# Finite Element Analysis for Surface Discharge Due to Interfacial Polarization at the Oil-Nanocomposite Interface

Jin-Hyun Choi[1], Su-Hun Kim[1], Kyunghoon Jang[2], Masayuki Hikita[2], and Se-Hee Lee[1]

[1]Department of Electrical Engineering, Kyungpook National University, Daegu 41566, Republic of Korea
[2]Kyushu Institute of Technology Fukuoka, Japan

**The propagation of surface discharge due to the interfacial polarization was numerically analyzed at the oil-nanocomposite interface by use of the fully coupled finite element analysis incorporating with the relative permittivity resulting from experimental works. To improve the insulation ability, the oil-nanocomposite interface on a pressboard has been proposed and this composite material can enhance the breakdown voltage in power systems. To specify the bulk relative permittivity, we measured the relative permittivity of epoxy resin with different percentage of nanosilica on the pressboard. This experimental results showed that the relative permittivity has a minimum point with respect to the amount of added nanosilica. To analyze the characteristics of surface discharge quantitatively with this experimental results, the fully coupled finite element analysis technique has been implemented and tested with various relative permittivity values of nanocomposite material. This phenomenon has been simulated by using the fully coupled governing equations with the Poisson's equation for electric field and charge continuity equations including the surface charge accumulation for charge transport. After verification of our numerical setup, the needle-bar electrode system has been proposed and tested for surface discharge propagation. The velocity of propagation speed at the oil-nanocomposite interface was compared with different percentage of nanosilica. Finally, the physical mechanism of surface discharge due to the interfacial polarization has been analyzed with the space charge density at the oil-nanocomposite interface based on the numerical results.**

***Index Terms*—Surface charge density, oil-nanocomposite interface, charge transport, permittivity difference**

## I. Introduction

Electric discharge phenomena are very complex and involve various influencing factors such as purity of the insulation, physicochemical components, and thermal conductivity. So far, studies on streamer propagation and surface discharge phenomena in insulating fluids have been mainly conducted by experimental methods [1]. Recently, many studies have been conducted to analyze the discharge characteristics and identify mechanisms by applying the multiphysics analysis technique by using the finite element method [2]. Most of the power devices are used in high voltage and high current environments and have to satisfy both insulation and cooling performance, so that multiphysics modeling can be extended and applied to various fields.

We, here, employed a multiphysical technique applicable to the 2-D model of surface discharge at the oil-nanocomposite interface. Composite permittivity changes of epoxy resin with nanosilica were measured experimentally and the mechanism of surface discharge were analyzed numerically.

## II. Relative Permittivity for Nanocomposite Material

A relative permittivity of pressboard covered with epoxy resin was measured by increasing the ratio of nanosilica into the epoxy resin under the experimental conditions. The measurement was carried out by impedance analyzer with increasing the amount of nanosilica after 3 hours and 24 hours of immersion. In both cases, the relative permittivity decreased with the weight ratio of 1 %, and then increased again. The reduction of the relative permittivity according to the addition rate of nanoparticles in the base epoxy resin is generally explained by the free volume theory based on the experimental methodology and the multi-core model [3]-[4].

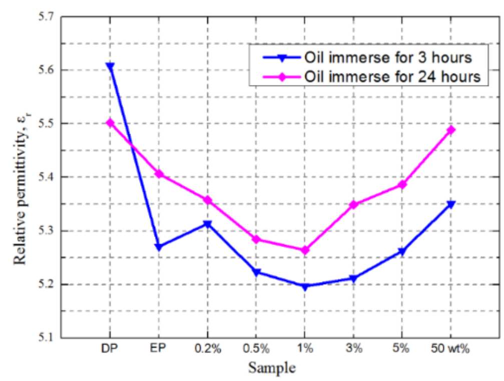


Fig. 1. Change of relative permittivity on amount of added nanosilica.

## III. Governing Equations and Surface Charge Density for Numerical Analysis

### A. Permittivity measurement on nanosilica addiction

For analyzing the surface discharge at the oil-nanocomposite interface, fully coupled governing equations can be introduced including ionization, recombination, and attachment effects. These equations were combined with the Poisson's equation for electric field and the three continuity equations including electrons $\rho_e$, negative ion $\rho_-$ and positive ion $\rho_+$, respectively, as [5]

$$-\nabla\cdot(\varepsilon\nabla V)=\rho_+ + \rho_- + \rho_e \tag{1}$$

$$\frac{\partial\rho_+}{\partial t}+\nabla\cdot\mathbf{J}_+ = G_I(|\mathbf{E}|)+\frac{\rho_+\rho_- R_\pm}{e}+\frac{\rho_+\rho_e R_{+e}}{e} \tag{2}$$

$$\frac{\partial\rho_-}{\partial t}+\nabla\cdot\mathbf{J}_- = -\frac{\rho_+\rho_- R_\pm}{e}+\frac{\rho_e}{\tau_a} \tag{3}$$

$$\frac{\partial\rho_e}{\partial t}+\nabla\cdot\mathbf{J}_e = -\,G_I(|\mathbf{E}|)-\frac{\rho_+\rho_e R_{+e}}{e}-\frac{\rho_e}{\tau_a} \tag{4}$$

where the subscript $\varepsilon$ is the dielectric permittivity, $t$ is the time, **J** is the current density, $G_1(|\mathbf{E}|)$ is the molecular ionization, $\tau_a$ is the time constant for electron attachment, and $\alpha$, $\eta$, and $\beta$ are the coefficients for ionization, attachment, and recombination.

The accumulated surface charge can be calculated by using the difference between total current densities in the normal component at the interface as [6]

$$\frac{\partial \sigma_s}{\partial t} = \mathbf{n} \cdot (\mathbf{J}_{liquid} - \mathbf{J}_{solid}) \quad (5)$$

$$\mathbf{J} = (\rho_+ \mu_+ - \rho_- \mu_- - \rho_e \mu_e)\mathbf{E} \quad (6)$$

where $\sigma_s$ is the surface charge density, **n** is the outward normal unit vector from the liquid to solid, and **E** is the electric field intensity.

### *B. Numerical analysis based on the surface charge density*

As shown in Fig. 2, the relative permittivity of dielectric fluid was 2.2 and that of solid insulator composed of pressboard and nanocomposite was changed to 2.8, 3.3, 3.8, 4.2, and 4.7 by using the needle-plate model with a spacing of 2.5 mm. The propagation mechanism analysis was performed by comparing the rate of streamer propagation and the amount of surface charge.

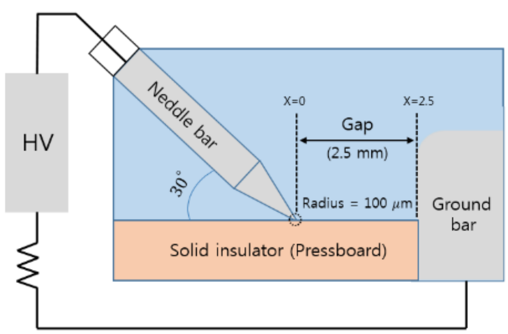


Fig. 2. Tip-plane electrode model in 2D.

In the case of composite permittivity 4.2, the speed of surface discharge at the oil-pressboard interface was measured about 12 km/s [7]-[8]. From our numerical setup, the mean velocity was 12.23 km/s, which is similar to the previous experimental results. As the permittivity difference increases, the propagation of surface charge becomes faster. With the positive streamer propagation, the positive ion was dominant at the interface. Fig. 3 compares the surface charge density at the oil-nanocomposite interface and the Coulomb force at 1.5 mm from the needle.

As the permittivity difference with insulating fluid increases, a larger electric field is concentrated at the oil-nanocomposite interface. The space charge increases due to the molecular ionization in the oil, and it progresses with receiving more electric force. At this time, the negative surface charge density at the oil-nanocomposite interface increases and the attractive force also increases between the space charge and the surface charge. Therefore, the space charge more closely adheres to the surface and creeps rapidly to cause insulation breakdown.

Fig. 4 shows the distributions of space and surface charge density according to the relative permittivity difference.

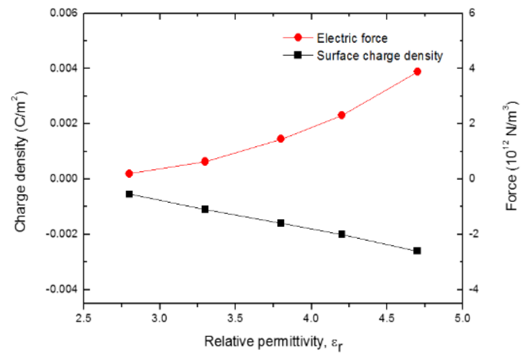


Fig. 3. Electrical force and surface charge density at 1.5 mm from starting point.

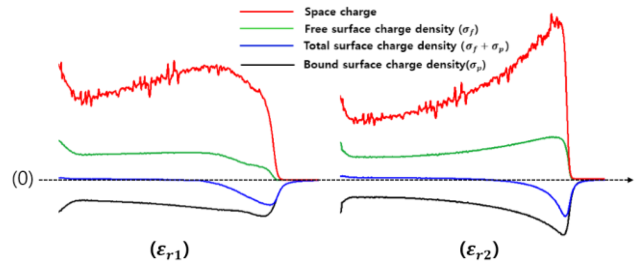


Fig. 4. Comparison of space charge and surface charge density according to the relative permittivity difference.

## IV. Result and Discussion

The amount of surface charge density accumulated and space charge is different along with the permittivity difference between liquid and solid. Therefore, the attraction between the surface and the space charge causes the advancement of the streamer and the change of the dielectric strength. In an extended paper, more detailed analysis will be discussed with the surface charge density and space charge at the oil-nanocomposite interface.

## References

[1] P. M. Mitchinson, P. L. Lewin, B. D. Strawbridge, and P. Jarman, “Tracking and Surface Discharge at the Oil-Pressboard Interface,” *IEEE Electrical Insulation Magazine*, Vol. 26, No. 2, March/April, 2010.

[2] Lee. H. Y., et al., “Numerical and Experimental Validation of Discharge Current With Generalized Energy Method and Integral Ohm’s Law in Transformer Oil,” *IEEE Trans. Magn*., vol. 50, pp. 257-260, 2014.

[3] J. K. Nelson and Y. Hu, "The Impact of Nanocomposite Formulations on Electrical Voltage Endurance," *IEEE International Conference on Solid Dielectircs*., vol. 2, pp. 832-835, 2004.

[4] Toshikatsu Tanaka, Masahiro Kozako, Norikazu fuse, and Yoshimichi Ohki, “Proposal of a Multicore Model for Polymer Nanocomposite Dielectrics,” *IEEE Trans. Dielectr and Electr.*, vol. 12, pp. 669-681, 2005.

[5] Lee, H. Y., et al., “Fully Coupled Finite Element Analysis for Surface Discharge on Solid Insulation in Dielectric Liquid with Experimental Validation,” *IEEE Trans. Magn*., vol. 52, 2016.

[6] Jouya Jadidian., et al., “Surface flashover breakdown mechanisms on liquid immersed on liquid immersed dielectrics,” *Appl. Phys. Lett*., 100, 2012.

[7] O. Lesaint., et al., “Positive streamer propagation in large oil gaps: Experimental Characterization of propagation modes,” *IEEE Trans. Dielectr. Electr. Insul*., vol. 5, pp. 360-370, Jun. 1998.

[8] G. Massala., et al., “Positive streamer propagation in large oil gaps: Electrical properties of streamers.” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 5, pp. 371-381, Jun. 1998.