PARTIAL DISCHARGE TESTING: A PROGRESS REPORT

PD – ANTHOLOGY OF NOTABLE PREVIOUS REPORTS

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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 that enables companies to observe the gradual deterioration of a machine stator winding and thus plan appropriate maintenance for the machine [1]. In 1998, at the first 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 - 21]. This paper presents a short anthology of notable documents from this collection.

The papers of most interest are:

- PD monitoring of 3-5kV rated windings (2014)
- PD monitoring of hydrogen-cooled windings (2016)
- PD monitoring of utility or industrial motors (2019)
- Stability of PD database trends (2022)
- PD monitoring for different manufacturers and ages (2004, 2006, updated 2023)

Calibration of online PD test results is theoretically impossible [3]; therefore, only results obtained using the same data collection method and noise/disturbance separation techniques are compared. This paper obtained all the data that was measured with a PDA-IV, TGA, Trac, or Guard test instrument. Data collected until the end of 2021 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, data from off-line testing, and data of unusual machine operating conditions were excluded, leaving over 27,000 statistically independent new results collected from about 8,500 machines. The Appendix presents the statistical summary of the averages to enable Trac, Guard, TGA, and PDA-IV test users to compare their test results to those of similar machines at a gross level.

2 INTRODUCTION

Partial discharges (PD) may occur in electrical insulation systems that operate at 3.3 kV and above. PD only occurs when gas-filled voids are present within the insulation, or a gas (usually air) is present on the insulation surface where there is high electric stress [24]. If the stress is high enough, the gas will experience an electrical breakdown, creating a spark of energetic electrons that will break molecular bonds in any organic polymer when the electrons hit the insulation. Thus, PD will age the insulation and may eventually cause failure. PD occurs in various high-voltage electrical apparatuses such as transformers, switchgear, power cables, bus bars, and rotating machines. Since each discharge causes a flow of charge, the PD can be detected by measuring the current pulses at the terminals of high-voltage equipment. Off-line PD testing has been a factory test for almost 100 years on equipment such as power cables. The purpose is to detect flaws created during manufacturing that led to PD and, eventually, insulation failure. In the past 50 years or so, owners of high-voltage equipment are also measuring PD over time on installed equipment. Many aging processes can create voids and gaps that can lead to PD, and so PD is often a symptom of thermal and thermo-mechanical aging processes. By monitoring the evolution of PD over time, either in off-line tests or by online monitoring while the equipment is operating normally, equipment owners have a powerful tool for determining when consideration of maintenance or equipment replacement is needed. More commonly, machine owners have been using offline and online PD testing to assess the condition of the stator winding insulation to determine if maintenance is required. Problems such as loose coils in the stator slots, contamination leading to electrical tracking, and thermal aging of the insulation are easily detected [25][26].

Many different types of PD testing equipment have been used for coils and complete stator windings. Most of them use a capacitor to detect the PD pulse currents in the presence of the 50/60 Hz high voltage. The instrumentation to measure the PD current pulses most commonly includes an analog-to-digital converter that determines the number, magnitude, and phase position (concerning the 50/60 Hz ac cycle) of the PD. However, almost every brand of PD detector works in a different part of the frequency spectrum. Since each partial discharge pulse results from a brief flow of electrons lasting only a few nanoseconds, by the Fourier transform, current pulses of frequencies from 0 Hz up to several hundred MHz are created by each discharge. Thus, PD can be detected in an extensive range of frequencies, impacting what is measured. Only instruments using very high frequency (VHF) bandwidths, 30-300 MHz, are included in this paper [25].

2.1 PD - A COMPARISON TEST

Partial discharges (PD) are tiny electrical sparks that occur when voids exist within or gaps 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. The number and magnitude of PD pulses will increase as the insulation degrades. 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 12 months has been used as a “rule of thumb” to indicate that rapid deterioration is occurring [26]. Suppose the rate of PD pulse activity increases rapidly or the PD levels are high compared to other similar machines, in that case, this fast increase is an indicator that visual inspections and 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

Previous papers concluded that when comparing PD data results from different machines; the following parameters must remain constant: [2] [4][5][6]

- Test instrument bandwidth and noise/disturbance separation techniques [1998, 2017]
- Type of sensors [1998, 1999, 2006, 2009]
- Operating voltage of the machines [1998, 2005, 2006, 2013]
- Operating gas coolant of the machines – PD is pressure dependent [1998, 2002, 2006, 2015, 2016]
- PD levels appear to be influenced by the quality of design, manufacturing, and installation, and not solely by operating hours or operating conditions [2000, 2001, 2004, 2007, 2008, 2010, 2014]
- Impact of ambient conditions [2012]
- Impact of resin penetration method, GVPI vs. VPI [2018]
- Utility versus Industrial application [2019]

Not as significant are the:

- Type of insulation system [2000, 2003, 2006]
- Machine type [1998, 1999, 2000, 2005]
- Winding type [1998, 1999, 2000, 2005]
- MW rating [2021]

Differences in operating loads and temperatures could also affect the results. Still, these depended on the stator winding condition, or more precisely the type of aging problems, and 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 regular machine operation, the VHF data acquisition instrument, either the PDA-IV or TGA, is temporarily connected. Alternatively, a Guard system is continuously 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, TGA, or Guard separates the winding PD from system noise and disturbances based on time-of-arrival and pulse characteristics, and measures also the number, magnitude, polarity, 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 the deterioration in the winding. The higher the PD magnitude, the more severe the damage. The second type of plot is three-dimensional (3-D), where the quantity (vertical axis) and magnitude (z-axis coming out of the page) of the PD versus the ac phase angle (horizontal axis) are displayed. Experience has indicated that such pulse phase analysis (which are also called pulse resolved PD plots) 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 among 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 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. At the same time, the NQN is proportional to the total amount of deterioration and is similar to the power factor tip-up. Since the Qm scalar quantity indicates how close the winding is to failure, the peak magnitude (Qm) will be used throughout this paper for comparisons [25].

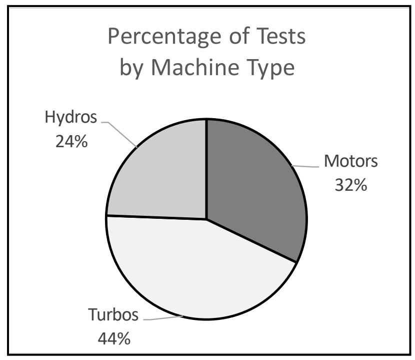
3.3 1997-2021 DATABASE

After the accumulation of all available test data through 2021, with over 750,000 records from tests using portable instruments only, a database was carefully compiled using the following selection criteria:

- only online tests are obtained during normal operation
- only one test result per sensor
- the most recent test at Full Load and Hot stator winding (FLH)
- any test with questionable results was discarded.
- Once these criteria were applied, over 27,000 statistically independent test results from over 8,500 assets were analyzed.

The following table shows 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	24%
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 of several different factors on the Qm, including:

- Sensor installation
- Voltage class
- Hydrogen pressure

The range in Qm from all the tests for the 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 45 mV, 50% (the median) had a Qm below 111 mV, 75% were below 239 mV and 90% of tests yielded a Qm below 488 mV. Thus, if a Qm of 500 mV is obtained on a 13.8 kV motor or turbine generator, then it is likely that this stator has quite deteriorated since it has PD results higher than 90% of similar machines. Significant stator winding insulation deterioration was observed in over two hundred cases where a machine was visually examined after registering a PD level of over 90% of similar machines [23].

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

Oper kV	**2 - <6kV**	**≥6 - <10kV**	**≥10 - <13kV**	**≥13 - <16kV**	**≥16 - <19kV**	**≥ 19kV**
25%	7	21	32	45	42	45
50%	24	55	78	111	85	90
75%	71	141	175	239	186	191
90%	208	308	368	488	346	507
95%	393	476	587	730	506	798

Table 2 illustrates a similar statistical distribution for hydrogen-cooled turbine generators where stator slot couplers (SSC) are installed. For these, both the operating voltage and the 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 SSCs – Slot PD

Rated V	**13-15 kV**			**16-18 kV**			**19-22 kV**			**23-26 kV**	
H_2 (kPa)	**76-138**	**145-207**	**214-345**	**75-207**	**214-345**	**>345**	**75-207**	**214-345**	**> 345**	**214-345**	**> 345**
H_2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
25%	0	0	2	0	0	0	2	0	0	0	0
50%	5	0	8	2	2	1	9	4	2	3	2
75%	20	13	17	15	10	4	23	16	9	12	7
90%	47	48	34	44	34	15	84	42	22	33	20
95%	60	86	47	77	47	22	237	67	36	93	30

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. Continuous PD monitors should set their alert levels to 75% for windings rated 4 kV and below, and 90% for assets rated above 4 kV. If the PD is higher than that found on 90% of similar machines, offline tests, and a visual inspection would be prudent.

4 PD MONITORING OF 3-5 KV MOTORS

In 2014, using online PD monitoring as part of the condition assessment for medium voltage 3-5 kV machines was determined to be possible and practical with several success stories. Trends and comparisons to the Iris database are feasible; however, there are some issues to be considered:

1. Correct coupler installation at the machine terminals to avoid attenuation of the PD signal.
2. Periodic monitoring may be suitable, but once notable PD (above 75% percentile of the population) is detected, or any change in PD magnitude up or down, or change in pattern, then continuous monitoring should be considered since at least for some failure mechanisms the time of detection to failure may be just a few weeks. In contrast, for others, it may be several months or years.
3. One common failure mechanism – surges to damaged inter-turn insulation – may not have PD as a symptom.
4. Manufacturers are not all the same, as shown below, where the PD measured from windings made by manufacturer C is significantly higher than that of the others (Figure 1)

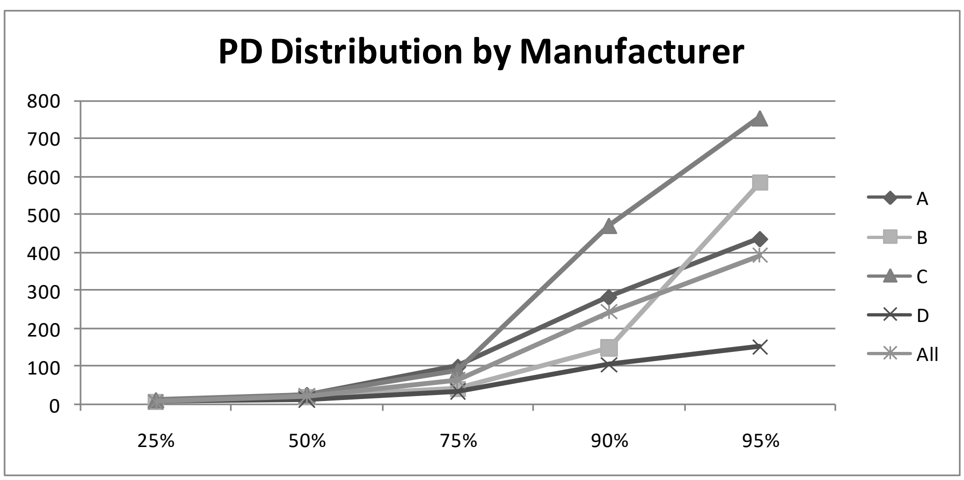


Figure 1. PD Magnitudes based on Manufacturer for 3-5kV Machines

5. Newer winding does not necessarily mean better quality, as shown below, where the PD of the 2001-2005 generation is higher than that of many of the older ones, though <1981 is the highest (Figure 2).

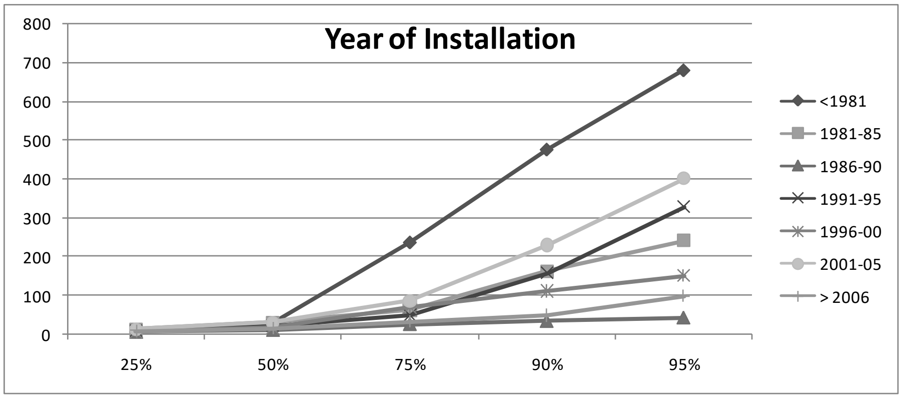


Figure 2. PD Magnitudes based on Year of Installation for 3-5 kV Machines

5 PD IN HYDROGEN-COOLED MACHINES

PD does 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 (Figure 3). 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 evidence of an inverse correlation between PD and hydrogen pressure in older windings, perhaps due to delamination or a characteristic of older insulation materials (Figure 4). For newer windings, a direct correlation is more likely, but not definitive (Figure 5). Because of this correlation, both voltage and hydrogen pressure must be considered when comparing results against the statistical database.

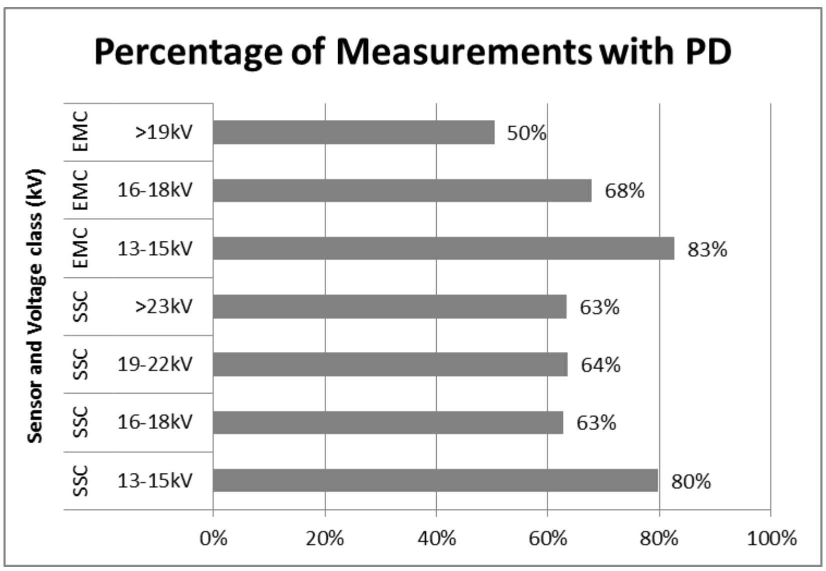


Figure 3. Percentages of measurements with discernible PD

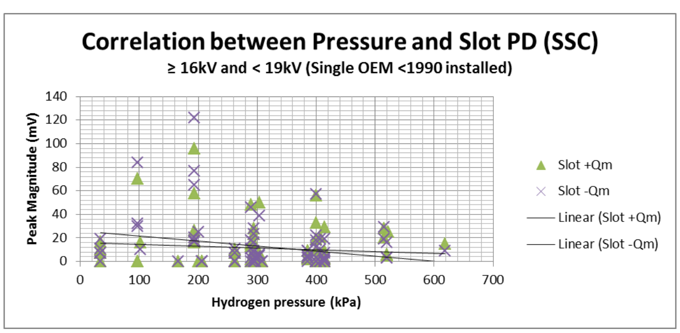


Figure 4. SSC Slot -- PD correlation with Pressure for Manufacturer D for windings installed before 1990 (≥16 kV-19 kV)

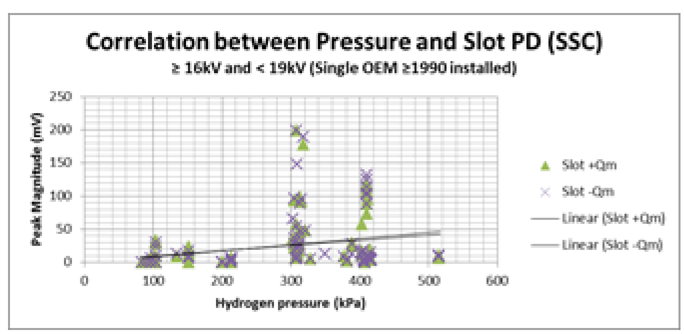


Figure 5. SSC Slot -- PD correlation with Pressure for Manufacturer C for windings installed in and after 1990 (≥16 kV-19 kV)

6 UTILITY VS. INDUSTRY MOTORS

In 2019, a comparison of the PD results between utility assets and industrial applications pointed to some theories. In summary, the following possibilities are revealed in the data comparison:

- PD Magnitudes
  - There was little difference in the PD magnitude rankings at the various percentiles for the 3-5 kV and 13-15 kV assets (Figure 6). This suggests little difference in the manufacturing quality and the stator windings' aging process, regardless of application.
  - In both the 5-7 kV and 10-12 kV (Figure 7) comparisons, the industrial assets were notably higher. This is unknown but may be due to the manufacturing process or the differences in operating stress. In the PD Progress paper of 2018, it was found that in the 10-12 kV range, some (before 1990 and after 2010) GVPI machines have higher PD activity than the conventional VPI process. Perhaps this contributes to the differences seen here.

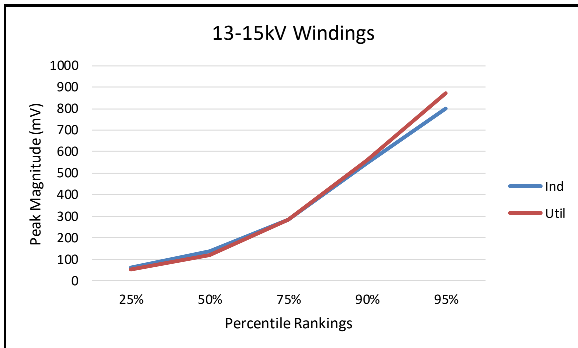


Figure 6. Comparison of the Industrial versus Utility applications with 13-15 kV rated windings

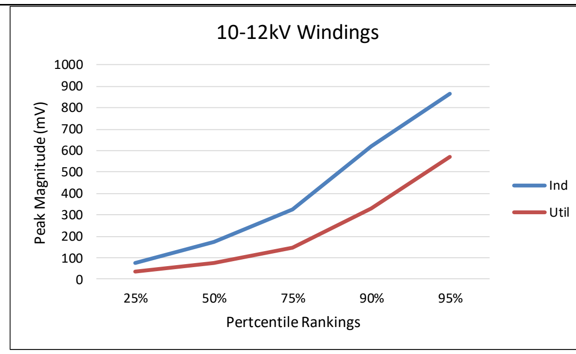


Figure 7. Comparison of the Industrial versus Utility applications with 10-12 kV rated windings

- Polarity Predominance
  - For all four (4) voltage categories, there is a minimal significant difference between the frequency of occurrence for negative, positive, or no polarity predominance. This suggests that the failure processes, or sources of the PD activity, are comparable between industrial and utility applications.

7 STABILITY OF PD RESULTS

In 2022, the database results in over 25 years were evaluated for stability. For 226 (96%) categories, the trends fluctuated minimally and were well within the statistical expectations of PD behavior, as shown in Figure 8. For these, it can be assumed that the values can be correctly used to analyze expectable levels of PD activity. (Refer to the 2022 paper for more information).

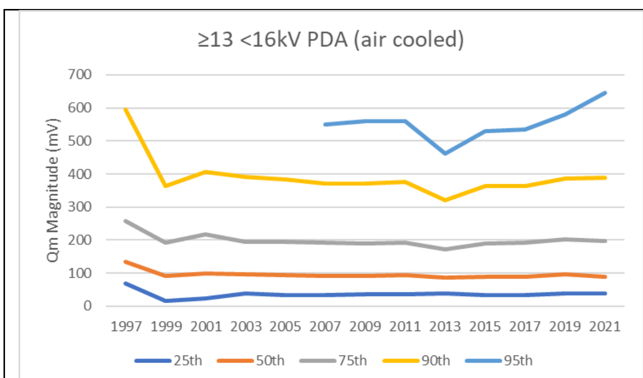


Figure 8. Stable Trend of C1/C2 PD percentiles (PDA, ≥13 kV <16 kV, air-cooled)

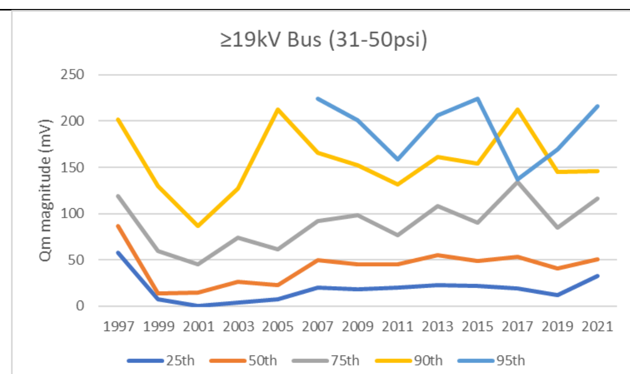


Figure 9. The trend of Machine PD percentiles – Unstable 90th - 95th (BUS, ≥19 kV, 31-50 psi)

The other seven (7) categories, example as shown in Figure 9, require judgment:

1. 90th and 95th (BUS, ≥19 kV, 31-50 psi)
2. 90th (BUS, ≥16 <19 kV, 21-30 psi)
3. 95th (SSC slot, ≥23 kV, 31-50 psi)
4. 90th and 95th (SSC endwinding, ≥23 kV, 31-50 psi)
5. 95th (SSC endwinding, ≥16 <19 kV, >50 psi)
6. 95th (SSC endwinding, ≥19 < 23 kV, 11-30 psi)
7. 95th (SSC endwinding, ≥23 kV, >50 psi)

Possible reasons for the variability are:

- Low magnitude Qm values where small changes significantly impact the trends
- Initially, a small sample size that has steadily increased over the years
- Small sample size throughout the years
- Possible incorrect recording of the operating parameters during testing, especially the actual operating gas pressure

8 PD SEPARATED BY MANUFACTURER AND AGE

In 2004 and 2010, and again in 2023 for this paper, PD levels in 6-9 kV motors, 13-15 kV turbine generators and motors with BUS couplers, and 13-15 kV hydrogenators with PDA couplers were analyzed based on the manufacturer and the year of installation. The older machines are expected to have higher PD, but in the recent analysis for all these three categories reviewed, there was one 5-year vintage that is unusually high. The reason for this was not investigated, but it suggests that some manufacturers may have had issues with manufacturing quality during this period.

All the manufacturers are expected to have similar results, valid for 75% of the machines. However, when you get above the 75% to 90% and 95%, at least one manufacturer category is significantly higher than the others. This variability indicates perhaps a lapse in quality control for these manufacturers.

8.1 MOTORS 6-9 KV

- The overall trend for all manufacturers is downward to suggest that newer machines have less PD activity than older machines. Thus, manufacturing and design are relatively good, except for the 2001-2005 vintage and the higher PD (95th percentile) for 2011-2015. This latter observation suggests a small number of windings with poorer manufacturing quality during these years. (Figure 11)
- One manufacturer (F) has a significantly higher level of the 75th percentile than other manufacturers, but the reason for this is yet undetermined. (Figure 10)

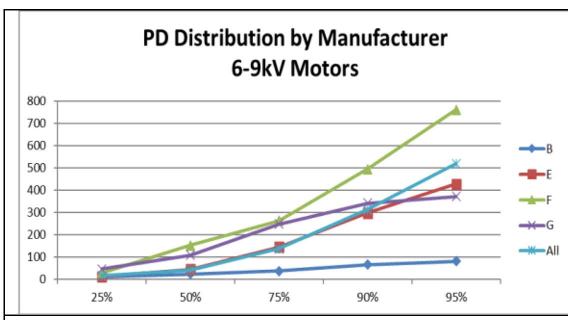


Figure 10. PD Magnitudes based on Manufacturer for 6-9 kV Machines

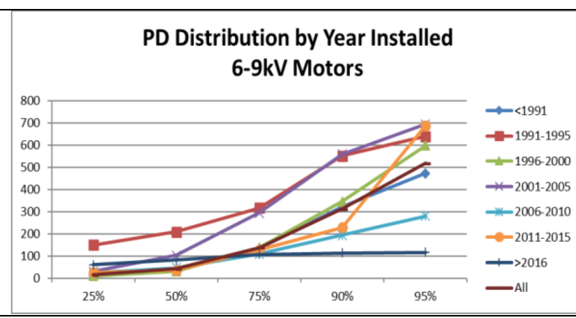


Figure 11. PD Magnitudes based on Year of Installation for 6-9 kV Machines

8.2 MOTORS/TURBOS 13-15 KV

- The overall trend for all manufacturers is stable, suggesting that newer machines have similar PD activity to older devices, and thus manufacturing and design are relatively the same. The 2011-2015 vintage machines are slightly higher than the other ages suggesting manufacturing quality control issues. (Figure 13)
- Two manufacturers (F and G) have notably higher PD levels for the 75th, 90^{th,} and 95th levels; the reason is indeterminate. (Figure 12)

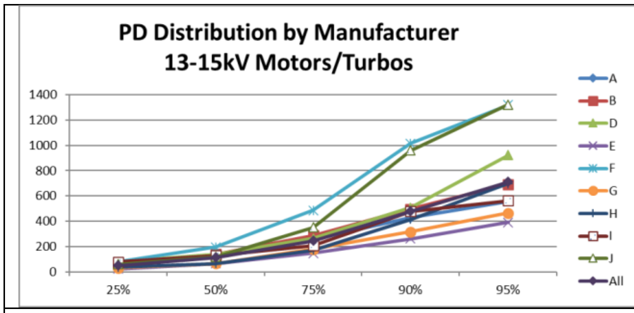


Figure 12. PD Magnitudes based on Manufacturer for 13-15 kV Motors/Turbos (BUS Coupler Installations)

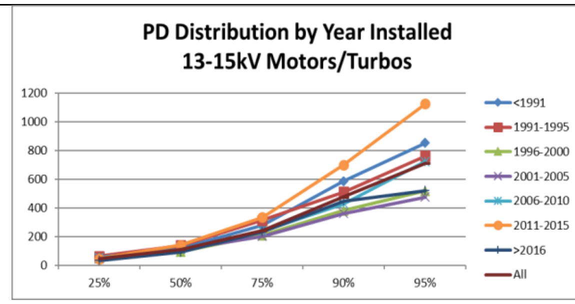


Figure 13. PD Magnitudes based on Year of Install for 13-15 kV Motors/Turbos (BUS Coupler Installations)

8.3 HYDROS 13-15 KV

- The overall trend for all manufacturers is downward to suggest that newer machines have less PD activity than older machines. Thus, manufacturing and design are relatively good, except for the 2006-2010 vintage, which has notably higher PD levels. As stated before, this may indicate manufacturing quality issues during this period. (Figure 15)
- One manufacturer (F) has notably higher levels of PD in the upper range; the reason is unknown. (Figure 14)

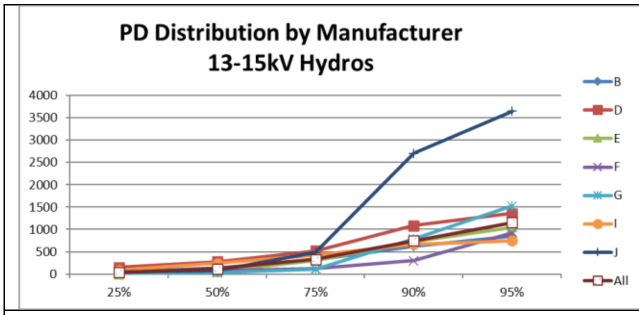


Figure 14. PD Magnitudes based on Manufacturer for 13-15kV Hydros (PDA Installs)

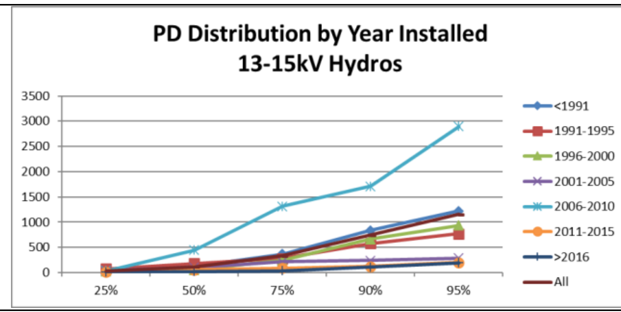


Figure 15. PD Magnitudes based on Year of Install for 13-15kV Hydros (PDA Installs)

9 CONCLUSION

Based on the 2022 paper, because of the stability in the calculated percentile values for 96% of the categories, using the values in the tables of Appendix 11 to assist in the evaluation of Negligible, Low, Typical, Moderate, and High PD levels would be advantageous. For the other seven (7) categories highlighted in the tables, the trend of the PD within the asset should be the predominant evaluation tool.

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, comparing results from similar machines is also possible. If the test instrument is a TGA, PDA-IV, Trac, or Guard and the sensors are either 80 pF capacitors or stator slot couplers, then the tables 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 level). In all cases, raising the flag means increasing the frequency of PD testing to determine the rate of deterioration and, when possible, conducting 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 set their alert levels to 75% or 90% of the database ranking.

The time of winding failure is usually the result of a deteriorated winding being subjected to 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, monitoring the PD characteristics of a stator winding makes it possible to determine which machines are more susceptible to failure and therefore, require maintenance.

10 REFERENCES

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11 APPENDIX – DATA ANALYSIS OF RESULTS FROM 1997-2021

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 2021, with over 750,000 results collected only from portable instruments. Since it has been well established that comparing PD results obtained using different types of sensors is ambiguous, data analysis requires separating the database based on the sensor type. The two basic types of sensors used in the data collection are 80 pF capacitors (cable-type and epoxy-mica type) and stator slot couplers (SSC). Furthermore, the data is separated based on gas cooling pressure and operating voltages. The results displayed are the averages of the percentile rankings for each category. If the values vary over time, then the entry is highlighted, and using that specific value should be considered ambiguous at best. Possible reasons for the variability are low (less than 200) sample size, incorrect entries of the operating parameters by the user during data collection, and the stochastic nature of PD when the magnitudes are low.

11.1 CAPACITORS – (AIR-COOLED MACHINES)

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

11.1.1 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	< 6	≥ 6 < 10	≥ 10 <13	≥ 13 <16	≥ 16 <19	≥ 19	
25%	7	21	32	45	42	45	25% of the results have Qm levels below this value
50%	24	55	78	111	85	90	50% of the results have Qm levels below this value
75%	71	141	175	239	186	191	75% of the results have Qm levels below this value
90%	208	308	368	488	346	507	90% of the results have Qm levels below this value
95%	393	476	587	730	506	798	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 ~200 mV for machines rated less than 13 kV, 239 mV for machines rated 13-15 kV, 186 mV for 16-18 kV, and 191 mV for those >19 kV.

A few machines with PD are much higher than the 90th percentile with Qm levels higher than 400-900 mV. These machines are suspected of having significant deterioration. Additionally, there is an approximate doubling of the Qm levels between 75% and 90%, which supports the definition of rapid deterioration as doubling over a twelve-month interval [IEC 60034-27-2].

11.1.2 Differential Method (PDA)

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

There are two significant differences in the directional and differential installations: the method of time-of-arrival disturbance separation and the actual location of the couplers. Since both time-of-arrival disturbance separation techniques work similarly, this difference should have little impact on the test results.

However, the difference in the sensor locations can significantly affect the results. A differential (PDA) installation in a larger hydro-generator uses sensors usually placed within one meter of the junction between the outgoing phase bus and the first coil/bar in the circuit. A sensor at this location will be susceptible 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 the statistical summaries for windings rated less than 16 kV. Thus, it is safe to say that for a 13.8 kV winding, regardless of installation type, the PD levels should be less than ~250 mV, and those machines with PD higher than 500 mV need further investigation.

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

Rated V	**<10**	**≥10 <13**	**≥13 <16**	**≥16 <19**	**≥ 19**	
25%	12	27	36	41	86	25% of the results have Qm levels below this value
50%	31	61	95	131	162	50% of the results have Qm levels below this value
75%	67	131	199	315	409	75% of the results have Qm levels below this value
90%	189	280	391	665	788	90% of the results have Qm levels below this value
95%	337	391	553	825	970	95% of the results have Qm levels below this value

11.2 CAPACITORS – (GAS-COOLED) (TGA)

PD or noise activity at the machine terminals outside the hydrogen environment can make stator winding insulation conditions challenging to interpret. Since PD is highly dependent on the electrical breakdown point of the gas medium, PD results from air-cooled machines are typically higher than machines cooled with either pressurized hydrogen or carbon dioxide. Therefore, comparing the results from machines using different gas media is not advisable. 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 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 misdiagnosis resulting from the capacitive sensors detecting core-iron problems and stator winding problems.

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

Rated V	**13-15 kV**			**16-18 kV**				**> 19 kV**		
H_2 (kPa)	**76-138**	**145-207**	**214-345**	**76-138**	**145-207**	**214-345**	**Over 345**	**145-207**	**214-345**	**Over 345**
H_2 (psig)	**11-20**	**21-30**	**31-50**	**11-20**	**21-30**	**31-50**	**>=51**	**21-30**	**31-50**	**>=51**
25%	27	19	13	48	33	25	6	42	21	12
50%	69	44	35	121	58	45	17	84	50	33
75%	154	90	77	256	205	111	38	152	100	76
90%	331	189	184	409	544[1]	245	129[1]	191	155	256
95%	695	351	469	439	969	373	302[1]	237	192	883

As expected, the PD results for gas-cooled machines are much lower than those for air-cooled machines. This is especially observable at higher pressures, where 75% of the tests for all operating voltages operated above 31 psig are below 100 mV and 90% generally below ~250 mV, less than observed on the air-cooled machines (Section 11.1.1). At the lower operating pressures, the PD levels are generally much higher, with a few machines having extremely high PD of Qm levels above 400 mV, which would require more tests and investigation. Please note that the three (3) highlighted entries have been unstable over the years, so judgment is required to use these values for decision-making.

[1] Fluctuations in the values over the years, results may be ambiguous.

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

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

Rated V	**13-15 kV**			**16-18 kV**			**19-22 kV**			**23-26 kV**	
(kPa)	**76-138**	**145-207**	**214-345**	**75-207**	**214-345**	**>345**	**75-207**	**214-345**	**> 345**	**214-345**	**> 345**
H_2 (psi)	**11-20**	**21-30**	**31-50**	**11-30**	**31-50**	**> 50**	**11-30**	**31-50**	**>50**	**31-50**	**>50**
25%	0	0	2	0	0	0	2	0	0	0	0
50%	5	0	8	2	2	1	9	4	2	3	2
75%	20	13	17	15	10	4	23	16	9	12	7
90%	47	48	34	44	34	15	84	42	22	33	20
95%	60	86	47	77	47	22	237	67	36	93[2]	30

The preferred sensor for turbine generators rated higher than 100 MVA is a stator slot coupler (SSC), especially for gas-cooled windings. 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 operate in a hydrogen environment, the overall slot PD is relatively low relative to the air-cooled windings. It should be observed that though most of the machines have slot Qm values less than about 30 mV, there are a few with levels higher than 60-200 mV. These should be subjected to further tests and inspections. The SSC is a high-frequency antenna that detects the PD pulses. Through pulse shape analysis, the TGA can discriminate 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 at the endwinding [15]. The endwinding PD is slightly lower than the slot PD, with 90% of all the tests less than approximately 20 mV. However, there are a few machines with Qm levels higher than 25 mV, requiring additional attention.

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

Rated V	**13-15 kV**			**16-18 kV**			**19-22 kV**			**23-26 kV**	
(kPa)	**76-138**	**145-207**	**214-345**	**75-207**	**214-345**	**>345**	**75-207**	**214-345**	**> 345**	**214-345**	**> 345**
H_2 (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	1	0	0	0	0	0	0	0	0
75%	1	0	4	3	1	1	1	1	3	1	1
90%	13	10	9	12	6	8	8	9	11	6[2]	7
95%	29	20	18	24	16	30[2]	22[2]	19	30	7[2]	17[2]

11.4 STATOR SLOT COUPLER – (AIR-COOLED)

Qm values for air-cooled machines with SSC sensors

Slot PD		
Rated V	**13-15kV**	**16-24kV**
25%	0	0
50%	10	1
75%	33	10
90%	83	60
95%	126	115

Endwinding PD		
Rated V	**13-15kV**	**16-24kV**
25%	1	0
50%	1	0
75%	13	1
90%	52	10
95%	62	18

A few air-cooled machines are being monitored with stator slot couplers. The majority of these machines have slot Qm levels less than roughly 30mV, but there are a few with extraordinarily high slot PD, over 90 mV, that would require further investigation. Unsurprisingly, the PD levels for the air-cooled machines with SSCs are generally higher than the gas-cooled ones. As previously described, because of the differences in the electrical breakdown points of the gas media, comparing results from air-cooled machines to those from gas-cooled ones is not recommended.

[2] Fluctuations in the values over the years, results may be ambiguous.