that when using SSCs, sources that are parallel and in series produce patterns that vastly differ. Therefore, it is important that PD summary numbers include both patterns. Through evaluation of a sample of the SSC data available, the following conclusions can be drawn:

- When using SSC sensors, if the PD sources are in parallel with the sensor (i.e., from the rest of the slot or the endwinding) then the polarity of the pulses detected will be opposite the direction in the void – similar to when capacitive coupler sensors are used.
- When using SSC sensors, if the PD sources are in series with the sensor (i.e., directly under the SSC) then the polarity of the pulses detected will be the same direction as in the void.
- Prime summary numbers include both sources of PD that are parallel and in series, and will thus provide customers a better method of monitoring the condition of their stator winding.
- It is anticipated that over 50% of the data collected using SSCs will show some change when shifted to prime summary numbers, but only a portion of these will be impacted significantly.
- Updated statistical databases for SSCs are required, as it is predicted that the values in the current published tables are lower than they should be.

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, stator slot couplers, or RFCTs installed on the ground lead of a surge capacitor, 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. Red flags should only be raised if the PD levels on a specific machine are doubling over a six-month interval, or if they are above the 90th percentile and steadily rising. In all cases, raising the red 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. 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 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.

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APPENDIX – DATA ANALYSIS OF RESULTS THRU 2007

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 2007 with over 140,000 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.

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.

Directional Method

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**	
Avg	98	119	156	219	140	167	
2 std dev[2]	572	438	652	868	662	681	
25%	8	26	29	53	44	25	25% of the results have Qm levels below this value
50%	25	70	74	122	77	80	50% of the results have Qm levels below this value
75%	67	152	181	245	160	162	75% of the results have Qm levels below this value
90%	235	273	382	477	285	469	90% of the results have Qm levels below this value
95%	487	375	563	771	394	784	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 181mV for machines rated less than 12kV, 245mV for machines rated 13-15kV, 160mV for 16-18kV and 162mV for those >19kV.

Additionally, there is at least a doubling of the Qm levels between the 75% and the 90%. In the chart to the left there are a few machines with PD much higher than the 90th percentile with Qm levels >500mV. These machines are suspected to have significant deterioration.

Differential Method

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

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[2] by definition 99% of the results are less than two standard deviations above the average, assuming the data distributions are normal, which is often not the case for PD data.

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 no significant difference between the statistical summaries for windings rated less than 15kV. Thus, it is safe to say that for a 13kV 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**	
Avg	108	94	161	218	256	
2 std dev[3]	568	404	667	842	850	
25%	14	20	34	39	77	25% of the results have Qm levels below this value
50%	35	49	92	109	142	50% of the results have Qm levels below this value
75%	88	99	191	260	311	75% of the results have Qm levels below this value
90%	262	208	371	576[4]	801	90% of the results have Qm levels below this value
95%	472	354	551	770	928	95% of the results have Qm levels below this value

Capacitors – (gas-cooled)

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. As a result, stator slot couplers (SSC) are the recommended sensors in these applications to avoid miss-diagnosis 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**			**16-18kV**				**> 19kV**		
H2 (psi)	**11-20·**	**21-30**	**31-50**	**11-20**	**21-30**	**31-50**	**>50**	**21-30**	**31-50**	**>50**
Avg	41	58	197	418	45	82	79	93	104	146
2 std dev[3]	59	130	622	914	923	706	833	327	492	665
25%	31	20	16	16	28	16	8	43	20	9
50%	73	46	35	123	39	46	17	94	50	26
75%	144	88	73	187	163	93	40	172	92	74
90%	318	226	182	337	667	273	166	217	166	177
95%	455	398	284	441	966	448	367	246	224	810

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 31psi are below 90mV and 90% generally below ~250mV, less than half of that observed on the air-cooled

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[3] by definition 99% of the results are less than two standard deviations above the average, assuming the data distributions are normal, which is often not the case for PD data.

[4] Fluctuations from previous years due to a low number of samples

machines (TGA). At the lower operating pressures the PD levels are much higher, with a few machines having extremely high PD of Qm levels >400mV, which would require more tests and investigation

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 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
Avg	10	16	9	14	22	5	66	12	8	12	8
2 std dev[5]	43	102	47	72	202	29	480	70	52	78	36
25%	0	0	0	0	0	0	3	0	0	0	0
50%	8	0	6	6	3	0	8	5	2	0	3
75%	15	17	15	22	15	6	24	17	9	6	7
90%	31	44	20	66	39	11	159[6]	45	18	13	22
95%	38	67	25	84	55	22	319	69	28	113	37

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 no noticeable 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. It should be observed that though the majority of the machines have slot Qm values less than ~20mV, there are a few with levels higher than 100mV. These should be subjected to further tests and inspections. The SSC is a high frequency antenna that will detect 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 portion of the bar or in the endwinding area.

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

Rated V	**13-15kV**			**16-18kV**			**19-22kV**			**23-26kV**	
H2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
Avg	4	4	3	6	3	2	1	2	5	3	2
2 std dev[5]	30	35	18	42	17	18	7	18	45	33	28
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%	3	0	3	7	0	0	0	0	3	0	0
90%	18	16	7	16	7	7	4	8	9	0	3
95%	23	32	11	41	14	10	6	17	20	2	8

The endwinding PD results are slightly lower than the slot PD results, with 90% of all the tests less than ~20mV. There are, however, a few machines with Qm levels higher than 30mV, and these machines require additional attention.

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[5] by definition 99% of the results are less than two standard deviations above the average, assuming the data distributions are normal, which is often not the case for PD data.

[6] Fluctuations from previous years due to a low number of samples

Stator slot coupler – (air-cooled)

Qm values for air-cooled machines with SSC sensors

	Slot PD			Endwinding PD		
	10-12kV	**13-15kV**	**16-24kV**	**10-12kV**	**13-15kV**	**16-24kV**
Avg	6	34	20	0	13	5
2 std dev[47]	22	188	116	0	62	51
25%	0	0	0	0	0	0
50%	1	9	0	0	3	0
75%	9	38	11	0	12	0
90%	16	84	72	0	42	3
95%	20	121	110	0	59	15

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 ~40mV, but there are a few with extraordinarily high PD, >100mV, and some with high endwinding PD that would require further investigation.

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[7] by definition 99% of the results are less than two standard deviations above the average, assuming the data distributions are normal, which is often not the case for PD data.