Application of Functionally Graded Material for Reducing Electric Field on Electrode and Spacer Interface

Muneaki Kurimoto, Katsumi Kato

Department of Electrical Engineering and Computer Science, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Masahiro Hanai, Yoshikazu Hoshina, Masafumi Takei

Toshiba Corporation, 2-1 Ukishima-cho, Kawasaki-ku, Kawasaki 210-0862, Japan

Hitoshi Okubo

Department of Electrical Engineering and Computer Science, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

ABSTRACT

For the size reduction and the enhancing reliability of electric power equipment, the electric field stress around solid insulators should be considered enough. For the relaxation of the field stress, the application of FGM (Functionally Graded Materials) with spatial distribution of dielectric permittivity (ε-FGM) can be an effective solution.

In this paper, we investigated the applicability of ε-FGM for reducing the electric field stress on the electrode surface with contact to the solid dielectrics, which was one of the important factors dominating a long-term reliability of the insulating spacer. Firstly, we carried out numerical simulation of electric field to confirm the reduction of the electric stress by U-shape permittivity distribution. Secondly, we investigated the fabrication feasibility of ε-FGM with the U-shape distribution. Thirdly, we estimated the long-term electrical insulation performance of the ε-FGM. Finally, we verified the applicability and the fabrication technique of the ε-FGM to solid dielectrics for improvement of the electric stress and the long-term insulation performance in electric power equipment.

Index Terms — Functionally graded material (FGM), Permittivity, Electric field, Spacer, Epoxy resin, Filler, Centrifugal force, Gas insulated switchgear (GIS)

1 INTRODUCTION

THESE days, electric power equipment tends to be compact and be operated under higher voltage. For the enhancement of insulation reliability and the compact design in gas insulated power equipment, the solid insulators play the crucial role of electrical insulation [1,2]. In order to improve the insulation performance of the solid insulators, we should consider the following two technical points. Firstly, we have to improve the insulation performance of solid dielectrics itself, for example, nanocomposite material application to the electric power equipment [3,4]. The second is the control of the electric field distribution in and around the solid insulating spacers [5,6].

In the practical gas insulated switchgears, the insulation performance around the spacer are made improved by various techniques, for examples, controlling the spacer shape, adding shield electrodes for electric field relaxation, the introduction of an embedded electrode, and so on. However, these techniques for the control of electric field lead to a more complicated structure of the equipment and increase the manufacturing cost. Thus, it is necessary to propose a new concept on solid spacers with keeping their simple structure and configuration.

We have proposed a new concept for spacer insulation; an application of a functionally graded material (FGM). For relaxation of electric field stress, the FGM spacer should have spatial distribution of dielectric permittivity inside. By the control of the distribution of dielectric permittivity, we could make the electric field distribution in and around the spacer more suitable under ac and impulse voltage applications. Thus, we have achieved the fundamental investigations of the FGM spacer in electric power apparatus [7-11].

In this paper, we investigated the applicability of FGM for reducing the electric stress on the electrode surface in contact with solid insulating materials, which was one of the important factors dominating a long-term insulating property of the solid

spacer. Firstly, we proposed the permittivity distribution for reducing electric stress on electrode surface in theoretical viewpoints. Then, we confirmed the electric field control effect of the proposed distribution by numerical calculation. Secondly, we fabricated FGM with the spatial distribution of dielectric permittivity (ε-FGM) proposed here. The ε-FGM was fabricated by precipitating fillers in resin with centrifugal force. Thirdly, we estimated the long-term performance of ε-FGM with the U-shape distribution. Finally, we verified the applicability and the fabrication technique of ε-FGM to solid dielectrics for improvement of the electric field stress and the long-term performance in electric power equipment.

2 PERMITTIVITY DISTRIBUTION IN SOLID SPACER FOR REDUCING ELECTRIC STRESS ON ELECTRODE SURFACE

2.1 U SHAPE PERMITTIVITY DISTRIBUTION

In order to relax the electric field stress on electrode surface, the higher permittivity should be given around both anode and cathode surfaces compared with the other intermediate parts of solid insulator. It can be explained by the equivalent capacitor circuits of solid spacer configuration under static field as shown in Figure 1. The high permittivity capacitors in the vicinity of both sides of electrodes cause potential contingent to the inner low permittivity capacitor, decreasing the electric field in the vicinity of the electrode. Thus, U-shape distribution of the permittivity is suitable for the relaxation of electric field stress on electrode surface from the theoretical viewpoints.
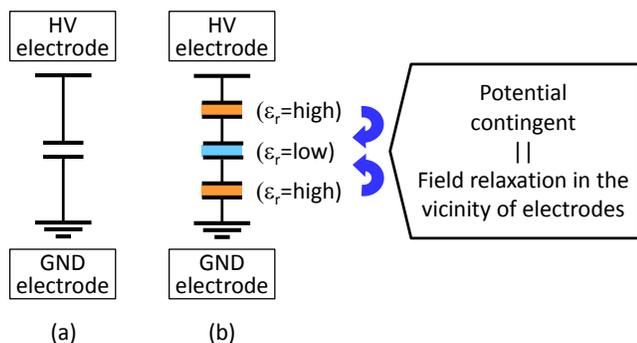

Figure 1. Equivalent capacitor circuits of solid spacer configuration, (a) uniform permittivity, (b) permittivity distribution for reducing electric field in the vicinity of electrodes.

2.2 CALCULATION MODEL FOR FGM SPACER

In order to confirm the field control effect of the proposed distribution of dielectric permittivity, we carried out the numerical calculation of electric field by finite element method (FEM). Figure 2 shows a calculation model. Calculations were carried out in a rotationally symmetric system. We arranged the cone-type spacer between the high voltage (HV) and grounded (GND) electrodes in a coaxial arrangement. The diameters of inner and outer electrodes were set to 80 and 200mm, respectively. We considered the electric field
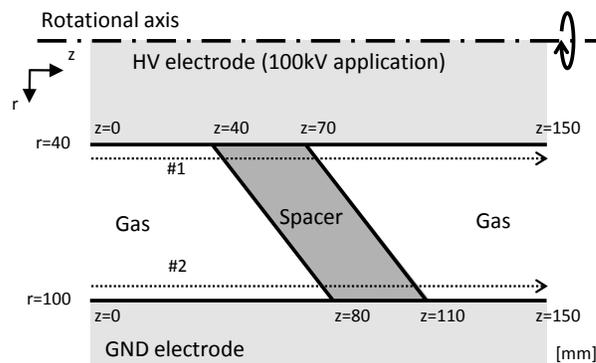

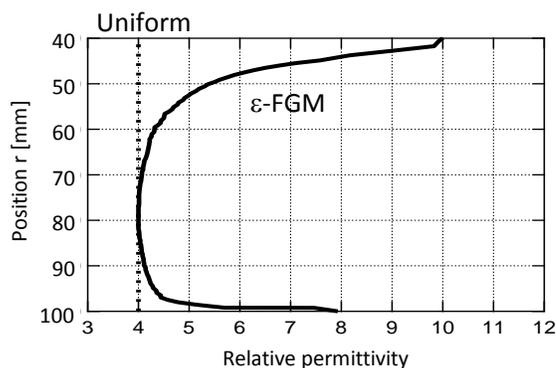**Figure 2.** Calculation model for cone spacer of GIS.

Figure 3. U-shape permittivity distribution of the spacer.

distribution along the paths #1 and #2 in Figure 2. Figure 3 shows the permittivity distribution (U-shape distribution) for the graded materials. This permittivity distribution was based on the optimized distribution of permittivity for minimizing the electric field stress around the cone spacer calculation model by computer-aided optimization technique for the FGM solid insulators [11]. Furthermore, in order to compare the performance, the spacer with uniform permittivity distribution (ε_r= 4.0) was also introduced.

2.3 CALCULATION RESULTS AND DISCUSSION

Figure 4 shows potential and electric field distribution around the solid spacer. By the introduction of the FGM spacer, the electric field distribution was improved. Especially, on the electrode surface in and around spacer, the ε-FGM with the U-shape permittivity distribution could reduce the electric field strength.

Next, we investigated the detail of electric field distribution as shown in Figure 5. We described the calculation results along the surface of HV and GND electrode (Path #1 and #2 in Figure 2). We found that electric field strength on the both electrode surfaces in contact with solid insulators were reduced by introduction of the FGM spacers. In addition, the FGM spacer also allowed us to reduce the intensified field strength at z= 70 in Figure 5 (a) and z= 80 in Figure 5 (b) of triple junctions.
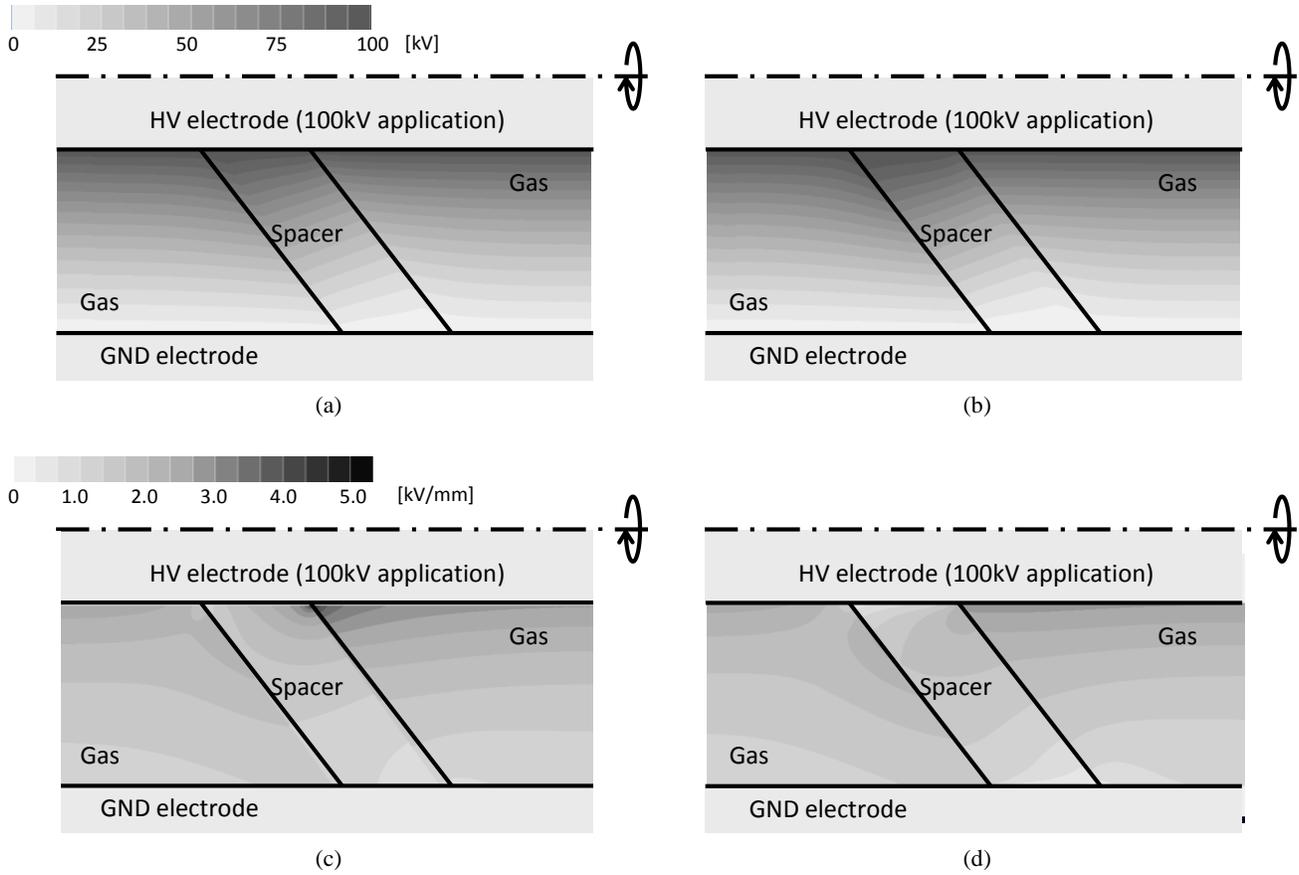
Figure 4. Potential and electric field distribution around cone spacer in GIS, (a) potential distribution of uniform spacer, (b) potential distribution of FGM spacer, (c) electric field distribution of uniform spacer, (d) electric field distribution of FGM spacer.
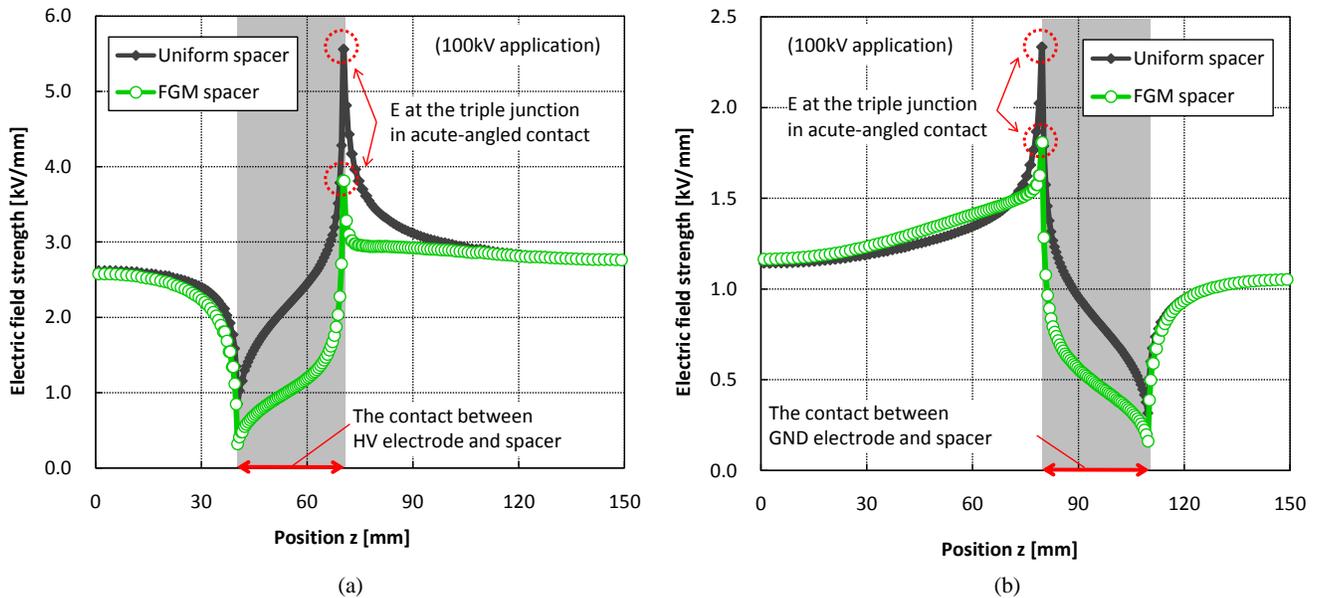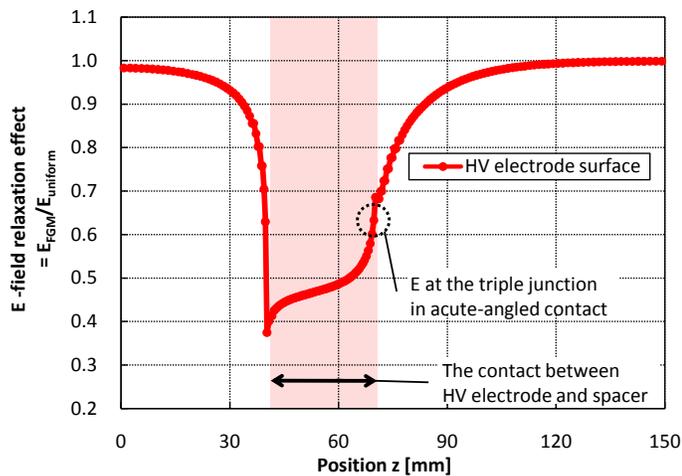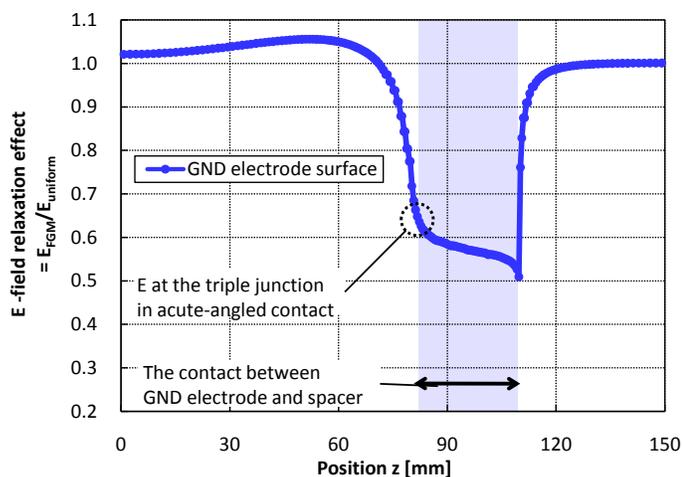

Figure 5. Electric field distribution on the HV and GND electrode surface, (a) electric field strength on the HV electrode surface, (b) electric field strength on the GND electrode surface.

Figure 6 shows the electric field relaxation effect on the electrode/spacer interface (= $E_{FGM}/E_{uniform}$). The result shows the relaxation effects of 0.38-0.63 on HV electrode/spacer interface and 0.51-0.62 on GND electrode/spacer interface by applying the U-shape FGM spacer.
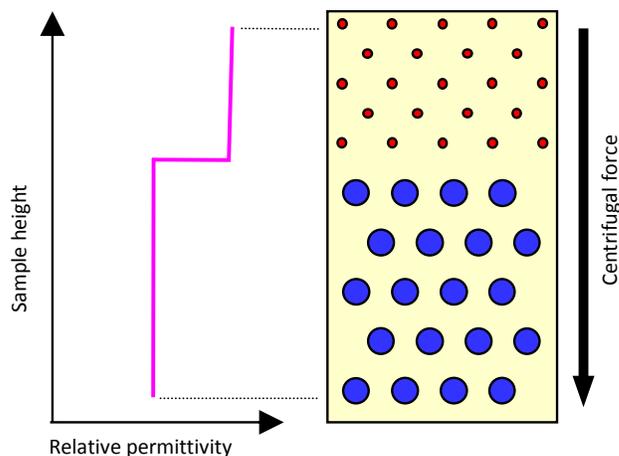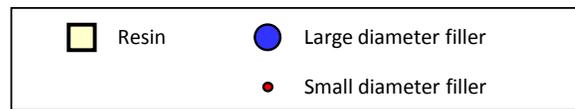

(a)

(b)

Figure 6. Electric field relaxation effect (E_{FGM} / $E_{uniform}$) by introduction of the U-shape FGM spacer, (a) HV electrode surface, (b) GND electrode surface.

(a)

(b)

Figure 7. The concept of fabrication of the U-shape permittivity distribution, (a) Before application of centrifugal force, (b) After application of centrifugal force.

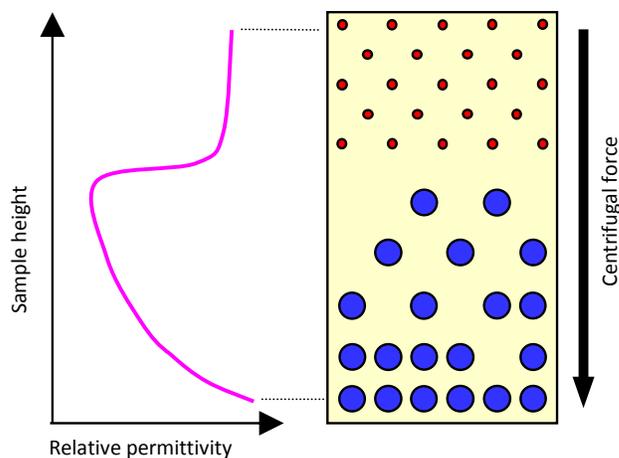# 3 FABRICATION OF FGM WITH "U-SHAPE" PERMITTIVITY DISTRIBUTION

3.1 FABRICATION OF FGM SAMPLE

We investigated the fabrication feasibility of ε-FGM with U-shape distribution. In order to fabricate it, we propose the new control method of permittivity distribution as shown in Figure 7. The basic idea is to use the filler with the different particle parameters and to apply centrifugal force.

Initially, the small diameter fillers are filled at upper part of the sample, and large diameter fillers are filled at lower part of the sample (Figure.7(a)). Then, by centrifugal force application, only the large diameter fillers move centrifugal direction. Finally, U-shape permittivity distribution can be obtained for the reasons as bellow (Figure.7 (b)).

(1) Permittivity in upper part does not change because the filler density does not change.
(2) Permittivity in mid-part becomes low as the filler density is reduced.
(3) Permittivity in lower part becomes high as filler density is increased.

The fabricated samples were based on epoxy resins. As a small diameter filler, we used TiO_2 with rutile crystal (average diameter= 0.59μm, $ε_r$= 114) and as a large diameter filler, we use Al_2O_3 (average diameter= 4.0μm, $ε_r$= 9.1). The specifications of chosen materials are shown in Table 1.

The fabrication process has the following five steps.

(1) Epoxy resin is mixed with hardener and fillers.
(2) The mixed sample is poured into test tubes. The lower part of the test tube is the mixed sample with Al_2O_3 and the upper part is the mixed sample with TiO_2.
(3) The sample is degassed enough for removal of bubbles.
(4) Centrifugal force is applied at 20°C until time duration depending on the cases.
(5) The sample is cured at 100°C.

Figure 8 shows the fabrication conditions. We controlled centrifugal forces and their application duration.

The results of permittivity distribution are shown in Figures 9 and 10. By slicing the sample with 1mm thickness, we could estimate the permittivity values from the measurement of capacitance at 1kHz using LCR meter. In these figures, continuous U-shape permittivity distributions could be obtained. By controlling parameters of centrifugal conditions, we succeeded in making various U-shape permittivity distributions.

In order to confirm the electric field control effect of the fabricated distribution, we carried out the numerical calculation. The obtained distribution of permittivity was applied to the spacer model in Figure 2. By the calculation, we obtained the electric field relaxation effect (= $E_{FGM}/E_{uniform}$) of 0.71-0.86 on HV electrode/spacer interface and 0.84-0.96 on GND electrode/spacer interface by applying the permittivity distribution of the sample C in Figure 9 to the spacer.

Table 1. Specifications of chosen materials.

	Epoxy	Hardener	Filler	
			TiO_2	Al_2O_3
Chemical structure	Bisphenol-A epoxy resin	Anhydride-type	TiO_2	Al_2O_3
Viscosity (20℃) [Pa·sec]	1.0 (at mixed condition)		-	-
Relative permittivity (1kHz, 20℃)	3.5		114	9.1
Specific gravity [g/ml]	1.17	1.21	4.2	3.95

(a) Sample configuration

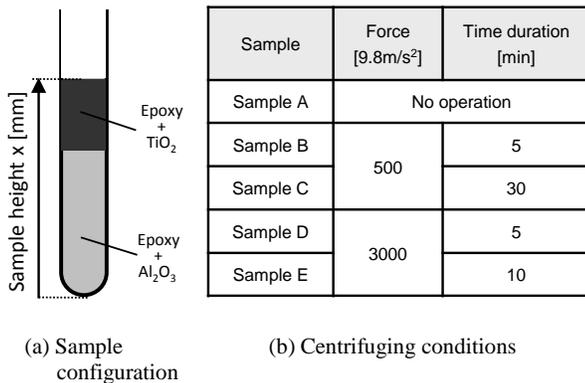| Sample	Force [9.8m/s²]	Time duration [min]
Sample A	No operation	
Sample B	500	5
Sample C		30
Sample D	3000	5
Sample E		10

(b) Centrifuging conditions

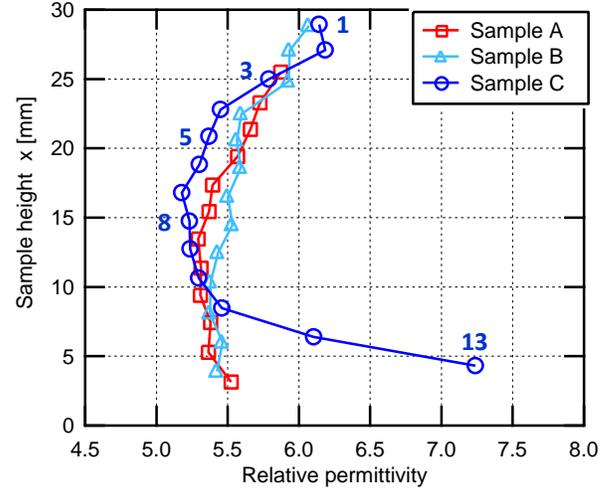**Figure 8.** Fabricating condition of FGM.

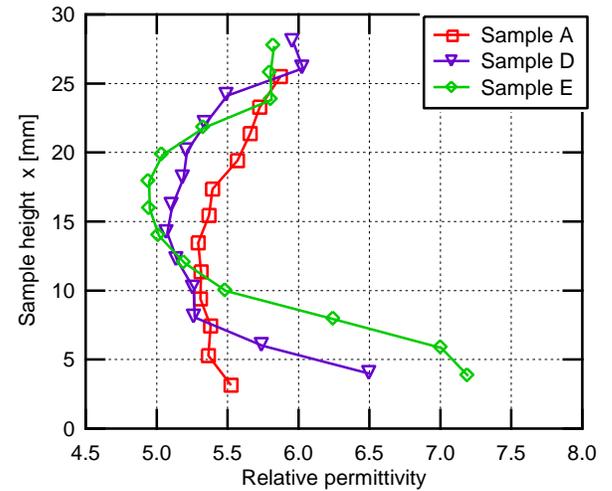**Figure 9.** Permittivity distribution of the samples (500G)

Figure 10. Permittivity distribution of the samples (3000G).

3.2 OBSERVATION OF FILLER DISTRIBUTION IN THE SAMPLE

In order to estimate filler distribution in the fabricated sample, we observed the sample section by SEM (Scanning Electron Microscope). Five points of sample C shown in Figure 9 (1, 3, 5, 8, 13) were chosen for observation. The reasons to choose above 5 points were as follows:

(1) Point 1 : around the interface with electrode surface
(2) Point 3 : around interface of double layer (upper side)
(3) Point 5 : around interface of double layer (lower side)
(4) Point 8 : around lowest permittivity
(5) Point 13 : around the interface with electrode surface

Figure 11 shows the observation results of the sample section. In this figure, black parts show epoxy resins and grey parts with irregular shape show TiO_2 particles and grey parts with spherical shape show Al_2O_3 particles. Firstly, let us pay attention to TiO_2 particles. From Figure 11, point 1 is almost

occupied by TiO_2 particles. The lower the observe point moves, the lower the density of TiO_2 particles becomes. Next, let us pay attention to Al_2O_3 particles. The lower the observe point moves, the higher the density of Al_2O_3 particles becomes.

From the result, TiO_2 and Al_2O_3 particles density corresponded to the measured permittivity distribution. We could confirm the availability of the control techniques of U-shape permittivity distribution.
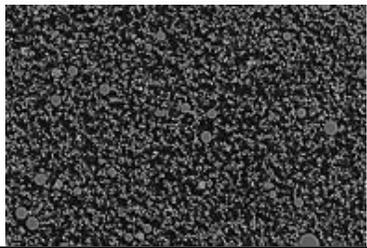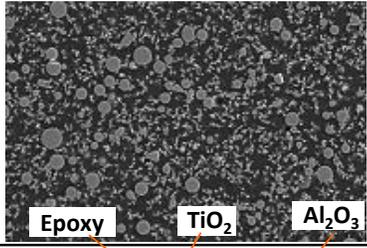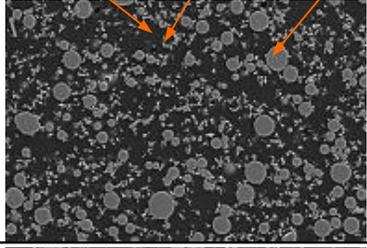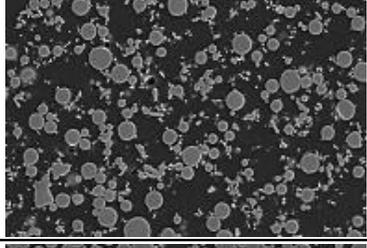

Measured position	SEM micrographs 20μm
Point 1	
Point 3	
Point 5	Epoxy TiO_2 Al_2O_3
Point 8	
Point 13	
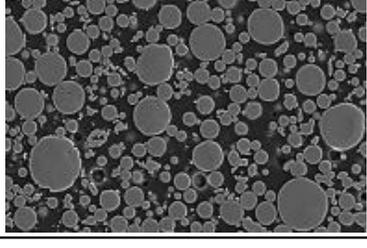
Figure 11. Observed micrographs of the section in the sample (Sample C).

4 ESTIMATION OF LONG-TERM PERFORMANCE OF FGM

4.1 ESTIMATION OF LIFE TIME

For consideration of the long-term performance of electrical insulation, the life time curve like voltage-time (V-t) or electric field–time (E-t) was used. Figure 12 shows a schematic illustration of the life time curve of solid dielectrics. The relationship between breakdown strength and life time was typically formulated as follows [1].

$$t = t_0 \left(\frac{E}{E_0} \right)^{-n} \qquad (1)$$

Where, E is a breakdown strength, t is an operation time, t_0 and E_0 are values on the life time curve as reference, n is a voltage endurance coefficient of epoxy insulators. For typical epoxy, n was obtained in the range from 10 to 20. Here, we should pay attention to the fact that the breakdown under the long-term voltage application is mainly derived from the defect around the electrode/spacer interface. So, we should make consideration for the electric field strength more on the electrode surface rather than that inside the insulator.

We investigated the FGM applicability to the extension of life time. At first, we calculated the maximum electric field strength on the electrode surface in contact with the solid spacer which has U-shape permittivity distribution. The life time was calculated by eq.(1). Then we compared the life time between FGM and uniform permittivity models.

4.2 FGM EFFECT TO LIFE TIME EXTENSION

For calculation of estimation of the life time, we arranged the solid spacer between parallel electrodes with gap distance of 25mm. The relative permittivity inside the spacer was distributed in the direction of the spacer height corresponding to the sample height "x" in Figure 9 and 10. The given
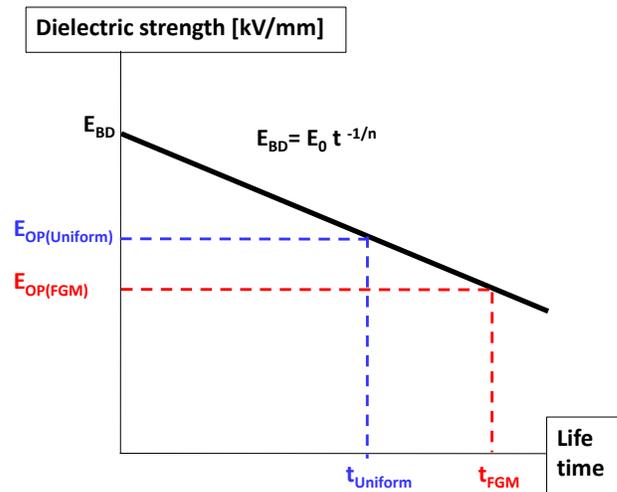

Figure 12. Schematic illustration of the life time curve of solid dielectrics.

permittivity distributions as the graded materials were the fabricated ε-FGMs which were the permittivity distribution (x= 4-29mm) of sample C in Figure 9 and the permittivity distribution (x= 3-28mm) of sample E in Figure 10.

Figure 13 shows the electric field distribution inside the spacer. The horizontal axis in this figure is the relative position "x" corresponding to the sample height "x" in Figure 9 and 10. We found that electric field strength on the both electrode surfaces in contact with solid insulators (x= 0, 20) was reduced by introduction of the FGM spacers.

Figure 14 shows the life time of ε-FGM. The life time was calculated from the electric field strength on the electrode surface (x= 20) because it was higher than one on the electrode surface (x= 0). The results show the life time of ε-FGM with sample C is 1.7-2.8 times (n= 10-20) as long as the uniform spacer and the life time of ε-FGM with sample E is 2.9-8.2 times (n= 10-20) as long as the uniform spacer. Consequently, we could verify that longer life time of solid dielectrics can be obtained by the ε-FGM application for the solid spacer.
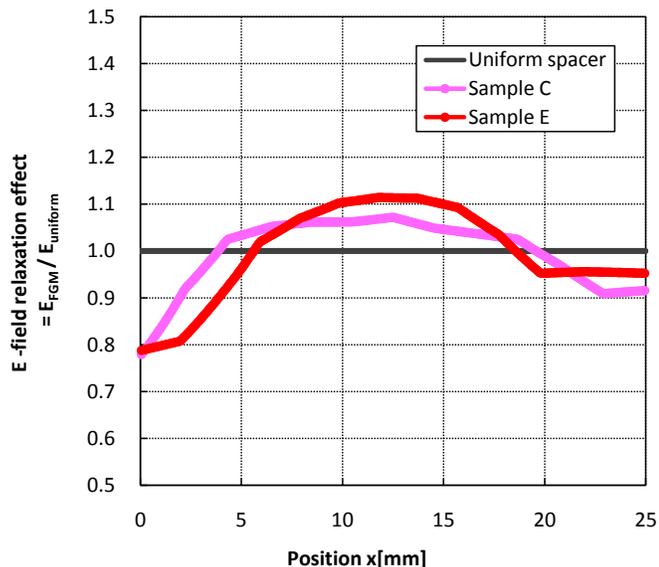

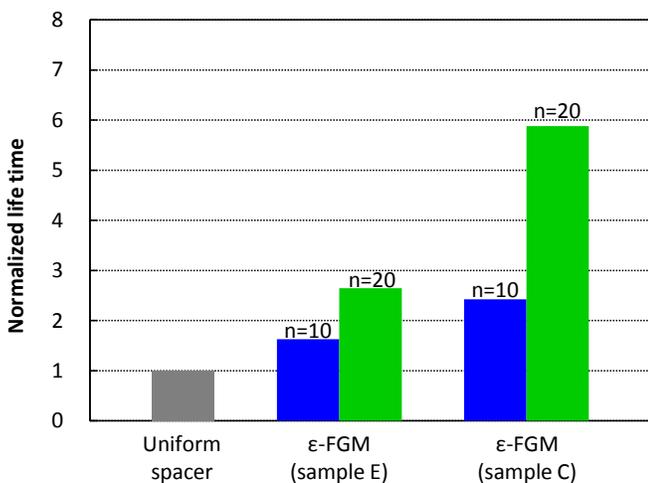**Figure 13.** Normalized electric field strength along the spacer height.

Figure 14. Life time of ε-FGM.

5 CONCLUSION

We proposed the application of FGM for reducing the electric field stress on the electrode surface in contact with solid insulators, which was one of the important factors dominating a long-term insulating property of the solid spacer. The FGM application effect was verified by numerical simulation of electric field and life time estimation. Furthermore, we actually fabricated the FGM spacer sample by use of a centrifugal force technique. The results are concluded as follows.

(1) From the numerical simulation, we found that the application of the FGM spacer with U-shape permittivity distribution could reduce the electric field stress on the both electrode surface in contact with solid insulators even if we applied a very simple shape of spacer.

(2) We made U-shape permittivity distribution and controlled it by applying the centrifugal force. By controlling parameters: centrifugal force, their application duration, we made various types of the U-shape permittivity distribution. These fabrication techniques are expected to be extended to the actual application of FGM to the electric power equipment.

(3) We estimated a long-term insulation performance for the fabricated FGM sample, and found the significant effect for life time extension by the application of FGM. Finally, we could verify that high performance of electrical insulation of solid spacer could be obtained by a permittivity graded FGM application.

ACKNOWLEDGMENT

REFERENCES

[1] CIGRE WG 15.03: "LONG-TERM PERFORMANCE OF SF$_6$ INSULATED SYSTEMS", CIGRE Report 15-301, 2002.

[2] T. Tanaka, T. Okamoto, K. Nakanishi and T. Miyamoto: "Aging and Related Phenomena in Modern Electric Power Systems", IEEE Transaction on Dielectrics and Electrical Insulation, Vol. 28, No.5, pp.826-844, 1993.

[3] M. F. Fréchette, C. W. Reed: "The Emerging Field of Nanodielectrics: an Annotated Appreciation", IEEE International Symposium on Electrical Insulation, pp.458-465, 2006.

[4] T. Tanaka, Y. Ohki, M. Ochi, M. Harada and T. Imai: "Enhanced Partial Discharge Resistance of Epoxy/Clay Nanocomposite Prepared by Newly Developed Organic Modification and Solubilization Methods", IEEE Transaction on Dielectrics and Electrical Insulation, Vol. 15, No.1, pp.81-89, 2008.

[5] A. Haddad, D. Warne: "Advances in High Voltage Engineering", The Institution of Electrical Engineers, 2004

[6] S. Okabe, N. Hayakawa, H. Murase, H. Hama, and H. Okubo: "Common Insulating Properties in Insulating Materials", IEEE Transaction on Dielectrics and Electrical Insulation, Vol. 13, No.1, pp.327-335, 2006.

[7]   M. Kurimoto, K. Kato, H. Adachi, S. Sakuma, H. Okubo: "Fabrication and experimental verification of permittivity graded solid spacer for GIS", IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp. 789-792, 2002.

[8]   H. Okubo, M. Kurimoto, H. Shumiya, K. Kato, H. Adachi, S. Sakuma: "Permittivity Gradient Characteristics of GIS Solid Spacer", Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials, pp. 23-26, 2003.

[9]   H. Shumiya, K. Kato and H. Okubo: "Feasibility Study on FGM (Functionally Graded Materials) Application for Gas Insulated Equipment", IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp.360-363, 2004.

[10] K. Kato, M. Kurimoto, H. Shumiya, H. Adachi, S. Sakuma and H. Okubo: "Application of Functionally Graded Material for Solid Insulator in Gaseous Insulation System", IEEE Transaction on Dielectrics and Electrical Insulation, Vol.13, No.2, pp.362-372, 2006.

[11] H. Okubo, H. Shumiya, M. Ito and K. Kato: "Optimization Techniques on Permittivity Distribution in Permittivity Graded Solid Insulators", IEEE International Symposium on Electrical Insulation, pp.519-522, 2006.

Masafumi Takei was born on 03 Nobemver 1955. He received the B.S. and M.S. degrees in electrical and electronic engineering from Tohoku University in 1979 and 1981 respectively. He joined Toshiba Corporation, Japan in 1981. He has been engaged in research on High voltage Gas-Insulated Switchgear and Solid Insulation Materials. Currently, he is a chief engineer of the High Voltage Gas-Insulated Switchgear Division. He is a member of IEE of Japan.

Hitoshi Okubo (M'81) was born on 29 October 1948. He received the Ph.D. degree in 1984 in electrical engineering from Nagoya University., He joined Toshiba Corporation, Japan in 1973 and was a Manager of HV laboratory of Toshiba. From 1976 to 1978, he was at the RWTH Aachen, Germany and the TU Munich, Germany. In 1989, he was an Associate Professor and presently he is a Professor at Nagoya University in Department of Electrical Engineering and Computer Science. He is a member of IEE of Japan, VDE and CIGRE.

Muneaki Kurimoto (S'08) was born on 10 May 1978. He received the M.S. degree in 2003 in electrical engineering from Nagoya University. He joined Aisin Seiki Corporation, Japan from 2003 to 2007. Currently, he is a graduate student in Nagoya University working towards his PhD degree in electrical engineering. He is a student member of IEE of Japan.

Katsumi Kato was born on 20 May 1969. He received the Ph.D. degree in 1997 in electrical engineering from Nagoya University. Since 1997, he has been on the faculty of Nagoya University. Currently, he is an Assistant Professor at Nagoya University in Department of Electrical Engineering and Computer Science. He is a member of IEE of Japan and IEJ.

Masahiro Hanai (M'06) was born on 07 March 1959. He received the Ph.D. degree in 2008 in electrical engineering from Nagoya University. He joined Toshiba Corporation, Japan in 1983. He has been engaged in research on High voltage insulation for Gas-Insulated Transformer and Gas-Insulated Switchgear. Currently, he is a chief engineer of the High Voltage & High Power Technology Division. He is a member of IEE of Japan and CIGRE.

Yoshikazu Hoshina was born in Saitama, Japan on 02 August 1964. He received the B.S. and M.S. degrees in electrical and electronic engineering from Tokyo Institute of Technology in 1988 and 1990 respectively. In 1993 he joined Toshiba Corporation, Kawasaki, Japan. He has been engaged in research on High voltage insulation for Gas-Insulated Switchgear. Currently, he is a manager of the High Voltage Technology Group. He is a member of IEE of Japan.