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Insulation Performance of Permittivity Graded FGM (Functionally Graded Materials) in SF_6 Gas under Lightning Impulse Conditions

Hitoshi Okubo, Hideki Shumiya, Masahiro Ito and Katsumi Kato
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, JAPAN
okubo@nuee.nagoya-u.ac.jp

***Abstract*- For the size reduction of electric power apparatus, the electric field stress around solid insulators is increasing and carefully to be considered. This concern may be solved by the application of FGM (Functionally Graded Materials).**

In this paper, we investigated the insulation performance of FGM insulator, from both experimental approach and numerical simulation. Firstly, we fabricated column and truncated cone spacers having the permittivity distributed characteristics. Secondly, we investigated the breakdown in SF_6 gas under lightning impulse conditions with theoretical discussion. Finally, we could verify the insulation performance of FGM, and confirmed the significant effect of FGM application for gas / solid composite insulation system.

I. Introduction

Due to the intention to make more compact design of electric power equipment, the electrical insulation design becomes more important. For the insulation design in the equipment, the solid insulators play the most critical role. In order to improve the insulation performance of the solid insulators, we need to control electric field distribution around the solid insulators. However, the techniques so far with additional materials or electrodes have been mainly introduced to control the field stress around the solid insulators. To make the equipment more compact with the simpler structure, we proposed FGM application to the solid spacer, and made the fundamental investigation of FGM [1-2]. In this paper, we investigated the insulation performance of FGM insulator, from both experimental approach and numerical simulation.

Firstly, permittivity graded spacers were fabricated with centrifugal force techniques by controlling the filler particle conditions. Then, we carried out dielectric breakdown experiments in SF_6 gas under the lightning impulse (LI) conditions.

Next, we calculated $TDIV_{50}$ (50% Theoretical Discharge Inception Voltage) of spacers by applying the Volume-Time theory [3-4]. Finally, we could verify the insulation performance of FGM in SF_6 gas under LI conditions, and confirmed the significant effect of FGM application for gas / solid composite insulation system.

II. Fabrication Of FGM Spacer

Firstly, we fabricated 2 application models for investigating the field relaxation effect of FGM;

Model-1: Column spacer (Conventional-1, FGM-1)
Model-2: Truncated cone spacer (Conventional-2, FGM-2)

Figure 1 shows specifications of spacer samples. Spacer samples were fabricated from epoxy resins (ε_r=3.5) mixed with fillers. For conventional spacers, crystal SiO_2 particle (ε_r=4.5) was applied. For FGM spacers, TiO_2 grain rutile crystal (ε_r=114) was mixed in the epoxy matrix and centrifugal force were applied. The permittivity distribution of the samples fabricated with the same conditions was measured. The result is shown in Figure 2. For both samples of Model-1 and Model-2, the permittivity distribution are found, from 4~20 for Model-1 and from 4~12 for Model-2, respectively. Figure 3 shows the electric field distribution around the spacer, calculated by finite element method (FEM). From these figures, concentrated electric field stress of each model was relaxed by applying the spacer of distributed permittivity.

III. Impulse Breakdown Test

For the experimental test, the column spacers were placed between rod-plane electrodes. The truncated cone spacers were placed between parallel plane electrodes. The electric field concentrated around spacers, and we investigated the relaxation effect of this concentrated electric field configuration by FGM application. In the experiment, a test spacer was located in the test vessel filled with 0.1~0.4MPa SF_6 gas, shown in Figure 4. According to the step up method, we applied the LI voltage till breakdown (BD). The impulse partial discharge (PD) was also measured (Sensitivity=50pC).

Figure 5 shows the measured results of breakdown voltage (BDV) and PD inception voltage (PDIV) as a function of gas pressure. In this figure, ● means the case of breakdown occurred without PD. ▲ means the one of breakdown with PD. ▼ means the one of just PD occurred. Black marker shows the case of positive LI voltage application, white marker shows one of negative LI voltage application. From this figure, no PD was detected in all results of FGM, that is, discharge characteristics of FGM is being similar to the one under quasi-uniform field. Especially under positive LI conditions, the results of FGM have significantly higher value than that of conventional; the improvement ratio is maximum 57% for Model-1, maximum 78% for Model-2. This can be interpreted that BDV is strongly improved due to the field relaxation effect by the introduction of FGM.

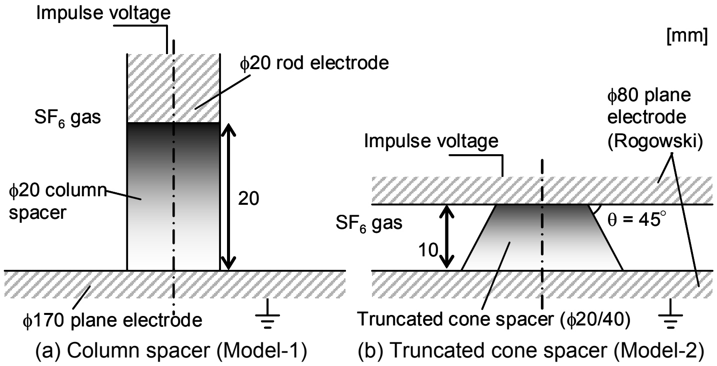


Fig.1 Specifications of 2 types of spacer samples.

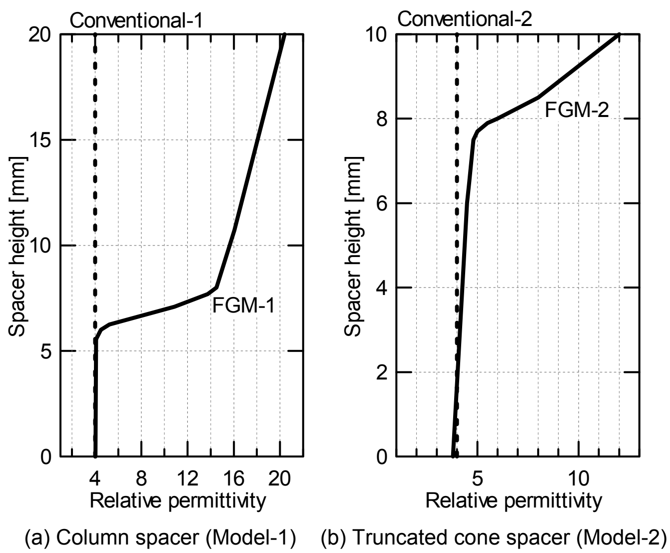


Fig.2 Permittivity distribution of spacer samples.

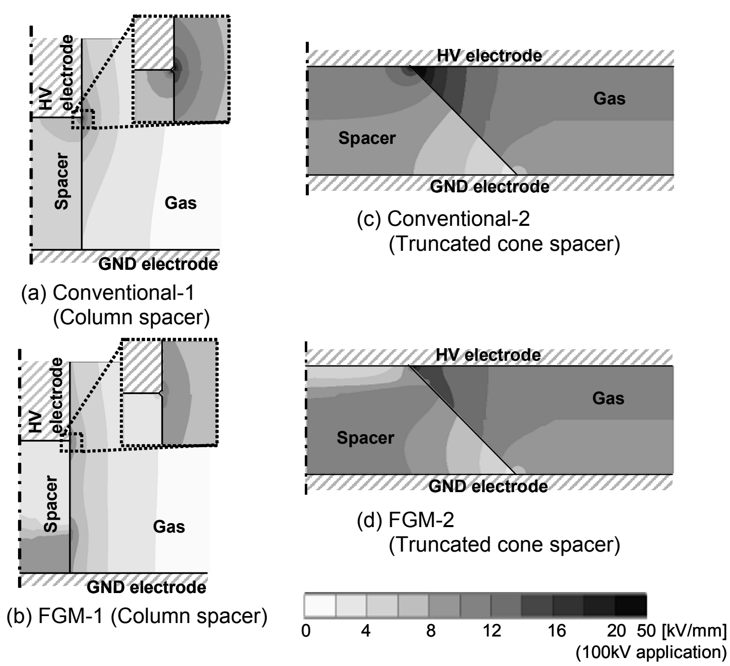


Fig.3 Electric field distribution around the spacer.

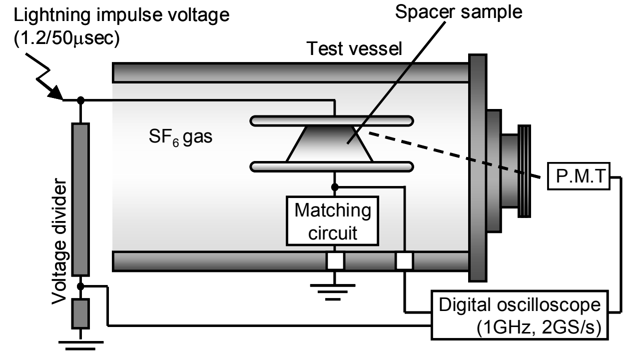


Fig.4 Experimental setup.

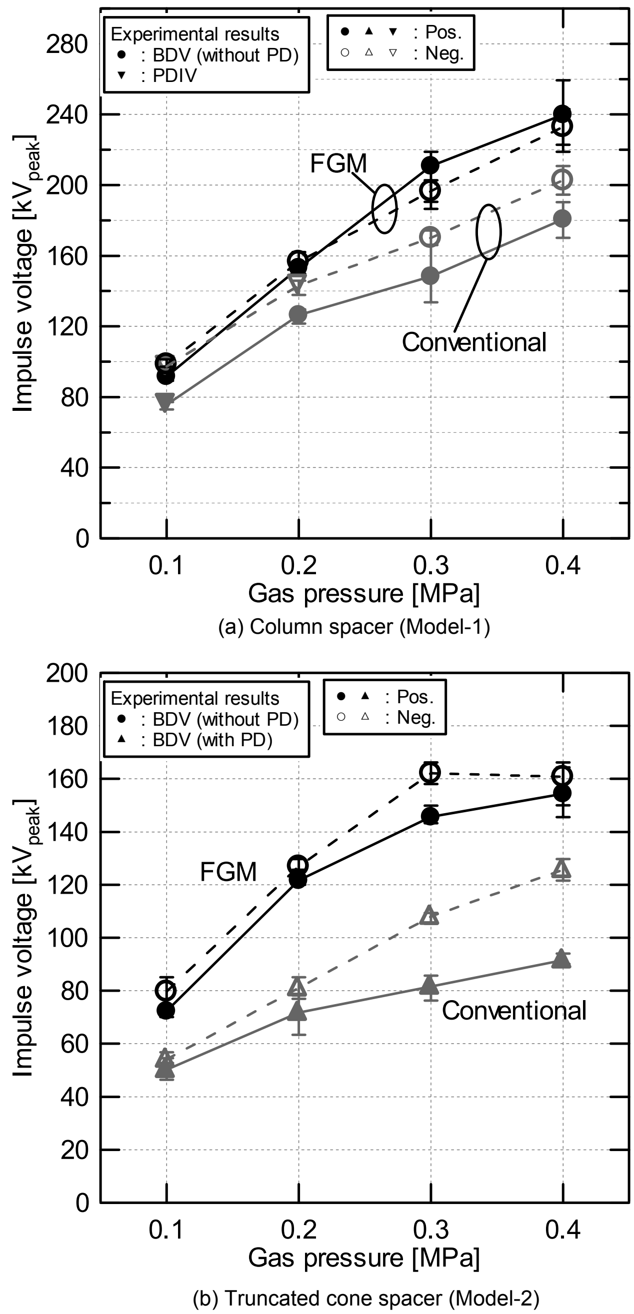


Fig.5 Impulse BDV characteristics on FGM spacers.

IV. Calculation Of Theoretical Discharge Inception Voltage

In the experimental conditions, positive LI applications are more critical for the electrical insulation performance than negative ones. Then, we calculated $TDIV_{50}$ (50% Theoretical Discharge Inception Voltage) under positive LI conditions.

It is mentioned that the process of streamer discharge propagation has the following 4 steps,

(1) Generation of initial electron
(2) Development of electron avalanche
(3) Transition of avalanche to streamer channel
(4) Streamer propagation to breakdown

Process (1) can be described as equation (1) [3-4]. From this equation, statistical time lags can be calculated,

$$\begin{cases} P(t) = 1 - \exp\left[-\int_0^t V_w dt \right] \\ V_w = \int_{V_{cr}} \frac{dn_e}{dt}\left(1 - \frac{\eta}{\alpha}\right) dV \end{cases} \quad (1)$$

Under positive LI conditions, it is mentioned that generation of initial electron is mainly detachment of SF_6^- ion which exists in gas gap, described as the term V_w in Eq. (1). Here, the term dn_e/dt means the ratio of initial electron generation per unit time, per unit volume (= [SF_6^- ion density] x [detachment ratio coefficient]). The term $(1-\eta/\alpha)$ means attachment of initial electron to SF_6 gas. V_{cr} is the volume which is satisfied $\alpha>\eta$ and streamer criterion described as the following equation [5-6],

$$\int_{x_{cr}} (\alpha - \eta)\, dx = K \quad (2)$$

Here, α is ionization coefficient, η is attachment coefficient, K is constant, x_{cr} is the path along line of electric force. The value of K is varied with gas species, K=18 for SF_6 gas [4, 6-7]. $(\alpha-\eta)$ for SF_6 gas is expressed as follows [6-7],

$$\frac{\alpha - \eta}{p} = 27\left(E/p - 87.75\right) \quad (3)$$

Here, E is electric field strength [kV/mm], p is gas pressure [MPa].

Process (2) can be considered in advance, by the calculation of streamer criterion in Eq. (1). Then, tip of avalanche has enough density of electron. Hence, process (3) is automatically included in the calculation of Eq. (1). From the above, we can calculate time transition of streamer discharge inception probability (SDIP). Here, we estimate the time t_{50} which calculated probability density becomes 50% density. After that, we can calculate typical SDIP of the applied LI voltage, as the probability $P(t_{50})$. Then, $TDIV_{50}$ can be calculated as the voltage of $P(t_{50})$ = 50%

In the $TDIV_{50}$ calculation, time transition of SF_6^- ion density distribution is needed to estimate by the following equations [3-4, 8],

$$\begin{cases} \frac{dn^+}{dt} = N_0 - K_r n^+ n^- - div(u_d{}^+ n^+ - D^+ \nabla n^+) \\ \frac{dn^-}{dt} = N_0 - K_r n^+ n^- - div(u_d{}^- n^- - D^- \nabla n^-) \\ u_d = \begin{cases} \mu E & (E < E_{cr}) \\ 0.6 + 0.7543\sqrt{E/E_{cr} - 0.999} & (E > E_{cr}) \end{cases} \end{cases} \quad (4)$$

Here, n^+, n^- is density of positive ions or negative ions. N_0 is ionization rate of SF_6 gas. K_r is ion-ion recombination constant. u_d^+, u_d^- is drift velocity of positive ions or negative ions [mm/μsec]. μ is low field ion mobility. E is electric field strength [kV/mm]. E_{cr} is theoretical discharge inception field calculated from $(\alpha-\eta)$. Time transition and spatial distribution of ion density can be calculated by defining the following three conditions,

(a) In gas region, $n^+ = n^-$.
(b) On electrode surface, n=0 fixed.
(c) Along gas-solid interface, *div* term in Eq. (4) is neglected.

V. Field Enhancement Effect By Surface Rouhness

For exact prediction of the insulation performance under LI conditions, we estimated the field enhancement effect by electrode surface roughness which affects field strength of the spatial region close to electrode surface. Then, we modeled the electrode surface roughness as shown in Figure 6. Axi-symmetric 3D model, which has the periodical roughness (R_1) and the localized projection (R_2), was arranged. From electric field calculation, we successfully introduced the field enhancement effect by electrode surface roughness.

Here, we measured the electrode surface roughness experimentally. Results are as follows; average surface roughness (Ra) = 0.29 ~ 1.29μm, maximum peak height (Rp) = 3Ra ~ 5Ra. Then, we regarded protrusion "r" equaled to Ra, and gave the field enhancement effect, and is r = 1μm.

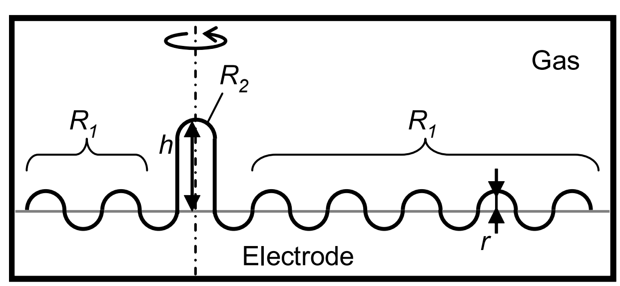


Fig.6 Modeling of electrode surface roughness.

VI. Calculated Results And Discussion

Calculated results are shown in Figure 7. From this figure, we confirmed that experimental results were well agreed with calculated ones for both spacer models. The gas pressure dependence was also well interpreted by the theoretical discussions. Then, the field relaxation effect by the introduction of FGM could directly contribute to improve the insulation performance under LI conditions. Consequently, in the consideration of "time transition of electric field distribution and distribution of initial electron source" and "field enhancement effect by electrode surface roughness", we successfully estimated the insulation performance of FGM under LI conditions.

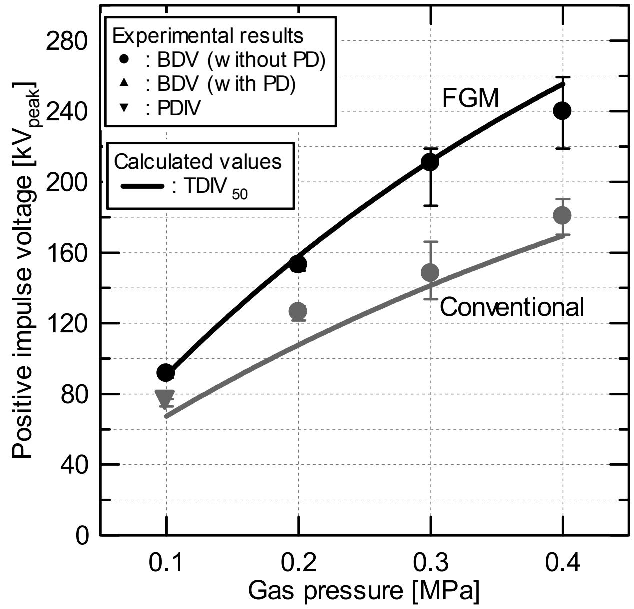
VII. Conclusions

For the compact design of gas insulated equipment, we proposed the application of FGM to the solid spacer. In order to verify the effect of FGM application for solid insulators, we introduced 2 models of spacer; column spacer model and truncated cone spacer model. Firstly, we fabricated permittivity graded spacers by applying the centrifugal forces. Next, we discussed the relaxation effect of electric field concentration by both numerical simulation and breakdown tests. The main results are summarized as follows.

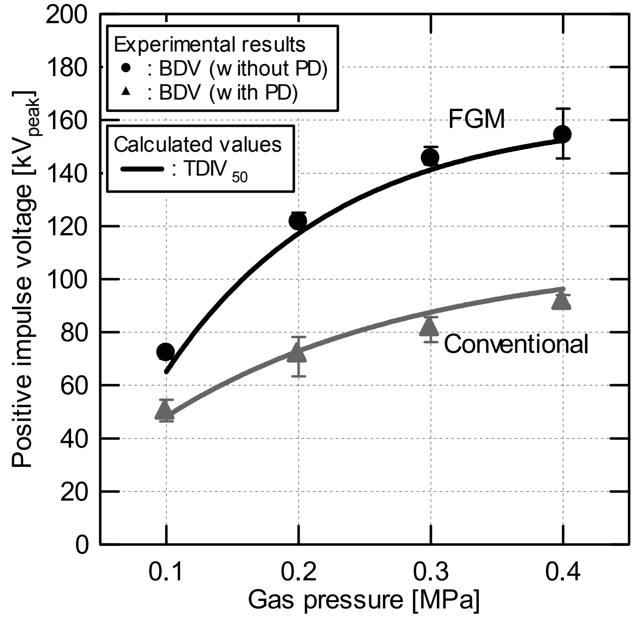
(1) We found the significant effect of BDV improvement in every experimental condition; spacer models, gas pressure and polarization of applied voltage (in the outstanding case, the improvement ratio is up to 78%). Furthermore, BDV improvement ratio of FGM against Conventional increased with the increase of gas pressure.

(2) From the viewpoint of comparing experimental results with calculated values, it could be interpreted that BDV is improved due to the field relaxation effect of FGM.

Finally, we could quantitatively verify the insulation performance of FGM in SF_6 gas under LI conditions, from both experimental approach and numerical simulation. And, we confirmed the significant effect of FGM application for gas / solid composite insulation system.



(a) Column spacer (Model-1)



(b) Truncated cone spacer (Model-2)

Fig.7 Positive polarity $TDIV_{50}$ as a function of gas pressure.

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