

Effect of Manufacturer Winding Age and Insulation Type on Stator Winding Partial Discharge Levels

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Introduction

Partial discharges (PD) are a symptom and sometimes a cause of many types of motor and generator stator winding insulation system deterioration mechanisms in utility generators. Since 1951, the on-line measurement of PD has been used to assess the need for motor and generator maintenance in stator windings [1]. More particularly, on-line PD measurement has been able to determine whether the electrical insulation is deteriorating because of loose coils in the slots, resulting in insulation abrasion; thermal deterioration or load cycling, which leads 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 whether 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.

There are many methods available to measure the PD activity in operating machines. The electrical techniques 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 to >1000 pF. An overview of the different means for detecting PD in machines is presented in a recent IEEE guide [7].

A particular challenge with PD measurements is encountered when a machine is operating and electrical interference (noise) is often present [7]. Noise sources include corona from the power system, slip ring/commutator sparking, sparking from poor electrical connections, and/or power tool operation. This noise obscures the PD pulses and may cause the technician to conclude that a stator winding has high levels of PD, when it is actually the noise. The consequence is that a good winding is incorrectly assessed as being defective, meaning that a false alarm is given, suggesting that the winding is bad when it is not. Such false

alarms reduce the credibility of on-line PD tests, and even today, many feel that on-line PD testing is a 'black art' best left to specialists.

Twenty-five years ago, the Canadian utility industry sponsored research to develop an objective on-line PD test for machines that could be performed and interpreted by plant staff with average training. The PD test that was developed emphasized separating PD pulses from electrical noise pulses. The noise separation methods depend on comparing the time of pulse arrival between a pair of 80-pF capacitive couplers and/or analyzing the shape of individual pulses from 80-pF capacitors or special antennae called the SSC [4], [8], [9]. To maximize the signal-to-noise ratio and thus reduce the risk of false indications, the sensors detect the PD at frequencies of 40 MHz [8]. These test methods have enabled utilities to assess the winding condition with their own staff. As a result, it is estimated that >50% of all utility generators rated 20 MW in the US and Canada have now been equipped with the required PD sensors. Globally, well over 4000 machines have the required PD sensors.

A large number of test results have been accumulated in a single database with the widespread application of the same on-line test methods. At the end of 2003, over 60,000 test results had been accumulated over 10 yr, and simple statistical analysis has been applied to the database to extract information that can help test users to interpret PD results better. In addition, experience has accrued on what operating and environmental parameters may affect the PD readings as well as the deterioration in the stator insulation condition. This article presents some of these important findings.

Data Presentation

All of the data presented in this paper were obtained using either 80-pF capacitive couplers or SSCs installed within the stator winding [4], [9]. As with most PD measurement systems, the number, magnitude and phase position with respect to the 60-Hz ac cycle are recorded once PD pulses are separated from the noise pulses. The pulse magnitude is measured in the absolute units of millivolts (mV), rather than picoCoulombs (pC), because of the difficulty in calibrating into pC as a result of the inductive-capacitive nature of a complete stator winding [7]. From each test, two summary indicators are extracted, representing all PD pulse data collected. The peak positive and negative PD magnitudes

(+Qm and -Qm) represent the highest PD pulses measured in mV, with a minimum PD repetition rate of 10 pulses/s. For the purpose of this study, the complete pulse magnitude and pulse phase analysis plots are not analyzed.

Qm is a reasonable predictor of winding insulation condition [3], [4]. A high Qm measured in a winding compared with a lower Qm in another winding usually implies that the former winding is more deteriorated. Initially, this was a surprise, as the mV readings were not calibrated for the capacitive load of the winding. We now believe that the Qm 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 by the most common instrumentation. Because 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.

Database to the End of 2003

All test results since approximately 1992 were combined into a single database. This totaled 63,342 tests until the end of 2003. This database contains many repeat tests, sometimes performed over many years. Also, many of the tests were done at different operating conditions. As described in [7], [10], machine operating conditions can affect the PD activity and thus add additional variability to the analysis. Therefore, 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; and
- tests were discarded where there was reason to believe the measurement was mislabeled.

The result of this culling is that, to the end of 2003, there were 4828, 3953, and 2211 statistically independent test results for hydrogenerator-, turbogenerator- and motor-stator windings, respectively, in the database.

Database Analysis Method

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

- operating voltage of the stator winding;
- rated power (i.e., MVA);
- hydrogen pressure, if the machine is a hydrogen-cooled turbogenerator;
- type of partial discharge sensor (80-pF capacitive coupler or SSC);
- insulation type (asphaltic mica, polyester mica, or epoxy mica);

- winding age; and
- winding manufacturer.

The range in Qm from all of the tests for the particular operating voltage, size, sensor type, etc. was established for each set of these factors. A cumulative version of the statistical distribution is shown in Table 1, which also shows the maximum Qm measured as well as the average Qm. For example, for a 13.8-kV stator, the average Qm from all tests was 312 mV. Twenty-five percent of tests had a Qm <38 mV, 50% (the median) of the tests had a Qm <96 mV, 75% were <194 mV, and 90% of tests yielded a Qm <392 mV. Thus, if a Qm of 500 mV is obtained on a 13.8 kV hydrogenerator, then it is likely that this stator will be deteriorated, as it has PD levels higher than in 90% of similar machines. In fact, in many dozens of cases where a machine was visually examined after registering a PD level higher than in 90% of similar machines, significant stator winding insulation deterioration was observed.

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

Effect of Operating Voltage

Table 1 illustrates the average and various percentiles of Qm distribution from hydrogenerators with 80-pF capacitors installed on the stator winding circuit ring buses, operating from 2 to 18 kV. There is usually a marked increase in the average and 90% Qm values measured as the operating voltage increases, at least where there is a large number of tests. From Table 1, it is clear that significant insulation deterioration seems to occur with a Qm of about 400 mV for a 13.8-kV stator; the same level of deterioration in a 18-kV

	6 to 9 kV	10 to 12 kV	13 to 15 kV	16 to 18 kV
25%	21 mV	42 mV	38 mV	93 mV
50%	38	74	96	213
75%	78	153	194	413
90%	2411	334	392	838 ²
Average	115	227	312	373
Maximum recorded	1870	3410	3680	3548

¹Variable because of the relatively small number of samples.
²Variable because of the strong influence of a few manufacturers.

Table 2. Distribution of Qm for air-cooled stators, 80-pF sensors on the terminals of motors and turbogenerators.

Operating voltage	2 to 4 kV	6 to 8 kV	10 to 12 kV	13 to 15 kV	>16 kV
25%	7 mV	17 mV	35 mV	44 mV	37 mV
50%	27	42	88	123	69
75%	100	116	214	246	195
90%	242 ¹	247	454	508	615 ²
Average	117	99	190	222	286
Maximum recorded	3200	1942	3200	3314	3200

¹Variable because of the strong influence of a few manufacturers.
²Variable because of the strong influence of a few manufacturers.

stator occurs at about 850 mV. Thus, the operating voltage has an important impact on how a particular Qm should be interpreted. Clearly, results from a 13.8-kV stator should not be confused with those from a 18-kV stator.

Table 2 illustrates the similar statistical distribution for motors and turbogenerators, where the 80-pF capacitors are installed at the machine terminals (rather than within the stator). The distributions show that, at the 90% level, turbos seem to have greater PD than hydros.

Hydrogen Pressure

The data collected show that 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 turbine generators). Table 3 shows the Qm distribution for high-pressure, gas-cooled machines with PD detected via 80-pF couplers on the machine terminals. Comparing Tables 2 and 3 shows that when the PD is measured at high pressure, there is a very much reduced level of Qm associated with similar deterioration levels. Table 3 also shows that, as operating hydrogen pressure increases, the 90% Qm

PD activity level decreases significantly. Clearly, before interpreting a PD result, one needs to know whether the machine is hydrogen or air-cooled, and if hydrogen-cooled, what the pressure was at the time of the measurement.

There are more than 600 large, hydrogen-cooled machines equipped with SSCs as the PD sensor. Table 4 shows the effect of voltage class and hydrogen pressure on the test results from SSC. Similarly, comparing Tables 3 and 4, it is obvious that the PD measured with SSC sensors should be interpreted differently from results acquired with capacitive sensors, that is, the 90% levels are usually lower with SSC than with capacitive couplers.

Winding Age

One surprising result from the statistical analysis of the database was the distribution of Qm as a function of winding age. Table 5 illustrates the PD results in the database from machines that were from 1 yr old to more than 50 yr old. There is no consistent trend, which is surprising because one would normally assume that older windings would be more deteriorated and thus have higher PD levels. This implies that both older windings and new windings can have about the same high PD activity. In fact, air-cooled windings manufactured in the past 5 yr seem to have higher PD activity than older machines. This may reflect the fact that modern windings tend to operate at higher thermal and electrical stresses than older machines [6]. Other explanations for the inconsistent pattern of PD versus winding age may include the observation that manufacturers of machines have a learning curve to climb as they adopt new design and manufacturing techniques or that utilities are continuously oscillating between proactive and breakdown maintenance strategies, depending on management policies.

Manufacturer

An analysis of the statistical distribution of PD for several manufactures was also performed. Table 6 shows the results

Table 3. PD magnitude distribution for hydrogen-cooled machines at different pressures equipped with 80-pF couplers.

Operating Voltage	13 to 15 kV			16 to 18 kV				> 19 kV			
	H ₂ (psi)	11 to 20	21 to 30	31 to 50	11 to 20	21 to 30	31 to 50	>50	21 to 30	31 to 50	>50
25%		27 mV	15 mV	3 mV	484 mV	18 mV	7 mV	4 mV	38 mV	4 mV	2 mV
50%		64	37	28	154	34	17	9	56	26	14
75%		125	71	75	521	53	34	25	131	74	41
90%		282	124	951 ²	791	143 ²	61	77	182	127 ¹	89
Average		141	64	346	301	58	98	32	92	60	34
Maximum recorded		2150	1390	3200	933	322	1958	367	351	574	482

¹Variable because of the relatively small number of samples.
²Variable because of the strong influence of a few manufacturers.

Operating voltage	13 to 15 kV			16 to 18 kV			19 to 22 kV			23 to 26 kV	
	H ₂ (psi)	11 to 20	21 to 30	31 to 50	21 to 30	31 to 50	>50	21 to 30	31 to 50	>50	31 to 50
25%	0	0	8	0	0	0	5	0	0	0	0
50%	0	0	13	5	3	0	10	0	0	0	0
75%	18	13	21	17	15	0	20	8	3	01	4
90%	102 ¹	38	40	33	59	7	42 ¹	35	11	39	12
Average	44	13	19	14	15	3	16	12	6	2	5
Maximum recorded	773	361	155	33	142	87	75	307	243	192	128

¹Variable because of the relatively small number of samples.
²Variable because of the strong influence of a few manufacturers.

for 13- to 15-kV stators from 8 different OEM based around the world. Note that the data cover all ages of machines and all insulation systems made by these manufactures over the years. Clearly, there are differences between the manufactures. For example, OEM E and F have relatively low PD on average, whereas manufacturer C has relatively high PD for its fleet of machines. The cause of the differences between manufacturers is unknown, but it may be due to different manufacturing processes, electric stress design levels, and assembly methods.

Winding Rating and Insulation System

Similar analysis was completed for the other factors previously listed. This analysis illustrated that the distribution of Qm did not depend on the power rating of the machine, as long as the voltage class, type of sensor, and type of cooling/pressure was held constant. That is, the 90% Qm level is the same for a 20 MW generator and a 200-MW generator, as long as the voltage class, etc. is the same.

Stator winding insulation systems are bonded with asphalt, polyester, or epoxy [11]. Additionally, the 90th Qm percentiles for stator windings bonded by asphalt, polyester, and epoxy are 285, 376, and 341 mV, respectively, for 13- to 15-kV hydrogenerators. Surprisingly, the asphaltic insulation systems have lower PD than the more modem systems. This is also the case for air-cooled motors and turbine generators

despite the fact that asphaltic windings are usually at least 40 yr old.

Conclusions

With thousands of machines monitored for as long as 25 yr with the same method, on-line PD testing has become a recognized, proven tool to help maintenance engineers identify which stator windings need off-line testing, inspections, and/or repairs. With over 63,000 test results acquired with the same test methods, what constitutes a winding with low, moderate, or high PD has been defined. Tables 1 through 4 enable test users to easily identify with some certainty which stators are likely to suffer from groundwall insulation deterioration, with only a single measurement on a machine. The practical importance of Tables 1 through 4 is that if one applies PD sensors to a machine and, in the first measurement, one obtains a Qm that exceeds the 90 percentile of the relevant Qm distribution, then one should be concerned enough at the PD level to take action, such as more frequent testing and/or off-line tests and inspections at the next convenient machine shutdown. Within the statistical accuracy possible with several thousands of independent results, it seems that critical PD levels only depend on operating voltage, hydrogen pressure, manufacturer, and the specific type of PD sensor and instrumentation used.

Yr. of Manufacture	1961 to 1965	1966 to 1970	1971 to 1975	1976 to 1980	1981 to 1985	1986 to 1990	1991 to 1995	1996 to 1999
25%	35	51	58	9	48	4	26	29
50%	102	143	141	20	104	19	80	79
75%	225	206	341	77	228	112	138	172
90%	526	380	548	214	1404	346	244	327
Average	212	186	242	89	367	115	130	164
Maximum recorded	2100	1200	1502	2156	3396	2509	2983	1760

Table 6. Effect of manufacturer on PD levels for 8 OEM (13- to 15-kV stators).

Manuf.	A	B	C	D	E	F	G	H
25%	48	23	44	81	10	34	17	114
50%	127	98	142	138	63	65	97	188
75%	287	205	338	239	157	106	201	278
90%	385	655	803	399	280	237	406	400
Average	183	263	325	192	113	115	225	242

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