

## ADVANCES IN INTERPRETING PARTIAL DISCHARGE TEST RESULTS FROM MOTOR AND GENERATOR STATOR WINDINGS

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*On-line partial discharge (PD) testing has been used for decades to help maintenance personnel detect stator winding insulation problems in motors and generators. Specifically, the test can often find loose, delaminated, overheated, and contaminated windings, well before these problems lead to failure. As a result, on-line PD testing has become an important tool for planning machine maintenance. The test has also found use in determining the effectiveness of any manufacturing or repair work. With the advent of electrical noise separation technology developed in the 1970s and 1980s, reliable on-line PD testing and basic interpretation was made possible by plant engineering staff with moderate training. The result has been the widespread application of the so-called PDA and TGA tests on machines throughout the world. Over 50% of utility generators rated over 20 MW in the USA and Canada now use this technology.*

*This widespread application has enabled the collection over the past ten years of a database with nearly 30,000 test results. The results of a statistical analysis of the PD results in this database shows that voltage class, machine cooling method, and type of partial discharge detector all are critical to interpreting test results, whereas machine power rating, insulation type and age of the winding are less important. Critical values of PD, which indicate significant risk of severe winding problems, are presented for different types of air-cooled and hydrogen-cooled machines. Thus*

*comparison of test results to the database allows a rough assessment of the stator winding insulation condition, without having to wait a few years for a trend to establish itself. However, the best assessment of the winding condition is still obtained from the trend in PD on a single machine over time. A doubling of the PD magnitudes every 6 months, under similar operating conditions is a consequence of a rapid rate of insulation deterioration. This paper shows that the PD is affected by machine operating conditions. Thus to obtain valid trends in PD data, the testing should be performed under similar operating and environmental condition*

### 1. INTRODUCTION

Partial discharges are both a cause and a symptom of many types of stator winding insulation system deterioration mechanisms in motors and generators rated 3300 V and above. Thus it is not surprising that the on-line measurement of partial discharges has been used to assess the need for maintenance in stator windings since 1951 [1]. More particularly, on-line PD measurement has been able to determine if the electrical insulation is deteriorating due to loose coils in the slots resulting in insulation abrasion; thermal deterioration or load cycling leading to insulation delamination; and electrical tracking caused by partly conductive contamination of the endwindings [1-7]. On-line PD testing is also able to determine if manufacturing or installation problems such as poor impregnation with epoxy, or coils being too close together in the endwinding, are severe enough to shorten the winding life.

Key Words: partial discharge, electrical insulation, stator winding, condition assessment

Many methods are available to measure the PD activity in operating machines. The electrical techniques all rely on monitoring the current or voltage pulse that is created whenever a partial discharge occurs. The earliest methods measured the PD pulse currents by means of a high frequency current transformer at the neutral point [1,2]. Shortly thereafter, high voltage capacitors connected to the phase terminals were used to detect the PD pulses [3-5]. Capacitor sizes ranged from 80 pF to over 1000 pF. More recently, RF antennae are also used to detect PD in operating machines [6]. A good overview of all the different means for detecting PD in machines is presented in a recent IEEE guide [7].

A particular challenge with PD measurements performed in normal motor or generator operation is that electrical interference (noise) often is present [7]. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, power tool operation, and electrostatic precipitator discharging. This noise obscures the PD pulses, and may cause the unwary technician to assume that a stator winding has high levels of PD, when in fact the high levels are caused by the noise. The consequence is that a good winding may be incorrectly assessed as being defective – that is a false alarm may be given that a winding is bad, when it is not. Such false alarms reduce the credibility of on-line PD tests, and even today, many feel on-line PD testing is a ‘black art’ best left to specialists.

Beginning 25 years ago, the Canadian utility industry sponsored research to develop an objective on-line PD test for machines that could be performed and basically interpreted by plant staff with only a few days training. The tests that were developed, now known generically as the PDA test (for hydrogenerators) and TGA test (for turbine generators and motors) emphasized separating PD pulses from electrical noise pulses. The noise separation methods depend on comparing the time of pulse arrival between a pair of capacitive couplers and/or analyzing the shape of individual pulses [4,6]. To maximize the signal to noise ratio, and thus also to reduce the risk of false indications, the sensors detect the PD at frequencies 40 MHz and higher [8]. The resulting test methods achieved their goal and have enabled utilities to assess the winding condition with their own staff. Around the world, over 4000 machines have the required sensors.

With the widespread application of the same on-line test methods, a tremendous number of test results have been accumulated in a single database. Simple statistical analysis has been applied to the database in order to extract information that can help test users to better interpret PD results. This paper presents some of the more important findings. However, the best means to determine if a winding is significantly

deteriorated is to monitor the trend in PD activity over time. Unfortunately, the PD magnitudes are not only affected by the degree of insulation deterioration, but the machine operating voltage, load, etc may also affect results. With the availability of on-line PD monitoring systems that continuously measure the PD on a motor or generator, while simultaneously acquiring machine-operating data, a better appreciation of the effect of operating conditions on PD activity has been obtained. Thus this paper also presents the ranges in operating condition that enable the measurement of valid trends of PD activity.

## 2. PD DATABASE

### 2.1 Data Presentation

All the data presented here is obtained using either 80 pF capacitive couplers (installed within the stator winding, or at the machine terminals) or stator slot couplers (SSCs), which are antennae installed under the wedges in stator slots containing phase end bars [4,6]. Once PD pulses are separated from noise, the number, magnitude, polarity, and phase position with respect to the 50/60 Hz ac cycle are recorded. The pulse magnitude is measured in the absolute units of millivolts, rather than picocoulombs, due to the difficulty in calibrating into charge, caused by the inductive-capacitive nature of a complete stator winding [7]. From each test, two summary indicators are extracted, representing all the PD pulse data collected. The peak positive and negative PD magnitudes (+Q<sub>m</sub> and -Q<sub>m</sub>) represent the highest PD pulses measured in mV with a repetition rate of 10 pulses per second. (Note that IEC 60270 defines the repetition rate for Q<sub>m</sub> to be 50 or 60 pps – this was found to cause problems in hydrogen-cooled machines where PD may not occur every ac cycle.) For the purpose of this study, the complete pulse magnitude and pulse phase analysis plots are not analyzed.

It has been noted in previous papers that Q<sub>m</sub> is a reasonable predictor of winding insulation condition [9, 10]. That is, a high Q<sub>m</sub> measured in a winding compared to a lower Q<sub>m</sub> in another winding, usually implies that the former winding has more severe problems. We believe that the Q<sub>m</sub> readings reported here might be somewhat absolute because the pulses are measured as traveling waves, and all oscillations after the first peak in a single PD event are disregarded. Since the surge impedance of a coil in a slot is roughly the same for all sizes and types of machines, the very wide band measurement of the first peak in a PD pulse does not ‘see’ the entire capacitive and inductive load of the stator winding, thus leaving the measurement free of the effects of LC oscillations and reflections.

## 2.2 Database to the End of 2000

All test results since about 1992 were combined into a single database. This totaled 28 563 tests until the end of 2000. This database contains many repeat tests, sometimes performed over many years. Also, many of the tests were done under different motor or generator operating conditions. As described in Section 3, machine-operating conditions can affect the PD activity, and thus adds additional variability to the analysis. Thus the database was carefully reduced such that:

- only on-line PD readings obtained when the machine was operating at or near full load at normal operating temperature are included
- there is only one test result collected per sensor, thus only the latest reading is extracted
- tests were discarded where there was reason to believe the measurement was mislabeled.

The number of statistically independent tests for each type of machine that remained is shown in Table I. Note that almost 50% of the reduced database comes from hydrogenerators, since this technology was first applied to such machines. 82% of the data was collected using capacitive couplers, with the other 18% came from SSCs.

Table I: Number of Independent Full Load Tests By Machine Type

Machine Type	No. of Tests	Percentage
Motor	1287	18
Hydro	3435	49
Turbo	2343	33

## 2.3 Database Analysis Method

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

- rated voltage of the stator winding
- rated power (i.e. size of machine)
- type of machine (motor, hydro or turbo)
- air or high-pressure hydrogen cooling
- insulation type (asphaltic mica, polyester mica or epoxy mica)
- sensor used and its location in the winding (PDA type) or on the terminals (Bus type)
- winding age.

For each set of the above factors, the range in Qm from all the tests for the particular voltage rating, size, sensor type, etc was established. For example Figure 1 shows a histogram of the percentage of Qm values in each mV range obtained with capacitive couplers on air-cooled stator windings of various voltage ratings (using all types of insulation systems). A cumulative

version of the histogram is shown in Table II, which also shows the maximum Qm measured as well as the average Qm. For example, for an air-cooled 11 kV stator measured with capacitive couplers on the machine terminals, the average Qm from all the tests was 148 mV, while 25% of tests had a Qm below 26 mV, 50% (the median) of the tests had a Qm below 73 mV, 75% were below 173 mV and 90% of tests yielded a Qm below 372 mV. Thus if a Qm of 400 mV is obtained on an 11 kV, air-cooled stator, then it is likely that this stator will have significant problems since it has PD levels higher than 90% of similar machines.

The effect of a particular factor on Qm was determined by comparing the average and 90 percentile levels between the two data sets composed of, for example, 11 kV machines and 13.8 kV machines. If there was a significant difference in the average and 90% distribution levels of Qm for the two sets, then we concluded that this factor is important to interpreting results.

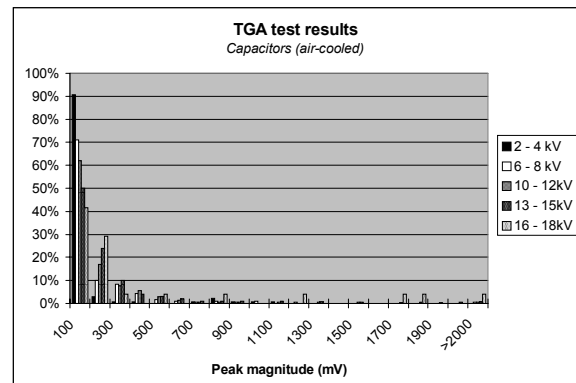


Figure 1 - Probability of occurrence of Qm levels in air-cooled machines measured with 80 pF couplers.

## 2.4 Results

Table II shows the average and various percentiles of Qm distribution measured by 80 pF capacitors at the stator terminals of air-cooled machines rated from 2 kV to 18 kV. As the rated voltage increases, there is a consistent and marked increase in the average and 90% Qm measured. Not unexpectedly, the voltage rating has a significant impact on the Qm. The higher the voltage rating, the higher the Qm that can be expected. In correlations with observed winding condition, we find that if the Qm is higher than the 90% level in the database for the same voltage class, then significant insulation problems will be observed in a winding. From Table II it is clear that significant insulation problems occur with a Qm of about 90 mV for a 3,3 kV stator, while the same severity of the problem in a 13,8 kV stator occurs about 460 mV. Thus the voltage rating, and probably the groundwall thickness, has an

important impact on how a particular Qm should be interpreted.

Table III shows the distribution of Qm for air-cooled stators equipped with 80 pF couplers mounted within the stator winding, very close to the phase end coils in a given circuit (often referred to as PDA couplers) in hydrogenerators. Comparing Tables II and III, there is relatively little effect of sensor location on the distributions; although terminal mounted sensors seem to yield slightly higher levels at many percentiles. One would expect the sensors closer to the coils with PD to yield higher readings. Perhaps the cause of this unexpected result is that some sources of PD may be more prevalent in motors and air-cooled turbogenerators (which constitute the majority of machines with terminal sensors) than in hydrogenerators.

Table II: Distribution of Qm for Air-Cooled Stators, 80 pF Sensors at the Terminals

Percentile	Rated Voltage				
	2-4 kV	6-8 kV	10-12 kV	13-15 kV	16-18 kV
25	2	13	26	37	41
50	12	39	73	100	101
75	36	136	173	213	407
90	91	287	372	459	1751
Average	57	110	148	213	497
Max Recorded	1116	2176	2074	3200	2717

Table III: Distribution of Qm for Air-Cooled Stators, 80 pF sensors Within the Winding

Percentile	Rated Voltage				
	6-8 kV	10-12 kV	13-15 kV	16-18 kV	>19 kV
25	0	28	21	79	95
50	31	67	93	215	170
75	51	146	193	414	304
90	109	293	373	833	538
Average	41	143	174	379	312
Max Recorded	325	3410	3396	3548	3552

The Qm distributions depend strongly on whether the stator is cooled by air at atmospheric pressure, or by a high-pressure gas such as hydrogen (used in large turbo generators) or carbon dioxide (used in some large nuclear motors). Table IV shows the Qm distribution for high-pressure, gas-cooled machines with PD detected via 80 pF couplers at the machine terminals. Due to the impact of gas pressure on PD, high-pressure gas cooled machines have a very much reduced level of Qm associated with similar percentiles. Clearly before interpreting a PD result, one needs to know whether the machine is hydrogen or

air-cooled and the pressures are similar. Similarly, comparing Tables IV and V, it is obvious that the PD measured with SSC sensors should be interpreted differently from results acquired with capacitive sensors. One reason the Qm levels are generally lower for SSCs is that these sensors only detect PD in the slot in which they are installed.

Table IV: Qm Distribution for Hydrogen-Cooled Machines with 80 pF Sensors

Percentile	Rated Voltage		
	10-12 kV	13-15 kV	>16 kV
25	0 mV	13 mV	7 mV
50	15	37	17
75	42	70	75
90	52	103	148
Average	21	68	76
Max Recorded	54	1564	1172

Table V: Qm Distribution for Hydrogen-Cooled Machines with SSCs, Slot PD

Percentiles	Rated Voltage			
	13-15 kV	16-19 kV	20-22 kV	23-25 kV
25	0	0	0	0
50	0	0	0	2
75	10	3	13	8
90	37	36	35	19
Average	15	12	13	8
Max Recorded	361	609	243	128

Similar analysis was done for the other factors listed above. The analysis showed that the distribution of Qm did not depend on the power rating of the motor or generator, as long as the voltage class, type of sensor and type of cooling was held constant. That is, the 90% Qm level is the same for a 20 MW and a 200 MW generator, as long as the voltage class, etc is the same. In addition, whether the stator is in a motor, hydrogenerator, or high-speed turbo generator had no effect on the Qm distribution. Within the very large standard deviation that does exist with such data, there does seem to be a small effect of the groundwall insulation bonding resin (asphalt, polyester or epoxy) on the Qm distribution. Polyester and asphalt bonding materials tended to have higher Qm at the lower percentiles, but this difference disappeared on the machines with a Qm higher than 90% of other machines. As a result, the 90% levels for all types of groundwall insulation systems seem to be well represented by Tables II-V.

Perhaps the most surprising result obtained from the statistical analysis of the database was that the distribution of Qm was essentially unaffected by the year the stator winding was installed. PD results in the database came from machines that were from a few

months old to greater than 50 years old. That there was no general trend that older machines have higher PD implies that both older windings and new windings can have high PD activity. A new stator winding does not guarantee that high levels of PD, and thus a rapid rate in insulation deterioration, can not occur.

### **3. IMPACT OF OPERATING CONDITIONS ON PARTIAL DISCHARGE**

#### *3.1 Importance of Trending PD*

Even with the ability to compare results to a database as described in Section 2, the trend in the PD activity over the years is still the most powerful means to determine the rate of insulation degradation. If the volume of a void or other defect is increasing, implying that the winding is closer to failure since more and more of the thickness of the insulation is compromised, then physical principles indicate that the magnitude of the PD will increase. Over 20 years of experience (where test results are compared to actual winding insulation condition) show that a doubling of  $Q_m$  every six months or so indicates rapid aging. Where such rapid increases in PD occur, pro-active maintenance is advisable, especially if the activity is already high in comparison to other similar machines in the database.

Winding deterioration is not the only factor that is known to affect  $Q_m$ . Various motor and generator operating conditions, as well as environmental factors, can also affect the PD activity. Although some of these influences have been known for over 15 years [10,11], the application of on-line continuous monitoring systems on hundreds of motors and generators has made the quantification of the effects much more rigorous [12,13].

The following describes the nature of the effect of each parameter. Note that although one may desire repeatable test conditions to ensure reliable trending, the following parameter effects are useful to help determine what failure mechanism may actually be occurring in any particular machine.

#### *3.2 Voltage Effect*

PD is very strongly affected by voltage, no matter what the failure process of the stator winding is. The higher the voltage, the greater the PD magnitude, and as well, the more voids within the insulation that are likely to experience PD [8]. Consequently, the motor or generator operating voltage must be maintained very close from test to test.

#### *3.3 Power or Load Effect*

Experience indicates that windings that are tight in the stator slot will not experience a load effect, i.e. change the PD activity as the load changes. However, if the windings are loose, then, as the load increases, the magnetic forces acting on the coils or bars will increase with the current squared. This will increase the maximum space between the coil surface and the stator core during the 100 or 120 Hz bar vibration induced by the forces, increasing the PD magnitude ( $Q_m$ ). The first published example showed that on a hydrogen-cooled synchronous condenser, the  $Q_m$  increased by more than 300% in changing the load from near 0 to full power [11]. Thus, if windings are loose, to enable reliable trending over time, the current must be kept constant. Furthermore, in synchronous machines, the ratio of reactive to real power should also be constant. Otherwise, the relationship between the instantaneous stator winding voltage and when the largest 'voids' will appear between the coil surface and the core will change, affecting the energy stored in the void capacitance at the point of breakdown. Since the load also impacts the winding temperature, the power/load effect may be confounded with the temperature effect.

#### *3.4 Temperature Effect*

The stator winding temperature, as measured between the top and bottom coils/bars in a slot, can either increase or decrease the PD activity. As with the load effect, if the winding is in good condition, there will be no temperature effect on PD.

A negative temperature effect occurs in delaminated groundwall insulation, which usually occurs as a result of long term overheating or load cycling. At low temperatures, PD occurs in the voids within the groundwall. As the winding heats up, the copper conductors and the insulation expands due to the coefficient of thermal expansion. Since the stator core remains at essentially the same temperature, the stator slot remains the same size. The expansion of the copper and the insulation thus squeezes any voids, both reducing the number of voids and the thickness of the voids. That is, as the temperature increases, the  $Q_m$  may decrease by 300% or more in a severely delaminated winding [12].

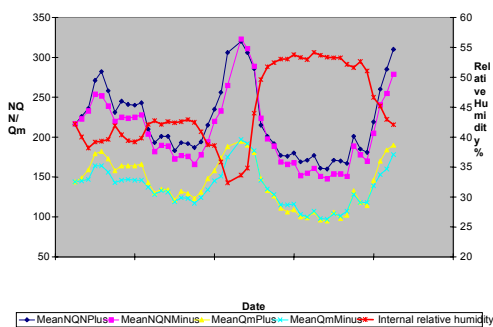
A positive temperature effect on PD can occur if there are problems with the semiconductive (slot) coating and/or the silicon carbide stress relief coating at the slot exits. Increasing temperature increases the resistance of these coatings, which reduces their effectiveness in controlling the electric stress, thus increasing  $Q_m$ . If the coatings are in good condition, no PD will occur in their vicinity, and thus, there will be no temperature effect.

### 3.5 Pressure Effect

The air or hydrogen pressures in the machine have a direct influence on the breakdown strength of the gas in a void or on the coil/bar surface. By Paschen's Law, the breakdown voltage (or stress) increases approximately linearly with pressure, which decreases the likelihood that any particular void will break down. Thus, as the gas pressure increases, the PD activity decreases. Normally, the usual atmospheric pressure changes from day to day will not have a significant (>25%) impact on the PD in air-cooled machines. However, the variations in hydrogen pressure can significantly affect PD activity in hydrogen-cooled machines [14]. Like the voltage effect, the pressure effect will occur whether or not there is significant deterioration of any kind.

### 3.6 Humidity Effect

If windings are clean and dry, and there is sufficient spacing between coils/bars in the endwinding, there will be no PD, and consequently there seems to be no humidity effect. However, with insufficient spacing, or with coils that are polluted and suffering from electrical tracking, PD will occur that can be strongly affected by the humidity. For contamination-induced PD, the effect could possibly occur because the higher the humidity, the more effectively the moisture in the air will grade the electric field, reducing the influence of electric field enhancements from electrical tracking, etc. Consequently, reduced PD usually exists at a higher humidity. Figure 2 shows the impact of ambient humidity on Qm for a 4,1 kV motor winding with known contamination. To date, insufficient data has been accumulated to conclusively pinpoint the allowable range in humidity where it is possible to limit the PD change to less than 25%.



**Figure 2: The effect of humidity on Qm for a 4,1 kV motor with known endwinding contamination. The readings were taken over a several day period with a continuous PD monitor.**

### 3.7 Implications for Reliable Trending

Table VI shows the parameters that can affect Qm, and thus which need to be controlled if a valid trend in winding condition is to be established. In general, if tests are repeated with parameters outside of the range shown, PD may increase or decrease by more than 25% due to the parameter alone. Thus to determine if a winding has deteriorated over time, one must compare tests with the parameters approximately the same. Otherwise, any increase in PD over the years may actually result from a decrease in temperature, an increase in load or an increase in voltage - NOT due to a deteriorating winding. Since it may be difficult to control these parameters during tests, their potential impact on the interpretation should be acknowledged. If the Qm is low in comparison to the 90th percentiles in Tables II-V, then only the voltage and gas pressure need to be controlled.

Table VI: Parameters that Need to be Controlled for Trending Tests

Parameter	Control Tolerance
Stator Voltage	+/- 2%
Load	+/- 10%
Real Power	+/- 10%
Reactive Power (including direction)	+/- 10%
Stator Winding Temperature	+/- 5 °C
Gas Pressure	+/- 30 kPa
Gas Humidity	?

## 4. CONCLUSIONS

1. With many thousands of machines monitored, some for as long as 25 years with the same method, on-line partial discharge testing has become a recognized, proven tool to help maintenance engineers identify which stator windings need off-line testing, inspections and/or repairs.
2. With almost 30 000 test results acquired with the same test methods, what constitutes a winding with low, moderate or high PD has been approximately defined. Tables II-V enable test users to identify to some degree which machines are likely to suffer from stator groundwall insulation deterioration, with only a single measurement on a machine. The levels are only valid with 80pF capacitors or SSC sensors.
3. Within the statistical accuracy possible with several thousands of independent results, it seems that critical PD levels only depends on voltage rating, whether the machine is air or hydrogen cooled, and the specific type of sensor and instrumentation used.

4. The trend in PD over time is still the most reliable way to identify which machines need maintenance. However, since the PD activity is not only affected by deterioration, but also by operating load, voltage, temperature, gas pressure and humidity, these factors must be similar for direct comparison of tests. Trend data acquired when these factors are about the same will enable the maintenance engineer to detect stator insulation problems at the earliest possible time.

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