EXPERIENCE WITH DIAGNOSTIC TESTING TO EVALUATE THE REMAINING USEFUL LIFE OF A HYDROGEN-COOLED GENERATOR

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Introduction – In regard to rewind or not to rewind a generator; from vendor's point of view, that is an easy question to answer, because they made the recommendation based on the visual examination and general experience. From owner's point of view, it is a challenging question to answer, because they have to make a cost-effective decision based on the careful evaluation of diagnostic test results. This paper presents experience of extending the remaining useful life of the stator winding of an aging hydrogen-cooled generator using various diagnostic tests. The test results of on-line and off-line partial discharge (PD) testing are summarized and analyzed. Methods of using a Doble M4000 to energize the winding at 8KV for off-line PD testing are also described.

Generator Information
The Dave Johnston plant is located five miles from the city of Glenrock, Wyoming. The following is the name plate data for Dave Johnston unit #3 generator:

Mfr. G.E. No. 8090653	Type ATB
Volts 13.8 KV KVA 255,000.	KW 230,000.
Stator Amperes 10,688	PF 0.9
Field amperes 1517	PSI H_2 30
Speed 3600 RPM	Cycles 60
Phase 3	Year commissioned 1964
Type Operation Base Load	Insulation Type Epoxy mica

Operating History
The generator, with an early version of epoxy-mica insulation, was put in service in 1964. It sustained a three-phase bus fault in 1981 when the flexible connectors of the outdoor bus failed. The overheated A-phase flexible connectors, which had high resistance contact surface due to the loose bolts, flashed over and caused an electrical fault. The fault propagated through an ungrounded system, which produced high capacitive voltages on B and C phases, and caused considerable damages to the equipment along the generator main bus which included indoor isolation phase bus, generator stand-off bushings and surge protectors. The six generator bushings did not survive the short time fault currents. The cooling air passages for the bushings were also impeded by hydrogen seal oil, the hydrogen seal oil entered the bushings due to improper sealing clearances. However, the stator winding was not damaged as the differential relay tripped the generator breaker within 8 cycles. The winding passed the DC Hi-Pot test at 32 KV. There was no other recorded major incident in the operating history.

Maintenance History
The machine went through a series of maintenance inspection over the years. In the mid 1980's, the stator winding started to show signs of deterioration with powdering and greasy dirt which could be caused by loose side packing, wedges and coil movements. A decision was made to re-wedge the stator in 1992, after a recommendation of rewedge from the OEM in 1990. The machine was re-wedged with 200-mil side ripple springs to replace the 90-mil springs. During the re-wedge, workers found several burned fillers from the slots. This gave strong indication that slot discharge activity had attacked the groundwall insulation. Based on the discovery of the corona activity, the OEM also recommended a stator rewind within five years.

After the re-wedge, partial discharge sensors, with directional method, were installed to track the partial discharge activity of the winding insulation. The partial discharge activity, however, was low compared to measurements of other hydrogen-cooled generator. The low activity could be the result of stator re-wedge which strengthen the stator structure and allowed very little coil movement.

In March 1999, a major maintenance outage was set to overview the insulation condition. The rotor was removed for extensive inspection and testing. The stator winding underwent many diagnostic tests such as: Insulation megger, Doble power factor tests; off-line partial discharge test, TVA corona probe test and DC Hi-Pot test.

The stator winding appeared to be in better condition than what was found in 1985. The overall condition was fairly clean with little grease and dusting. There were only minor signs of radial movements, loose braces and tie-wire in the end winding, there was no sign of wedge looseness. This indicated that the stator winding was in fine condition with respect to a 33-year old machine. The stator rewedge in 1992 has obviously improved the rigidity of the stator winding structure and slowed the process of insulation deterioration. This can be also verified by the consistent results of Doble Power Factor tests, on-line and off-line partial discharge tests. The stator was cleaned and repainted after the normal wears and tear at the end winding were tightened and repaired.

The overall condition of the rotor was good, the structure including the air vents were not damaged or greasy. It was difficult to make further assessment without removing the retaining rings. There were minor loose blocks at both ends in the past. An on-line testing of the field winding condition with a flux probe in autumn 1999 indicated that there were no shorted turns.

Diagnostic Testing

1. Doble Power Factor Test

Test results showed the overall insulation condition continued to deteriorate slowly with voids and delaminations in last 12 years. The trend data (Table #1) shows the power factor continues to rise and the tip-up was high at 1.8. Doble power factor test will be conducted again in 2003, the trend data will be used in conjunction with other test results for consideration of a rewind if the percent power factor rises beyond 4.

Table #1. Doble Power Factor Test Summary

	1988			1992			1994			1999		
	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ
GST 2KV %PF	1.53	1.48	1.6	1.52	1.38	1.46	1.57	1.55	1.58	1.49	1.42	1.45
GST 8KV %PF	2.73	2.9	2.67	2.66	2.89	2.88	3.16	3.2	3.23	3.32	3.22	3.32
GST PF Tip-up	1.1	1.11	1.07	1.12	1.41	1.35	1.59	1.65	1.6	1.83	1.8	1.87

2. DC Hi-Pot Test

The DC Hi-Pot test, in accordance with vendor's recommendation, was conducted during each maintenance outage in last 20 years for reliability assurance of the stator winding. Table #2 shows four of the seven test results. The consistent trend data indicates that the stator winding insulation has deteriorated at a modest rate. A decision was made in 1999 to reduce the maximum test voltage from 35 KV to 30 KV as the machine aged.

Table #2. Micro Ampere Leakage of DC Hi-Pot Test

	1985			1992			1994			1999		
	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ	Aϕ	Bϕ	Cϕ
μ amps at 10 KV				0.5	0.9	0.5				0.65	0.7	1.4
μ amps at 12 KV	0.8	0.8	0.8	0.8	1.5	0.9	1.1	1.4	1.3	1.	0.8	1.8
μ amps at 14 KV	1.	1.	1.	1.4	1.3	1.3	1.3	1.5	1.5	1.2	1.1	2.7
μ amps at 16 KV	1.3	1.3	1.1	1.6	2.	1.8	1.4	1.6	1.6	1.5	1.3	2.5
μ amps at 18 KV	1.5	1.3	1.4	2.	2.	1.9	1.5	1.8	1.8	1.6	2.2	3.1
μ amps at 20 KV	1.5	1.6	1.4	2.	2.5	2.	1.6	1.9	1.9	1.8	2.6	3.6
μ amps at 22 KV	1.4	1.6	1.4	2.5	2.5	2.	2.	2.0	2.	1.9	2.7	3.8
μ amps at 24 KV	2.6	2.6	2.	2.8	3.	2.4	2.1	2.5	2.1	2.	3.2	4.2
μ amps at 26 KV	2.4	2.4	2.2	3.2	3.	2.	2.3	6.	4.5	2.1	4.	6.
μ amps at 28 KV				3.6	3.	2.5	2.4	7.6	6.	3.	4.3	7.
μ amps at 30 KV										3.1	4.5	8.5
μ amps at 35 KV	8.	7.	7.	10.	11.	10						

3. On-line Partial Discharge Test

Six capacitive couplers, two couplers per phase, were installed in the generator in 1994. One coupler was installed at the isolated phase bus close to the generator and the other at the isolated phase bus with some distance from the first one. The two capacitive couplers on each phase work as a pair to eliminate noise from outside the generator using the "time-of-flight" technique. A partial discharge analyzer (PDA) can perform PD tests during normal machine operation. PD test results are displayed in the form of pulse polarity, magnitude, number, and phase position. Subsequent data analysis provides further information, such as, maximum PD values, normalized quantity number (NQN), historical trending of PD test results, variation of PD activity with temperature and load, etc.

On-line partial discharge testing has been performed since 1995. A phase-resolved PD distribution in phase C from testing in 1999 is shown in Fig. 1. The three-dimension graph indicates the PD magnitude, PD pulses per second and the PD position against the 60 Hz sine wave. The PD activity in this generator was low due to effect of hydrogen gas pressure on the PD activity. The positive and negative pulse distribution has an equal distribution, this indicates that there were partial discharges within the groundwall insulation. The internal voids within groundwall insulation, created by poor impregnation during manufacture or by other aging mechanisms during machine operation, produced groundwall partial discharges under high voltage stress. Groundwall discharges can occur at delaminations or areas where bonding material is incompletely cured.

The PD measurement did not show sign of slot discharges, indicating that the stator re-wedge in 1992 tightened the winding and hence eliminated the slot discharges. The PD test results in 1995 and 1999 are compared in Fig. 2. which shows that the PD activity has been stable since 1995. There was no significant development of stator insulation deterioration.

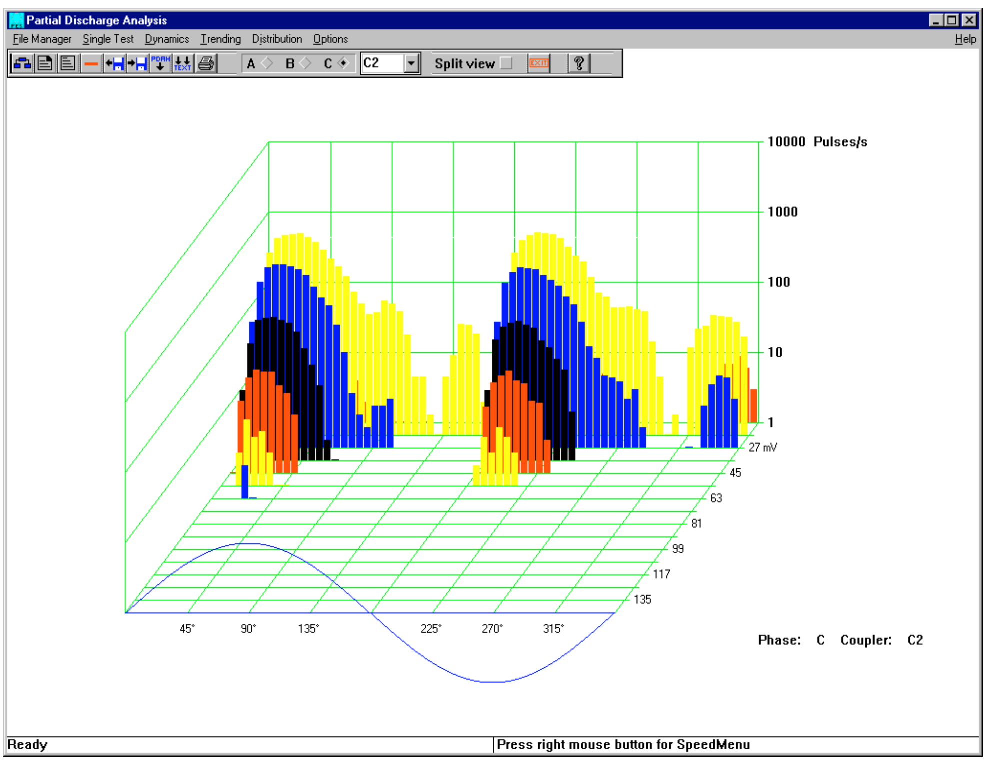

Fig. 1 Phase-resolved PD test results in 1999.

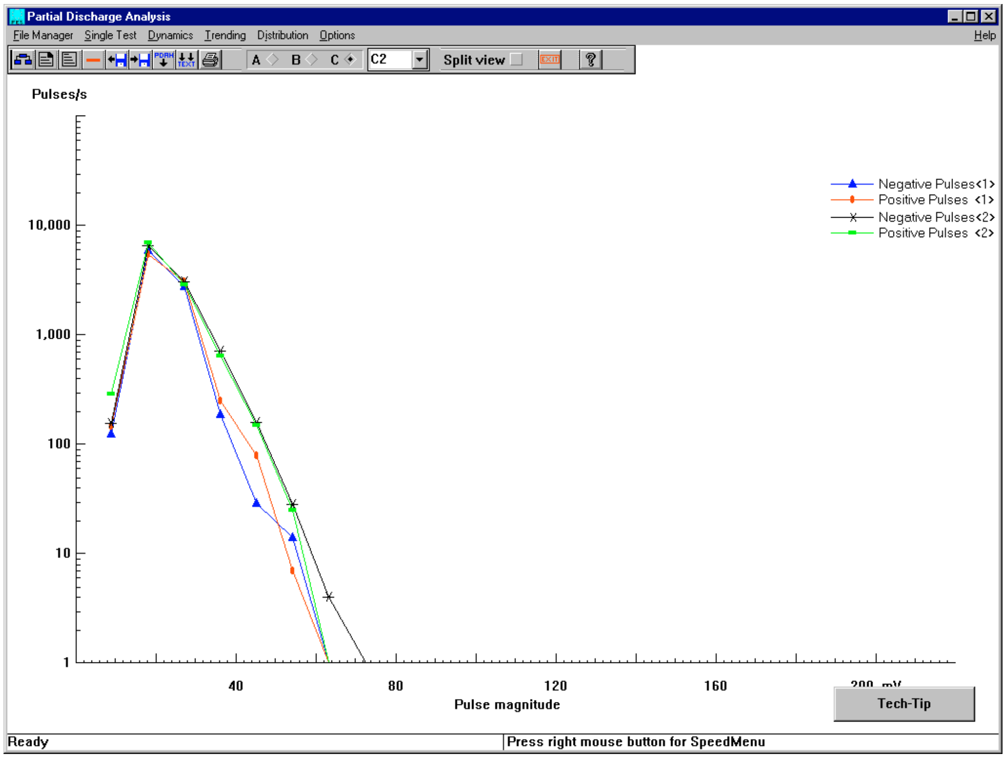

Fig. 2 Comparison of the PD test result in 1995 and 1999.

4. Off-line Partial Discharge Test

It is important that the same PD sensors and instrument be used to compare the on-line and off-line PD test results on the same generator. If PD instruments with different frequency bandwidths or different PD measurement units (e.g. pC, mV) are used, test results between on-line and off-line PD testing cannot be directly compared. In order to make the test results comparable, the same capacitive couplers (C1 and C2) and the partial discharge analyzer (PDA) were applied to the off-line PD test.

The set-up of the off-line PD test is shown in Fig. 3. A Doble M-4000 tester was used to apply 8 kV line-to-ground voltage to the stator winding, the low voltage lead and the test-set ground lead were connected to the machine ground. A resonant reactor (RR) was used to neutralize the capacitive current of a 255 MVA generator. Using the ground-specimen test mode, each phase was tested with the other two phases grounded.

The PD distribution is shown in Fig. 4. By comparing Fig. 2 and Fig. 4, the on-line testing result is similar to that of the off-line testing. This indicated that the hydrogen pressure accompanying the on-line testing did not affect the PD activity much in this case. This may be because the nature of the partial discharges in this generator is internal, hence influence of the hydrogen pressure to the PD activity is not strong. This case also demonstrates that on-line PD testing on a hydrogen-cooled generators is valid.

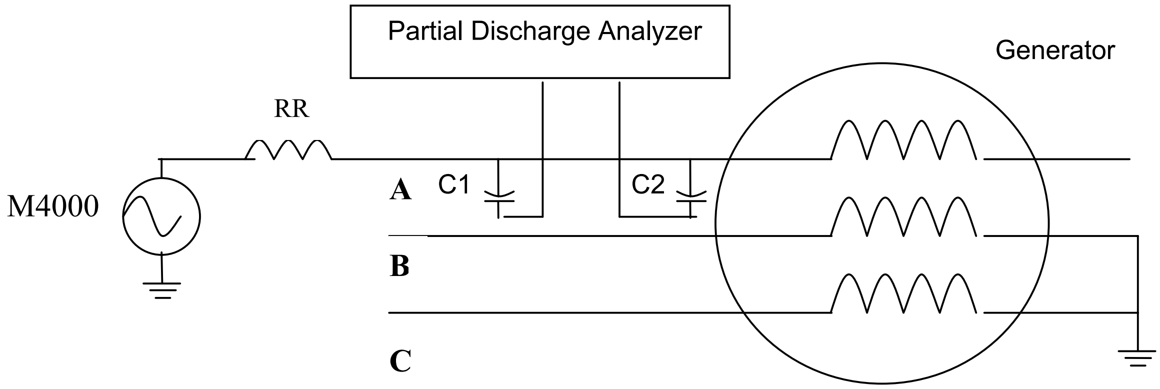

Fig. 3 Set-up of the off-line partial discharge test.

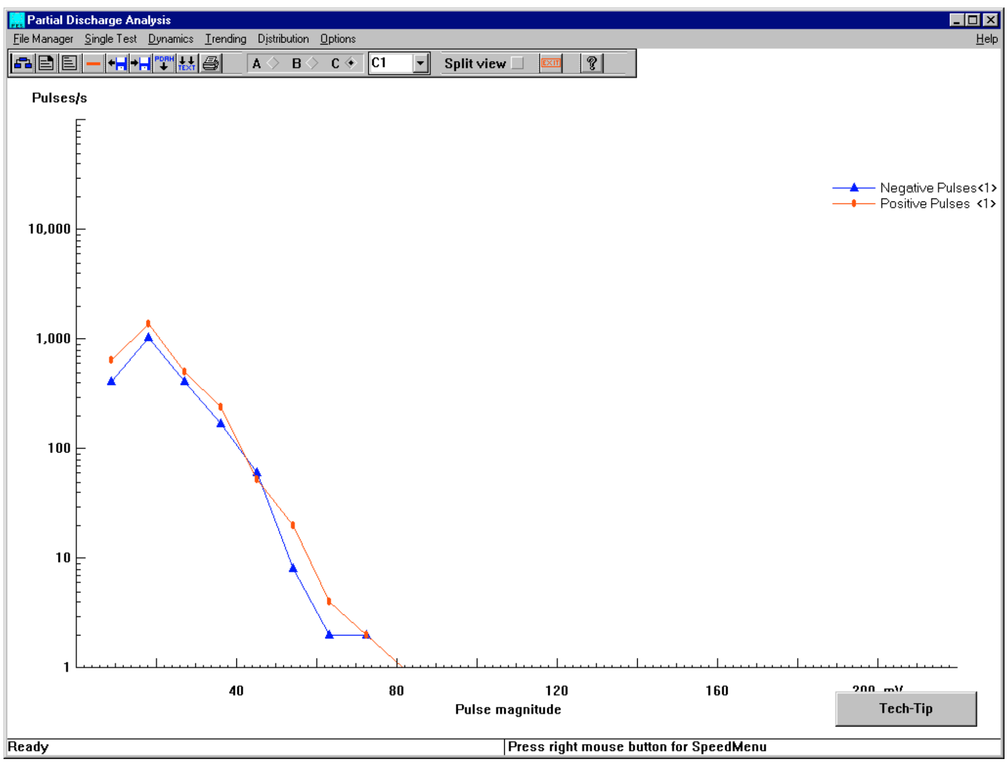

Fig. 4 PD pulse number against PD magnitude (off-line testing).

5. Corona Probe Test

The corona probe is a portable instrument for locating partial discharge in each slot with the winding energized. It supplements on-line PD measurements by pinpointing the exact location of PD activity within the stator winding. A 8 kV line-to-ground voltage from the Doble M-4000 tester was applied to the stator winding. Corona probe testing was performed by scanning, slot by slot, overall of the stator winding.

All of the probe readings were below 20 mA with the majority of the readings below 10 mA. This indicates that the stator winding is in a good shape. The test result is consistent with the on-line and off-line PD test results, indicating the low partial discharge activity in the stator winding.

6. Third Harmonics Neutral Voltage Monitoring

In order to provide 100% stator winding ground fault protection, a third harmonic undervoltage relay was added in 1987. The 180 Hz under voltage protection can provide adequate protection for 0-30 percent of the stator winding measured from the neutral toward the machine terminal. The level of the third harmonic voltage at the neutral is dependent on the operating conditions of the generator. At full load, the third harmonic voltage was about 8 volts. This voltage will either go to zero when there is a ground fault at the neutral end or increase dramatically when the neutral end insulation becomes severely deteriorated. For insulation diagnostic purposes, the third harmonic voltage at full load was monitored and trended in the data logger. The 180 Hz neutral voltage has been consistently 8 volts at full generation in the last 14 years without any variations.

Conclusions

With the support from management, efforts of implementing the diagnostic test to evaluate the insulation condition have been satisfactory. Based on the consistent results of on-line and off-line partial discharge (PD) tests, Doble power factor tests and DC Hi-pot tests, it is reasonable to assume safe operation of the machine for another seven years. Meanwhile, on-line PD testing, rotor magnetic flux testing and a generator condition analyzer will monitor the well being of the generator.