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On-Line Partial Discharge Measurement in Hydrogen-Cooled Generators

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***Abstract*— Turbine generators in nuclear, coal, oil and some gas-fired power plants are normally rated above a few hundred megawatts. Such machines tend to be hydrogen-cooled (and above 500 MW or so, both direct-water and hydrogen-cooled). Hydrogen-cooling has many advantages, but one of the important features is the suppression of partial discharge (PD) activity by the hydrogen gas at high pressure. On-line PD testing is widely used to determine the condition of the insulation in air-cooled windings, but there has been some controversy about the effectiveness of on-line PD testing to detect insulation problems in hydrogen-cooled machines. This paper will present a statistical summary of on-line PD measured on over 1000 hydrogen-cooled turbine generators, together with some specific case studies. It seems clear that on-line PD can detect problems such as loose windings in the stator slot, and electrical tracking due to severe, partly-conductive pollution. However, other issues do not seem to be detected. For the same amount of deterioration, the PD levels appear to be lower in the hydrogen-cooled machines, compared to air-cooled machines.**

Keywords—Partial Discharge, Hydrogen-Cooled Windings, Stator Winding Insulation

I. INTRODUCTION

On-line partial discharge testing is now used on more than 13,000 air-cooled rotating machines rated 3.3 kV and above, as a means to determine when the stator winding insulation system is deteriorating and at risk of failure [1-5]. By monitoring the PD in such air-cooled machines, plant owners can determine their maintenance priorities and hopefully take action to repair or replace the winding before an in-service failure occurs. Although on-line PD testing has been found to be useful for monitoring the insulation condition of the stator windings of air-cooled machines, there are still some concerns about its effectiveness on hydrogen-cooled turbine generators.

This concern about the effectiveness of on-line PD may be due to two reasons. Most hydrogen-cooled turbine generators (which in the 1950s tended to be turbine generators rated more than 100 MVA, but now may be rated over 500 MVA) use hydrogen at a high pressure (typically 200-400 kPag or about 29-58 psi-g), since a high pressure gas is much more effective at cooling the rotor winding than atmospheric pressure hydrogen. As is well known from Paschen's law, as the gas pressure increases, the breakdown electrical stress of the gas increases. Thus, high-pressure hydrogen-cooled machines tend to experience less PD, everything else being equal. In addition, unlike air-cooled machines where the PD creates corrosive gases (ozone and nitric acid), PD in hydrogen does not create a corrosive gas that can accelerate the deterioration of the insulation and metallic structure of the generators.

This paper presents examples of PD in hydrogen-cooled generators to show that PD does occur and can be meaningful.

II. PD DETECTION METHODS

On-line PD was measured in over 1000 machines that were cooled by hydrogen. The PD was detected by one of two methods [6]. The first method used 80 pF capacitive PD sensors connected at the terminals of the machine operating in the VHF frequency range. Two sensors per phase were used to help distinguish electrical disturbance from the power system using the time of flight method [2, 3, 6]. Since electrical sparking within about 1 m of the machine-side capacitive PD sensor might be erroneously classified as stator PD using the time of flight method, an alternative method used UHF antennae-type PD sensors installed in the stator slot (called the stator slot coupler or SSC). In this latter method, both power system disturbance and sparking at the machine terminals are separated from stator PD by means of the shape of the detected pulses [2, 3, 6]. A detailed comparison of the sensitivity of the SSC and capacitive sensors is given in [7].

The PD data was recorded by an instrument called the TGA-SB that separates PD from disturbances and displayed the phase-resolved PD patterns.

III. DOES PD OCCUR IN HYDROGEN-COOLED STATOR WINDINGS?

Above a very low pressure, as the pressure of a gas increases, the electrical stress needed to cause electrical breakdown of a gas increases [8]. The breakdown stress at 100 kPa (that is, 0 kPag) of hydrogen is close to that of air, at about 3 kV/mm. At 300 kPa (200 kPag), the electrical breakdown stress is about 7 kV/mm. Thus, when all other things are equal, fewer voids within the groundwall insulation or defects on the surface of the insulation are likely to have sufficient stress to cause breakdown, and result in PD. Therefore, a stator winding at high hydrogen pressure is likely to exhibit fewer PD pulses per second. However, as long as voids do attain the breakdown threshold stress for the gas pressure, then PD can occur. Figs. 1 and 2 show classic phase-resolved PD patterns obtained from two hydrogen-cooled generators. Since the patterns in Figs. 1 and 2 are almost textbook examples of PD patterns, clearly PD does occur in hydrogen-cooled machines.

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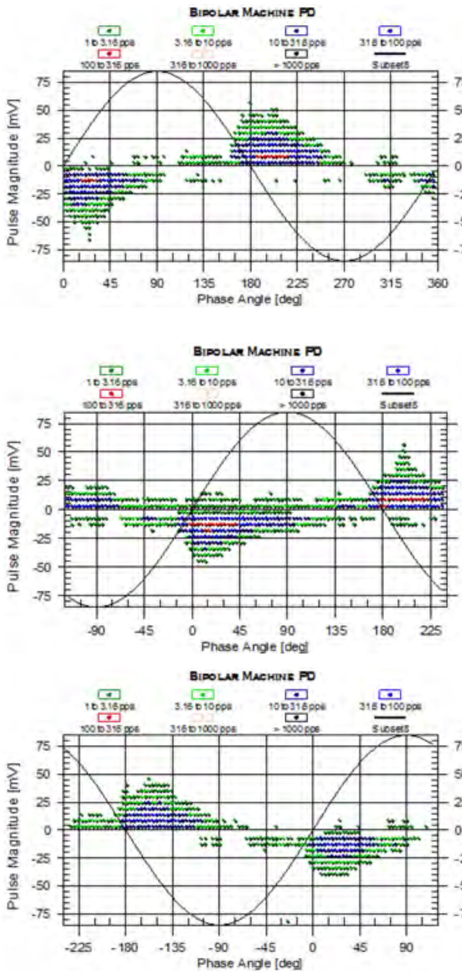

Fig. 1: Phase-resolved PD plots for 3 phases using 80 pF capacitive sensors on a generator operating at 18 kV, 117 MW and 200 kPag. The horizontal scale is the phase angle of the power frequency. The vertical scale is the PD magnitude in mV. The color of the dots represents the PD pulse repetition rate.

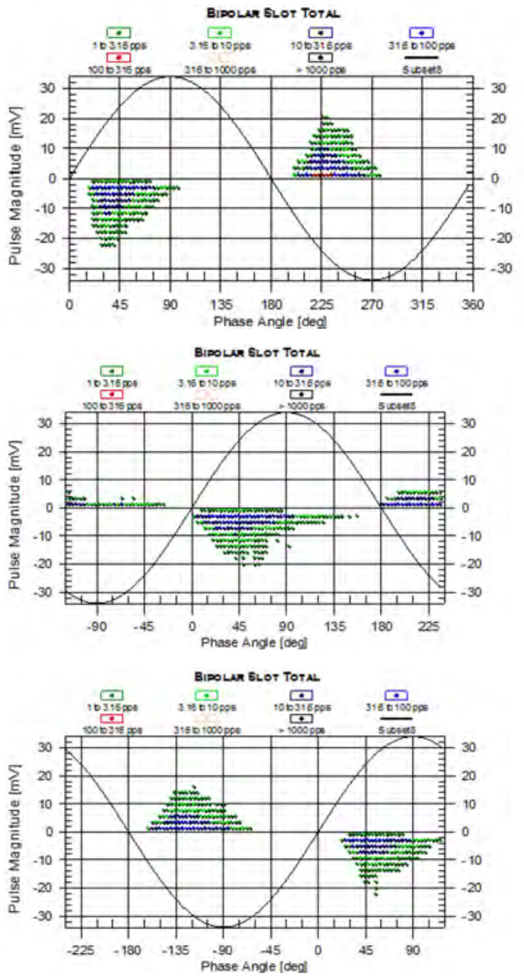

Fig. 2: PD plots using antennae sensors from a generator operating at 24 kV, 467 MW and 410 kPag. The data from phases A, B and C (top to bottom) are phase shifted to reveal any phase-to-phase PD in the endwinding.

In off-line tests when the stator is tested in air at atmospheric pressure, the PD magnitudes in voids within the groundwall or defects on the surface also seem to have much higher magnitudes than when the winding is tested in high pressure hydrogen [9, 10]. The reasons for this reduction in magnitude are not clear (at least to the authors), since in principle, an increase in the stress is needed to cause breakdown in a high-pressure gas void and, thus, should increase the energy stored in the void prior to breakdown, increasing the PD magnitude. Fig. 3 shows that the PD magnitude during normal service is affected by the hydrogen pressure. Specifically an increase in hydrogen pressure decreases the PD magnitude. This confirms the results from off-line test data in [9, 10].

Although it seems obvious that PD on the surface of stator bars would be affected by a high hydrogen pressure, we were not certain that the pressure inside any voids within the groundwall insulation would be affected by the hydrogen pressure within the generator. To address this question, over 20 years ago we performed an experiment that indirectly indicated that the pressure within a void almost instantaneously equalized to increasing or decreasing hydrogen pressure outside of the groundwall insulation [11]. This was ascribed to the laminated nature of the groundwall insulation, the high permeability of the mica paper tapes, and that the transport mechanism for the hydrogen gas was by effusion, rather than by diffusion. Thus, it seems that the gas pressure within a groundwall void is essentially the same as hydrogen pressure within the generator.

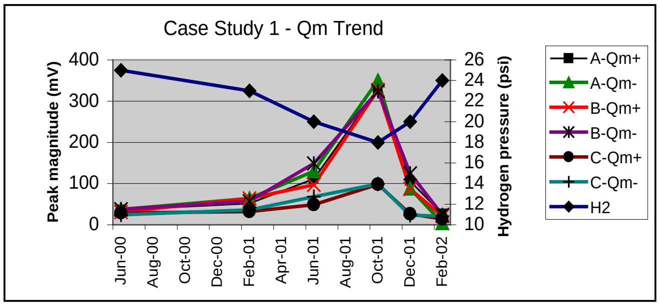

Fig. 3: Effect of hydrogen pressure on peak PD magnitude in an operating 60 MVA, 13.8 kV hydrogen-cooled turbine generator.

IV. STATISTICAL SUMMARY

We have collected PD data from more than 1000 hydrogen-cooled generators. About 60% of these windings were measured with 80 pF capacitive sensors, while data was collected from about 400 machines using the antenna sensors. Fig. 4 shows the mix of voltage and hydrogen gas pressure of the generators for each type of sensor. As expected, as the rated voltage increases (and usually the power rating), there tends to be an increase in the rated hydrogen pressure of the generator.

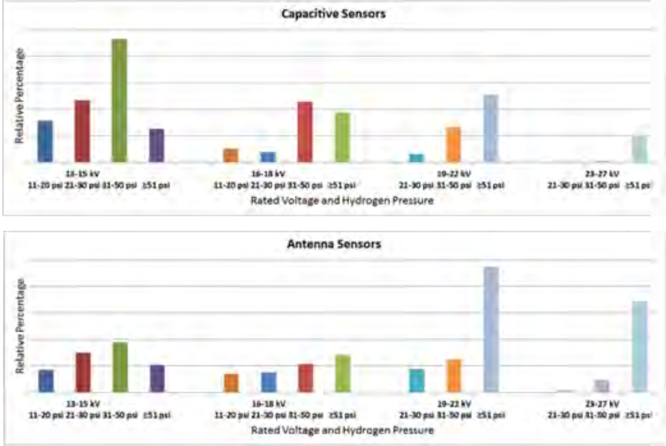

Fig. 4: Percentage of generators in database in arbitrary voltage and hydrogen pressure ranges, for both types of PD sensors.

Over 400,000 test results from both air-cooled and hydrogen-cooled machines have been collected into one large database and statistically analyzed [12]. Tables I and II show the cumulative probability of the peak PD magnitude Qm (as defined in IEEE 1434 and IEC 60034-27-2) for hydrogen-cooled generators. For example, in Table I where the PD was measured with 80 pF capacitive couplers, for machines operating at 16-18 kV and operating between 214-345 kPag hydrogen pressure, 25% of the machines have a Qm <24 mV, 50% of machines have a Qm <43 mV, 75% of machines have a Qm <85 mV, etc. Although there are anomalies, generally speaking, for windings in the same voltage group, the partial discharge peak magnitude is lower as the pressure increases.

For windings operating in the same pressure range, windings operating at higher voltages usually experience stronger partial discharge. The data tends to be less reliable at the combinations of low rated voltage and high pressure; or high voltage and low pressure, since there are relatively few machines with these combinations.

Historically, we have found that if the Qm on a particular machine is higher than 90% of similar machines, there is a very high probability that the stator bars are vibrating in the slot or there is surface electrical tracking in the endwinding [1].

The Qm data in Table II shows that 25-50% of hydrogen-cooled machines have no detectable PD when measured with the UHF sensor, which is the sensor type that is least prone to disturbances [7]. This would confirm the belief that high pressure hydrogen does suppress PD. Experience with PD measurements in air-cooled machines shows that all stators rated greater than 6 kV have detectable PD. Zero Qm levels do not occur with the capacitive PD sensors in Table I since there is always some residual disturbance present.

V. EXAMPLES

Several papers have been published on PD in hydrogen-cooled machines by users of either the 80 pF sensors or the UHF antennae. McDermid showed that there was a strong effect of load on the PD activity in 17 kV, 160 MVAr hydrogen-cooled synchronous condensers [13]. The Qm ranged from 600 mV at low load (3 MVAr) to 1200 mV at 140 MVAr at a hydrogen pressure of 200 kPag. Visual examination of the winding showed that most of the wedges were loose, some were migrating out of the slot and there was damage to the slot conductive coating [13].

Yaboah described how on-line PD measurements using 80 pF capacitive couplers was used to delay the rewind of a 187 MVA, 22 kV, hydrogen-cooled machine for 9 years [14]. The Qm was essentially flat over time, and the Qm was less than 50 mV at 230 kPag. However, the Qm did increase on one phase to 400 mV in 2003, at which time the decision was made to rewind the stator.

Fig. 5 shows the on-line PD data from an 18 kV turbine generator operating at 207 kPag. On Phase A, the Qm is +258 mV. The activity is considered to be at a Moderate level according to Table I. When the generator was removed from service, it was clear that the stator bars were moving in the slot since there was evidence of greasing (Fig. 6) as well as loose wedges and damage to the stress relief coatings.

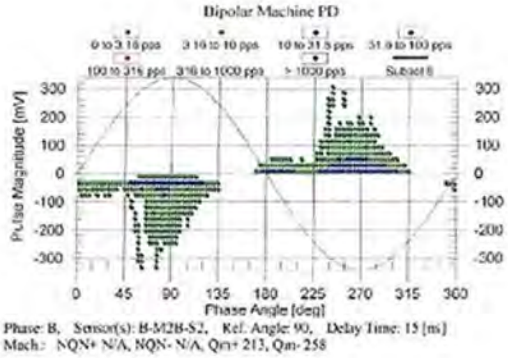

Fig. 5: Phase-resolved PD on a 150 MVA generator operating at 18 kV and 207 kPag. The PD sensors are 80 pF capacitors.

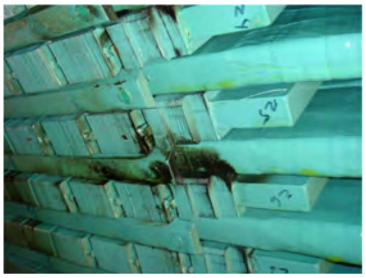

Fig 6: Photograph of a 150 MVA hydrogen-cooled turbine generator that had extensive greasing at the slot exits due to loose bars in the slot. The side packing was also abraded. The associated PD data is shown in Fig. 5.

VI. WHAT FAILURE PROCESSES CAN ON-LINE PD DETECT?

In air-cooled machines, it is clear that on-line PD monitoring can detect many problems, such as: loose windings in the slot, delamination of the groundwall insulation due to thermal aging, degradation of the stress control coatings, coils/bars that are too close together in the endwindings; electrical tracking in the endwindings due to partly conductive contamination, amongst other deterioration mechanisms. However, in our experience, most of these problems are unlikely to occur in high-pressure hydrogen-cooled machines. The most common problem that we have detected in such hydrogen-cooled generators is loose windings in the slot. In a few situations on-line PD monitoring has detected electrical tracking in the endwinding.

VII. CONCLUSIONS

PD does in fact occur in hydrogen-cooled stator windings. This PD has been detected using both 80 pF capacitive sensors and UHF antenna installed in the stator slots. 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. In hydrogen-cooled machines, the PD is most sensitive to loose bars in the slot.

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TABLE I. CUMULATIVE PROBABILITY OF OCCURRENCE OF QM (in mV) VERSUS PRESSURE AND RATED VOLTAGE FOR PD MEASURED WITH 80 PF CAPACITIVE SENSORS CONNECTED TO THE MACHINE TERMINALS. THIS DATA IS MORE LIKELY TO BE CORRUPTED BY DISTURBANCES ON THE MACHINE TERMINALS.

	Operating Voltage (kV)									
	13-15 kV			**16-18 kV**				**19 kV and higher**		
Pressure (kPag) / ***Probability***	***76-138***	***145-207***	***Over 207***	***76-138***	***145-207***	***214-345***	***Over 345***	***145-207***	***214-345***	***Over 345***
25%	33	20	16	17	34	24	9	43	23	9
50%	91	46	43	81	86	43	18	89	55	28
75%	189	94	81	146	333	85	38	163	108	77
90%	438	198	198	268	791	194	141	203	161	548
95%	756	393	485	389	976	307	322	239	206	951

TABLE II. CUMULATIVE PROBABILITY OF OCCURRENCE OF QM (in mV) VERSUS PRESSURE AND RATED VOLTAGE FOR PD MEASURED WITH UHF ANTENNAE INSTALLED WITHIN STATOR SLOTS.

	Operating Voltage (kV)										
	13-15 kV			**16-18 kV**			**19-22 kV**			**23-27 kV**	
Pressure (kPag) / ***Probability***	***76-138***	***145-207***	***Over 207***	***75-207***	***214-345***	***Over 345***	***75-207***	***214-345***	***Over 345***	***214-345***	***Over 345***
25%	0	0	0	0	0	0	1	0	0	0	0
50%	9	0	9	0	5	2	9	7	3	8	3
75%	31	14	17	13	15	10	23	19	11	31	9
90%	48	66	32	58	22	24	97	41	25	66	18
95%	60	92	47	90	34	32	229	57	39	100	29