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고압전동기 고정자 권선의 절연열화 평가

Assessment of Insulation Deterioration in Stator Windings of High Voltage Motor

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(Hee-Dong Kim · Tae-Sik Kong)

Abstract - To assess the insulation deterioration of stator windings, diagnostic and AC breakdown tests were performed on the eleven high voltage (HV) motors rated at 6kV. After completing the diagnostic tests, the AC overvoltage test was performed by gradually increasing the voltage applied to the stator windings until electrical insulation failure occurred, to obtain the breakdown voltage. Stator winding of motors 1, 3, and 8 failed at above rated voltage at 14 kV, 13.8kV, and 16.4kV, respectively. The breakdown voltage of three motors was higher than expected for good quality windings in 6kV motors. Based on deterioration evaluation criteria, the stator winding insulation of eleven HV motors are confirmed to be in good condition. The turning point of the current, P_{i2}, in the AC current vs. voltage characteristics occurred between 5kV and 6kV, and the breakdown voltage was low between 13.8kV and 16.4kV. There was a strong correlation between the breakdown voltage and various electrical characteristics in diagnostic tests including Pi2.

Key Words : Assessment, Insulation deterioration, Stator winding, High voltage motor, Diagnostic test, Breakdown voltage, Dissipation factor, Partial discharge

1. Introduction

Failures caused by stator winding insulation deterioration of high voltage (HV) motors operating in power plant facilities can have a serious impact on the power system reliability. In an operating motor, several stresses including thermal, electrical, mechanical, and environmental stresses can give rise to defects like void in insulating materials. As the continuous and diverse motor operating stresses gradually accelerate the insulation deterioration, the voids grow in quality and size. This process triggers a sharp decrease in dielectric strength and ultimately results in the insulation breakdown [1].

According to a survey performed by the Electric Power Research Institute (EPRI), 37% of all motor failures can be attributed to stator winding problems among 7,500 large motors in utility generation stations (rated 2.3kV and above) [2]. Meanwhile, the Japanese established a judgement criteria for insulation deterioration as a result of rigorous studies by its motor manufacturers on the diagnostic tests, which were carried out in the mid of 1970s and 1980s to evaluate insulation condition of HV motor stator windings [3]. Nondestructive testing that applys the rated voltage or below to the windings is commonly used as diagnostic tests. Insulation quality indicators such as insulation resistance, polarization index (PI), AC current, dissipation factor (tanδ), and partial discharge (PD) magnitude have been the most commonly used indicators for assessing the insulation condition. In Korea, these tests have become widespread from the early 2000s, and now private companies also actively carry out the test. In particular, HV motors that have been in service for more than 10 years are tested once every three years during its planned maintenance period. A noticeable variation in the trend of the above-mentioned insulation condition indicators over time is observed for signs of insulation degradation [4].

In this paper, diagnostic and AC breakdown tests were carried out on stator windings of eleven 6kV motors in a thermal power plant. The insulation deterioration of motor stator windings was assessed by analyzing the correlation between breakdown voltage and electrical characteristics of the diagnostic tests.

2. Insulation specimen under investigation and experimental procedure

Table 1 shows the nominal ratings of eleven HV motors in a thermal power plant. The insulation system for HV motors generally consist of mica tapes and binders such as asphalt, polyester and epoxy resins. Motors 1 and 3 were manufactured in 1975 with polyester resin-bonded, mica tapes stator insulation and have been

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in service for more than 35 years. The stator windings of the rest of the nine HV motors were made of mica tapes and epoxy resin-bonded insulations. Motors 4 and 10 were manufactured in 1994 and 1997, respectively. The rewind program for motor stator insulation began in 1989 based on the insulation condition estimated from the diagnostic test results. As a result, stator rewind of seven HV motors excluding motors 1, 3, 4, and 10 was recommended and all the motors have rewound between 1989 and 2003, as summarized in Table 1. The surface of coils was wound with overlapping layers of tape, and the motor stators were made from standard insulating processes consisting of a prebake, global VPI (Vacuum Pressure Impregnation) cycles, and thermal curing. The assessment criteria for motor stator coils with polyester or epoxy resins and mica tapes performed a significant role for avoiding unexpected insulation failure.

Table 1 Nominal ratings of HV motors

HV motor No.	Rated capacity [kW]	Rated voltage [kV]	Insulation class	Year of manufacture or rewind	Maintenance history
1	4,900	6	B	1975	Original
2	4,900	6	F	2001	Rewound
3	4,900	6	B	1975	Original
4	4,900	6	F	1994	New
5	4,900	6	F	2003	Rewound
6	1,050	6	F	2001	Rewound
7	400	6	F	1991	Rewound
8	2,700	6	F	1989	Rewound
9	2,700	6	F	1993	Rewound
10	3,000	6	F	1997	New
11	1,200	6	F	1998	Rewound

The diagnostic tests included measurements of polarization index (PI), AC current, dissipation factor (tan δ) and partial discharge (PD) magnitude. PI was measured using an automatic insulation tester (Megger, S1-5010) at DC 5kV for each motor before applying AC voltage to the stator windings. Devices such as the Schering bridge (Tettex Instruments), coupling capacitor and PD detector (Tettex Instruments, TE 571) were used to measure the AC current, dissipation factor and PD magnitude. The Schering bridge consists of a HV supply (Type 5283), bridge (Type 2818) and resonating inductor (Type 5285). AC voltage was applied to the HV motor stator windings through a schering bridge connected to the windings while the coupling capacitor (Tettex Instruments, 4,000pF) amplified the signals from the windings by sending it to the coupling unit (Tettex Instruments, AKV 572) for the PD detector to analyze the PD magnitude and pattern. The frequency band of the PD detector ranged from 40 kHz to 400 kHz. Since the magnitude of the PD in HV motor stator windings ranges between 1,300 and 9,200pC at 1.25 times of the line-to-ground voltage, it was measured in a general laboratory where background noise ranged between 400 and 500pC. The diagnostic and AC breakdown tests were carried out on the stator windings from the eleven 6kV motors at a voltage between 1.0 to 6.6kV. After the diagnostic tests were completed, a variable HV supply (AC 50kV) and a bridge (Type 2819) were used to gradually increase the AC voltage applied to each motor in 1kV intervals until electrical breakdown occurred in the stator windings to measure the AC current, dissipation factor and the breakdown voltage. The diagnostic test method that provides a good estimate of the breakdown voltage for motor stator insulation was investigated based on this data.

3. Results and discussion

The insulation condition indicators measured from the diagnostics tests include the PI, the increase rate of charging current (ΔI), the increase of dissipation factor (Δ tanδ), 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}) [3]. The insulation condition can be assessed by comparing the diagnostic test results between the different 6kV motors with similar insulation[4].

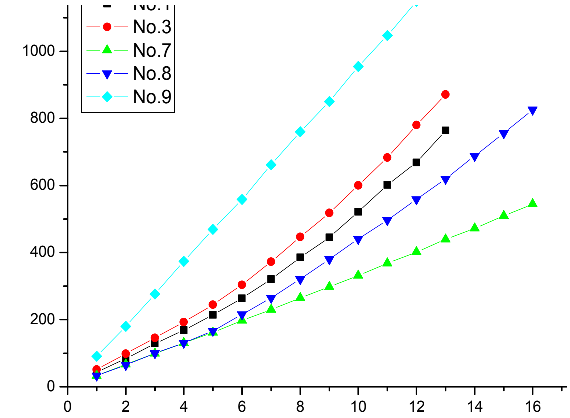
When the stator insulation is dry, the PI will also tend to be high, in the range of 2.16 to 10.81 as shown in Table 2. The PI (above 2.0) of all eleven motors indicated that the stator insulation is in dry condition [5]. Fig. 1(a) shows the change in current where the three phases encapsulated AC voltage was gradually increased in motors 1, 3 and 7~9 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 there is no established evaluation criteria to confirm insulation deterioration for 6kV motors, and ΔI was calculated based on the data from 6.6kV motor to apply its insulation deterioration criteria to 6kV motors. As summarized in Table 2, ΔI ranged from 5.48% to 9.29% in motors 1, 3 and 8 at 6.6kV while ΔI at 13kV ranged between 39.3%

and 46.65%. The ΔI of motors 7 and 9 at 6.6kV were 1.78% and 5.44%, respectively. An ΔI of over 10% in 6.6kV motors is usually considered to indicate deteriorated insulation [6]; however, eleven HV motors were determined to be in good condition because their ΔI were low with values between 0.90% and 9.29% at 6.6kV. But for motors 1, 3, and 8, ΔI were fairly high with 40.43%, 39.3% and 46.65%, respectively when the motors were analyzed based on ΔI at 13kV. For motors 7 and 9, ΔI at 13kV were low with 4.93% and 7.03%, respectively.

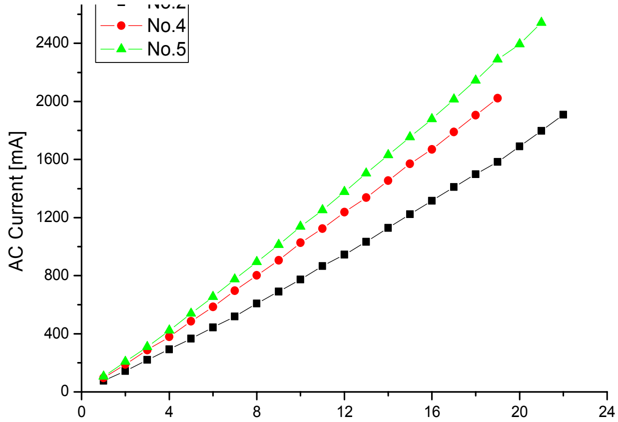
Table 2 Test results of PI and AC current for 6kV motors

HV motor No.	PI	ΔI[%] at 6.6[kV]	ΔI[%] at 13[kV]	P_{i1}[kV]	P_{i2}[kV]
1	2.99	5.48	40.43	3.6	6
2	8.13	3.68	9.64	5.5	10
3	10.81	7.41	39.3	3.5	5.2
4	7.28	4.46	6.82	4.3	8.3
5	3.80	7.28	13.72	5.0	8.7
6	9.80	6.38	29.6	4.8	10
7	4.28	1.78	4.93	5.0	12
8	5.55	9.29	46.65	3.8	5
9	2.16	5.44	7.03	5.0	9.6
10	6.44	1.41	9.58	5.4	10
11	6.02	0.90	2.95	4.2	11

The P_{i1} voltage for motors 1, 3 and 8 were 3.6kV, 3.5kV and 3.8kV, respectively, and their P_{i2} voltage were 6kV, 5.2kV and 5kV, respectively. The P_{i1} and P_{i2} voltages for motors 1, 3, and 8 were relatively lower compared to those of other motors. As shown in Fig. 1(a), the AC current vs. voltage traces for motors 7 and 9 were almost linear. The P_{i1} voltages for motors 7 and 9 were both 5.0kV while their P_{i2} voltages were 12kV and 9.6kV, respectively. These results indicate that the stator winding insulation of motors 7 and 9 are in very good condition. As shown in Fig.1(b), the AC current vs. voltage traces for motors 2, 4 and 5 were almost linear. The P_{i1} voltage for motors 2, 4 and 5 were 5.5kV, 4.3kV and 5.0kV, respectively, and their P_{i2} voltage were 10kV, 8.3kV and 8.7kV, respectively. And the P_{i1} voltage for motors 6, 10 and 11 were 4.8kV, 5.4kV and 4.2kV, respectively, and their P_{i2} voltage were 10kV, 10kV and 11kV, respectively.



(a) Motors 1, 3 and 7~9



(b) Motors 2, 4 and 5

Fig. 1 Comparison of AC current vs. voltage characteristics in HV motors

The change in the dissipation factor while AC voltage applied to the stator winding was gradually increased until it reached the breakdown voltage, is shown in Fig. 2. As the applied voltage increases and the dissipation factor increases. The Δtanδ had to be calculated based on the data from a 6.6kV motor to apply the available insulation deterioration criteria to a 6kV motor as in the case of ΔI. As it can be seen from Fig. 2, the dissipation factor increased abruptly between 3.5kV and 5kV. As summarized in Table 3, for motors 1 to 11, the Δtanδ measurements were between 0.24% and 7.56% (according to [6], Δtanδ above 8.5% is considered to indicate bad insulation condition). Therefore, the insulation condition of the stator winding for all eleven motors were assessed to be in good condition because their Δtanδ values were below 8.5%. As in the ΔI case, Δtanδ for motors 1, 3, an 8 were fairly high with 22.28%, 19.41%, and 23.34%, respectively, when the motors were analyzed based on the Δtanδ measurement at 13kV. AC breakdown voltages were high (above 19.8kV) for motors with tanδ lower than 16%. But the AC breakdown voltages were relatively low between 13.8kV and 16.4kV for motors 1, 3, and 8, which had high value of tanδ above 16% in Fig. 2 [6]. As shown in Fig. 2, tanδ for motors 2, 7 and 9 were below 8%, and their Δtanδ measurements were also low with 4.56%, 2.66% and 3.42%, repsectively, at 13kV. Thus tanδ for motors 7 and 9 were low as motor 2. It is expected that electrical breakdown occurred at relatively high voltage (above 19.8kV).

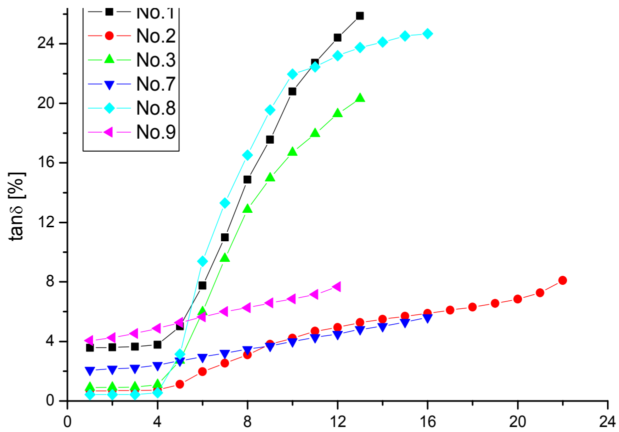


Fig. 2 Comparison of tanδ vs. voltage characteristics for HV motors

Table 3 Test results of PDIV, tanδ, PD magnitude and breakdown voltage for 6kV motors

HV motor No.	PDIV [kV]	Δtanδ[%] at 6.6[kV]	Δtanδ[%] at 13[kV]	PD Magnitude [pC] at 4.33[kV]	Breakdown voltage [kV]
1	3.4	4.78	22.28	4,400	14.0
2	3.5	1.57	4.56	6,000	22.0
3	3.8	6.42	19.41	3,200	13.8
4	3.5	2.35	3.49	6,300	19.8
5	3.5	3.94	4.27	9,200	21.1
6	3.5	4.78	11.39	2,800	22.3
7	4.1	1.15	2.66	2,600	17.0
8	3.8	7.36	23.34	6,400	16.4
9	4.2	2.13	3.42	1,300	12.9
10	4.5	0.75	5.32	5,400	25.2
11	4.5	0.24	1.28	4,200	19.8

The partial discharge inception voltage (PDIV) 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. PDIV refers to the voltage when the PD magnitude starts to exceed the background noise level of hundreds of pC, and goes above 1,000pC. As can be seen from Fig. 2, since dissipation factor abruptly increases between the range of 3.5kV and 5kV, PDIV is also expected to occur within this range. The PDIV measurements at the site were between 3.4kV and 4.5kV, as predicted. This voltage is also consistent with the P_{i1} in Fig.1, as stated earlier. Therefore, when insulation deterioration occurs in the HV motor stator windings, increasing point of dissipation factor, P_{i1} of AC current and PDIV both decrease, and dielectric breakdown voltage also decreases[6].

As in the cases of ΔI and Δtanδ measurements, PD magnitude had to be calculated based on the data from the 6.6kV motor to apply its insulation deterioration criteria to the 6kV motor, as there was no criteria for the 6kV. The PD magnitude of the stator windings form all eleven motors ranged between 1,300 and 9,200pC at 4.76kV (1.25 times of the line-to-ground voltage). Since the PD magnitude under 10,000pC at 4.76kV is considered to indicate good insulation condition, all eleven motors were assessed to be in fair condition [6]. From the results of the ΔI, Δtanδ and PD magnitude measurements analyzed at 6.6kV, insulation deterioration evaluation criteria for 6.6kV motor were proved to be valid for the 6kV motor.

For the eleven HV motors, the ΔI and Δtanδ measurements are compared at 6.6kV and 13kV as shown in Tables 2 and 3. When the values of ΔI and Δtanδ are high, the breakdown voltages is low (between 13.8kV to 16.4kV), as can be seen for motors 1, 3, and 8. If dielectric strength of 6kV motors is above 2E+1kV or 13kV, its insulation condition is generally considered to be good enough for operation. Thus motors 1, 3, and 8 were qualified to be operated although the tests showed signs of dielectric strength deterioration. For significantly degraded insulation, almost all the defects may contribute to high dissipation factor even at low voltage [4]. Motors 1 and 3 have been in operation for more than 35 years and these motors were subjected to excessive insulation aging by thermal, electrical or mechanical stresses. When exposed to thermal stress for a long period of time, the internal gas pressure increases and adhesive strength of epoxy to mica surface decreases causing insulation structural defects, which leads to delamination at the interface between mica and epoxy. As the total number of defects increase, the insulation quality indicators such as ΔI and Δtanδ become worse [7]. Electrical stress also as a significant impact on the process of insulation deterioration and the breakdown.

Motors 2 and 5 were tested after they had been rewound after more than 9 years and 7 years of operation, respectively. Motors 2 and 5 (4,900kW, 6kV) had identical ratings and load, and the ΔI measurements at 13kV were 9.64% and 13.72%, and their Δtanδ measurements at 13kV were low with 4.56% and 4.27%, respectively. As shown in Fig. 1(b), the value of P_{i1} for the two motors was 5.5kV and 5.0kV, while P_{i2} occurred between 10kV and 8.7kV. The breakdown voltage measurements were high at 22.0kV and 21.1kV, respectively, as expected for motors with good results from the diagnostics tests. Motors 4 and 10 have been in operation for more than 16 years and 13years, respectively, and they have not been rewound at the time of insulation testing. The ΔI measurement of motors 4 and 10 at 13kV were 6.82% and 9.58%, and theirΔtanδ measurements at 13kV were low with 3.49% and 5.32%,respectively. The P_{i1} for both motors were 4.3kV and 5.4kV, and P_{i2} occurred between 8.3kV and 10kV. As expected, the breakdown voltage was high at 19.8kV and 25.2kV. Motors 6 and 11 have been in operation for more than 9 years and 12 years, respectively, after rewinding the stator. The ΔI measurements of motors 6 and 11 at 13kV were 29.6% and 2.95%, and their Δtanδ measurements at 13kV were 11.39% and 1.28%, respectively. The P_{i1} measurements for both motors were 4.8kV and 4.2kV, and P_{i2} occurred at 10kV and 11kV. The breakdown voltage was relatively high at 22.3kV and 19.8kV. It can be seen from the measurements summarized in Tables 2 and 3 that the stator insulation from six motors (2, 4, 5, 6, 10 and 11) was in good condition.

The ΔI measurements for motors 7 and 9 at 13kV were 4.93% and 7.03% and their Δtanδ at 13kV were relatively low at 2.66% and 3.42%, respectively. As shown in Fig. 1(a), P_{i1} for both motors were 5kV, and P_{i2} occurred between 12kV and 9.6kV. The breakdown voltage occurred at relatively low voltage, at 17kV and 12.9kV, respectively. The lowest breakdown voltage was measured at 12.9kV for motor 9, which is lower than that expected for good stator windings in 6kV motor. As stated earlier, the insulation of the two HV motors was in very good condition and electrical breakdown occurred due to the defects in HV lead cable. It is suspected that electrical breakdown between the lead cable and outer casing or stator core kept from P_{i2} occurring. Electrical breakdown for the remaining nine motors also occurred in their slot end portion.

The relationship among the three types of measurements is complicated in analysis of diagnostic test results. The three types of measurements included AC current, dissipation factor, and partial discharge. The electrical stress distribution under AC voltage is quite different for motors with good insulation. It may become even more complicated for significantly deteriorated insulation. Different type of defects may be responsible for failure of severely degraded insulation under diagnostic and AC breakdown tests. More research is required to clarify the relationship between diagnostic and AC breakdown tests [10].

Since motors are subject to frequently starts/stops and thermal stress, and electrical and mechanical stresses are concentrated on the slot end of stator windings in HV rotating machines, most electrical breakdowns occur at the slot end [6, 8]. Failures of HV motor stator winding insulation usually occur due to defects in the groundwall or turn insulation, and the failure mechanism involves the gradual development of a weakness in the insulation. This weakness is usually caused by a trapped void that is gradually and continuously grows in size due to a combination of the above-mentioned operating stresses and corona or PD activity [9]. The condition of new and rewound motor insulation is almost the same in the results of diagnostic and AC breakdown tests shown above.

The breakdown voltage, P_{i2}, and the results of diagnostic tests of new, old and rewound motors were measured with regard to mica-insulated coils impregnated with polyester and epoxy resins. A strong correlation between the breakdown voltage and the various diagnostic tests including P_{i2} could be observed. WhenP_{i2} occurred between 5kV and 6kV in the AC current vs. voltage characteristics, the breakdown voltage was low between 13.8kV and 16.4kV.W hen P_{i2} measurement was both 10kV, the breakdown voltage was high between 22.3kV and 25.2kV. This shows that there is a strong positive correlation between the breakdown voltage and P_{i2}.

As stated earlier, P_{i2} occurred more than 5kV and all motors with stand 2E+1kV the stator winding need not rewind. These motors have a minimum remaining service life. The breakdown voltage of stator winding is higher than the 2E+1kV test voltage and the dielectric strength is still higher [10]. Based on test results of insulation deterioration, KEPCO now has established a diagnostic method of applying a 2E+1kV a cover potential test to HV motors in order to estimate a remaining service life.

4. Conclusion

In this paper, a number of diagnostic and AC breakdown tests have been performed on the stator winding obtained from eleven 6kV motors in a thermal power plant. The conclusions drawn from the tests can be summarized as follows:

The results of diagnostic tests that include the AC current, dissipation factor and PD magnitude indicated that the stator windings from the eleven 6kV motors are in good condition. At 6.6kV and 13kV, when the ΔI and Δtanδ measurements are high, the breakdown voltage of motors 1, 3, and 8 were relatively low between 13.8kV and 16.4kV. Thermal stress causes insulation structure defects, and as the total number of defects increases, diagnostic characteristics such as ΔI and Δtanδ become worse.

Insulation condition of new and rewound motors were almost the same according to the results of diagnostic and AC breakdown tests.

The voltage at which dissipation factor shows an abrupt increase is almost the same as that of the PDIV measurements. This voltage is also consistent with the P_{i1} of AC current vs voltage characteristics. When the insultion quality indicators such as the dissipation factor, PDIV, and ΔI indicated good insulation condition, the electrical breakdown voltage was relatively higher. The breakdown voltage showed a positive correlation with the various electrical characteristics in diagnostic tests assessed in this paper. The correlation was especially strong with to the value of P_{i2}. In the future AC breakdown test will be performing many 6kV motors. These results will be used to estimating the remaining service life of motor stator windings.

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References

[1] I.M. Culbert, H. Dhirani and G.C. Stone, *Handbook to Assess the Insulation Condition of Large Rotating Machines*, (EPRI,EL-5036,1989).

[2] G.C. Stone and J.Kapler, "Stator Winding Monitoring", IEEE Industry Applications Magazine, pp. 15-20, 1998.

[3] H. Yoshida and U. Umemoto, "Insulation Diagnosis for Rotating Machine Insulation", IEEE Trans. on Electrical Insulation, Vol. EI-21, No. 6, pp. 1021-1025, 1986.

[4] B.K. Gupta and I.M. Culbert, "Assessment of Insulation Condition in Rotating Machine Stators", IEEE Trans. on Energy Conversion, Vol. 7, No.3, pp. 500-508, 1992.

[5] IEEE Standard 43-2000, "IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery"

[6] Hee-Dong Kim, "Judgement Criterion of Insulation Deterioration in 4.16kV and 6.6kV Motor Stator Windings", Trans. KIEE. Vol. 58, No. 4, pp. 788-794, 2009.

[7] 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.

[8] H.G. Sedding, R. Schwabe, D. Levin, J. Stein and B.K. Gupta, "The Role of AC & DC Hipot Testing in Stator Winding Aging", IEEE EIC/EMCW Conference, pp. 455-457, 2003.

[9] J.H. Dymond, N. Stranges, K. Younsi, and J.E. Hayward, "Stator Windings Failures: Contamination, Surface Discharge, Tracking", IEEE Trans. on Industry Applications, Vol. 38, No. 2, pp. 577-582, 2002.

[10] J.E. Timperley and J.R. Michalec, "Estimating the Remaining Service Life of Asphalt-Mica Stator Insulation", IEEE Trans. on Energy Conversion, Vol. 9, No.4, pp. 686-693, 1994.

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