A Study on the Breakdown Mechanism of Rotating Machine Insulation

Hee-Gon Kim, Hee-Soo Kim, and Yong-Kwan Park

Abstract

A lot of experiments and analyses have been done to determine the aging mechanism of mica-epoxy composite material used for large generator stator windings in order to estimate remaining life of the generator for last decades. After degrading artificially the mica-epoxy composite material, the surface analysis is performed to analyze breakdown mechanism of insulation in air and hydrogen atmosphere; i) In the case of air atmosphere, it is observed that an aging propagation from conductor to core by partial discharge effect and the formation of cracks between layers is widely carbonized surface. ii) In case of hydrogen atmosphere, the partial discharge effect is reduced by the hydrogen pressure(4kg/cm^2). Potassium ions forming a sheet of mica is replaced by hydrogen ions, which can lead to microcracks. It is confirmed that the sizes of crack by SEM analysis are 10~20[μm] in diameter, 200~400[μm] in length under air, and 1~5[μm] in diameter, 10~50[μm] in length under hydrogen atmosphere respectively. The breakdown mechanism of stator winding insulation materials which are composed of mica-epoxy is analyzed by the component of materials with EDS, SEM techniques. We concluded that the potassium ions of mica components are replaced by H^+, H_3O^+ at boundary area of mica-epoxy and/or mica-mica. It is proposed that through these phenomena, the conductive layers of potassium enable creation of voids and cracks due to thermal, mechanical, electrical and environmental stresses.

I. Introduction

The insulation breakdown due to degradation of generator insulation materials in service is inevitable. To prevent this insulation breakdown, the techniques of prediction and assessment of insulation condition are required greatly. Over the past a few decades, the aging condition of a generator has been estimated by non-destructive tests, however, the accurate estimation in various operation condition is not accomplished by complicated aging processes and required high techniques[1]. In large generators and motors in power plants, stator winding insulation is exposed to a combination of thermal, electrical, vibrational, thermo-mechanical and environmental stresses during service operation. In the long term, the multi-stresses cause an aging which leads to final insulation breakdown. For the reason, it is important to estimate the remaining insulation integrity of the winding after a period of service time. Previous studies have utilized non-destructive values such as insulation resistance, polarization index, dielectric dissipation factor and partial discharge to diagnose an insulation condition and the relationship of these values and breakdown voltage have proposed new life factors by way of a comparison of model bars and the stator windings of an operating generator[2]. However, according to the types of insulation material and test conditions, opposite opinions existed, too[3]. At present, because not only how to determine remaining life or breakdown voltage is not cleared but also the remaining life by abstract and experimental studies are estimated, it is judged that more accurate life assessment and expectation by way of a searching examination of aging process is deserved as an economic and academic study[4].

In this paper on this basis, after aging artificially stator winding insulation materials, the degrading mechanism is determined through the analysis of the surface and component by using SEM, EDS techniques. To simulate the stator winding of an operating generator more precisely and to supplement the defects of insulation diagnosis, we discussed the cause of insulation breakdown under air and hydrogen.

II. Experimental System

The stator winding studies in this paper is used in the water-cooled generator of 500[MVA], 22[kV]. To test the insulation breakdown of material by accelerated aging, an end winding has

Manuscript received February 10, 1997; accepted April 19, 1997.
H. G. Kim and H. S. Kim are with KEPRI, 103-16, Munji-dong, Yusung-ku, Taejon, Korea.
Y. K. Park is with Sungkyunkwan Univ., 300, Chunchun-dong, Jangan-ku, Suwon, Korea.

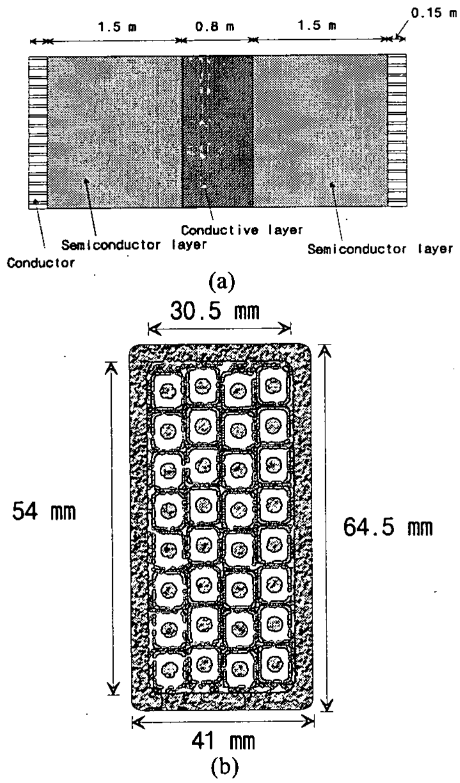


Fig. 1. The dimensions of stator winding used by testing.

been manufactured with straight line type as shown in Fig. 1(a). Fig. 1(b) shows the front view of stator winding. Also, to compare electric aging test of stator winding in hydrogen with that in air, a pressure hydrogen apparatus which can measure electric aging of stator winding under pressure hydrogen is manufactured and applied to 420[Hz], 27.5[kV/mm] voltage a stator winding. The bushing of 77[kV] is installed at upper part of a pressure hydrogen apparatus. As shown in Fig. 1(a) (b), specimens are made as follows:

1. The stator winding (30.75×54[mm]) with a strand (4.27×7.14 [mm]) is wound mica-epoxy tape, 1/2 folds and 14 wind.
2. It is inserted in tank and hardened at 130[℃].
3. A conductive bonding material is spread.
4. After a glass tape is wound, it is dried more than 8 hours in air.

A low resistance painting is applied on the straight line part of a stator winding and a high resistance painting is applied on the arm part. The final dimension of stator winding is 41×64.5 [mm]. A general method to age electrically is to heighten the voltage. And the typical insulation of a stator winding is designed to operate between 2 [kV/mm]~3 [kV/mm]. In accelerated aging specimen with voltage above 6 [kV/mm], aging is progressing abnormally, so it is tested with a limit value of 5.5 [kV/mm], which does not generate partial discharge[5]. JSM-6400 Model, SEM is manufactured by Jeol Co. has been used equipped with EDS, 6209 Model from Oxford Co.

Ⅲ. Results and Discussions

1. Surface Analysis of Insulation Breakdown Specimens

The specimens which are obtained in ruptured parts of stator winding which is broken in air are shown in Fig. 2. To investigate insulation breakdown on the specimens, ruptured parts were divided into 4 parts, in depth 1.25 mm. Fig. 3 shows the surface of failed samples under hydrogen atmosphere. As shown in Fig. 2, on specimens ruptured in air, it can be observed that carbonization of conductor electrode is narrow because partial discharge effects on the crack area is occured layer by layer. However, propagating from the middle of insulation material to core side, the carbonization is distributed over wide areas. The surface of failed samples under hydrogen atmosphere is carbonized more narrowly because partial discharge is reduced by the presence of hydrogen ion and the effect of pressure. On components made of mica, a potassium ion that atomic radius is big, is replaced by hydrogen ion that atomic radius is small. It is expected that the microcracks which are formed by rearrangement of ions, absorb the stress and heat generated from partial discharge. Therefore, in this case, the carbonized areas are narrow.

Metal ions such as potassium which can be replaced by hydrogen in metal layers, form the interface parts of mica-mica and mica- epoxy because these conductive layers are progressed by the connection following up the passage of time. As the failed time is shortened, the carbonized parts created by a partial discharge heat are narrow and breakdown aspects are straight. Also, the formation of conductive potassium layers is generated a tree degradation by the effects of localized high electric field which is created to an adjacent area of conductive layers. Fig. 4 shows the surface of materials by SEM and its analysis by EDS. The breakdown area of the outer surface indicates peaks corresponding to, and which are the elements of muscovite mica. The diameter and the length of a tree channel was approximately 10~20[μm] and about 200~400[μm] respectively. For more detailed analysis, on failed sample under air atmosphere, metallic elements as *Na, Mg, Fe, Ca,* have revealed. It is assumed that a mica is altered as *Mg, Fe* are replaced by *Al*, $AlO(OH_2)$ (aluminum octahedrons) layers and *Si* of SiO_4 (tetrahedrons) layers of mica components ionized by partial discharge heat which is generated when insulation material is failed. Especially, *Na* is altering paragonite ($NaAl_2(OH)_2Si_3AlO_{10}$) by replaced potassium, and *Ca* is altering margarite ($CaAl_2(OH)_2Si_2Al_2O_{10}$). Also, when components as *Ma, Fe* ionized in air are replaced by *Si, Al*, a mica forms a negative electric charge and it can be assumed that the components of *Mg, Fe* provide space that a

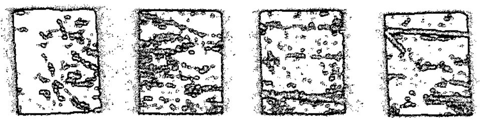


Fig. 2. The 4-divided surface of insulation breakdown layers in air.

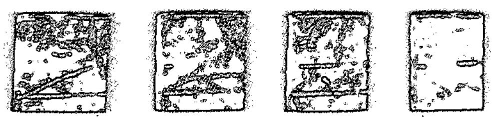


Fig. 3. The 4-divided surface of insulation breakdown layers in hydrogen.

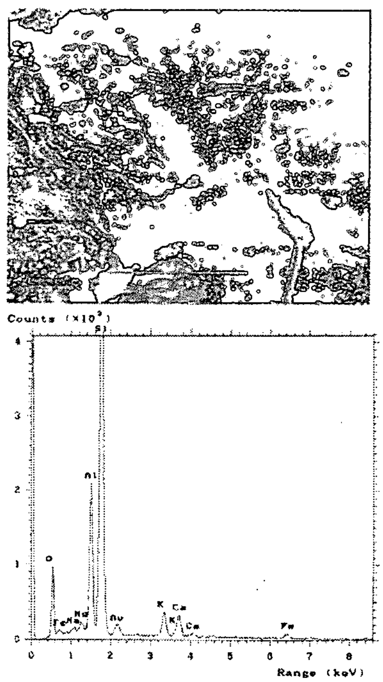


Fig. 4. The EDS and SEM analysis of breakdown sample in air.

potassium ion can occupy[6, 7].

When compared with the diameter of cracks of conductor and core sides, in case of air atmosphere, a tree channel initiates especially from an edge of the conductor of interface sites near the half-lapped mica tape. The diameter of the tree channel at copper side is 1~5[μm], while the diameter of core side is 50~100[μm]. It can be assumed that cracks are as progressive as possible to a core side, and that the effects of partial discharge is bigger. However, in case of hydrogen atmosphere, the tree channel of copper conductor side is bigger because of generation of partial discharge restricted by the effects of hydrogen pressure in the core side. As shown in Fig. 5, the results of failed samples under hydrogen atmosphere are that the diameter and the length of the tree channel are approximately 1~5[μm], 10~50[μm] respectively.

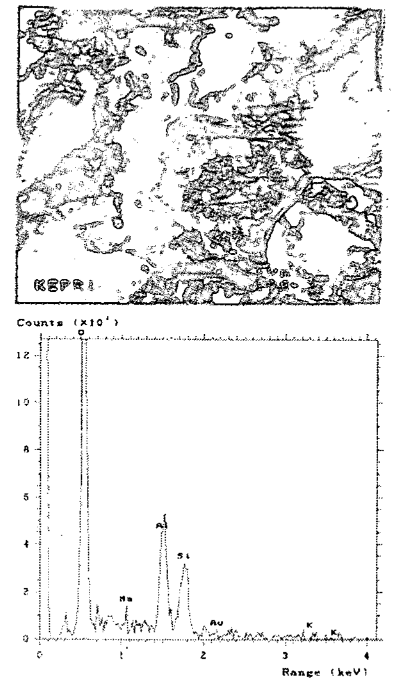


Fig. 5. The EDS and SEM analysis of breakdown sample in hydrogen.

2. The Analysis of Layer for Failed Samples

Fig. 6~Fig. 7 show the insulation layers of mica-epoxy material observed by SEM. The failed samples under air atmosphere are indistinguishable from layer-by-layer and cracks over 10[μm] length are observed. The physical and chemical reaction of thermal stress is forecast by way of these macroscopic phenomena. It can be assumed that the breakdown mechanism for the sound site of stator winding has been failed by the effects of mechanical vibration due to magnetic force.

Furthermore, the shear and compressive stresses are generated by the temperature change due to joule heat and the difference of thermal expansion coefficient among mica-epoxy-fiber glass. Fig. 7 shows the curved parts by these stresses and thermal aging gives rise to such chemical degradation as depolymerization, oxidation of organic material and generation of radical etc. Consequently, the gas pressure inside voids is increased. By decreasing the bonding force due to epoxy of mica surface, the delamination is generated at the interface sites of mica-epoxy and the total defects are increased by adding thermal stress accompanied during thermal aging. The increase of defects enables the non-destructive parameter values such as dielectric factor tip-up to be low extremely and can seriously affect on the life of stator winding insulation material.

The isolated delamination generated by the chemical degradation process of thermal aging can be expected by taking parameters such as partial discharge and dielectric dissipation factor due to insulation diagnosis of mica-epoxy material. But, the

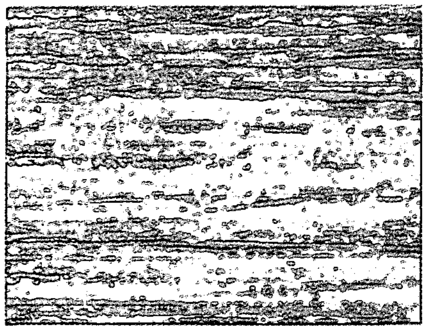


Fig. 6. The analysis of breakdown sample insulation layers in air.

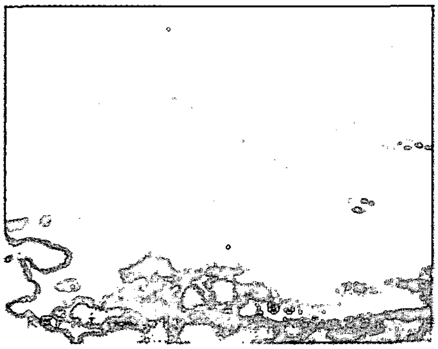


Fig. 7. The analysis of breakdown sample insulation layers in hydrogen.

increase of $\Delta \tan\delta$ by thermal aging is not changing the breakdown voltage on the long time of thermal aging exposure[8]. For this reason, a thermal aging can be considered as an indirect factor[9]. Also, the mechanical fatigue solicitation leads to structural defects of insulation material. The strain of stator winding insulation material is generated by start-up/shut-down of low cycle and magnetic force of high cycle on operation. At the first stage, small delaminations or voids are generated at the interface sites of mica-mica or mica-epoxy. After all, as isolated delaminations are linked to vertical cracks, the distance between electrodes is smaller, and the breakdown voltage is decreased. If these delaminations and cracks exist as voids in insulation material, not only partial discharge in the defects of material but also the electrical stress and chemical corrosion of insulation material is occured. However, in case of mica insulation, it can be assumed that the electrical characteristic of mica which oppresses partial discharge and the increase of a pressure inside material reduce partial discharge greatly.

Fig. 7 shows the curved parts of layer by layer due to shear and compression stress and microcracks which is thought as the effect of H, H_3O. Especially, what a large number of microcracks are observed can be explained by brittleness phenomena of hydrogen generating the depolymerization, the formation of radical as hydrogen ions is diffused in composite material.

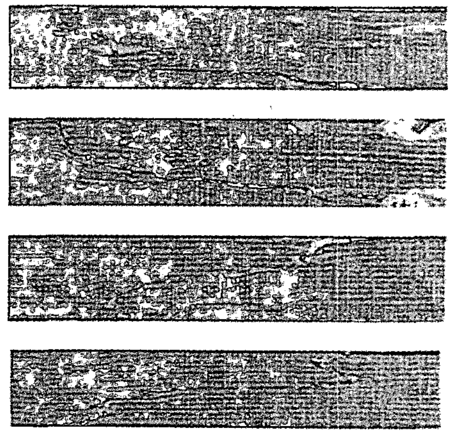


Fig. 8. The breakdown model of stator winding materials in air by optical microscope.

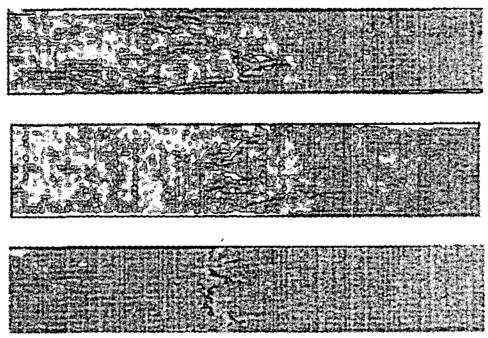


Fig. 9. The breakdown model of stator winding materials in hydrogen by optical microscope.

3. The Fracture Models of Mica-epoxy Material

The breakdown mechanism of insulation material under normal operation condition initiates due to the presence of voids which are filled with gas. It can be assumed that the energy which accepted from applied electric field acts as the converter which is transformed mechanical, and thermal energy in insulation material. These conversion mechanisms include the insulation breakdown due to partial discharge happening to poor parts of gas layers relatively in voids with the generation of electron and ion.

The ionized particles acting in insulation material propagate with the formation of tree channel toward a surface by corrosions for the diffusion process in material and then the insulation breakdown is generated. As based on the analysis of the surface of insulation material, insulation layers, fracture parts by SEM and EDS techniques, we can consider the breakdown process of composite material as follows: The isolated defects generated by mechanical stress are connected with each other, grown up and exceeded the allowable material strength. Then, the growth of defects can occurred due to mechanical fracture. In addition to application electrical stress simultaneously, the insulation break-down due to a treeing is generated and then mechanical fracture occurs. That is why applied voltage is increased by low permitivity of defect areas and breakdown voltage in defects is decreased. After all, big partial discharge is often generated by growth of defects and the trees are changed abnormally by local distorted electric field. In the early stages, isolated delaminations are mainly is distributed over the interface area of epoxy-mica and/or mica-mica. If the repetition number of multi-stress is increased, a tree channel is propagated by way of small delamination of the layers and cracks are formed until the tip of the tree channel reaches the middle of the insulation layer. Furthermore, if the high electric field is applied to these delamination and crack parts, partial discharges are generated and tree is being progressed continuously[10, 11].

Mica flake, fiber glass debris and by-products from the epoxy generated by partial discharge form a conductive tree channel wall, which present the alleviating effects of partial discharge intensity the tree channel is steadily propagated in an axial direction as shown in Fig. 8. When the tip of such a tree channel reaches the middle of the insulation, a large area of delamination(approximately 4-5[cm]) occurs at this central position(Fig. 8). A tree channel initiates again at the delamination site as described above, producing small areas of delamination until breakdown ensues. The number of discharge initiation sites depends on the level of electric stress at the edge of the electrode in epoxy-mica insulation. Such stress concentration regions are presented to interface sites of the half-lapped mica tape adjacent to the edge of the electrode. The life for such an insulation structure is expected to be shortened because, after partial discharge is initiated at the interface site of the void layers, a tree channel can be propagated easily through the void layers to the outer insulation by the delimitation mechanism previously defined. With these alleviating effects, the creation of an ionized gas which is generated by continuous partial discharge and the extinction by the diffusion inside epoxy-mica system are repeated and partial discharge according to Patchen's law is repeated a creation and a extinction. The other type of breakdown process way is described as follows. The fracture mechanism which occurs around the middle of the groundwall insulation is the same as in a previous model. But it shall be assumed that the insulation breakdown model for the delamination occurring around the middle of mica-epoxy system is linked to cracks which are formed at the other area as shown in Fig. 8. It is observed that the expected fracture model is identified to the fracture by fatigue of an aged specimen under air atmosphere observed by optical microscope. Fig. 9 shows the aged specimens under hydrogen atmosphere by optical microscope. It is confirmed that local small voids are distributed to all the area of insulation materials in terms of the effects of hydrogen ions and delaminations generated by heat created when epoxy resin is hardened, are linked together. It is observed that the fracture aspects appeared to be straight.

IV. Conclusions

In order to inquire the aging and insulation breakdown mechanism of the mica-epoxy insulation material which is used in the large generator stator winding, as an intensive research has been carried out from electric, mechanical, material viewpoint. It can be concluded as follows ;

1) For stator winding aged artificially under air and hydrogen, the surface analysis has been performed to look into breakdown mechanism of insulation. In case of air atmosphere, traces which are carbonized widely from conductor to core by partial discharge effect are observed. In case of hydrogen atmosphere, partial discharge is decreased by effects of hydrogen ion and pressure (4[kg/cm^2]}. Also, potassium ions which restrict a sheet of mica are replaced by hydrogen ions, and lead to microcracks. It has been confirmed by SEM analysis that the sizes of crack are 10~20[μm] in diameter, 200~400[μm] in length under air and 1~5[μm] in diameter, 10~50[μm] in length under hydrogen atmosphere respectively.

2) In case of air atmosphere, the two model failed by the progress of the tree generated by continuous partial discharge in voids and mechanical stresses applied to defects has been observed. In case of hydrogen atmosphere, it has been observed that model failed by hydrogen and potassium ions appeared to be straight.

3) The breakdown mechanism of stator winding insulation materials which are composed of mica-epoxy, has been studied by SEM and EDS techniques. The experimental results have shown that the potassium ions of mica components are replaced by, at boundary area of mica-epoxy and/or mica-mica. Through these phenomena, it has been proposed that the conductive layers made of potassium enable the voids to form and the cracks to create by high electric field.

References

[1] J. Anders, "A Probabilistic Model for Evaluation of Remaining Life of Electrical Insulation in Rotating Machines", *IEEE Trans., Energy Conversion* Vol. 5, No.4, 1990, pp. 761-767.

[2] G. C. Stone, "Toward Assessing the Remaining Life of Rotating Machine Insulation", *Proceeding 18th EEIC*, 1987, pp. 71-76.

[3] J. L. Drommi, "Use of Partial Discharge Measurements as Stator Bar Acceptance Criteria", *4Th Int. conf. on Generator and Motor Partial Discharge Testing,* 1996.

[4] H. N. Geeta, "Estimation of Residual Life in Electrical Insulation", *5TH, Int. Conf. Dielectric.,* 1988, pp. 155-158.

[5] A. M. Breitenstein, "Accelerated-Frequency Hydrogen-Atmosphere Voltage Endurance Testing of Micaceous Insulation

Systems", *IEEE Trans. Power Apparatus and System,* 1969, pp. 1389-1393.

[6] W. D. Kingery, "Introduction to Ceramics", Second Edition, Willy Interscience Publication, 1976.

[7] J. F. Shackelford, "Introduction to Materials Science for Engineers", Macmillan Publishing Company, 1985.

[8] K. Kimura, "The Role of Microscopic Defects in Multistress Aging of Micaceous Insulation", *IEEE Trans. Dielectric and Electrical Insulation* Vol. 2, No. 3, June 1995.

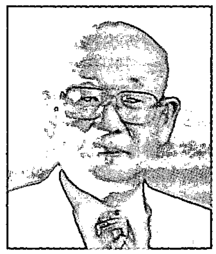
[9] A. Futakawa, "Mechanical Fatigue Characteristics of High Voltage Generator Insulation", *IEEE Trans. Electric Insulation,* Vol. EI-13, No. 6, 1978, pp. 395-405.

[10] J. P. Novak, "Ionization and Excitation Behavior in a Micro-cavity", *IEEE Trans. on Dielectric and Electrical Insulation,* Vol. 2, No. 5, 1995, pp. 724-728.

[11] V. Homburg, "Basic Investigation of a Macroscopic Interface between Two Solid Dielectrics", *IEEE Int. Symposium on Electric Insulation,* 1994, pp. 446-449.

Hee-Gon Kim was born in Korea on November 4, 1964. He received B. S., M. S. and Ph. D. degrees in electrical engineering from the Sungkyunkwan University in 1987, 1992, and 1997 respectively. Currently, he is working in Power Generation Research Laboratory, Korea Electric Power Research Institute. His present research is in the area of insulation diagnosis or rotating machine and monitoring system of generator.

Hee-Soo Kim was born in Korea on May 29, 1971. He received B. S. and M. S. degrees in mechanical engineering from the Chonnam National University in 1993 and 1995 respectively. Currently, he is working in Mechanical Engineering Institute, Korea Electric Power Research Institute. His present research is in the area of rotating machinery.



Yong-Kwan Park was born in Korea on September 16, 1935. He received B. S., M. S. and Ph. D. degrees in electrical engineering from the Inha University in 1958, 1977, and 1987 respectively. Since 1982, he has been with department of electrical engineering at Sungkyunkwan University as a professor. His current research interests are in breakdown mechanism of insulation material and high voltage machine.