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Optimization Techniques on Permittivity Distribution in Permittivity Graded Solid Insulators

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Abstract- **We have proposed a new concept for solid insulation; an application of FGM (Functionally Graded Materials). By controlling the distribution of dielectric permittivity inside solid insulators, we can achieve the efficient field control with keeping simple configuration of solid insulators.**

In this paper, we described a computer-aided optimization technique for the FGM solid insulators. By controlling the filler particle concentration in the matrix, an optimized field distribution is obtained. From the calculation results, we confirmed that the proposed optimization method could obtain novel distributions of permittivity, which have the highest performance of the field control effect. Finally, we could confirm the significant effect of FGM application for gas / solid composite insulation system.

I. INTRODUCTION

These days, electric power equipment tends to be compact and be operated under higher voltage. In the equipment, the solid insulators play the most critical role for electrical insulation. To improve the insulation performance of the solid insulators, we need to control electric field distribution around the solid insulators [1-3]. However, conventional techniques for the control of electric field lead to the complicated structure of insulators and increase the manufacturing cost. Then, it is necessary to propose a new concept on insulators with keeping their simple structure and configurations. Hence, we proposed FGM application to the solid spacer, and made the fundamental investigation of FGM [4-6].

In this paper, we propose a computer-aided optimization technique for FGM application. In the optimization process, permittivity distribution of the FGM insulator is sequentially modified for minimizing the electric field stress in and around FGM insulators. In order to verify the optimization efficiency, we carried out optimized distributions of permittivity in the cone spacer calculation model. We compared the result of optimized FGM spacer, with one of conventional spacer which has a uniform distribution of permittivity.

From the calculation results, we confirmed that the proposed optimization method could calculate novel distributions of permittivity, which have higher performance of the field control effect. Finally, we could confirm the significant effect of FGM application for gas / solid composite insulation system.

II. CONCEPT OF FGM

In the FGM solid insulators, spatial distributions of permittivity are given for the control of the electric field distribution in and around the solid insulators, as shown in Figure 1. Conventional materials have constant permittivity distribution, on the contrary, FGMs have continuously graded permittivity distribution by the arrangement of filler particles (Material B) in the matrix material (Material A). Material A as a matrix is considered to be epoxy for example. As a filler, Al_2O_3, SiO_2 or TiO_2 particles are applied with several 10 μm ~ sub μm diameter. In order to relax the stress concentration, the application of FGM is expected to be effective by giving the suitable permittivity (ε_r) distribution inside the insulators.

III. OPTIMIZATION OF PERMMITIVITY DISTRIBUTION

From practical design viewpoints, we should take care of the dielectric strength under a lightning impulse voltage application for the insulation design of gas insulated equipment, because the impulse ratio of SF_6 gas is relatively small. Therefore, the field distribution is mainly determined by the permittivity arrangement in insulation space. For the control of electric field, field optimization technique which modifies contour of electrode or solid insulators, as shown in Figure 2; is usually applied [7-9]. On the contrary, in the FGM optimization, we just modify permittivity distribution in the solid insulators keeping with simple contours of electrodes and solid insulators.

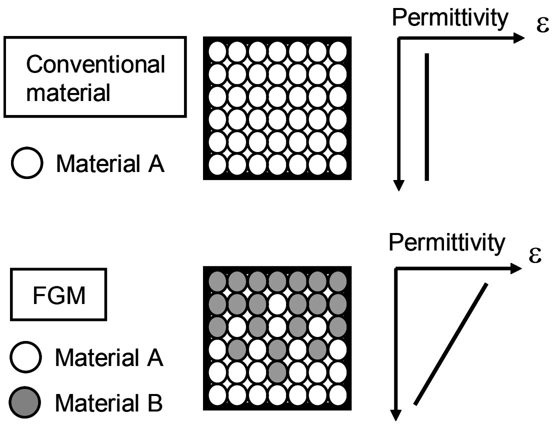

Fig.1 Concept of FGM.

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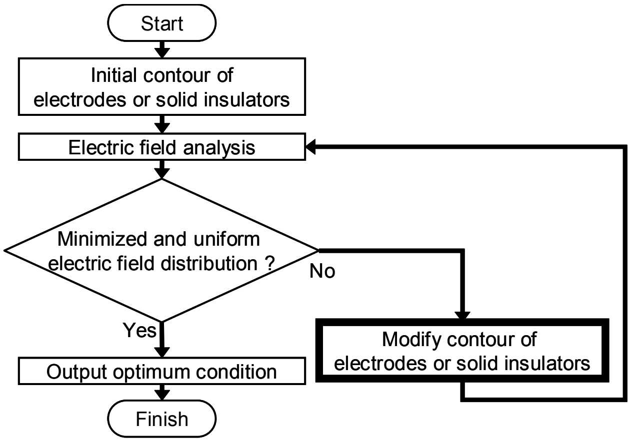
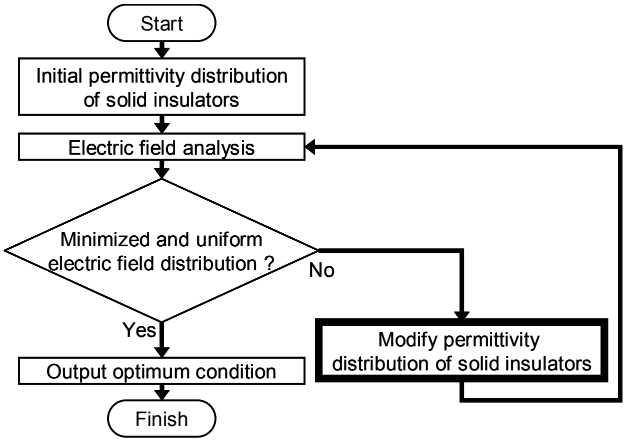


(a) Contour optimization



(b) Permittivity distribution optimization

Fig.2 Differences in the optimization process.

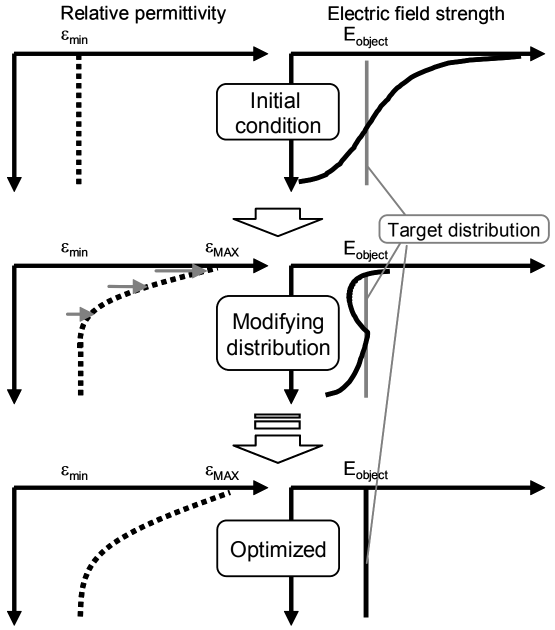
For improvement of the field distribution with FGM application to solid insulators, we need to optimize the permittivity distribution for FGM. Then, we investigate the optimizing method with numerical simulation. As field calculation, we used a finite element method (FEM). Here, we define the optimum permittivity distribution as "the distribution which can relax the field stress most effectively in and around the insulator". We optimize the field strength of each FEM element, and calculate the optimum permittivity distribution with the method proposed shown in Figure 3.

In this algorism, permittivity distribution of FGM insulator is separated to triangle elements generated by FEM calculation. According to the Gauss' law, it is mentioned that the optimum ε_r distribution is similar distribution of the field objected. Then, we can calculate the optimum ε_r distribution with the following method, (a) ~ (b) are repeatedly carried out.

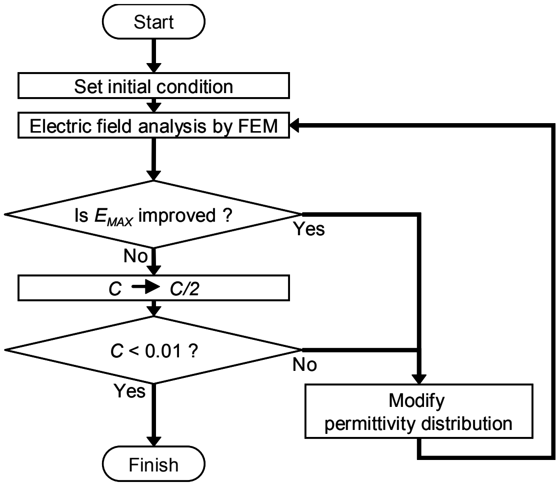
(a) Field strengths inside insulator are calculated each FEM element, P_i $(1 < i < n)$.

(b) Permittivity distribution inside insulator is modified with P_i $(1 < i < n)$, by the following equation,

$$\varepsilon_i' = \varepsilon_i \cdot \frac{E_i}{E_{object}} \cdot \frac{\varepsilon_{MAX}}{\varepsilon_{\min}} \cdot C \qquad (1)$$



(a) Concept of optimization



(b) Flowchart of calculation

Fig.3 Calculation of optimum permittivity distribution.

Here, ε_i, ε_i' is relative permittivity at P_i (before modifying, after modifying). E_i is electric field strength at P_i. E_{object} is objective value of electric field strength. ε_{MAX}, ε_{min} is maximum or minimum value of relative permittivity. C is coefficient for modifying permittivity distribution.

From the above, we can automatically calculate the optimum permittivity distribution. Calculation conditions are given as follows; E_{object} = (Applied voltage)/(Gap length between electrodes). Initial value of C = E_{object}/(1st calculated value of E_{MAX}). ε_{min} is 4 fixed, ε_{MAX} is changed from 8 to 200. If $C < 0.01$, calculation is finished. $C < 0.01$ means the range that variation of E_{MAX} becomes less than 0.1kV/mm. In each calculation, optimum permittivity distribution is calculated between the given ε_r range ($\varepsilon_{min} < \varepsilon_r < \varepsilon_{MAX}$).

IV. CALCULATION AND RESULTS OF FIELD OPTIMIZATION WITH FGM

We investigated the applicability of FGM to the cone-type spacer in gas insulated switchgears (GIS) as an example. Figure 4 shows a calculation model. Calculations were carried out in a rotationally symmetric system. We arranged the cone-type spacer between the HV and grounded (GND) electrodes in a coaxial arrangement.

The optimization of permittivity distribution for FGM was carried out with the above method. Furthermore, in order to comparewith FGM, the permittivity distribution is given uniformly ε_r=4 to the spacer as the conventional spacer material that consists of epoxy resins mixed with SiO_2 filler. In the calculation, we focused on the field distribution in whole region to be investigated. In addition, we considered the detailed field distribution along the paths #1-5 in Figure 4, which may be important for the insulation performance of the actual gas insulated equipment.

Figure 5 shows field distributions around spacer. From this figure, optimized FGM can significantly relax the field stress in and around spacer, and the field distribution could be more uniform as possible. Figure 6 shows the optimized permittivity distribution. Calculated distribution is continuously and complexly graded in the spacer. Field utilization factor characteristics of optimized FGM spacer is shown in Figure 7. Applying optimized permittivity distribution to FGM, we can confirm that utilization factor is improved as becoming ε_{MAX} higher. In this calculation model, it is confirmed that optimum FGM can improve utilization factor up to 0.63 (the value when permittivity distribution of ε_r=1 constant was given to the spacer). Utilization factor comes to be saturated as becoming ε_{MAX} higher ($\varepsilon_{MAX}/\varepsilon_{min}$>20), in other words, the field control effect by FGM application come to be saturated as becoming ε_r higher.

From the actual application view points, solid insulators are made of low permittivity materials like epoxy and the total permittivity will be controlled by filler materials, like SiO_2, Al_2O_3 and TiO_2, etc. From the above, we can define the optimum permittivity range for FGM. And, the optimum range for this calculation model could be $4 < \varepsilon_r < 80$.

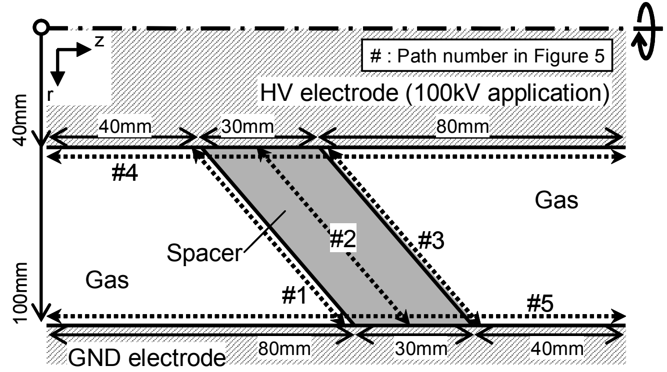
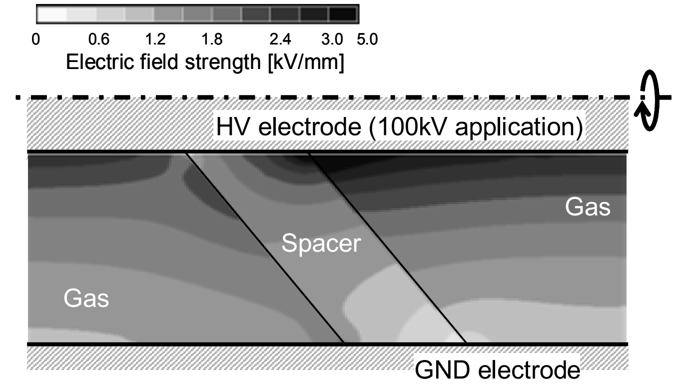
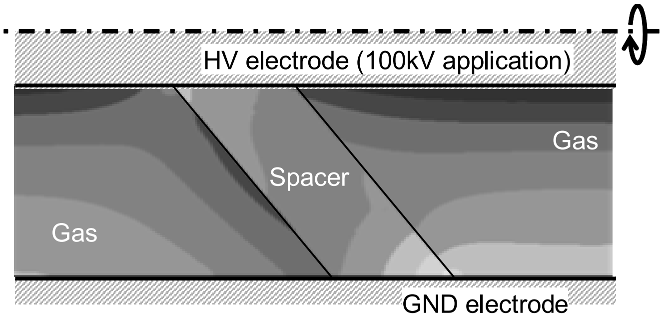


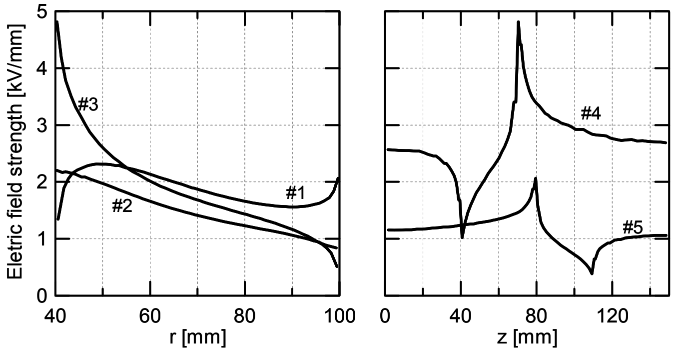
Fig.4 Calculation model for the cone spacer of GIS.



(a-1) Equi-field contour

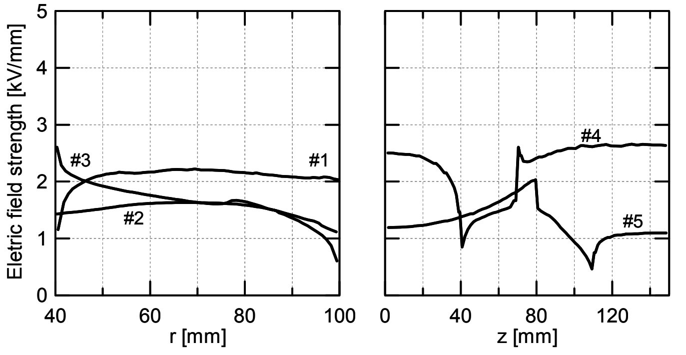


(b-1) Equi-field contour



(a-2) Along path #1-5

(a) Conventional spacer (ε_r = 4 uniform)



[#: Path number shown in Figure 4]

(b-2) Along path #1-5

(b) Optimized FGM spacer ($4 < \varepsilon_r < 80$)

Fig.5 Electric field distribution around the spacer.

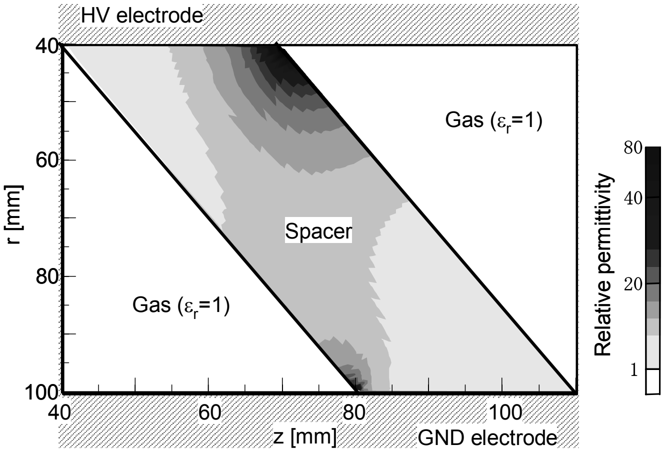


Fig.6 Optimized permittivity distribution of FGM. ($4 < \varepsilon_r < 80$)

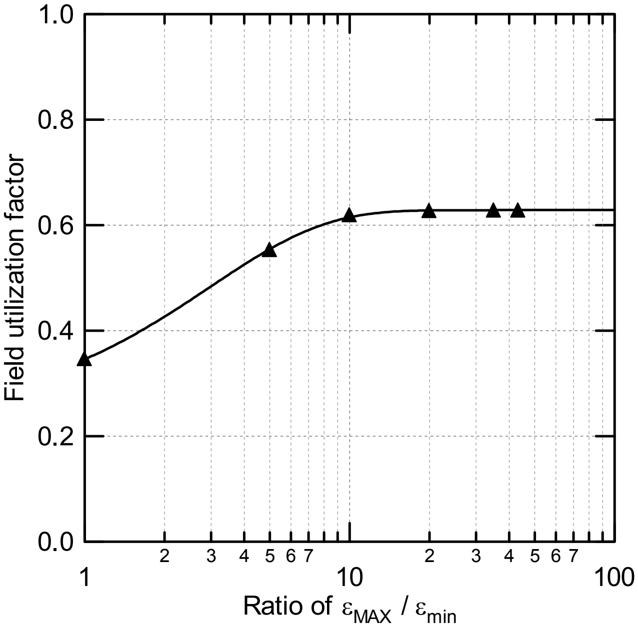


Fig.7 Field relaxation effect of optimized FGM.

V. CONCLUSIONS

For the compact design of gas insulated equipment, we proposed the application of FGM to the solid spacer. The investigation results are concluded as follows.

Firstly, we proposed a computer-aided optimization technique for the FGM solid insulators. In the optimization process, permittivity distribution of the FGM solid insulator is sequentially modified for minimizing the electric field stress in and around FGM solid insulators. Consequently, we successfully developed the optimization techniques on permittivity distribution in FGM solid insulators.

Next, in order to verify the optimization efficiency, we carried out the optimized distributions of permittivity in the cone spacer calculation model. We compared the result of the optimized FGM spacer with one of the conventional spacer which has a uniformly distribution of permittivity. From the calculation results, we confirmed that the proposed optimization method could obtain novel distributions of permittivity, which have the highest performance of the field control effect.

Finally, we could confirm the significant effect of FGM application for gas / solid composite insulation system.

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