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Changes in Insulation Characteristics of High-Voltage Motor Stator Windings with Temperature and Moisture

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Abstract: This research shows that all of the insulation characteristics (insulation resistance, partial discharge, dissipation factor, and alternating leakage current) of HV motor become worse at high temperature. It is also shows that partial discharge and insulation resistance are reduced at moisture absorption. Therefore, to accurately analyze the insulation degradation trend, it is necessary that those tests always be conducted under the same conditions (temperature and moisture content).

Keywords: High-Voltage Motor, Insulation, Temperature, Moisture Absorption, Partial Discharge

1. Introduction

Defects in the insulating material of the stator windings of high-voltage (HV) motors may arise during manufacturing or may be caused by thermal, mechanical, electrical, or chemical degradation after long-term operation. The possibility of sudden failure is likely to occur mostly caused from insulation deterioration [1]. Damage to the insulating material of the stator windings accounts for approximately 37% of such defects [2]. After the long-term operation of HV motor stator windings, voids may form in the insulating material as a result of multiple factors, with degradation continuing until dielectric breakdown occurs [3].

Several studies were conducted to evaluate the condition of stator winding insulation and analyze the effects of deteriorating factors on insulation system under accelerated aging process [4, 5].

The failure a HV motor due to dielectric breakdown can lead to the sudden stoppage of an entire system, possible as large as a power plant, leading to massive losses. Therefore, insulation diagnosis that is capable of evaluating the integrity of the insulating material of HV motors is becoming more and more important. One means of examining the integrity of the insulation involves dielectric strength testing whereby a voltage equal to double the HV motor's rated voltage plus 1 kV is applied for a certain period to determine whether the insulation is damaged. However, this method is used only in special cases, such as the factory testing required for the quality assurance of newly fabricated HV motor stator windings or rewound HV motors. For HV motors that exhibit issues in the field, a test that applies a voltage 1.25–1.5 times the rated voltage for 1 min is used in those cases in which there are problems with the insulation characteristics. This test is only infrequently applied, however [6, 7]. In general, to diagnose HV motors used in domestic industrial sites, test voltages are limited to within the rated voltage, and insulation resistance, polarization index, alternating current, dissipation factor, and partial discharge tests are usually conducted [8].

One of the important factors that determines the service life of the HV motor insulating material is the temperature. The service life of the insulating material is known to decrease by 50% for every 10°C increase in temperature, although there are other factors depending on the properties of the insulating material [9]. Therefore, the temperature of the HV motor stator windings is managed as a major monitoring item because any increase during the operation of the motor will accelerate the degradation of the insulation and possibly lead to a sudden failure [10].

In the present study, tests were conducted on a 6.6-kV HV motor in both the moist and dry states to investigate any changes in its characteristics. In addition, its insulation characteristics were analyzed by measuring the magnitudes of the insulation resistance, alternating current (AC), dissipation factor, and partial discharge as its temperature was varied from 100°C to 20°C.

2. Experimental Method

To investigate the changes in the insulation characteristics of an HV motor when moist and dry, the 6.6-kV HV motor stator windings, as used in power plants, were first steam cleaned and then subjected to an insulation diagnosis test while a large amount of moisture remained on the surfaces of the stator windings. Then, the stator windings were heated in a drying oven at 105°C for 12 h and then allowed to cool naturally to ambient temperature (21°C). The same test was repeated once the windings were dry, after which the results of the two tests were compared and analyzed. Figure 1 shows the cleaning of the HV motor with steam, while Figure 2 shows the insulation diagnosis test.

Figure 1. *Steam cleaning.*

Figure 2. *Insulation diagnosis test.*

In addition, to investigate how the insulation characteristics vary as the temperature changes, an insulation diagnosis test was conducted while the HV motor was being allowed to cool from 105°C in the atmosphere. The insulation was tested each time the surface temperature of the stator windings fell by 20°C, until they reached the ambient temperature (21°C). Figure 3 shows the HV motor in the drying oven.

Figure 3. *HV motor in drying oven.*

Insulation resistance, AC, dissipation factor, and partial discharge tests were conducted. The insulation resistance test involves applying DC 5,000 V, with the resistance being measured after 1 min. This test is used to confirm the basic insulation state required for operation and high-voltage applications. The AC test measures the current while the AC voltage is increased as shown in Figure 4. The test is conducted to obtain the AC current increase rate (ΔI) that represents the increment in the current at the rated voltage, compared to the current at the initial test voltage. The dissipation factor test measures the dissipation factor (tanδ) value while the test voltage is increased, as shown in Figure 5. The test also obtains the dissipation factor increase rate (Δtanδ) that represents the increment in the dissipation factor at the rated voltage compared to the dissipation factor at the initial voltage.

The rate of increase of the AC current (ΔI) and the rate of increase of the dissipation factor (Δtanδ) are closely associated with the partial discharge phenomenon. Discharge does not occur at low voltages, but occurs in any voids in an insulation system as well as in gaps between the windings and slots as the test voltage increases, thereby increasing the AC current and dissipation factor values. When slot discharge occurs, the partial discharge pulses at 180°–270° voltage phase angle are greater than at 0°–90°. [11, 12]

The AC and dissipation factor tests are used to examine the average degradation state of the insulating material because they determine the current and dissipation factor values for the insulating material.

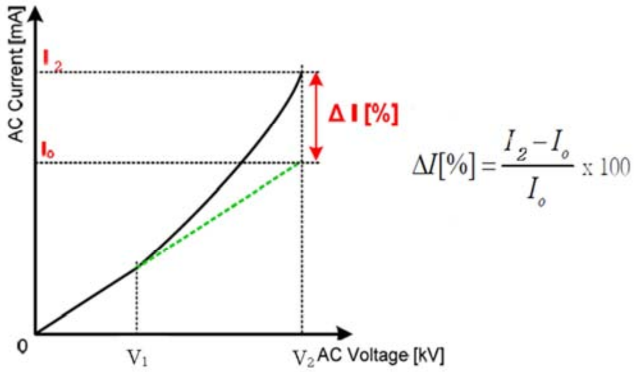

Figure 4. *Voltage-AC current.*

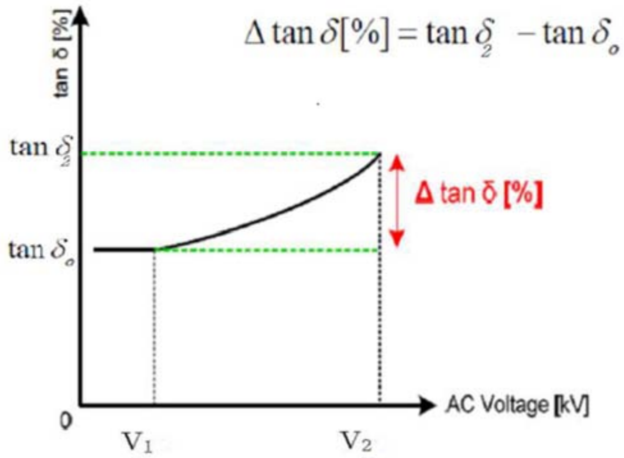

Figure 5. *Voltage-dissipation factor.*

The partial discharge test determines the largest of the generated partial discharge pulses at each instant while the test voltage is being increased. Given that the largest discharge pulse will be generated by the largest defect, this test can estimate the maximum size of a defect in an insulation system.

3. Results and Discussion

3.1. Changes in Insulation Characteristics Caused by Moisture Absorption

To investigate the changes in the insulation characteristics of a HV motor due to moisture absorption, insulation diagnosis tests were conducted when the motor was cleaned with steam, leaving moisture on the windings of the motor, and after the motor had been heated in a drying oven at 105°C for 12 h, after which it was allowed to cool to ambient temperature.

Table 1 lists the results of the insulation resistance measurements. The insulation resistance was found to be low immediately after the steam cleaning because a large amount of surface leakage current flowed through the moisture present on the surfaces of the stator windings. The resistance increased significantly, however, after the moisture had been removed by heating. This indicates that the insulation resistance is greatly affected by the presence of moisture.

Table 1. *Change in insulation resistance according to the amount of moisture on the stator windings.*

Test item	Insulation resistance [MΩ]
Test voltage	DC 5,000 [V]
Moist	132
Dry	8,600

Table 2 and Figure 6 show the results of the AC test. When a given voltage was applied, a higher current flowed while the windings were moist than when they were dry. However, the rate of increase of the AC current due to the increase in the test voltage was higher when the windings were dry than when they were moist.

Table 2. *Change in AC test results according to the amount of moisture on the stator windings.*

Voltage [kV]	AC current [mA]	
	Moist	Dry
0.95	162.2	115.9
1.91	324.4	231.8
2.86	486.1	347.9
3.81	648.2	472.2
4.76	811.2	596.1
5.72	974.6	731.4
6.6	1123.4	866.5
I0	1,120.96	800.98
ΔI [%]	0.22	8.18

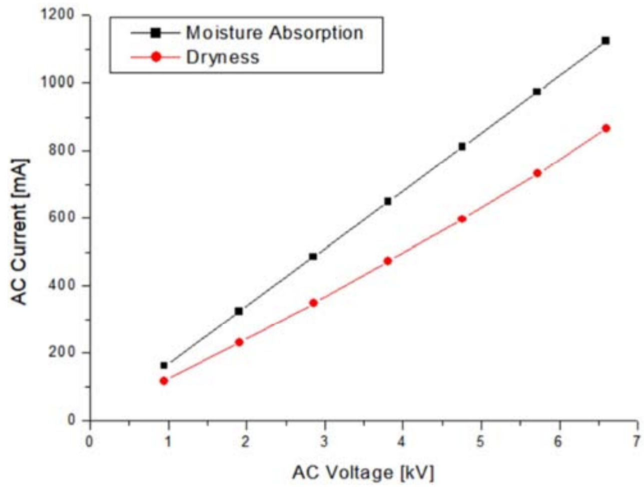

Figure 6. *Change in AC current according to the amount of moisture on the stator windings.*

Table 3 and Figure 7 show the results of the dissipation factor test. When a given voltage was applied, the dissipation factor (tanδ) was higher when the windings were moist than when they were dry, but the rate of increase of the dissipation factor was higher when the stator windings were high.

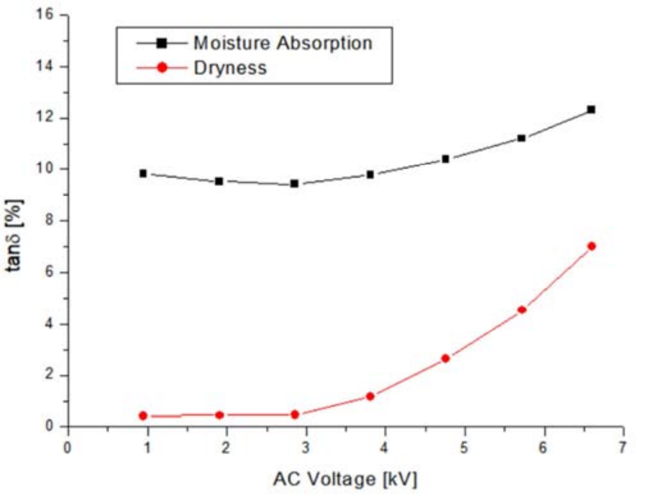

Figure 7. *Change in the dissipation factor according to the amount of moisture on the stator windings.*

Table 3. *Change in dissipation factor according to the amount of moisture on the stator windings.*

Voltage [kV]	tanδ [%]	
	Moist	Dry
0.95	9.81	0.42
1.91	9.53	0.43
2.86	9.42	0.46
3.81	9.78	1.41
4.76	10.4	2.64
5.72	11.2	4.54
6.6	12.3	7.01
Δtanδ [%]	2.88	6.58

Table 4 lists the results of the partial discharge test. The partial discharge value was higher when the stator windings were dry than when they were moist. The partial discharge inception voltage (PDIV) was lower when the windings were dry, indicating that the discharge started at a lower voltage but a larger discharge occurred when the stator windings were dry than when they were moist.

Table 4. *Change in discharge test results according to the amount of moisture on the stator windings.*

Voltage [kV]	Partial discharge magnitude [pC]	
	Moist	Cleaned/dry
PDIV [kV]	3.69 kV	2.9 8kV
3.81 kV (phase voltage)	900	4,600
6.6 kV (line voltage)	2,400	13,400

The AC, dissipation factor, and partial discharge tests are all associated with the partial discharge phenomenon that arises in an insulation system. Partial discharge occurs in any voids in the insulating material or in the gaps between the stator windings and slots. Partial discharge occurs when the potential difference is higher than the dielectric strength between both poles in these parts. However, when these parts are filled with moisture, even if a potential difference arises between both poles, the discharge phenomenon does not occur because a current flows. In particular, in the event of a slot discharge caused by damage to the semiconducting layer due to vibration of the stator windings in the slots, moisture can easily penetrate the gaps between the windings and slots, thereby making discharge difficult but causing a current to flow [12, 13].

Therefore, the current and dissipation factor values were larger when the stator windings were moist than when they were dry, but the rate of increase of the AC current (ΔI) and that of the dissipation factor (Δtanδ) were lower. In addition, partial discharge started at a lower voltage, while a larger discharge occurred when the stator windings were dry.

3.2. Change in Insulation Characteristics with Temperature

The HV motor was placed in a drying oven at 105°C for 12 h, and was then removed from the oven and allowed to cool naturally until it reached ambient temperature (21°C). Starting at 80°C, the insulation resistance, AC, dissipation factor, and partial discharge tests were conducted each time the surface temperature of the stator windings dropped by 20°C, such that the changes in the insulation characteristics with the temperature could be analyzed.

Table 5 lists the measured insulation resistances at each temperature.

Table 5. *Change in insulation resistance with temperature.*

Winding temperature [°C]	Insulation resistance [MΩ]
21	16,600
40	6,450
60	2,070
80	465

The insulation resistance measurements revealed that the insulation resistance was inversely proportional to the temperature of the stator windings.

Table 6 and Figure 8 show the results of the AC test at different surface temperatures of the stator windings. When a given voltage was applied, the AC current increased with the temperature. The rate of increase of the current (ΔI) as a result of an increase in the test voltage was also proportional to the temperature.

Table 6. *Changes in AC test results with temperature.*

Voltage [kV]	AC current [mA]			
	21°C	40°C	60°C	80°C
0.95	115.9	116.8	117.3	118.3
1.91	231.8	233.8	235.5	240.6
2.86	347.9	353.6	359.6	372.4
3.81	472.2	479.2	488.0	510.0
4.76	596.1	605.3	622.6	651.5
5.72	731.4	753.0	775.8	812.4
6.6	866.5	889.7	915.8	953.4
I0	800.98	807.9	813.77	831.39
ΔI[%]	8.18	10.13	12.54	14.68

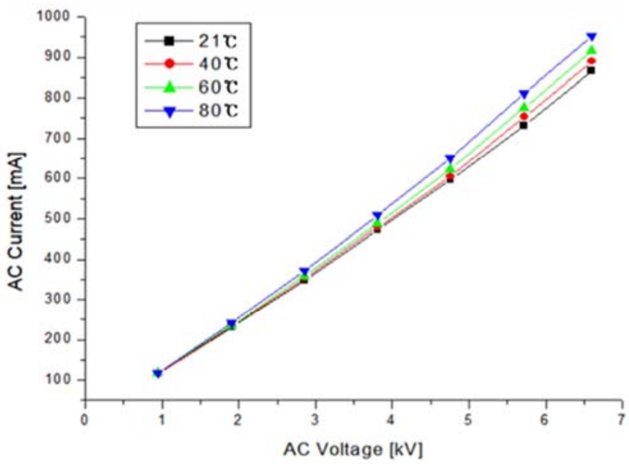

Figure 8. *Changes in AC current with temperature.*

The results of the dissipation factor test at each temperature are shown in Table 7 and Figure 9. In the same way as in the AC test, when a given voltage was applied, the dissipation factor value increased with the temperature. The rate of increase of the dissipation factor (Δtanδ) with the voltage increase was also proportional to the temperature. In addition, as shown in Figure 9, the dissipation factor started to increase from a lower test voltage as the temperature increased.

Table 7. *Changes in dissipation factor test results with temperature.*

Voltage [kV]	tanδ [%] 21°C	40°C	60°C	80°C
0.95	0.42	0.97	1.98	3.05
1.91	0.43	1.01	2.09	3.27
2.86	0.46	1.2	2.75	4.21
3.81	1.41	2.11	3.79	5.58
4.76	2.64	3.46	5.32	7.43
5.72	4.54	5.67	7.53	9.75
6.6	7.01	7.98	10.2	13.2
Δtanδ[%]	6.58	6.97	8.11	9.93

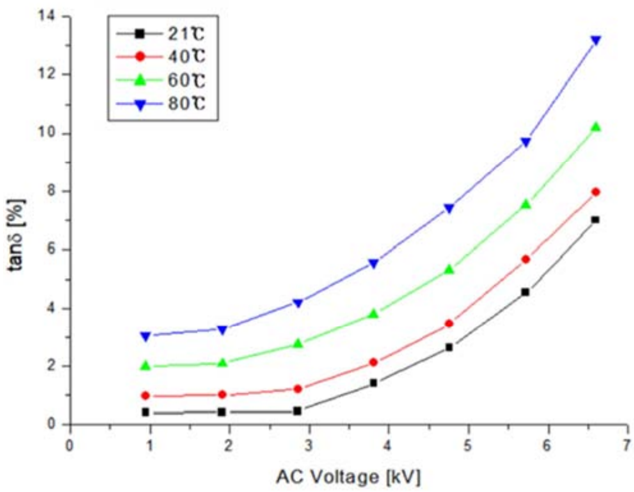

Figure 9. *Changes in dissipation factor with temperature.*

The results of the partial discharge test at different HV motor stator winding temperatures are listed in Table 8. When the partial discharge was measured, external noise was observed between 400 and 600 pC. In the same way as in the AC and dissipation factor tests, for a given test voltage, the partial discharge value increased with the temperature.

The PDIV value, which is the voltage at which partial discharge begins, decreased as the temperature increased, indicating that partial discharge started earlier as the temperature increased.

The partial discharge exceeded the criteria value of 30,000pC at 80°C and 6.6kV [14]

Table 8. *Changes in partial discharge test results with temperature.*

Winding temperature	Partial discharge [pC] Noise [pC]	PDIV [kV]	3.81 [kV]	6.6 [kV]
21°C	500	2.98	4,600	13,400
40°C	450	2.31	5,800	17,400
60°C	600	2.01	7,400	28,100
80°C	550	1.58	14,500	35,500

The AC current, dissipation factor, and partial discharge values increased in proportion to the temperature. This appears to be because the mobility of the electric charges increased with the temperature, such that the electric charges moved more easily despite there being less energy, thereby causing a more active partial discharge.

4. Conclusions

Tests were conducted to investigate the insulation characteristics of high-voltage (HV) motors according to the amount of moisture on the stator windings and their temperature. The results were as follows.

The insulation resistance was lower, the alternating current (AC) and dissipation factor were higher, and the rates of increase of the current (ΔI) and dissipation factor (Δtanδ) were lower when the stator windings were moist than when they were dry. In addition, the partial discharge was lower while the partial discharge inception voltage (PDIV) was higher. The rates of increase of the current (ΔI) and dissipation factor (Δtanδ), as well as the partial discharge are all closely related to the discharge phenomenon. This appears to be because moisture penetrates the gaps between the stator windings and slots, where discharge occurs, and reduces the potential difference between both sides when moisture is present, such that partial discharge does not occur but a current flows.

The effect of temperature on the test results was such that the insulation resistance decreased but the AC current and dissipation factor values increased with the temperature. Furthermore, the rates of increase of the current (ΔI) and dissipation factor (Δtanδ), as well as the partial discharge, all increased while PDIV decreased. It was found that the partial discharge was initiated at a lower voltage while the discharge increased with the temperature.

Therefore, for HV motors operating in environments in which the stator windings would be prone to absorbing moisture, such as in the salty air near the ocean, or underground, it is necessary to fully dry them prior to subjecting them to any tests because their insulation characteristics vary with the amount of moisture on their stator windings. Given that the results of the insulation resistance, AC, dissipation factor, and partial discharge tests, all of which are applied to the diagnosis of winding insulation, vary with the temperature of the windings, any such tests should only be implemented once the HV motor has cooled to the ambient temperature. Conducting such tests immediately after stopping the motors would result in errors in the analysis of results due to the high winding temperature.

For an insulation degradation analysis, it is more effective to analyze trends by keeping records of the results of previous tests, rather than relying on the absolute values of the test results. Therefore, to accurately analyze the insulation degradation trend, it is necessary that those tests always be conducted under the same conditions (temperature and moisture content). To this end, after cleaning a HV motor, it is desirable to dry it in an oven and then conduct the necessary tests only once it has cooled to ambient temperature.

References

[1] CIGRE Study Committee SC11, EG11.02, “Hydrogenerator Failures-Result of the Survey,” 2003.

[2] Motor Reliability Working Group, Report of Large Motor Reliability Survey of Industrial and Commercial Installations, Part I, IEEE Transactions on Industry Applications, vol. A-21, no. 4, p. 863, 1985.

[3] H. D. Kim, "Analysis of insulation aging mechanism in generator stator windings," J. KIEEME, vol. 15, no. 2, pp. 119–126, 2002.

[4] H. D. Kim, “Analysis of Insulation Quality in Large Generator Stator Windings,” Journal of Electrical Engineering & Technology, vol.6, no.2, pp.384-390, 2011.

[5] H. D. Kim, “Analysis of Insulation Aging Mechanism in Generator Stator Windings,” Journal of the KIEEME, vol.15, no. 2, pp. 119-126, 2002.

[6] IEEE Std. 95-1977, Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High direct Voltage, pp. 13, 1977.

[7] IEEE Std. 56-1997, IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10,000 kVA and Larger), pp. 12, 1997.

[8] H. D. Kim, T. S. Kong, Y. H. Ju, B. H. Kim "Analysis of insulation quality in large generator stator windings," J. Electr. Eng. Technol., vol. 6, no. 2, pp. 384–390, 2011.

[9] IEEE Std. 43-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, p. 10, 2000.

[10] EPRI Research Project 2814-35 Final Report, Electric Motor Predictive and Preventive Maintenance Guide, pp. 4–2, 1992.

[11] IEEE Standard, "Trial-use guide to the measurement of partial discharges in rotating machinery," IEEE Std 1434-2000, pp. 40, 2000.

[12] 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.

[13] T. S. Kong, “Analysis of partial discharge patterns for generator stator windings,” Am. J. Electr. Power Energy Syst., vol. 4, no. 2, pp. 17–22, 2015.

[14] J. H. Dymond, N. Stanges, K. Younsi and J. E. Hayward, “Stator Winding Failures : Contamination, Surface Discharge, Tracking”, IEEE Trans. on Industry Application, Vol. 38, No. 2, pp. 577-583, 2002.

[15] H. Yoshida and U. Umemoto, “Insulation Diagnosis for Rotating Machine Insulation”, IEEE Trans. on Electric Insulation, Vol. EI-21, No 6, pp. 1021-2025, 1986.