PARTIAL DISCHARGE TESTING: A PROGRESS REPORT

VIBRATION SPARKING – PD PATTERNS

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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 [4 - 15].

Some turbine generator stator windings have apparently failed due to a mechanism variously referred to as spark erosion or vibration (contact) sparking. This mechanism is different from the slot-based electrical discharge typically seen [1, 3]. Vibration sparking can produce relatively intense sparking between the surface of the stator bar and the core and may erode the groundwall insulation much more quickly than slot discharges. Since this mechanism is driven by the magnetic flux in the core while electrical slot PD can only occur on higher voltage bars, vibration sparking can occur at any point of the winding, including at the neutral. This paper describes data collected from couplers installed at the neutral to evaluate pulse patterns and magnitudes that may indicate the presence of the vibration sparking failure process.

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. Data collected through 2009 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 over 15,000 statistically independent results. 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 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].

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]

- 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]

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 bases 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 2009 DATABASE

After the accumulation of all available test data through to 2009 with over 225,000 records, a database was carefully compiled using the following selection criteria:

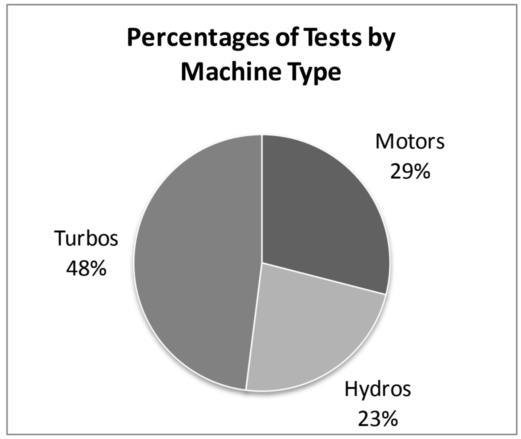
- only on-line tests obtained during normal operation
- only one test result per sensor
- the most recent test at Full Load and Hot stator winding temperature (FLH)
- any test with questionable results was discarded

Once these criteria were applied, about 15,000 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	29%
Hydros	23%
Turbos	48%



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

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 35 mV, 50% (the median) had a Qm below 91 mV, 75% were below 189 mV and 90% of tests yielded a Qm below 372 mV. Thus if a Qm of 400mV 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

Oper kV	6-9kV	10-12kV	13-15kV	16-18kV	> 19kV
25%	13	19	35	36	76
50%	34	48	91	110	137
75%	70	102	189	278	255
90%	236	229	372	588	718
95%	364	376	560	768	861

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 kV	2-5kV	6-9kV	10-12kV	13-15kV	16-18kV	> 19kV
25%	8	28	30	53	43	34
50%	20	70	70	119	77	79
75%	63	147	160	242	153	205
90%	230	277	341	454	287	454
95%	437	404	525	701	556[1]	776

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.

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

4 TWO SLOT-BASED FAILURE MECHANISMS

4.1 SLOT DISCHARGE

With the introduction of the epoxy mica insulation system in the 1950s, an important class of failure mechanisms sometimes referred to as “slot discharge” became more likely. Slot discharge refers to the observation that partial discharges (PD) may occur on the surface of the bar (half-coil), either within the stator core slot, or just outside of the slot. Figures 1-2 show photos of bars experiencing slot discharge considered as fairly serious and corrective action would be considered necessary.

There are three general sources of this slot discharge [17, 18]:

- Loose bars - where vibration of the bar in the slot abrades and destroys the slot conductive coating and ground-wall insulation.
- Poorly manufactured slot conductive coating - occurs when the slot conductive coating is not fulfilling its function due to excessively high initial resistance or poor application of the coating to the ground-wall [18].
- Poor connection of the conductive coating to ground i.e. where the bar is not properly grounded due to the presence of an insulating film or insulating side-packing between the slot conductive coating and the stator core [17].

Figure 1. Stator bar where the ground insulation was abraded since the bar was loose in the slot

Figure 2. Wedges destroyed by slot PD.

Often it may be difficult to determine which of these three processes initiated the slot discharges, since the appearances may be similar and one process may cause another to eventually occur. In all cases, the energy for the discharge comes from the capacitive energy of the electric field, and thus these processes occur *only* on the bars at the higher voltage end of each phase.

In general, PD in the slot is a very slow-acting deterioration mechanism on mica insulation systems. Failure would not be expected for many decades without extraneous influences, e.g, vibration, or defective bar insulation. In air-cooled machines, the slot discharges create ozone. If produced in sufficiently high concentration, ozone can cause numerous other problems, including health hazards, and may require a rewind.

4.2 VIBRATION SPARKING

Vibration sparking (VS) is similar looking but is actually a completely different deterioration process from classic slot discharge. The mechanism is driven by the magnetic flux in the core and whereas PD can only occur on higher voltage bars, vibration sparking can occur at any point of the winding, including at the neutral.

The first instance of vibration sparking first occurred during the late 1950s in hydrogen-cooled turbine generators, when hard (polyester and epoxy) insulation systems were first introduced. It seems to occur rarely, but there are several instances since the 1960s on both motors and generators.

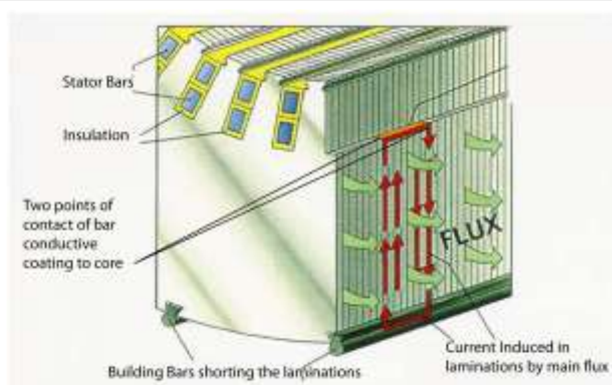


Figure 3. Vibration Sparking Mechanism

Figure 4. Borescope Vibration Sparking Damage to Bar Insulation

The root cause of VS is too low a resistance of the slot conductive coating, together with vibration of the stator coil or bar. The energy to drive the VS mechanism is substantial since it is driven by the main magnetic flux in the stator core. A comprehensive description of the physics involved has been made by Liese [18]. Liese has estimated that the resistance of the slot conductive coating should be no lower than 300 to 2000 ohms per square to prevent the mechanism.

Due to this low resistance, a current loop may exist axially along the bar, radially through the core laminations, axially along the keybars at the back of the stator core, and radially back to the bar (Figure 3). If a bar is allowed to vibrate, the current in this loop will be interrupted at a contact point from the bar to the core iron. The interruption of this current will form an arc from the bar surface to the core. If the conductive coating resistance of a bar is low, this current will be of significant magnitude and the resulting arc can damage the groundwall insulation by an erosion process. The use of improved wedging systems can largely eliminate the bar movement. In more recent times, side vibration has occurred on large air-cooled turbo generators with deep, narrow slots.

Figure 5. Bars removed from an air-cooled turbine generator suffering from both VS and the loose-coil form of slot discharge.

Vibration sparking is a relatively fast deterioration mechanism and has caused service failure in a relatively short time. Figure 4 shows borescope pictures of damage to a modern epoxy-mica groundwall insulation caused by vibration sparking. The stator winding of a generator of similar design failed in service after about 4 years of operation.

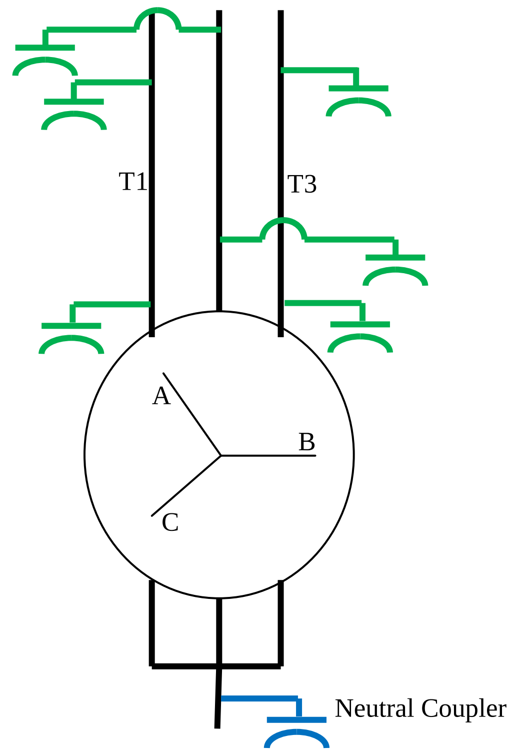
As previously stated, it may be difficult to distinguish the evidence of VS and slot discharge PD. If a bar is a high voltage bar, there may be no way to be certain, but if a deteriorated bar is from a low-voltage portion of the winding, it is certain to be VS. Figure 5 show bars that appear to have both VS and PD damage. The slot portion can be difficult to inspect. If there are radial ventilation ducts, a good inspection can be made via borescope (Fig. 4). If there are no radial ducts, some indication may be observable at the ends of the slots.

5 PULSE CHARACTERISTICS

There are several somewhat unpredictable factors involved in the rate of deterioration resulting from slot discharge and from vibration sparking. Vibration sparking is normally considerably more aggressive than pure PD, and PD can take several forms. As a result it is not possible to define clear rules for predicting deterioration rates. Well-made mica insulation systems have proven to be highly resistant to PD and high frequency pulses. Significant levels, without any extraneous influences, seem not to penetrate the mica tapes even after 20 or 30 years of service.

Vibration sparking and slot discharge due to loose coils, however, can be very aggressive. If there is sufficient clearance in a slot to allow significant movement, e.g., 0.1 mm, failure may occur in less than 2 years of operation. If clearance is small, e.g., 0.01 mm, failure may not occur for several years.

5.1 SENSOR LOCATIONS



In a typical motor or generator, three to six sensors are installed at the high voltage end of the winding, as shown here. Note the sensors are capacitors.

By installing two sensors per phase at the high voltage end, it is possible to discern which high frequency pulses (PD) are originating from within the winding from those from other sources. This method, called a directional Bus install, makes it possible to monitor pulse activity occurring in high voltage bars/coils while the machine is on-line and in the presence of system noise.

Because vibration sparking (VS) can occur anywhere in the winding, including the neutral end, it is advisable that a 7th coupler be installed at the neutral end of machines where VS is expected. At the neutral end, there is insufficient voltage to have PD, so pulses detected by the neutral end sensor are either cross-coupled from other sources, or may be indications of VS.

5.2 COMPARISON OF CHARACTERISTICS

Failure processes have unique pulse characteristics that can be used to determine the likelihood that a specific process is occurring. Though these characteristics can be used to evaluate pulse plots to determine the possibility that a process is occurring within a winding, it should be noted that not all characteristics may be observable for any one asset or testing cycle. However, the table below that compares the expected pulse characteristic patterns for the two slot-based failure processes discussed in this paper: slot discharge and vibration sparking, has proven to be useful.

Table 1. Comparison of Pulse Characteristics

Pulse Characteristic	Slot Discharge	Vibration Sparking
Neutral coupler activity	No – confined to high voltage bars/coils	Yes – widespread activity
Trend	Yes – the magnitude of the PD will increase as the deterioration worsens	Unknown – but likely the magnitudes would increase as the deterioration worsens
Position relative to AC cycle	Classic positions of 45° and 225°	Zero crossings of 0° and 180° at both the neutral and line-end
Polarity predominance	Positive due to the surface activity	No – similar materials
Load dependence	Yes, direct – if bars are loose No – if problem is due to poor contact to ground	Yes, direct – bars will be loose
Temperature dependence	Yes – but can be either direct or inverse due to the impact of temperature on the conductivity of the carbon-based material and thermal expansion of materials	

- *Neutral coupler activity* – when the occurrence of PD is dependent upon high electrical stress it is confined to the high voltage bars; however, when it is driven by the magnetic flux, pulses can occur throughout the winding including in the slots of the neutral coils/bars
- *Trend* – increases in pulse magnitude and/or count rate over time as the deterioration worsens
- *Position relative to AC cycle* – the location of the pulses relative to the AC cycle indicate both the primary source of electrical stress, such as phase-to-ground clustering around 45° and 225° and mechanically dependent results at the zero crossings of 0° and 180°
- *Polarity predominance* – when the materials on either side of the pulse have different electrical characteristics, then there will be polarity predominance.
- *Load dependence* – changes in pulse pattern with changes in load. A direct dependence is when the pulse magnitude increases with the higher mechanical forces of the larger load.

- *Temperature dependence* – changes in pulses with changes in operating temperature. A direct dependence is when the pulse magnitude increases at the higher operating temperature, whereas, an inverse dependence is when the magnitude decreases at the higher operating temperature.

5.3 SLOT DISCHARGE (PD)

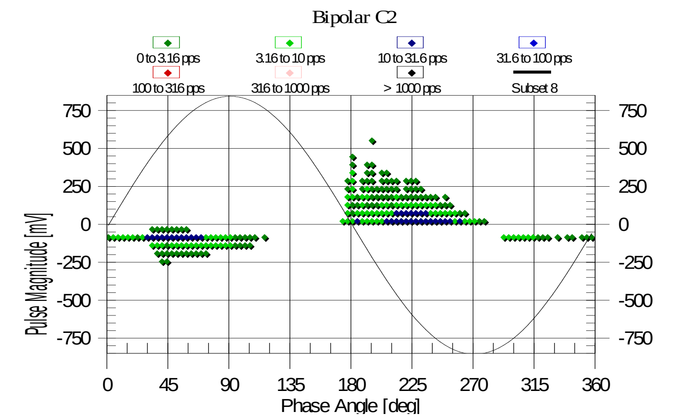


Figure 5. Positive PD Predominance

Partial discharge (PD) due to slot discharge will focus on the highest voltages in each phase of the winding, and *can only occur* on the higher voltage portion of the winding, i.e., typically the top one-third of the winding. The presence of slot discharge activity is suspected when the positive PD occurring between 180-270° relative to the AC cycle is significantly higher than that of the negative PD occurring between 0-90°, as shown in Figure 6.

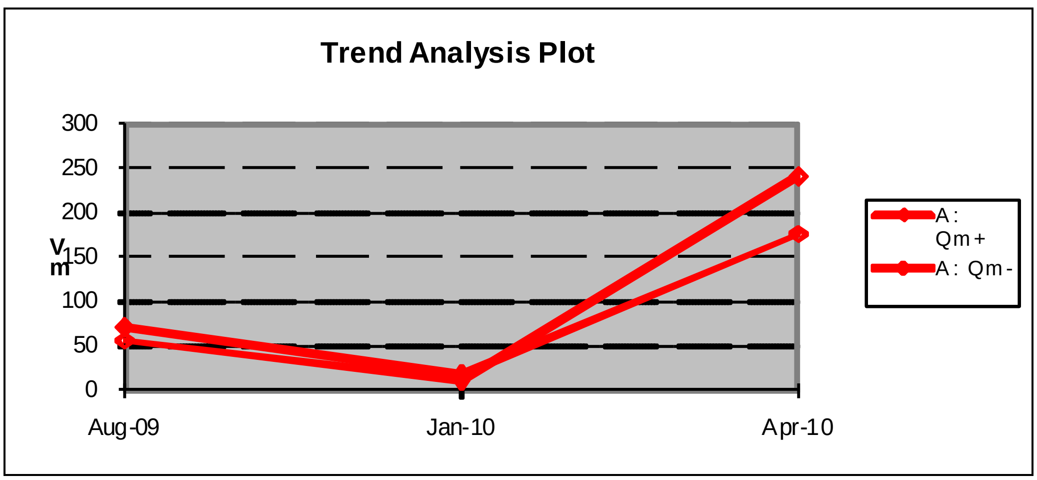
If the PD is also directly load dependent, that is, the PD increases with larger mechanical forces due to higher load current, then it is highly likely that the bars are loose. This data is collected using sensors installed at or near the highest voltage bars in the winding.

5.4 VIBRATION SPARKING

If questionable conditions are observed in the low-voltage portion of the winding, the condition of concern **cannot** be slot discharge. Vibration sparking can only occur in the slot portion of the winding, but as previously indicated, can occur throughout the entire phase of the windings irrespective of bar voltage.

5.4.1 Trend

Unlike with sensors connected at the high voltage end (See Appendix, page 14), as of yet no verified statistical database exists for evaluating the magnitude of pulse activity detected by the sensors installed at the neutral end, but it is possible to trend the results. Increases in the activity are presumed to be indicative of changes in the winding condition.



Neutral End Coupler Trend

Case 1:

13.8kV

161.0MW

2001Steam Turbine

5.4.2 Statistical Comparison

As discussed above in Section 3.4 and in previous papers, the use of statistical comparisons has been useful in providing some insight as to the level of partial discharge activity within a winding. The tables below extracted from the full database, include results from windings that either have or are known to be susceptible to vibration sparking.

Table 3. Distribution of Qm for air-cooled Turbine Generators with 80 pF Sensors (line end sensors)

	Susceptible to VS		All Turbine Generators	
Oper kV	**13-15kV**	**16-18kV**	**13-15kV**	**16-18kV**
25%	20	36	53	43
50%	53	58	119	77
75%	314	93	242	153
90%	983	155	454	287
95%	1130	215	701	556

There is no consistent difference between the results above in Table 3 from the line-end sensors for those windings known to be VS susceptible versus the entire database. The variability that is observed is likely due to the size of the sampling database and not due to the presence and/or absence of VS.

Table 4, below, displays the statistical breakdown for data collected from the neutral end sensors. Since there is no electrical stress at the neutral end, then the presence of any activity is either from VS, noise or cross-coupling (See Section 5.4.6). When data suspected to be from these external sources are removed from the database, the remaining statistical results are different, as shown in Table 5 below. These tables may provide some guidance for analysis; however, it is the comparison of patterns from the line-end and neutral sensors that provide the most information; see Section 5.4.3.

Table 4. Distribution of Qm for air-cooled Turbine Generators with neutral end sensors

Oper kV	13-15kV	16-18kV
25%	28	44
50%	42	134
75%	121	514
90%	202	943
95%	222	1013

Table 5. Distribution of Qm for air-cooled Turbine Generators with neutral end sensors (without suspected external sources))

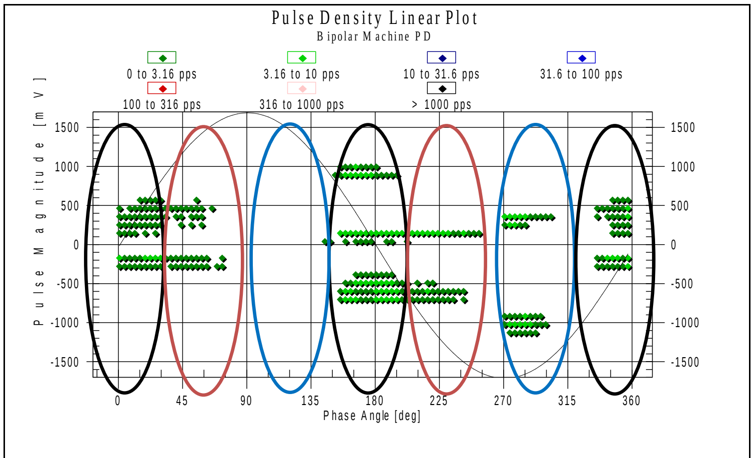
Oper kV	13-15kV	16-18kV
25%	25	39
50%	40	59
75%	60	317
90%	122	777
95%	159	930

Disclaimer: please be advised that the sample size for Tables 3, 4, and 5 above are small, and therefore, wide fluctuations in the tabulated data from year to year may occur.

5.4.3 Position Relative to AC Cycle/Polarity Predominance

Vibration sparking is driven by the air gap magnetic flux; therefore, the expected locations for the pulses relative to the AC cycle are at the current zero crossings of 0° and 180° (which should be near the voltage zero crossings). The 7th, or neutral, coupler is located on the neutral end and therefore all three phases will be detected simultaneously by one sensor. Based on the data analyzed for the generation of tables 3 and 4 above, 65% of the 13-15kV rated machines and 92% of the 16-18kV machines have patterns that include clusters at the zero crossings.

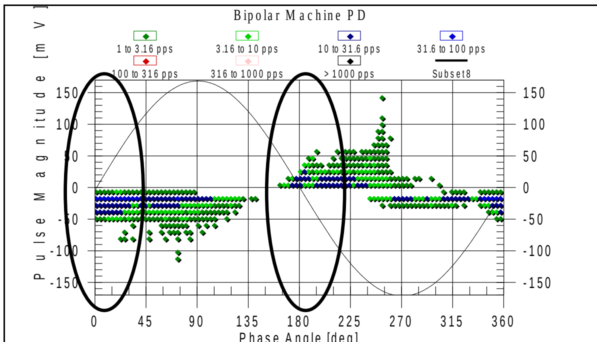
As mentioned above, if vibration sparking is occurring, then one of the conditions is that the voltage stress coating within the slot section is too conductive [18]. Due to this phenomenon then the electrical characteristics of the surface of the coil and the core are similar, so the resultant pattern should not have polarity predominance. Less than 8% of all of the results included in the tables in Section 5.4.2 above have polarity predominance.



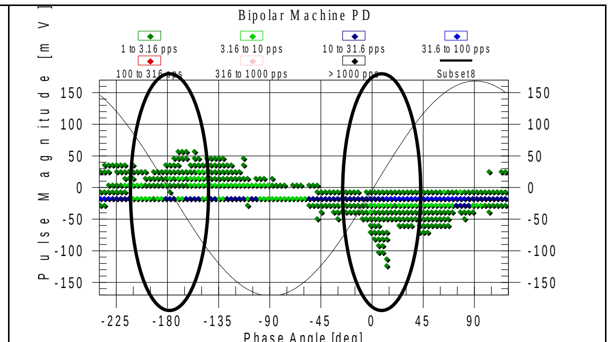
Case 2: Neutral End Coupler (shows all 3 phases)

Case 2: 15.8kV -- 152.7MW
2008 Steam Turbine

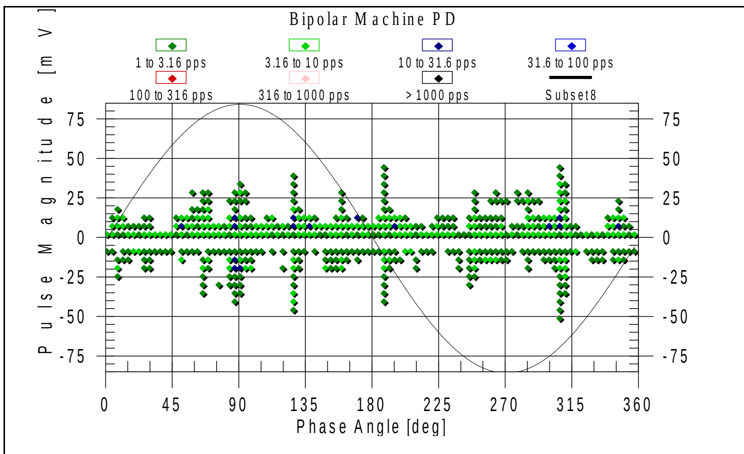
- Zero Crossings (0°/180°): The activity evident in this unit's neutral end may be an indication of vibration sparking. The activity appears at six (6) distinct phase locations: 0°/180°, 60°/240° and 300°, which would be the zero crossings of the different phases. It is also noteworthy that the highest level occurs at the 0°/180° crossing, or A-phase.
- Note that similar patterns at 0°/180° crossings are also discernible from the sensors located at the high voltage end (shown below).
- This may be an indication of vibration sparking.



Case 2: A-phase Line End Coupler



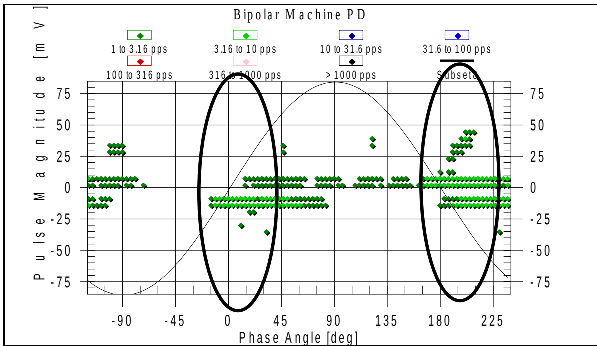
Case 2: C-phase Line End Coupler



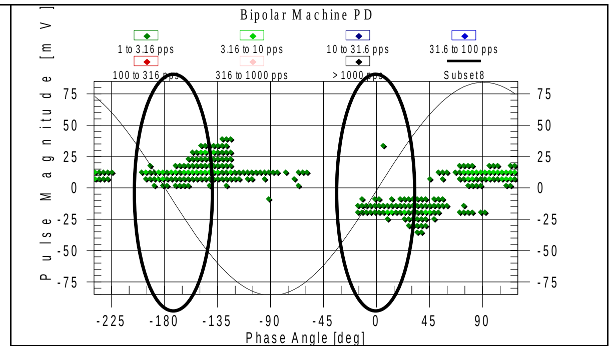
Case 3: Neutral End Coupler (shows all 3 phases)

Case 3: 18kV – 196MW
2000 Combustion Turbine

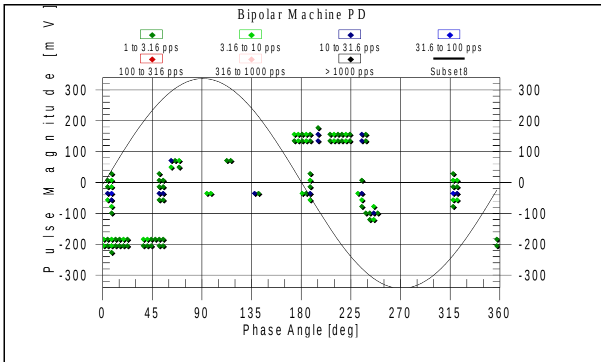
- Zero Crossings (0°/180°): The narrowband activity appears at six (6) distinct phase locations: 0°/180°, 60°/240° and 300°, which would be the zero crossings of the different phases.
- Note that similar patterns at 0°/180° crossings are also discernible from the sensors located at the high voltage end (shown below).
- This may be an indication of vibration sparking.



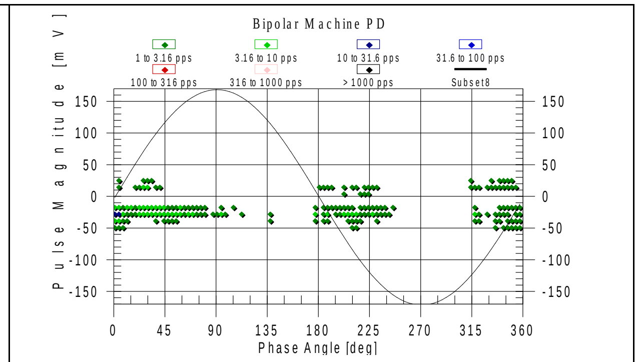
Case 3: B-phase Line End Coupler



Case 3: C-phase Line End Coupler



Case 4: Neutral End Coupler (shows all 3 phases)



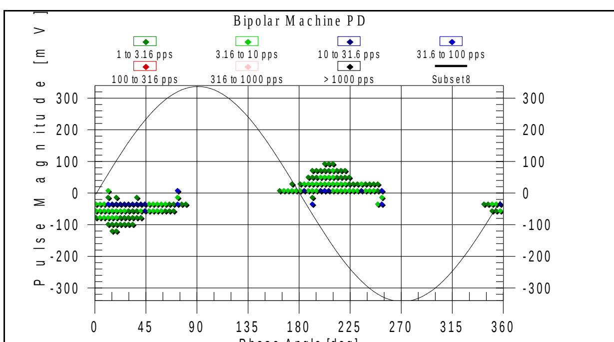
Case 4: A-phase Line End Coupler

18kV – 196MW 2000 Combustion Turbine
Note the narrowband pulses across the neutral end coupler, and the similarity of the clusters near the zero crossings for the A-phase sources. This may be an indication of vibration sparking.

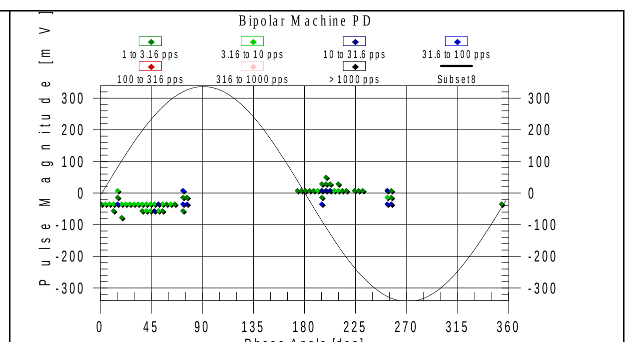
5.4.4 Load Dependence

In order for vibration sparking to occur, there must be mechanical movement of the coils/bars within the slots. Increases in VS-type pulses (patterns near zero clusters) at higher operating loads and similar temperatures are usually an indication of movement. As previously stated, both vibration sparking and slot discharge due to coil movement are relatively aggressive failure mechanisms and should be corrected.

Case 5 below shows two test results taken from line-end sensors of susceptible windings within the same timeframe but at loads that differ by 44%. The magnitude, though relatively low, is noticeably higher (80%) at the higher load suggestive of potential coil/bar movement. This winding should be frequently tested and closely monitored.



Case 5: Operating: 130MW, 13.2MVar, 57°C
Qm: +97, -95

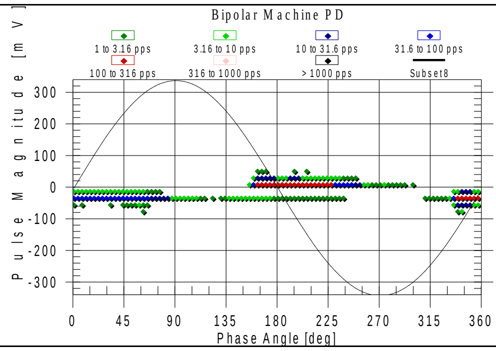


Case 5: Operating: 90MW, 11.2MVar, 52°C
Qm: +54, -59

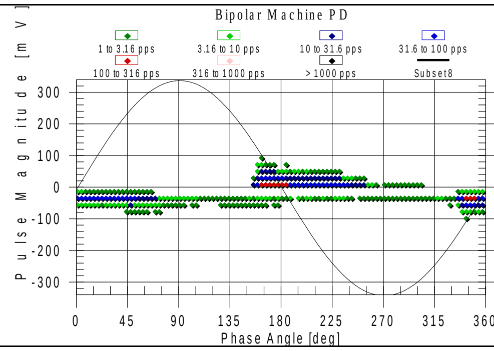
Increase in positive activity is 80% with a 40MW (44%) change in load which suggests coil/bar vibration

5.4.5 Temperature Dependence

Since the voltage stress coating used in the slot section is predominantly carbon, small changes in temperature may greatly impact the patterns that are VS-type, that is, near the zero crossings. Carbon is more conductive at higher temperatures; therefore, it is possible that the patterns would have direct temperature dependence, that is, would increase at higher temperatures, as shown below in Case 6 for line-end sensors of susceptible windings. However, also at higher temperatures the materials will expand; so it is also possible that the levels would have inverse temperature dependence, that is, the decrease at higher temperatures. This latter pattern is more common for most failure mechanisms and discussed in other papers [1, 4].



Case 6: Operating: 118MW, 5MVar, 71°C
Qm: +69, -65

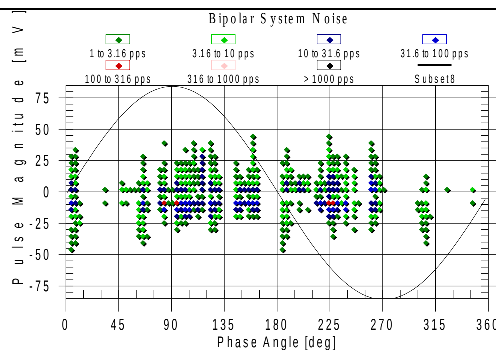


Case 6: Operating: 165MW, 23MVar, 87°C
Qm: +95, -78

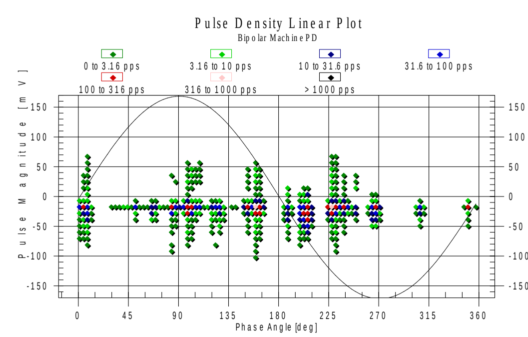
Increase in positive activity is 37% with a 16°C change in temperature which indicates activity involving the voltage stress coatings

5.4.6 Limitations

The neutral end coupler is a single-ended installation, as such, the configuration does not allow for direction-of-arrival discrimination of pulses that are originating from outside the winding from the system. Therefore, it is possible that some of the activity detected by the neutral end sensor is not originating from within the winding, but from external sources or from cross-coupling.



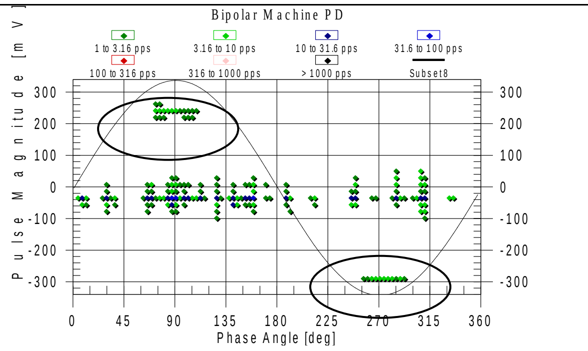
Case 7: Neutral End Coupler (shows all 3 phases)



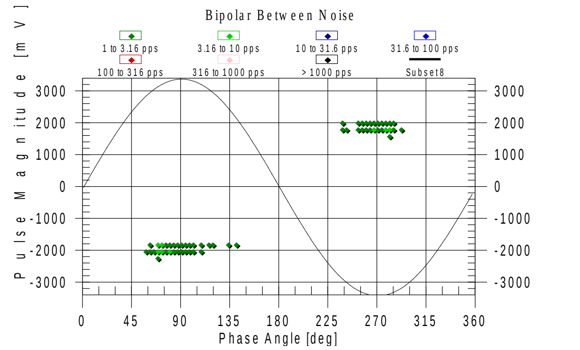
Case 7: A-phase Line End Coupler

13.8kV – 160MW 2001 Steam Turbine
Note the similarity of the results and the notable narrowband clusters evenly spaced across the AC cycle. Because the narrowband patterns are similar, it is likely this activity is actually cross-coupling of a static excitation system.

Cases 8 and 9 below show such possible scenarios. Where for the neutral end coupler there is a noticeable relatively higher magnitude cluster around the 90° and 270° phase positions. However, when examining the line end sensors, specifically the A-phase system end coupler we see a similar cluster at even higher magnitude originating between the line end machine and system sensors.

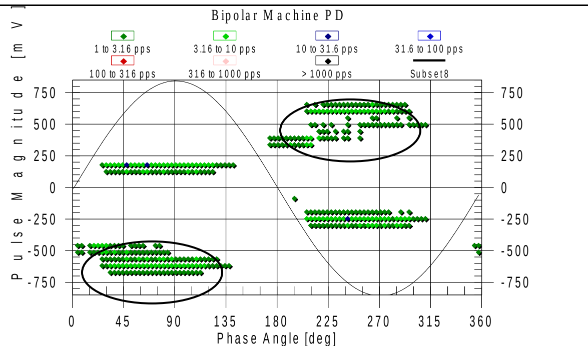


Case 8: Neutral End Coupler (shows all 3 phases)

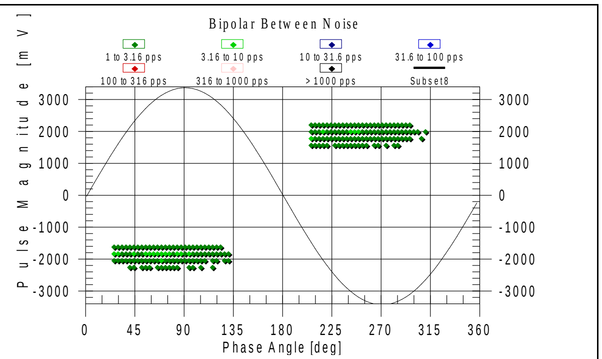


Case 8: A-phase Line End Coupler (system side)

18kV – 196MW 2000 Combustion Turbine
Further investigation of the line end couplers revealed a large C-phase to ground dependent source originating away from the unit beyond the C-phase line-end system coupler.



Case 9: Neutral End Coupler (shows all 3 phases)



Case 9: A-phase Line End Coupler (system side)

18kV – 196MW 2000 Combustion Turbine
Further investigation of the line end couplers revealed a large A-phase to ground dependent source originating between the two sensors approximately 2m (6ft) from the A-phase machine sensor.

6 CONCLUSION

For years, monitoring of the partial discharge activity has proven beneficial for detection of stator winding failure processes that affect the high voltage coils/bars in windings, including slot discharge. It is also possible that similar test configurations that use an additional sensor at the neutral end can provide insight as to the presence or absence of vibration sparking. Based on data collected to date, it is not the overall magnitude of the activity of the line-end sensors and/or the neutral end sensors (Section 5.4.2), but the patterns of the detected pulses that are more relevant (Section 5.4.3). Therefore, interpretation of neutral end data should also include comparison of the patterns to the line-end machine and system couplers, identifying pattern location relative to the AC cycle, and analysis of the impact of load and temperature changes to the pulse activity. From this analysis of data collected online, hypotheses regarding the likelihood of the presence of vibration sparking can be made.

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. 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 90^{th} 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.

7 REFERENCES

1. J.F. Lyles, T.E. Goodeve, and G.C. Stone, "Using Diagnostic Technology for Identifying Generator Winding Maintenance Needs," *Hydro Review Magazine*, June 1993, pp. 59-67.
2. V. Warren, "How Much PD is Too Much PD?" *Proc. Iris Rotating Machine Conference,* Dallas, TX, March 1998.
3. IEEE 1434-2000 "IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery."
4. V. Warren, G.C. Stone, "Recent Developments in Diagnostic Testing of Stator Windings," IEEE Electrical Insulation Magazine, September 1998.
5. V. Warren, "Further Analysis of PD Test Results" *Proc. Iris Rotating Machine Conference,* Scottsdale, AZ, March 1999.
6. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* New Orleans, LA, June 2000.
7. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Washington, D.C., June 2001.
8. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* San Antonio, TX, June 2002.
9. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Santa Monica, CA, June 2003.
10. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* New Orleans, LA, June 2004.
11. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Scottsdale, AZ, June 2005.
12. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Toronto, ON, June 2006.
13. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* San Antonio, TX, June 2007.
14. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Long Beach, CA, June 2008.
15. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* New Orleans, LA, June 2009.
16. V. Warren, "Partial Discharge Testing – A Progress Report" *Proc. Iris Rotating Machine Conference,* Orlando, FL, June 2010.
17. P. Lonseth, V.R. Mulhall, "High Intensity Slot Spark Discharge – Its Causes And Cure", IEEE International Symposium on Electrical Insulation, Montreal, June 1976, Paper C4.
18. F.T. Emery, "The Application Of Conductive And Stress Grading Tapes To Vacuum Pressure Impregnated, High Voltage Stator Bars", Electrical Insulation Magazine, July 1996, pp15-22.
19. M. Liese, M. Brown, "Design-Dependent Slot Discharge and Vibration Sparking on High Voltage Windings", to be published, IEEE Trans DEI, August 2008.

8 APPENDIX – DATA ANALYSIS OF RESULTS THRU 2009

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 2009 with over 225,000 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.

8.1.1 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.

8.1.1.1 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	87	118	146	208	163	186	
25%	8	28	30	53	43	34	25% of the results have Qm levels below this value
50%	20	70	70	119	77	79	50% of the results have Qm levels below this value
75%	63	147	160	242	153	205	75% of the results have Qm levels below this value
90%	230	277	341	454	287	454	90% of the results have Qm levels below this value
95%	437	404	525	701	556[2]	776	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 160mV for machines rated less than 12kV, 242mV for machines rated 13-15kV, 153mV for 16-18kV and 205mV for those >19kV.

Additionally, there is at least a doubling of the Qm levels between the 75% and the 90%. There are a few machines with PD much higher than the 90th percentile with Qm levels >230-450mV. These machines are suspected to have significant deterioration.

8.1.1.2 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 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

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

differential (PDA) results, though there are some minor variances, there is little significant difference between the statistical summaries for windings rated less than 19kV. Thus, it is safe to say that for a 13kV winding, regardless of installation type, the PD levels should be less than ~275mV 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	98	98	162	224	230	
25%	13	19	35	36	76	25% of the results have Qm levels below this value
50%	34	48	91	110	137	50% of the results have Qm levels below this value
75%	70	102	189	278	255	75% of the results have Qm levels below this value
90%	236	229	372	588	718	90% of the results have Qm levels below this value
95%	364	376	560	768	861	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. 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**			**16-18kV**				**> 19kV**		
H2 (psig)	**11-20**[3]	**21-30**	**31-50**	**11-20**	**21-30**	**31-50**	**>50**	**21-30**	**31-50**	**>50**
Avg	218	104	119	140	178	103	36	105	68	146
25%	43	19	17	15	31	19	9	43	18	15
50%	106	41	39	93	58	51	16	94	45	35
75%	255	83	77	161	163	110	28	172	98	87
90%	503	193	201	327	667	251	54	217	152	353
95%	901	408	537	457	966	355	104	246	201	879

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 110mV and 90% generally below ~250mV, less than half of that observed on the air-cooled machines (TGA). At the lower operating pressures the PD levels are much higher, with a few machines having extremely high PD of Qm levels >800mV, which would require more tests and investigation

8.1.2 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**

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

H2 (psi)	11-20	21-30	31-50	11-30	31-50	> 50	11-30	31-50	>50	31-50	>50
Avg	26	20	12	167	11	3	42	19	10	12	7
25%	0	0	0	0	0	0	1	0	0	0	0
50%	8	0	9	7	3	0	9	8	3	0	3
75%	29	14	17	20	14	4	24	22	10	0	8
90%	47	57	27	55	37	9	97	50	23	13	19
95%	55	81	45	81	53	15	232	67	36	113	31

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. 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 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 [15].

8.1.2.1 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	3	4	6	2	5	4	4	6	3	3
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	6	6	0	1	1	3	3	0	0
90%	20	9	12	14	8	12	11	12	12	0	3
95%	34	19	17	32	16	42	31	19	25	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.

Stator slot coupler – (air-cooled)

Qm values for air-cooled machines with SSC sensors

Slot PD		
Rated V	**13-15kV**	**16-24kV**
Avg	31	17
25%	0	0
50%	16	0
75%	40	10
90%	92	57
95%	119	97

Endwinding PD		
Rated V	**13-15kV**	**16-24kV**
Avg	12	5
25%	0	0
50%	3	0
75%	16	0
90%	42	5
95%	56	12

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, >90mV, and some with high endwinding PD that would require further investigation.