

# Characteristics of Insulation Diagnosis and Failure in Gas Turbine Generator Stator Windings

Hee-Dong Kim<sup>†</sup>

**Abstract** – In order to evaluate the insulation deterioration in the stator windings of five gas turbine generators (137 MVA, 13.8 kV) which has been operated for more than 13 years, diagnostic test and AC dielectric breakdown test were performed at phases A, B and C. These tests included measurements of AC current, dissipation factor, partial discharge (PD) magnitude and capacitance.  $\Delta I$  and  $\Delta \tan \delta$  in all three phases (A, B and C) of No. 1 generator stator windings showed that they were in good condition but PD magnitude indicated marginally serviceable and bad level to the insulation condition. Overall analysis of the results suggested that the generator stator windings were indicated serious insulation deterioration and patterns of the PD in all three phases were analyzed to be internal, slot and spark discharges. After the diagnostic test, an AC overvoltage test was performed by gradually increasing the voltage applied to the generator stator windings until electrical insulation failure occurred, in order to determine the breakdown voltage. The breakdown voltage at phases A, B and C of No. 1 generator stator windings failed at 28.0 kV, 17.9 kV, and 21.3 kV, respectively. The breakdown voltage was lower than that expected for good-quality windings (28.6 kV) in a 13.8kV class generator. In the AC dielectric breakdown and diagnostic tests, there was a strong correlation between the breakdown voltage and the voltage at which charging current increases abruptly ( $P_{i1}$ ,  $P_{i2}$ ).

**Keywords:** Insulation deterioration, Generator, Stator windings, Dielectric breakdown, Diagnostic test, Breakdown voltage

## 1. Introduction

Sudden electrical breakdown of the stator winding in a generator under operation can result in significant financial losses to utilities due to unplanned trouble, and can seriously harm the reliability of the power system. Failures in generator stator windings occur as a result of insulation deterioration initiated by voids that are created in the insulation material from the combined effects of thermal, electrical, mechanical, and environmental stresses during long-term operation [1, 2].

Many on-line and off-line insulation diagnostic tests have been developed and used over a long period of time for insulation quality assessment. Some commonly used off-line tests for verifying the condition of the insulation include the insulation resistance, polarization index (PI), AC current, dissipation factor, and partial discharge (PD) tests whose results are comprehensively analyzed to evaluate the overall insulation deterioration. These diagnostic tests are also performed regularly in Korea for assessing the insulation condition of generator stator windings, and the Japanese deterioration judgment criterion has been used for assessment [3, 4].

In this paper, diagnostic and AC dielectric breakdown

tests were carried out on stator windings of five gas turbine generators (137 MVA, 13.8 kV) in a thermal power plant. The insulation condition of generator stator windings was assessed by analyzing the correlation between breakdown voltage and electrical characteristics of the diagnostic test.

## 2. Experimental Procedure

Five gas turbine generators (137 MVA, 13.8 kV) had been in service for more than 13 years. These five generators with air cooled systems were manufactured by the same company.

The diagnostic test included measurements of polarization index (PI), AC current, dissipation factor ( $\tan \delta$ ) and partial discharge (PD) magnitude. PI was measured using an automatic insulation tester (Megger, S1-5010) at DC 5 kV for each motor before applying AC voltage to the stator windings. Devices such as the mobile insulation diagnosis & analyzing system (MIDAS, Tettex Instruments, 2880), coupling capacitor (Tettex Instruments, 9,000 pF) and PD detector (Robinson, DDX 9101) were used to measure the AC current, dissipation factor and PD magnitude. AC voltage was applied to the generator stator windings through a MIDAS connected to the windings while the coupling capacitor amplified the signals from the windings by sending it to the broadband matching unit (Tettex

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Instruments, 9103) for the PD detector to analyze the PD magnitude and pattern. The frequency band of the PD detector ranged from 30 kHz to 400 kHz. Since the magnitude of the PD in No. 1 generator stator windings ranges between 21,900 and 141,000 pC at 1.25 times of the line-to-ground voltage, it was measured in a thermal power plant where background noise ranged between 740 and 820 pC. The diagnostic and AC dielectric breakdown tests were carried out on the stator windings from No. 1 generator at a voltage between 1.0 to 28.0 kV. After the diagnostic tests were completed, a variable HV supply (AC 50 kV) was used to gradually increase the AC voltage applied to each phase of generator in 1 kV intervals until electrical breakdown occurred in the stator windings to measure the AC current, dissipation factor and the breakdown voltage. The diagnostic test method provides a good estimate of the breakdown voltage for generator stator insulation.

### 3. Test results and Discussion

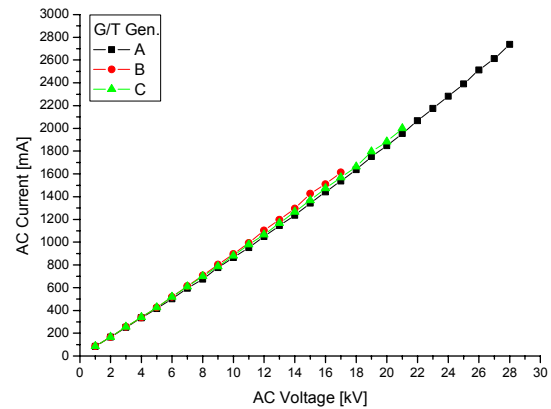
The insulation condition indicators measured from the diagnostics tests include the PI, the increase rate of charging current ( $\Delta I$ ), the increase of dissipation factor ( $\Delta \tan \delta$ ), the maximum PD magnitude and the voltage at which charging current increases abruptly ( $P_{i1}$ ,  $P_{i2}$ ): the first turning point voltage ( $P_{i1}$ ) and the second turning point voltage ( $P_{i2}$ ). The insulation condition can be assessed by comparing the diagnostic test results between the three phases of generator stator windings [5].

The PI will also tend to be high, in the range of 6.32 to 7.18 as shown in Table 1. The PI (above 2.0) of generator indicated that the stator windings are suitable for overvoltage testing [6]. Fig. 1 shows the change in current where the three phases encapsulated AC voltage was gradually increased in No. 1 generator until insulation breakdown occurred. As can be seen from Fig. 1, there are two turning points ( $P_{i1}$ ,  $P_{i2}$ ) where AC current soared suddenly. As summarized in Table 1,  $\Delta I$  at 13.8 kV ranged among 6.48%, 9.51%, and 6.71%, respectively. The  $\Delta I$  of below 12% in a 13.8 kV generator is usually considered to indicate healthy insulation [7]; however, generator was determined to be in good condition because their  $\Delta I$  was low with values between 6.48% and 9.51% at 13.8 kV.

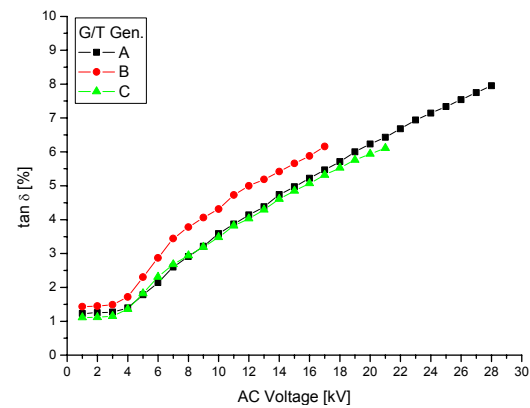
The  $P_{i1}$  voltage in phases A, B, and C of generator was 4.8 kV, 3.0 kV and 4.0 kV, respectively, and their  $P_{i2}$  voltage were 10.2 kV, 6.1 kV, and 9.3 kV, respectively. As the shown in Fig. 1, the AC current vs. voltage traces for generator was almost linear. These results indicate that the

**Table 1.** Test results of PI and AC current in No. 1 generator

Generator	PI	$\Delta I$ [%] at 13.8 kV	$P_{i1}$ [kV]	$P_{i2}$ [kV]
Phase A	6.32	6.48	4.8	10.2
Phase B	7.18	9.51	3.0	6.1
Phase C	6.55	6.71	4.0	9.3



**Fig. 1.** Comparison of AC current vs. voltage characteristics in No. 1 generator



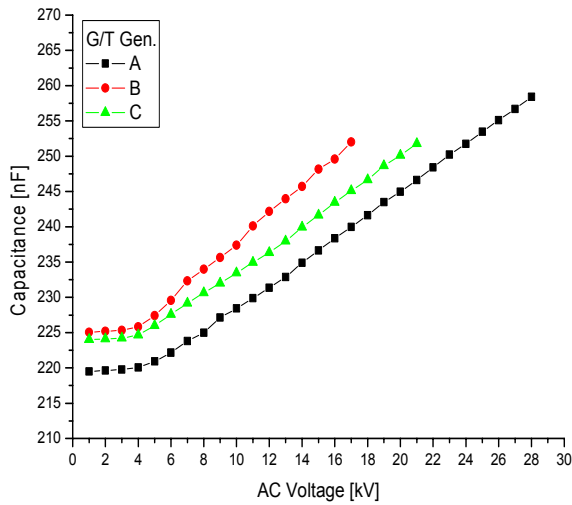
**Fig. 2.** Comparison of  $\tan \delta$  vs. voltage characteristics in No. 1 generator

**Table 2.** Test results of dissipation factor and capacitance in No. 1 generator

Generator	$\Delta \tan \delta$ [%] at 13.8 kV	$\tan \delta$ increase voltage [kV]	$\Delta C$ [%] at 13.8 kV	$\Delta C$ increase voltage [kV]
Phase A	3.33	3	6.51	4
Phase B	4.02	3	8.91	4
Phase C	3.28	3	6.65	4

stator winding insulation of generator is in good condition.

The change in the dissipation factor while AC voltage applied to the stator winding was gradually increased until it reached the breakdown voltage, as shown in Fig. 2. The  $\Delta \tan \delta$  had to be calculated based on the data from a 13.8 kV generator. As it can be seen from Fig. 2, the dissipation factor increased abruptly about 3 kV. As summarized in Table 2,  $\Delta \tan \delta$  in phases A, B, and C of No. 1 generator were 3.33%, 4.02% and 3.28%, respectively. According to [7],  $\Delta \tan \delta$  above 6.5% is considered to indicate bad insulation condition. Therefore, the insulation condition of the stator winding for all three phases of generator was assessed to be in good condition because their  $\Delta \tan \delta$  values were below 4.02% at 13.8 kV.



**Fig. 3.** Comparison of capacitance vs. voltage characteristics in No. 1 generator

**Table 3.** Test results of noise, PD magnitude and breakdown voltage in No. 1 generator

Generator	System Noise [pC]	DIV [kV]	PD Magnitude [pC] $E/\sqrt{3}$	PD Magnitude [pC] $1.25E/\sqrt{3}$	Breakdown Voltage [kV]
Phase A	820	3.8	20,500	21,900	28.0
Phase B	790	3.2	60,200	141,000	17.9
Phase C	740	3.7	23,000	26,300	21.3

The capacitances measured as a function of applied voltage (up to 28.0 kV) in three phases of generator stator windings is shown in Fig. 3. The  $\Delta C$  had to be calculated based on the data from a generator. As it can be seen from Fig. 3, the capacitances increased abruptly about 4 kV. As summarized in Table 2,  $\Delta C$  measurements in phases A, B, and C of No. 1 generator were among 6.51%, 8.91% and 6.65%, respectively. The values of the capacitance and dissipation factor in three phases A, B, and C of generator increased abruptly at 4 kV and 3 kV test voltages, as shown in Figs. 2 and 3.

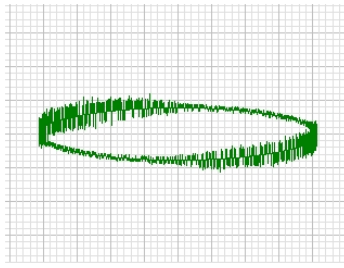
The discharge inception voltage (DIV) and PD magnitude were measured while three phases encapsulated AC voltage was applied to the stator windings and the results are summarized in Table 3. The DIV refers to the voltage when the PD magnitude starts to exceed the background noise level of hundreds of pC, and goes above 1,000 pC. As can be seen from Figs. 2 and 3, the dissipation factor and capacitance increases the range of about 3 kV and 4 kV, respectively. DIV is also expected to occur within this range. The DIV measurements at the site were from 3.2 kV and 3.8 kV, as predicted. Therefore, when insulation deterioration occurs in the generator stator windings, increasing point of dissipation factor,  $P_{11}$  of AC current and DIV both decrease, and dielectric breakdown voltage also decreases. The PD magnitude in phases A, B, and C of No. 1 generator ranged among 21,900, 141,000, and 26,300 pC at 10kV (1.25 times of the line-to-ground

voltage).  $\Delta I$  and  $\Delta \tan \delta$  in all three phases (A, B and C) of No. 1 generator stator windings showed that they were in good condition but PD magnitude indicated marginally serviceable and bad level to the insulation condition. The PD magnitude below 30,000 pC in phases A and C of generator was assessed to be in marginally acceptable condition. Periodic diagnostic test is strongly recommended for trending the insulation condition of these phases. Since the PD magnitude in phase B above 30,000 pC is considered to indicate bad insulation condition [7].

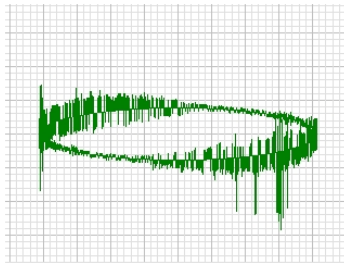
The values of the PI, AC current, dissipation factor, and PD magnitude in the generator stator windings are shown in Tables 1~3. In all three phases of the stator windings, No. 1 the PI measurements were above 2.0, indicating that the stator winding is suitable for overvoltage testing [6]. As stated earlier, the  $\Delta I$  and  $\Delta \tan \delta$  values in phases A, B, and C indicated that the insulation is in good condition, whereas the PD magnitude measurements suggested marginally serviceable and bad level condition. The point at which the dissipation factor in the  $\tan \delta$ -voltage curve increased was approximately 1~1.8 kV lower than the voltage at which  $P_{11}$  appeared in the AC current-voltage characteristics. The voltage of the capacitances increased abruptly was also similar to the DIV. Therefore, as mentioned in the results of the generator stator windings, the  $P_{11}$  of AC current, the point at which the dissipation factor and capacitance increases, and the DIV tend to be low when the insulation is bad condition [8].

After the diagnostic test was completed, an AC overvoltage test was performed by gradually increasing the voltage applied to the stator windings until electrical insulation failure occurred, in order to determine the breakdown voltage. The breakdown voltage at all three phases (A, B and C) of No. 1 generator stator windings failed at 28.0 kV, 17.9 kV, and 21.3 kV, respectively. The breakdown voltage was lower than that expected for good-quality windings (28.6 kV) in a 13.8 kV class generator. The actual breakdown voltage of the No. 1 generator stator winding was lower than the 2E+1 kV test voltage and the dielectric strength of each individual winding is still lower [9, 10].

The PD magnitudes of positive ( $0^\circ \sim 180^\circ$ ) and negative ( $180^\circ \sim 360^\circ$ ) polarity in phase B of the No. 1 generator stator windings are shown in Fig. 4, when AC voltage was applied at 8 kV (the line-to-ground voltage) and 10kV. Given that the PD magnitudes of positive ( $0^\circ \sim 90^\circ$ ) and negative ( $180^\circ \sim 270^\circ$ ) polarity are symmetrically similar in Fig. 4(a), the PD pattern in phases A, C was attributed to internal discharge [8]. Internal discharge occurs in the voids created inside the groundwall insulation materials after a long period of operation. It accounts for almost 70% of PD patterns in generators or high-voltage motors. The negative polarity predominance normally indicates slot discharge, as illustrated in Fig. 4(b). This discharge generates in the air gap, between the magnetic core and the side of stator bars [11]. As described above, the PD pattern



Discharge = 60,200 pC  
(a) Voltage = 8 kV



Discharge = 141,000 pC  
(b) Voltage = 10 kV



(c) Removal of semiconductive tapes

**Fig. 4.** PD magnitude of No. 1 generator stator windings

was presented internal discharge at 8 kV in phase B. And the PD pattern changed slot and spark discharges at 10 kV the increase with the voltage. The semiconductive tape on one side of the bar was abraded away in phase B, as illustrated in Fig. 4(c). As a result of bar vibration, the erosion of the coating will leave bare insulation at high voltage facing the metallic grounded core [8].

Fig. 5 shows the surface erosion at the bar end of the phase B in No. 1 generator stator windings. The presence of discharges at the bar ends causes progressive degradation of the semiconducting and voltage grading paint surfaces [12]. The semiconducting and voltage grading paints are used to suppress surface discharge in the slot portion of the winding [11]. Consequently, when the phase B of No. 1 generator was dielectric breakdown, spark discharge occurs at the bar ends and grading paint surfaces as shown in Fig. 4(b). This discharge is presented in pulses between positive ( $0^\circ$ ) and negative ( $360^\circ$ ) polarity.

As mentioned above, Table 4 shows the relationship



**Fig. 5.** Bar end erosion in No. 1 generator stator windings

**Table 4.** Correlation between diagnostics results and breakdown voltages in five generators

Generator No.		$\Delta I[\%]$ at 13.8 kV	$\Delta \tan \delta[\%]$ at 13.8 kV	PD Magnitude [pC] $E/\sqrt{3}$	Breakdown Voltage [kV]
1	A	6.48	3.33	20,500	28.0
	B	9.51	4.02	60,200	17.9
	C	6.71	3.28	23,000	21.3
2	A	6.06	3.20	25,700	32.0
	B	6.37	3.14	27,000	28.6
	C	6.99	3.61	21,400	23.7
3	A	8.05	3.53	17,500	33.8
	B	6.58	3.02	13,000	20.5
	C	7.51	3.20	21,000	35.6
4	A	3.76	1.87	5,800	26.8
	B	4.31	2.04	23,400	23.5
	C	4.52	2.41	44,600	19.9
5	A	4.39	2.67	8,000	37.4
	B	4.44	2.69	7,400	35.7
	C	4.40	2.59	6,400	30.7

between diagnostic test and breakdown voltage among No. 1 generator and the other four generators. Diagnostic test includes AC current, dissipation factor, and PD magnitude. Phase B of No. 1 generator which had the highest values in AC current, dissipation factor, and PD magnitude showed the lowest breakdown voltage of 17.9 kV. Phase C of No. 4 generator which had the second highest values in PD magnitude showed the breakdown voltage of 19.9 kV. When phase C of No. 4 generator was dielectric breakdown, spark discharge occurs at the bar ends and grading paint surfaces like the phase B of No. 1 generator. However, when precisely analyzing the relationship between results of generator diagnostic test and breakdown voltage, it is hard to decide on the matter of rewinding. When diagnostic tests on generator stator winding are continuously executed, it is useful to analyze trend of insulation condition.

Table 5 shows the relationship among  $P_{i1}$ ,  $P_{i2}$  and breakdown voltage. When phase B of No.1 generator had the lowest breakdown voltage of 17.9 kV, the  $P_{i1}$  and  $P_{i2}$  were the lowest with 3.0 kV and 6.1 kV, respectively. Also, when phase A of No. 5 generator had the highest breakdown voltage 37.4 kV, the  $P_{i1}$  and  $P_{i2}$  were the highest with 6.7 kV and 15.9 kV, respectively. When carefully examining the relationship among  $P_{i1}$ ,  $P_{i2}$  and breakdown

**Table 5.** Correlation among  $P_{i1}$ ,  $P_{i2}$  and breakdown voltages in five generators

Generator No.		$P_{i1}$ [kV]	$P_{i2}$ [kV]	Breakdown Voltage [kV]
1	A	4.8	10.2	28.0
	B	3.0	6.1	17.9
	C	4.0	9.3	21.3
2	A	5.0	10.9	32.0
	B	4.9	10.4	28.6
	C	4.0	9.0	23.7
3	A	5.0	11.0	33.8
	B	4.0	8.7	20.5
	C	5.8	11.7	35.6
4	A	4.5	11.2	26.8
	B	4.0	9.1	23.5
	C	3.7	8.5	19.9
5	A	6.7	15.9	37.4
	B	5.8	11.8	35.7
	C	5.0	10.7	30.7

voltage, an interesting result came up. The higher the breakdown voltage, the higher the  $P_{i1}$  and  $P_{i2}$  become and in a likely manner, the lower the breakdown voltage, the lower the  $P_{i1}$  and  $P_{i2}$  become. As mentioned above, it is only possible to operate when a 13.8 kV class generator can endure dielectric strength (28.6 kV) of stator windings for one minute. It is possible to continuously operate if breakdown voltage is 30.7 kV as in phase C of No. 5 generator and if the  $P_{i1}$  and  $P_{i2}$  measure above 5.0 kV and 10.7 kV, respectively. As a result, other than the five generators that were finished rewinding after breakdown test, 11 other generators are in operation. In the future, insulation condition on the other 11 generators will be evaluated as applied voltage increases to 17.25 kV, which is 1.25 times the rated voltage (13.8 kV). If the  $P_{i1}$  and  $P_{i2}$  are measured to be higher than 5.0 kV and 10.7 kV, respectively, generators will be kept on operating and if they are below, rewinding will be performed.

#### 4. Conclusion

In this paper, a number of diagnostic and AC breakdown tests have been performed on the stator windings obtained from five gas turbine generators in a thermal power plant. The conclusions drawn from the tests can be summarized as follows:

The measurements of  $\Delta I$  and  $\Delta \tan \delta$  in all three phases showed the No. 1 generator stator windings to be in good condition, although the PD magnitude measurement indicated that the insulation is marginally acceptable and bad condition. The overall analysis of the results suggested that the No. 1 generator stator windings were in marginally serviceable condition and that the PD patterns in all three phases could be attributed to internal, slot and spark discharges. At 8 kV and 10 kV, when the PD magnitude measurements are high, the breakdown voltage in phases A, B, and C of No. 1 generator were relatively low among

28.0 kV, 17.9 kV, and 21.3 kV, respectively.

The voltage at which capacitance shows an abrupt increase is also similar as that of the DIV measurements. The point at which the dissipation factor in the  $\tan \delta$ -voltage curve increased was approximately 1 kV or 1.8 kV lower than the voltage at which  $P_{i1}$  appeared in the AC current-voltage characteristics.

The results of the breakdown tests performed on the generator stator windings showed that there was a strong positive correlation among the  $P_{i1}$ ,  $P_{i2}$  and the breakdown voltage. These results may be used as a guide to assess insulation condition of the other 11 generators.

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