

Numerical Analysis of Liquid Discharge Considering Lossy Dielectric Material Immersed in Insulating Oil

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The liquid discharge was examined through the finite element method with a lossy dielectric material immersed in insulating oil considering both the dielectric permittivity and conductivity. Until now, the liquid discharge analysis with the lossy dielectric material has rarely been reported with the 3-carrier system consisting of positive ion, negative ion, and electron. To verify our numerical setup, one carrier analysis model, first, was constructed to test the space and surface charges with the lossy dielectric barrier. The charge propagation was validated by comparing it with theoretical results. Based on this model, we extended it to 3-carrier model for analyzing the effects of lossy dielectric material in a streamer channel. This study provides insights into streamer propagation characteristics and charge accumulation behavior as a function of dielectric permittivity and conductivity, offering a foundation for further analysis of discharge phenomena in insulating oil.

Index Terms—The lossy dielectric particle, Insulating oil, Streamer propagation, Liquid discharge

I. INTRODUCTION

Power transformers are one of the most important equipment in power system, and liquid insulation such as insulating oil is used to maintain a stable power supply incorporating with dielectric materials. Insulating oil has high insulation strength and good cooling efficiency. However, as it circulates through the transformer, it is likely to be contaminated by impurities. Impurities consist of non-metallic particles from the wear of the pressboard and metal particles that have fallen off the enclosure or iron core. In particular, non-metallic particles have been reported to account for 90% of the impurities inside the transformer[1]. These impurities are a source of degradation of the insulation strength of the insulating oil by accumulating space charge and causing partial discharge. Therefore, it is necessary to study the space charge accumulation behavior with impurities in insulating oil. In general, impurities can be considered as lossy dielectric materials with the permittivity and conductivity. Until now, however, the analysis of lossy medium has rarely been discussed. To deal with these problems, we developed an analysis model that couples the current continuity equation with the charge continuity equations and validated our proposed method by comparing it with theoretical results. Finally, we successfully extended a 3-carrier model for liquid discharge analysis with the lossy dielectric barrier in insulating oil.

II. VERIFICATION WITH ONE-CARRIER DISCHARGE MODEL

A lossy dielectric particle with the permittivity ϵ_2 and the conductivity σ_2 is in a medium with the permittivity ϵ_1 and the conductivity σ_1 . DC electric field $E_0\hat{z}$ is applied to the medium. The steady-state electric field of a lossy dielectric particle can be calculated by dividing the inside and the outside of the particle, and is expressed as [2]

$$E_{in} = \frac{3\sigma_1 E_0}{2\sigma_1 + \sigma_2} \hat{z} \quad (1)$$

$$E_{out} = E_0 \left[\left(1 + \frac{2R^3(\sigma_2 - \sigma_1)}{r^3(2\sigma_1 + \sigma_2)} \right) \cos\theta \hat{r} - \left(1 - \frac{R^3(\sigma_2 - \sigma_1)}{r^3(2\sigma_1 + \sigma_2)} \right) \sin\theta \hat{\theta} \right] \quad (2)$$

The surface charge on the lossy dielectric particle is calculated as the difference between the electric flux density of the medium and particle as

$$\sigma_s(r=R) = \epsilon_1 E_{out} - \epsilon_2 E_{in} = \frac{3(\sigma_2 \epsilon_1 - \sigma_1 \epsilon_2) E_0}{2\sigma_1 + \sigma_2} \cos\theta \quad (3)$$

where θ is the polar angle in the spherical coordinate. The surface charge density on the top of the particle is of the opposite sign compared to that on the bottom part of the particle. The total charge on the particle is zero.

The analysis model has a heterogeneous interface consisting of liquid with ϵ, μ and solid with ϵ, σ . The governing equations of the analysis model consist of the current continuity equation and the positive charge continuity equation. The governing equations are expressed as

$$\nabla \cdot (\epsilon \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E}) = 0 \quad (4)$$

$$\frac{\partial \rho_+}{\partial t} + \nabla \cdot (\rho_+ \mu_+ \vec{E}) = 0 \quad (5)$$

where ϵ is the permittivity, σ is the conductivity, and $\vec{E}$ is the electric field. ρ_+ is the positive charge and μ_+ is the mobility of the positive charge. To validate the analysis model, the material properties of region 1, which consists of transformer oil with the relative permittivity of 2.2 and the conductivity represented by $\rho_+\mu_+$, and region 2, which consists of the pressboard particle with the relative permittivity of 2.4 and the conductivity of 1×10^{-12} S/m, were used. The model was verified by comparing the electric field of the lossy dielectric particle, the surface charge, and the total charge.

Fig. 1 shows the electric field distribution of the analysis model as a function of time. The inside of the electric field for the lossy dielectric particle calculated from the analysis model is 1.4×10^8 V/m, which is consistent with the theory. The surface

charge density on the upper and lower parts of the particle has opposite values, and the total charge reaches zero around 1500 ms. In an extended paper, the results will be discussed in detail.

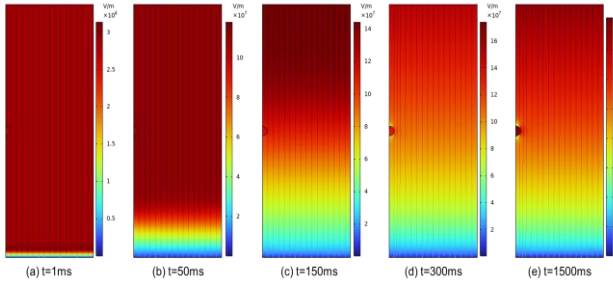


Fig. 1. The electric field distribution of the analysis model with the lossy dielectric particle as a function of time.

III. EXTENSION TO THE THREE-CARRIER'S CHARGE TRANSPORT MODEL WITH A LOSSY DIELECTRIC PARTICLE

Fig. 2 shows the numerical model of the needle-plate electrode with the dielectric particle located where the gap distance between the needle and particle, d_1 , is 2.5 mm.

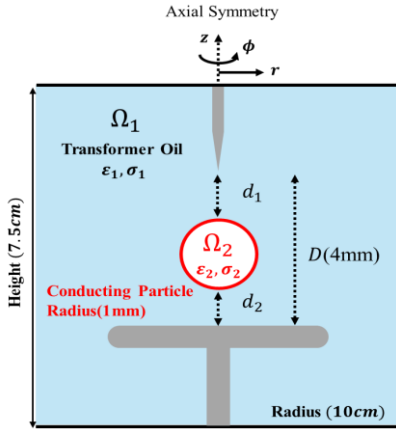


Fig. 2. Axisymmetric numerical model with the lossy dielectric particle in the insulating oil.

A. Governing Equations

The numerical model is used to describe the streamer propagation in insulating oil. The governing equations are expressed as [3]

$$\nabla \cdot (\varepsilon \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E}) = 0 \quad (6)$$

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot (\rho_p \mu_p \vec{E}) = G_i \left(|\vec{E}| \right) + \frac{\rho_p \rho_e R_{pe}}{q} + \frac{\rho_p \rho_n R_{pn}}{q} \quad (7)$$

$$\frac{\partial \rho_n}{\partial t} - \nabla \cdot (\rho_n \mu_n \vec{E}) = \frac{\rho_e}{\tau_a} - \frac{\rho_p \rho_n R_{pn}}{q} \quad (8)$$

$$\frac{\partial \rho_e}{\partial t} - \nabla \cdot (\rho_e \mu_e \vec{E}) = -G_i \left(|\vec{E}| \right) - \frac{\rho_p \rho_e R_{pe}}{q} - \frac{\rho_e}{\tau_a} \quad (9)$$

where ε is the permittivity, σ is the conductivity, and $\vec{E}$ is the electric field. ρ_p , ρ_n , and ρ_e denote the positive ion, negative ion and the electron, respectively. μ_p , μ_n , and μ_e denote the mobility of the positive ion, negative ion, and the electron, respectively.

R_{pn} and R_{pe} are the recombination rate of ion-ion and ion-electron. τ_a is the electron attachment time.

B. Numerical Results

Fig. 3 shows the electric field distribution of the numerical model. The particle has the relative permittivity of 2.4 and a conductivity of 1×10^{-12} S/m. The streamer is caused by the ionization of neutral molecules around the needle electrode due to the high electric field strength. Due to the particle's low electrical conductivity, the streamer cannot fully penetrate the particle, and the space charges pass through the particle, migrating along its surface.

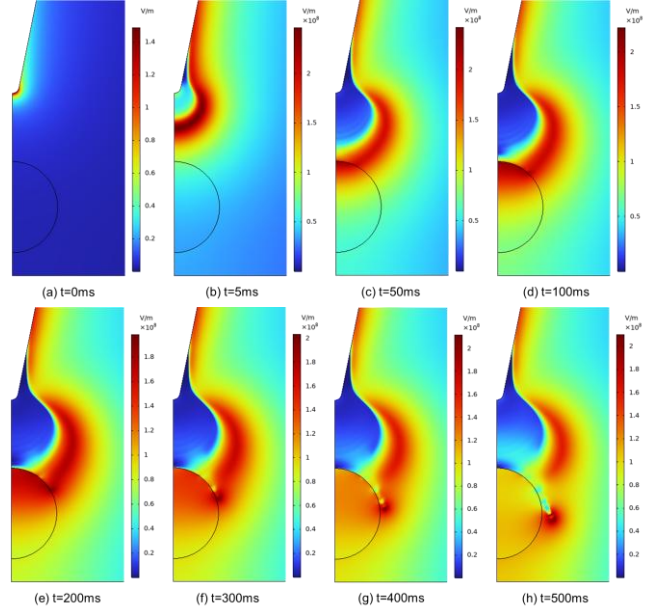


Fig. 3 The electric field distribution of the numerical model with the lossy dielectric particle in insulating oil as a function of time.

IV. CONCLUSION

In this paper, we analyzed streamer propagation with the lossy dielectric particle under the liquid discharge. The proposed model overcomes the limitations of the previous model, which cannot consider the lossy dielectric materials, by introducing the current continuity equation. As a result, the analysis model was successfully validated by comparing the electric field and surface charge of the particle with the theory. Based on this analysis model, we extended it to 3-carrier model to analyze the effect of the lossy dielectric particle on streamer propagation. In an extended paper, we will analyze the streamer propagation characteristics and the charge accumulation as a function of the dielectric permittivity and conductivity.

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