Stator Insulation Quality Assessment for High Voltage Motors Based on Probability Distributions

Hee-Dong Kim† and Chung-Hyo Kim*

Abstract – Stator insulation quality assessment for high voltage motors is a major issue for the reliable maintenance of industrial and power plants. To assess the condition of stator insulation, nondestructive tests were performed on the sixty coil groups of twelve motors. After completing the nondestructive tests, the AC voltage applied to the stator winding was gradually increased until insulation failure in order to obtain the breakdown voltage. The stator winding of each motor was classified into five coil groups; one group with healthy insulation and four groups with four different types of artificial defects. To analyze the breakdown voltage statistically, Weibull distribution was employed for the tests on the fifty coil groups of ten motors. The 50th percentile values of the measured breakdown voltages based on the statistical data of the five coil groups of ten motors were 26.1kV, 25.0kV, 24.4kV, 26.7kV and 30.5kV, respectively. Almost all of the failures were located in the line-end coil at the exit of the core slot. The breakdown voltages and the types of defects showed strong relation to the stator insulation tests such as in the case of dissipation factor and ac current. It is shown that the condition of the motor insulation can be determined from the relationship between the probability of failure and the type of defect.

Keywords: Motor, Nondestructive Tests, Probability Distributions, Stator insulation

1. Introduction

Industrial surveys and other studies on machine reliability show that the winding insulation is the most vulnerable component in high voltage (HV) rotating and stationary electric machines [1, 2]. Since the insulation of the electric machine windings is continuously exposed to a combination of thermal, electrical, mechanical, and environmental stresses during operation, the insulation material deteriorates gradually over time. Thermal stress causes the formation of voids in the mica barrier, weak bonding between layers, and delamination. Electrical and mechanical stresses also contribute to the formation of voids in the insulation, and environmental stress causes rupture of the chemical bonds of the insulation. The synergistic effect of the stresses causes gradual deterioration of stator winding insulation, which leads to eventual electrical failure. Winding insulation problems must be taken seriously since they not only lead to catastrophic machine failure that results in forced outages, but they can also cause casualties or serious injuries due to fire, electric shock, or arc flash hazards. Therefore, many off-line and on-line diagnostic testing methods have been developed over the last century for monitoring the winding insulation condition to guarantee the reliable operation of electric machines [2].

There are many different types of nondestructive and destructive tests used for evaluating the degree of insulation degradation in high voltage motors. Nondestructive tests include measurements of insulation resistance, ac current, capacitance, dissipation factor (tanδ), and partial discharge (PD). To assess the insulation condition in power plants, periodic nondestructive tests must be performed in high voltage motors [3, 4]. Destructive testing of the stator winding can be conducted by gradually increasing ac voltage until the insulation fails. Analysis of breakdown voltage is considered a more sensitive indicator and a more reliable way of estimating insulation deterioration than nondestruc-tive tests.

This paper describes several test results from both nondestructive and destructive tests in sixty coil groups of twelve high voltage motors. Weibull probability distribution is employed to analyze the ac breakdown voltage from a selected group of coils.

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2. Test SPECIMEN and eXPERIMENTAL PROCEDURE

To assess the deterioration of stator winding insulation in high voltage motors, a total of 576 coils were manufactured for twelve motors (48 slots) of 6.6kV. All 48 coils for each motor (12 turn coil) were inserted in the stator slot when performing the tests. The 48 coils were classified into five groups. Where one group of coils (E) was healthy, artificial defects were introduced into the other four coil groups (A~D). The four different types of coils inserted in the four coils groups were shorted turn (strand), internal separation between conductor and groundwall insulation, large void within the groundwall insulation, and removal of semi-conductive tape. All the coil groups other than coil group D have the semi- conductive tape on the outer surface of the slot section. Table 1 summarizes the description of each coil group (A~E), and the number of windings with each defect. A photograph of the test motor with the five coil groups of the high voltage motor is given in Fig. 1. Twelve motors were manufactured with identical coil groups having the artificial defects. Nondestructive tests were performed on the individual coil groups of twelve motors to obtain the statistical data.

Table 1. Description of defects in the five coil groups of each motor

Coil Group	Defect Classifications	Winding Numbers
A	Shorted turn (strand)	10
B	Internal separation between conductor and GW insulation	10
C	Large void within GW insulation	8
D	Removal of semi-conductive tape	10
E	Healthy	10

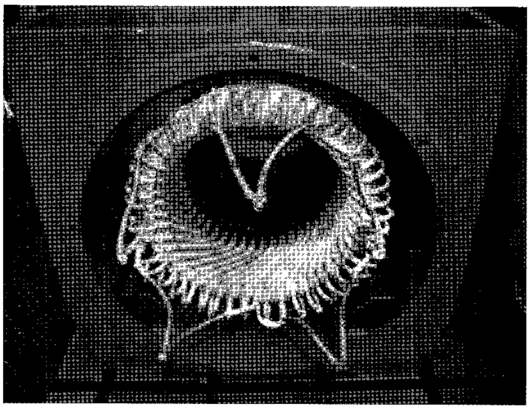

Fig. 1. Five coil groups of a motor with artificial defects

The ac current and dissipation factor (tanδ) were measured using a commercial Schering bridge in all five coil groups of motor stator windings. The Schering bridge consists of a HV power supply (Tettex, Type 5283), bridge (Tettex, Type 2818), and resonating inductor (Tettex, Type 5288). The ac current and tanδ measurements were obtained between 0.95 kV and 6.6 kV for all five coil groups. ΔI is the difference between the actual measurement of the current at 6.6kV and ideal expected current at 6.6kV estimated based on the increase in current. Δtanδ is the difference between the tanδ measurements at 2 kV and at 6.6 kV. Partial discharge measurements were also obtained in accordance with IEC 270 using a wide band (40~400 kHz) partial discharge detection system (TE-571) in a calibrated measuring circuit. The AC breakdown test was performed using a variable ac power supply.

3. Results and Discussion

Before the ac breakdown test was performed, nondestructive tests that include the ac current, dissipation factor (tanδ), and partial discharge tests were performed on the sixty coil groups of twelve motors. The measurements of the ac current and tanδ were obtained with the voltage between 0.95kV and 6.6 kV for each individual coil group for the twelve motors. For each coil group (A~E) of the twelve motors, the minimum and maximum values of ΔI and Δtanδ were excluded from the statistical analysis (ten of sixty coil groups for the twelve motors have been removed). For each coil group, the average of the ΔI and Δtanδ measurements with the minimum and maximum values removed are summarized in Table 2.

Table 2. Average of ΔI and Δtanδ measurements

Coil Group	△tanδ [%]	△I [%]
A	4.31	5.35
B	6.62	10.90
C	7.74	9.87
D	11.03	15.21
E	1.37	1.89

According to [5], coils with the values of ΔI and Δtanδ lower than 8.5% and 6.5%, respectively, are acceptable at 6.6 kV. It can be seen in Table 2 that the measurements of ΔI and Δtanδ for coil groups A (shorted turn) and E (healthy) have the lowest values. The values of ΔI and Δtanδ being below 8.5% and 6.5% indicate that the stator winding insulation in coil groups A and E is in serviceable condition. The values of the ΔI and Δtanδ measurements in coil groups B, C, and D are above the 8.5% and 6.5% threshold, which indicate that they must be replaced since they have deteriorated significantly. The insulation of coil group B appears to be prone to delamination and debonding between the conductor and insulation. The tanδ values of coil group C (void in GW insulation) at 0.95 kV and at 6.6 kV were measured to be 6.2~8.0% and 11.0~16.0%, respectively. The tanδ values of coil group D (no semiconductive tape) at 0.95 kV and 6.6 kV were between 0.5~2.0% and 11.0~22.4%, respectively, which was roughly eight times higher than those for the healthy coil group (group E). In significantly degraded insulation the tanδ measurements were high even at low voltage due to the defects [6].

Table 3. The results of PD measurement

Coil Group	PD magnitude [nC]					
	Noise [pC]	DIV [kV]	3.81 [kV]	4.76 [kV]	6.0 [kV]	6.6 [kV]
A	410	4.3	1.1	2.2	3.8	5.6
B	470	3.4	1.7	3.7	6.0	6.9
C	430	3.7	1.3	2.5	6.3	8.8
D	450	3.3	2.9	8.7	14.0	17.0
E	420	3.5	1.3	2.0	4.0	5.7

As in the case of the ΔI and Δtanδ measurements, the data with the minimum and maximum values of PD magnitudes were removed in the statistical analysis for each coil group (A~E). For each coil group, the external noise, discharge inception voltage (DIV) and the average PD magnitude with the minimum and maximum values removed are summarized in Table 3. The PD magnitudes were measured for each individual coil group at 3.81 kV, 4.76 kV, 6 kV, and 6.6 kV, respectively. As the voltage was increased from 3.81 kV to 6.6 kV, the PD magnitudes increased, as expected. It can be seen that the PD magnitudes at line-to-ground voltage (3.81kV) and at 4.76 kV are in good condition for the five coil groups. The PD magnitudes at 6.6 kV were 5,600pC, 6,900pC, 8,800pC, and 5,700pC for coil groups A, B, C, and E, and unacceptably high for coil D at the same voltage. High levels of PD at relatively low voltage raise concern about the insulation condition for coil group D. The PD magnitudes in coil group D are high enough to cause significant damage to the insulation. When the PD is increased greatly, this is likely to deteriorate the stator winding insulation at a fast rate leading to failure.

The PD pattern in the coil group A, C, and E measurements indicated internal discharges, and the PD patterns of coil groups B and D indicated discharge at conductor surface and slot discharges, respectively, as expected from the artificial defects. Although the PD magnitude of coil group D are much higher than that of coil group C, internal discharge causes more serious insulation problems than slot discharge. Several defects may be responsible for breakdown of severely degraded insulation under ac tests. PD will occur if voids are present within the groundwall insulation, and the PD magnitudes are proportional to the size of the void in which the PD occurred. The dissipation factor test is an indirect way of determining if PD is occurring in the stator winding of high-voltage motor [6]. It can be seen in the tanδ and PD measurements of coil groups C and D that the energy consumed by the PD is larger for higher tanδ values.

The AC breakdown test, which is a test applied to high voltage motor insulation to test the suitability of service, was performed on the sixty coil groups of twelve motors to confirm the results of the nondestructive test. As in the nondestructive tests, the minimum and maximum breakdown voltages were removed from the measurements of each coil group (A~E). The results of the average of the breakdown voltage measurements from the ten coils groups are summarized in Table 4. Breakdown of coil groups A, B, C, D, and E occurred at an average of 25.9 kV, 27.4 kV, 23.1 kV, 26.5 kV, and 30.4 kV, respectively, which indicates that the stator insulation is in serviceable condition.

Table 4. Measurements of the average breakdown voltage

Coil Group	BreakdownVoltage [kV]	Failure Location
A	25.9	Line-end coil
B	27.4	Line-end coil
C	23.1	Line-end coil
D	26.5	Line-end coil
E	30.4	Line-end coil

Most of the failures occurred in the line-end coil at the exit of the core slot section; only the failures in the two coil occurred in the slot section. It can be seen in Table 4 that the breakdown voltage of the healthy coil group (E) is higher than that of the coil groups with artificial defects (A~D). The lowest breakdown voltage was observed in the coil group with a large void introduced in the bulk of the GW insulation (Coil group C). Although the ΔI, Δtanδ, and PD measurements for both coil groups A and E show that they are in good serviceable condition, the breakdown voltage of the healthy coil group (E) is higher than that of the coil group with a shorted turn (A). It has been reported in the literature that many of the stator winding failures in motors are initiated from a turn insulation failure, and the failure occurs within a short period of time since the initiation of the shorted turn under normal operation [7]. The relationship between the nondestructive and ac breakdown tests is even more complicated for significantly deteriorated insulation.

Figure 2 shows the Weibull plot of the ac breakdown voltage for the five coil groups A~E described in Table 1. It is possible to estimate the failure rate of fifty coil groups of ten motors from the Weibull distribution analysis for breakdown voltage. The 50th percentile (median) values of the measured breakdown voltages based on statistical data in coil groups A, B, C, D, and E were 26.1kV, 25.0kV, 24.4kV, 26.7kV, and 30.5kV, respectively. It can be seen in Table 4 that the data is similar to the average values of the measured breakdown voltage. This result indicates that destructive testing is more reliable although nondestructive testing is performed to estimate insulation deterioration rate for breakdown voltage.

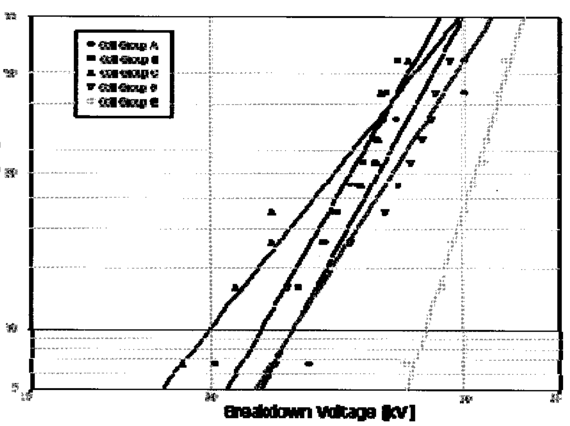

Fig. 2. Weibull plot of the breakdown voltage for five coil groups

4. Conclusion

In this paper, the degree of insulation degradation was estimated from nondestructive and destructive testing on fifty coil groups of ten high voltage motors. Artificial defects such as shorted turn (A), separation between the coil and insulation (B), voids in GW insulation (C), and removal of semiconductive coating (D) were introduced in the four groups of coils, and one of the coil groups was healthy (E). The measurements of ΔI and $\Delta\tan\delta$ indicated that the insulation of coil groups A and E are in serviceable condition, but the insulation of coil groups B, C, and D are in poor condition. The PD magnitudes at 4.76 kV were around 2200pC, 3700pC, 2500pC, 8700pC, and 2000pC for coil groups A, B, C, D, and E, respectively. These results indicated that the stator insulation of the five coil groups is in good serviceable condition. It has been observed in the tests that internal discharge (B) causes more serious insulation problems than slot discharge (D). The 50th percentile (median) values of measured breakdown voltages based on the statistical data in coil groups A, B, C, D, and E were 26.1kV, 25.0kV, 24.4kV, 26.7kV, and 30.5kV, respectively. This data is in close proximity to the average of the breakdown voltage measurements. It has also been observed that almost all of the failures were located in the line-end coil at the exit from the core slot section. The test results show that destructive testing is more reliable although nondestructive testing is performed to estimate insulation deterioration rate for breakdown voltage.

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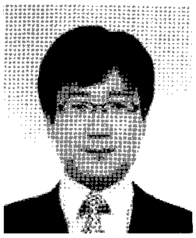

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