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Analysis of Insulation Quality in Large Generator Stator Windings

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Abstract – To evaluate the condition of stator winding insulation in generators that have been operated for a long period of time, diagnostic tests were performed on the stator bars of a 500 MW, 22 kV generator under accelerated thermal and electrical aging procedures. The tests included measurements of AC current (ΔI), dissipation factor (tanδ), partial discharge (PD) magnitude, and capacitance (*C*). In addition, the AC current test was performed on the stator winding of a 350 MW, 24 kV generator under operation to confirm insulation deterioration. The values of ΔI, Δtanδ, and PD magnitude in one stator bar indicated serious insulation deterioration. In another stator bar, the ΔI measurements showed that the insulation was in good condition, whereas the values of Δtanδ and PD magnitude indicated an incipient stage of insulation deterioration. Measurements of ΔI and PD magnitude in all three phases (A, B, C) of the remaining generator stator windings showed that they were in good condition, although the Δtanδ measurements suggested that the condition of the insulation should be monitored carefully. Overall analysis of the results suggested that the generator stator windings were in good condition. The patterns of PD magnitude in all three phases (A, B, C) were attributed to internal discharge.

Keywords: Deterioration, Generator, Diagnostic test, Accelerated aging, Stator bar, Partial discharge, Dissipation factor

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 downtime, which can seriously harm the reliability of the power system. Failures in generator stator windings occur as a result of insulation deterioration initiated by voids created in the insulation material from the combined effects of thermal, electrical, mechanical, and environmental stresses during long-term operation [1], [2]. Therefore, accelerated aging tests were conducted under laboratory conditions in countries such as the USA, Canada, and Japan to analyze deterioration characteristics and, ultimately, to use the analysis results for evaluating the insulation condition and remaining life of the generators [3]-[5].

Many on-line and off-line insulation diagnostic tests for insulation quality assessment have been developed and used over a long period of time. Some commonly used off-line tests for verifying the insulation condition include 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 is used for assessment [6].

In this paper, insulation tests were performed on 500 MW, 22 kV generator stator bars by increasing rated voltage according to accelerated aging hours. In addition, diagnostic tests were performed off-line on a 350 MW, 24 kV generator that was operated for more than 30 years to assess the insulation condition.

2. Construction of generator stator bars and accelerated aging test

Two insulation class B stator bars were manufactured for a 500 MW, 22 kV generator as shown in Fig. 1. The stator bars were placed under accelerated aging to check insulation deterioration in generator stator windings. Direct liquid cooling was applied to the stator bars, which were composed of turn and groundwall insulations. Glass fiber and synthetic enamel were used for the copper conductor, while epoxy-mica tape was used for forming a 5.5 mm-thick groundwall insulation around the turn insulation. The copper strand of the stator bar was 4.27 mm × 7.14 mm in size, and the conductor of the stator bar was 30.7 mm × 54.1 mm. The length of the stator bar was 6,750 mm and the length of the end-windings for the two stator bars was 1,080 and 1,230 mm, respectively.

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Accelerated aging tests were performed on the two stator bars under stress conditions of accelerated electrical and thermal aging. For electrical stress, up to 27.5 and 22 kV (1.732 times higher than the rated line-to-ground voltage of 12.7 kV and 1.25 times higher than the rated voltage of 22 kV, respectively) were applied to stator bars #1 and #2, respectively. As shown in Fig. 1, thermal aging of #1 was performed with circulated cooling water heated at 65 °C, whereas #2 was equipped with four electrical heaters (130 °C) in addition to the cooling water (65 °C).

Fig. 1. Accelerated aging tests for generator stator bars #1 and #2

3. Experimental procedure

The polarization index (PI) was measured using a commercially available automatic insulation tester (Megger, S1-5010) at DC 5 kV in individual phases before applying AC voltage to the stator windings. Commercially available equipment, namely, Schering bridge (Tettex Instruments), coupling capacitor, and PD detector (Tettex Instruments, TE 571), were used to measure AC current, dissipation factor, and PD magnitude, respectively. The Schering bridge consists of a high voltage (HV) supply (Type 5283), a bridge (Type 2818), and a resonating inductor (Type 5285). A HV supply and control system (Tettex Instruments, Type 5284), Schering bridge (Tettex Instruments, Type 2816), resonating inductor (Tettex Instruments, Type 5288), coupling capacitor, coupling unit, and PD detector were used to measure AC current, dissipation factor, and PD magnitude in 22 kV generator stator bars under accelerated aging and 24 kV generator stator windings. The HV supply and control system, Schering bridge, and resonating inductor were used to obtain the AC current and dissipation factor measurements. For PD measurements, AC voltage was applied to the generator stator winding through a connected HV supply and control system. The coupling capacitor (Tettex Instruments, 4,000 pF) amplified signals from the winding, which were sent to the coupling unit (Tettex Instruments, AKV 572) and then to the PD detector (Tettex Instruments, TE 571) that measures the magnitude and pattern of PD. The frequency band of the PD detector ranged from 40 to 400 kHz. Given that the PD magnitude in the generator stator bar ranged between 13,700 and 50,000 pC in line-to-ground voltage, it was measured in a general laboratory where the background noise ranged from 300 to 900 pC. Therefore, the PD magnitude detected in the laboratory included background noise. After the off-line diagnostic tests were completed in the water-cooled 350 MW, 24 kV generator, the HV supply (50 kV) and bridge (Type 2819) were used to increase the AC voltage applied to the stator windings gradually in 1 kV intervals up to 40 kV to measure the AC current, dissipation factor, and PD magnitude.

4. Test results and discussion

4.1 Insulation condition evaluation of generator stator bars under accelerated aging

Before performing the accelerated aging test, stator bar #1 was tested for water absorption for a long period of time with the cooling water heated to 65 °C. However, stator bar #2 was newly manufactured for the test. Measurements of AC current, dissipation factor, PD magnitude, and capacitance were analyzed after accelerated aging was performed on the two stator bars for 17,600 h.

4.1.1 Analysis of AC current, dissipation factor, and PD magnitude

The AC current and $\tan\delta$ measurements as a function of voltage (up to 22 kV) for stator bars #1 and #2 after 17,600 h of accelerated aging are shown in Figs. 2 and 3, respectively. The rates of increase in the AC current (ΔI) and dissipation factor ($\Delta\tan\delta$) for both bars were measured and analyzed by plotting the AC current and the dissipation factor as a function of the AC voltage. When the applied voltage was 1.25 times higher (15.88 kV) than the rated generator voltage, the insulation was considered to be in good condition if the value of ΔI was below 5.0% according to [6]. As shown in Fig. 2 and Table 1, the ΔI values of stator bars #1 and #2 calculated at 12.7 kV were 44.71% and 4.18%, respectively. In comparison the ΔI values of stator bars #1 and #2 calculated at 15.88 kV were 50.05% and 4.65%, respectively. The ΔI measurement of stator bar #1 indicated significant deterioration because it was 10 times higher than the criterion value of 5.0%, whereas stator bar #2 was in good condition. In addition, the P_{i1} (the first point where the voltage increased suddenly) values of stator bars #1 and #2 were 3 and 7 kV, respectively, whereas the P_{i2} values in Fig. 2 were 7.2 and 13 kV, respectively (Table 2). Thus, the longer the accelerated aging, the lower the voltage at which the dissipation factor suddenly increases. Stator bar #1 showed rapid insulation degradation compared to stator bar #2, which was in the early stages of deterioration.

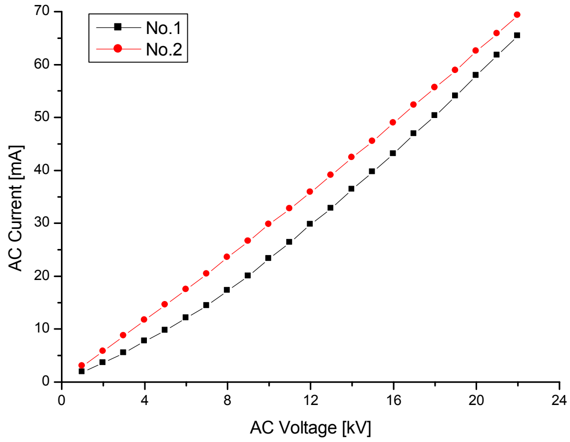


Fig. 2. Characteristics of AC current versus voltage for stator bars #1 and #2

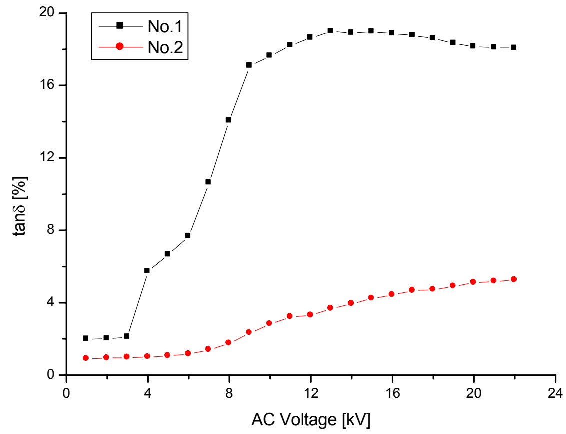


Fig. 3. Characteristics of the tanδ-voltage relationship for stator bars #1 and #2

When the voltage is 1.25 times higher (15.88 kV) than the generator operating voltage, the insulation is considered to be in good condition if the value of Δtanδ is below 2.0%. A Δtanδ value between 2.0% and 6.5% is considered to be a cautionary level; at a value above 6.5%, the insulation is considered to be in bad condition [6]. As shown in Fig. 3 and Table 1, the Δtanδ measurements of stator bars #1 and #2 calculated at 12.7 kV were 16.9% and 2.72%, respectively, and those of stator bars #1 and #2 calculated at 22 kV were 15.76% and 4.31%, respectively. The Δtanδ measurement of stator bar #1 indicated significant degradation because it was 2.4 times higher than the criterion value. In comparison, the Δtanδ measurement of stator bar #2 suggested that keen attention is required. The dissipation factors of stator bars #1 and #2 showed gradual increases until the voltage reached 3 and 7 kV, respectively, after which they increased abruptly. As shown in Fig. 2, the increase in dissipation factor due to applied voltage occurs at 3 and 7 kV in stator bars #1 and #2 after the bars had undergone 17,600 h of accelerated aging. The longer the accelerated aging, the lower the voltage at which the dissipation factor suddenly increases. Therefore, as in the case of the P_{i1} above, stator bar #1 showed rapid insulation degradation compared to stator bar #2, which was in the early stages of deterioration.

Table 1. Comparison of insulation diagnosis results for stator bars #1 and #2

Accelerated aging time [h]	ΔI [%] at 12.7 kV		Δtanδ [%] at 12.7 kV		PD magnitude [pC] at 12.7 kV	
	#1	#2	#1	#2	#1	#2
0	1.33	2.53	1.02	1.34	3,200	4,100
4,780	3.76	2.64	1.65	1.84	7,800	5,700
9,690	5.04	3.14	2.65	1.90	10,000	6,000
16,870	18.65	4.00	4.23	2.69	25,000	12,600
17,600	44.71	4.18	16.9	2.72	50,000	13,700

The values of ΔI and Δtanδ, as well as the change in PD magnitude in stator bars #1 and #2 measured as a function of accelerated aging hours are shown in Table 1. The insulation is interpreted to be in good condition if the line-ground PD magnitude is below 10,000 pC. PD magnitude measurements between 10,000 and 30,000 pC indicate a cautionary level, and those above 30,000 pC indicate bad conditions. The PD magnitudes in stator bars #1 and #2 at the rated voltage were 50,000 and 13,700 pC, respectively. This indicates that stator bar #1 is in bad condition and stator bar #2 requires keen attention. From the measurements of ΔI, Δtanδ, and PD magnitude, it can be concluded with confidence that significant deterioration has taken place in stator bar #1. Tests indicated that stator bar #2 is in the incipient stages of deterioration because the ΔI test indicated good insulation conditions, whereas the Δtanδ and PD magnitude measurements suggested that keen attention is required.

Table 2. Characteristics of AC current and tanδ for stator bars #1 and #2

Accelerated aging time [h]	P_{i1} [kV]		Voltage at which dissipation factor suddenly increases [kV]	
	#1	#2	#1	#2
0	10.7	12.0	8	10
4,780	10.5	11.6	8	9
9,690	9.0	10.5	7	8
16,870	5.2	9.3	6	8
17,600	3.0	7.0	3	7

4.1.2 Capacitance analysis

The capacitances measured as a function of applied voltage (up to 22 kV) in stator bars #1 and #2 after 17,600 h of accelerated aging are shown in Fig. 4. The capacitance of stator bar #1 increased from 4.75 nF at 1 kV to 7.76 nF at 22 kV, showing a large change of 3.01 nF. As described above, stator bar #1 had deteriorated significantly and was close to dielectric breakdown. Thus, the capacitance increased abruptly at a low voltage of 3 kV. However, the capacitance of stator bar #2 was 7.73 nF at 1 kV and 8.34 nF at 22 kV, showing a much smaller change of 0.61 nF. Stator bar #2 was in the early stages of deterioration and the value of the capacitance increased significantly at 8 kV. The values of the capacitance and dissipation factor in stator bars #1 and #2 increased at similar test voltages, as shown in Figs. 3 and 4. Considerable increase in the dissipation factor and decrease in the capacitance indicated a significant increase in the amount of voids within the groundwall insulation. The increase in average effective airgap due to the voids should decrease the capacitance between the copper strands and the groundwall insulation [7]. Before the two stator bars were placed under the accelerated aging procedure, the capacitance measurements of stator bars #1 and #2 were 8.73 and 8.12 nF, respectively. However, after stator bar #1 deteriorated significantly as a result of accelerated aging, its capacitance showed a large change compared to that of stator bar #2. This result is consistent with the conclusion of other study [7]. Therefore, the change in capacitance increases with accelerated aging and the value of the capacitance usually increases at a lower voltage.

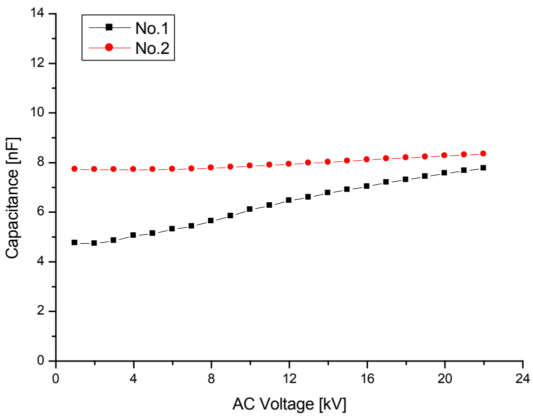


Fig. 4. Characteristics of capacitance versus voltage for stator bars #1 and #2

4.2 Insulation condition evaluation of aged generator stator windings

Measurements of the PI, AC current, dissipation factor, and PD magnitude were performed to analyze the insulation deterioration of aged generator stator windings and to set up the criteria for evaluating its lifetime. A 350 MW, 24 kV generator cooled by water and hydrogen at a thermal power plant was operated for more than 30 years with regular stops on weekends. It has been operating for more than 10 years since its original stator winding was replaced. Diagnostic tests were carried out on this generator by applying test voltages up to 40 kV, 1.67 times higher than the rated voltage.

4.2.1 Analysis of AC current

The AC current measured when an AC voltage of 1 to 40 kV was applied to the 350 MW, 24 kV generator (Fig. 5). The ΔI measurement is below 5.0% when the voltage is 1.25 times higher (17.32 kV) than the generator line-to-ground voltage . If the value generator line-to-ground voltage is applied, the insulation is considered to be in good condition [6]. As shown in Table 3, the ΔI measurements for phases A, B, and C at 17.32 kV were 2.42%, 3.80%, and 3.36%, respectively, indicating good insulation conditions. However, at 40 kV, the ΔI measurements increased threefold to 10.31%, 10.72%, and 10.72% for the three phases, respectively. The measured value of P_{i1} for phases A, B, and C were approximately 12 kV, and their P_{i2} values were present at 29 kV.

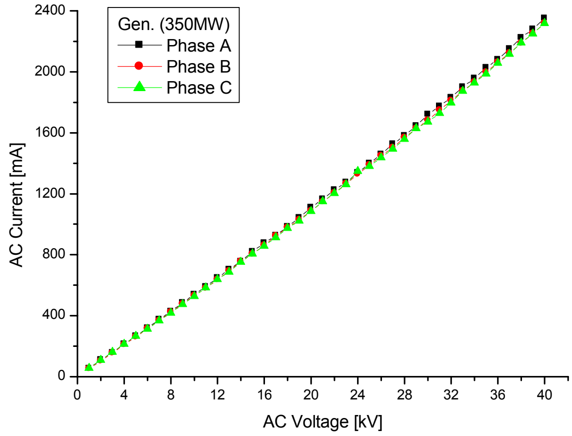


Fig. 5. Characteristics of AC current versus voltage in generator stator windings

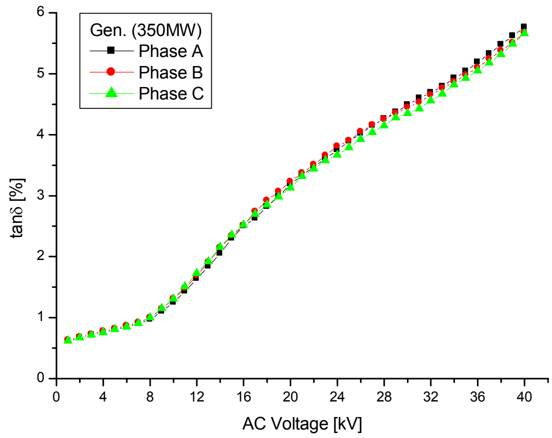


Fig. 6. Characteristics of tanδ versus voltage in generator stator windings

4.2.2 Analysis of dissipation factor

The tanδ measurements as a function of the AC voltage applied to generator stator windings are shown in Fig. 6. At the rated voltage of 24 kV, the insulation is considered to be in good condition if the value of Δtanδ is below 2.0%, whereas attention is required if this value is between 2.0% and 6.5% [6]. The Δtanδ of phases A, B, and C at 24 kV were 3.03%, 3.08%, and 2.95%, respectively. This indicates that keen attention is required, as shown in Table 3. However, at 40 kV, the values of Δtanδ for phases A, B, and C increased twofold to 5.76%, 5.67%, and 5.66%, respectively. Given that the dissipation factor increased gradually until 8 kV and then abruptly at 9 kV, the discharge inception voltage (DIV) was expected to exceed 9 kV. DIV refers to the voltage at which the PD magnitude exceeds 1,000 pC in generator stator windings.

4.2.3 Analysis of PD magnitude

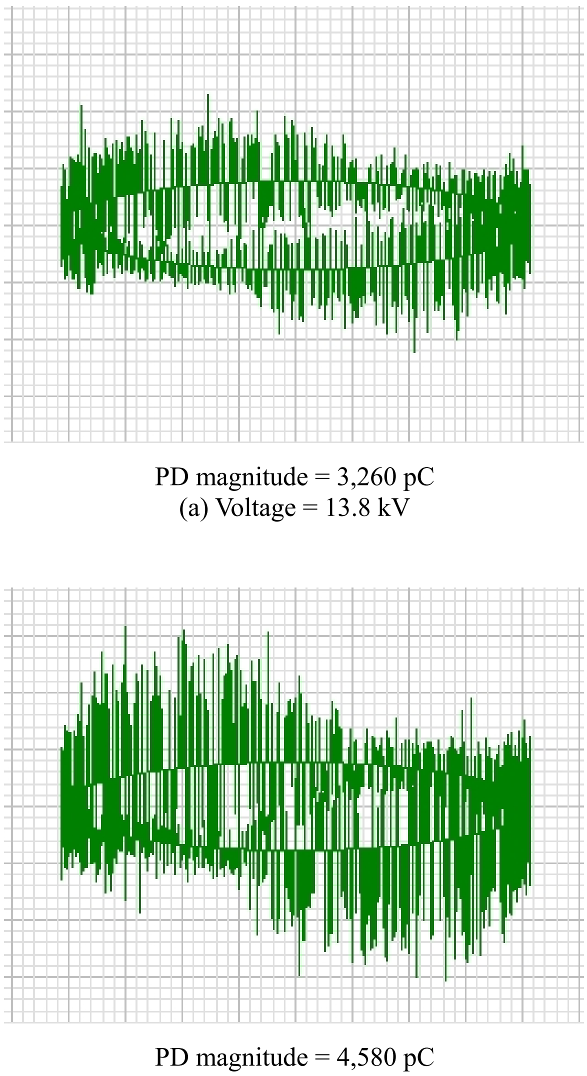
Measurements of system noise, DIV, and PD magnitude at the three phases (A, B, C) of the generator stator windings are summarized in Table 3. System noise values at phases A, B, and C were 900, 700, and 800 pC, respectively. The corresponding DIV values were 9.9, 10.1, and 10.4 kV. As expected, PD magnitude increased as voltage gradually increased above the rated line-to-ground voltage from 13.8 to 30 kV (1.25 times higher than the rated voltage). It is important to determine the amplitude of the voltage at which the insulation condition is evaluated. The insulation is considered to be in good condition if PD magnitude is below 10,000 pC at the rated line-to-ground voltage [6]. The PD magnitudes at phases A, B, and C at the rated line-to-ground voltage were 4,200, 3,250, and 3,150 pC, respectively, indicating good insulation conditions. The PD magnitudes for phases A, B, and C at voltages of 24 and 30 kV (1.25 times higher than the rated voltage) were above 10,000 pC.

Table 3. Comparison of PD magnitude in a generator stator winding

Generator (350 MW)	System noise [pC]	DIV [kV]	PD magnitude [pC]			
			E/√3 at 13.8 kV	1.25E/√3 at 17.32 kV	E at 24 kV	1.25E at 30 kV
Phase A	900	9.9	4,200	6,700	10,800	16,700
Phase B	700	10.1	3,260	4,580	10,300	17,000
Phase C	800	10.4	3,150	6,600	11,260	16,700

The PD magnitudes of positive (0°–180°) and negative (180°–360°) polarity in phase B of the generator stator windings, when line-to-ground voltages of 13.8 kV and 17.32 kV (1.25 times higher than the line-to-ground voltage) were applied, are shown in Fig. 7. Given that the PD magnitudes of positive (0°–90°) and negative (180°–270°) polarity are symmetrically similar, the PD pattern was attributed to internal discharge [2], [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 values of PI, AC current, dissipation factor, and PD magnitude in the generator stator windings are shown in Table 4. In all three phases of the stator windings, the PI measurements were above 2.0, indicating that the stator insulation is in fair condition [9]. As stated earlier, the ΔI and PD magnitude measurements in phases A, B, and C indicated that the insulation is in good condition, whereas the Δtanδ value suggested that attention is required. In addition, when the insulation was in fair condition, the point at which the dissipation factor in the tanδ-voltage curve increased was about 2 kV or 3 kV lower than the voltage at which P_{i1} appeared in the AC current-voltage characteristics. The P_{i1} was also similar to the DIV. Therefore, as mentioned in the accelerated aging test results on the generator stator bars, the P_{i1} of AC current, the point at which the dissipation factor increases, and the DIV tend to be high when the insulation condition is fair. However, these voltages decrease with an increase in accelerated aging time in generator stator bars [7]-[9].



PD magnitude = 3,260 pC
(a) Voltage = 13.8 kV

PD magnitude = 4,580 pC
(b) Voltage = 17.32 kV

Fig. 7. PD magnitude of generator stator windings

Table 4. Summary of insulation diagnosis results in generator stator windings

Test item	PI	ΔI[%] at 17.32 kV	Δtanδ[%] at 24 kV	PD magnitude [pC] at 13.8 kV
Criteria for good condition	Above 2.0	Below 5.0	Below 2.0	Below 10,000
Phase A	3.83	2.42	3.03	4,200
Phase B	6.65	3.80	3.08	3,260
Phase C	8.16	3.36	2.95	3,150

5. Conclusion

Off-line diagnostic tests were performed on 500 MW, 22 kV generator stator bars under accelerated aging, and on the stator windings of a 350 MW, 24 kV generator that has been operated for over 30 years. The conclusions drawn from a comprehensive analysis of the test results can be summarized as follows:

(1) The values of ΔI, Δtanδ, and PD magnitude in stator bar #1 indicated significant insulation deterioration. The values of ΔI in stator bar #2 indicated the insulation to be in good condition, whereas the values of Δtanδ and PD magnitude indicated an incipient stage of insulation deterioration. A comparison of the capacitance values between stator bars #1 and #2 showed that the variation in stator bar #1 is larger than that in stator bar #2, which has a relatively healthy condition. The value of P_{i1} and the voltage at which the dissipation factor increased became lower as the stator bars were aged for longer time periods. Stator bar #1 showed rapid insulation deterioration compared to stator bar #2, which was in the early stages of deterioration.

(2) The measurements of ΔI and PD magnitude in all three phases showed the generator stator windings to be in good condition, although the Δtanδ measurement indicated that the insulation requires careful attention. The overall analysis of the results suggested that the generator stator windings were in good condition and that the PD patterns in all three phases could be attributed to internal discharge. When the insulation was in fair condition, the point at which the dissipation factor increased in the tanδ-voltage characteristics was approximately 2 or 3 kV lower than the voltage at which P_{i1} appeared in the AC current-voltage characteristics (similar to the DIV). Therefore, the P_{i1} of the AC current, the voltage at which the dissipation factor increases, and the DIV tend to be high when the insulation is in good condition. These voltages decrease with accelerated aging.

(3) The results of the diagnostic tests performed on the generator stator bars showed that there is a strong positive correlation between the degradation in insulation condition and the duration of accelerated aging. The remaining service life of generator stator windings is predicted by comparing the results of the diagnostic and accelerated aging tests. These results may be used as a guide to assess the insulation conditions of generators.

Acknowledgements

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References

[1] Hee-Dong Kim, "Analysis of Insulation Aging Mechanism in Generator Stator Windings", *Journal of the KIEEME,* Vol. 15, No. 2, pp. 119–126, 2002.

[2] Hee-Dong Kim, "Assessment of Insulation Condition in Operating Large Turbine Generator", *Trans. KIEE*, Vol. 53C, No. 6, pp. 324–329, 2004.

[3] R. Morin, R. Bartnikas and P. Menard, "A Three-Phase Multi-Stress Accelerated Electrical Aging Test Facility for Stator Bars", *IEEE Trans. on Electrical Conversion,* Vol. 15, No. 2, pp. 149–156, 2000.

[4] Y. J. Kim and J. K. Nelson, "Assessment of Deterioration in Epoxy/Mica Machine Insulation", *IEEE Trans. on Electrical Insulation,* Vol. 27, No. 5, pp. 1026–1039, 1992.

[5] K. Kimura and Y. Kaneda, "The Role of Microscopic Defects in Multistress Aging of Micaceous Insulation", *IEEE Trans. on Dielectrics and Electrical Insulation,* Vol. 2, No. 3, pp. 426–432, 1995.

[6] Y. Ikeda and H. Fukagawa, "A Method for Diagnosing the Insulation Deterioration in Mica-Resin Insulated Stator Windings of Generator", Yokosuka Research Laboratory Rep. No. W88046, 1988.

[7] H. Zhu, C. Morton and S. Cherukupalli, "Quality Evaluation of Stator Coils and Bars under Thermal Cycling Stress", *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation,* pp. 384–387, 2006.

[8] C. Hudon and M. Belec, "Partial Discharge Signal Interpretation for Generator Diagnostics", *IEEE Trans. on Dielectrics and Electrical Insulation,* Vol. 12, No. 2, pp. 297–319, 2005.

[9] Hee-Dong Kim, Young-Jun Lee and Young-Ho Ju, "Characteristics of Insulation Aging in Large Generator Stator Windings", *Trans. KIEE,* Vol. 58, No. 7, pp. 1375–1379, 2009.

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