

STATOR INSULATION QUALITY ASSESSMENT FOR HIGH VOLTAGE MOTORS BASED ON PROBABILITY DISTRIBUTIONS

HEE-DONG KIM, CHUNG-HYO KIM

KEPCO Korea Electric Power Research Institute, 103-16 Munji-dong, Yuseong-gu, Daejeon 305-380, Korea

Stator insulation quality assessment for high voltage motors is a major issue for reliable maintenance of industrial and power plants. To assess the condition of stator insulation, nondestructive tests are performed on the sixty coil groups of twelve motors. The stator winding of each motor is 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 is 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 are strongly related to the stator insulation tests such as the 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.

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 formation of voids in the mica barrier, weak bonding between layers, and delamination. Electrical and mechanical stresses also contribute to formation of voids in the insulation, and environmental stress causes rupture of the chemical bonds. The synergistic effect of the stresses causes gradual deterioration of stator winding insulation, which leads to eventual electrical failure.

There are many different types of nondestructive and destructive tests used for evaluating the degree of insulation degradation in HV motors. Nondestructive tests include measurements of insulation resistance, ac current, capacitance, dissipation factor ($\tan\delta$), and partial discharge (PD). To assess the

insulation condition in power plants, periodic nondestructive tests must be performed in HV 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 nondestructive tests.

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

2. Test Specimen and Experimental Procedure

To assess the deterioration of stator winding insulation in HV motors, a total of 576 coils were manufactured for twelve motors (48 slots), where the motor is a 6.6kV motor. All 48 coils for each motor (12 turn coil) are inserted in the stator slot when performing the tests. The 48 coils are classified into five groups where one group of coils (E) is healthy, artificial defects are introduced into four coil groups (A~D). The four different types of coils inserted in the four coils groups are shorted turn (strand), internal separation between conductor and groundwall (GW) insulation, large void within the GW 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 HV motor is shown in Figure 1. Twelve motors were manufactured with identical coil groups with the artificial defects. Nondestructive tests were performed on the individual coil groups of twelve motors to obtain the statistical data.

The ac current and dissipation factor ($\tan\delta$) 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), and bridge (Tettex, Type 2818). The ac current and $\tan\delta$ measurements were obtained between 0.95kV and 6.6kV 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. $\Delta \tan\delta$ is the difference between the $\tan\delta$ measurements at 2kV and at 6.6kV. PD 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.

Table 1. Defect classifications in five coil groups of motor

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

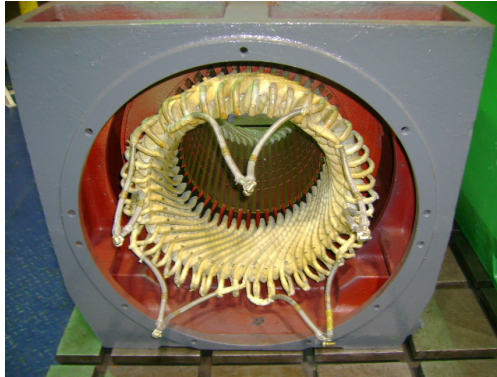


Figure 1. Five coil groups of motor with healthy and artificial defects

3. Results and discussion

Before the ac breakdown test was performed, nondestructive tests that include the ac current, dissipation factor ($\tan\delta$), and partial discharge tests were performed on the sixty coil groups of twelve motors. The measurements of the ac current and $\tan\delta$ were obtained with the voltage between 0.95kV and 6.6kV 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 $\Delta\tan\delta$ were removed in the statistical analysis (ten of sixty coil groups for the twelve motors have been removed). The average of the ΔI and $\Delta\tan\delta$ measurements with the minimum and maximum values removed are summarized in Table 2.

According to [5], coils with the values of ΔI and $\Delta\tan\delta$ lower than 8.5% and 6.5%, respectively, are acceptable at 6.6kV. It can be seen in Table 2 that the measurements of ΔI and $\Delta\tan\delta$ for coil groups A and E have the lowest values. The values of ΔI and $\Delta\tan\delta$ 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 $\Delta\tan\delta$ 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. Coil group B appears to be prone to delamination and debonding between the conductor and insulation. The $\tan\delta$ values of coil group C at 0.95kV and at 6.6kV were measured to be 6.2~8.0% and 11.0~16.0%, respectively. The $\tan\delta$ values of coil group D (no semiconductive tape) at 0.95kV and 6.6kV were between 0.5~2.0% and 11.0~22.4%, respectively, which was roughly eight times higher than those for coil group E (healthy).

Table 2. The measured results of ΔI and $\Delta \tan\delta$

Coil Group	$\square \tan\delta$ [%]	$\triangle I$ [%]
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

Table 3. The results of PD measurement

Coil Group	PD magnitude [pC]					
	Noise [pC]	DIV [kV]	3.81 [kV]	4.76 [kV]	6 [kV]	6.6 [kV]
A	410	4.3	1100	2200	3800	5600
B	470	3.4	1700	3700	6000	6900
C	430	3.7	1300	2500	6300	8800
D	450	3.3	2900	8700	14000	17000
E	420	3.5	1300	2000	4000	5700

As in the case of the ΔI and $\Delta \tan\delta$ 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 3.81kV, 4.76kV, 6kV, and 6.6kV, respectively. As the voltage was increased from 3.81kV to 6.6kV, the PD magnitudes increased, as expected. It can be seen that the PD magnitudes at line-to-ground voltage (3.81kV) and at 4.76kV are in good condition for the five coil groups. The PD magnitudes at 6.6kV 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. The PD magnitudes in coil group D are high enough to cause significant damage to the insulation. 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.

The AC breakdown test, which is a test applied to HV motor insulation to test 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 25.9kV, 24.8kV, 24.1kV, 26.5kV and 30.4kV, respectively, which indicates that the stator insulation is in serviceable condition. 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 C with a large void in the bulk of the GW insulation. Most of the failures occurred in the line-end coil at the exit of the core slot section; only the failures in two coils occurred in slot section.

Table 4. The results of the average breakdown voltage

Coil Group	Breakdown Voltage [kV]	Failure Location
A	25.9	Line-end coil
B	24.8	Line-end coil
C	24.1	Line-end coil
D	26.5	Line-end coil
E	30.4	Line-end coil

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 data is similar to the average values of the measured breakdown voltage. This results shows that destructive testing is more reliable although nondestructive testing is performed to estimate insulation deterioration rate for breakdown voltage.

Figure 2. Weibull plot of breakdown voltage for five coil groups

4. Conclusion

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 (coil group C) causes more serious insulation problems than slot discharge (coil group D). The 50th percentile (median) values of 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. 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.

References

1. H.A. Toliyat and G.B. Kliman, *Handbook of Electric Motors*, (Marcel Dekker, 2004).
2. H.G. Sedding, R. Schwabe, D. Levin, J. Stein and B.K. Gupta, *IEEE EIC/EMCW Conf*, 455 (2003).
3. B.K. Gupta and I.M. Culbert, *IEEE Trans. on EC*, **Vol. 7**, 500 (1992).
4. G.C. Stone, H.G. Sedding, B.A. Lloyd and B.K. Gupta, *IEEE Trans. on EC*, **Vol. 3**, 833 (1988).
5. H. Yoshida and U. Umemoto, *IEEE Trans. on EI*, **Vol. 6**, 1021 (1986).