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Corona Discharge Behaviors with Presence of Floating Electrode in Air Insulation using Numerical Model Analysis

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ABSTRACT
This paper deals with numerical analysis method for analyzing the partial discharge behaviors in terms of corona discharge in the presence of a floating electrode under lightning impulse voltage. To analyze the corona discharge behaviors at 0.5 mm short electrode gap system as basic research work between main conductor and floating electrode, we considered fully coupled numerical model based on the charge continuity equations for positively charged ion, negatively charged ion and free electrons. Poisson's equation is coupled with hydro-dynamic drift-diffusion equations derived from the three kinds of charge continuity equation. Fowler-Nordheim field emission is assumed that the electron emission by electric field is used as boundary conditions for main conductor and floating electrode. As a results, it is found that the floating electrode creates a non-uniform electric field distribution with a large field enhancement, causing ionization to initiate corona discharge. In other words, floating electrode is early corona discharge inception by collecting the induced charge developed by high voltage electrode. This result is expected to be applicable to various corona discharge generating systems as well as insulation design of power apparatus with presence defects such as a floating metal particle under lightning impulse voltage.

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Introduction
The electrical partial discharge and flashover phenomenon occurs by electric field concentration in natural environment, insulation materials and high voltage systems. The knowledge of the mechanisms of corona discharge characteristics in terms of initiation and development are very useful to design and manufacture the various electric devices and systems. In other words, engineers want to understand the corona discharge inception, development, propagation and occurrence position in insulation air in the presence of floating electrode.

In this paper, we have focused on the influence with/without floating electrode on a partial discharge system. The numerical analysis model for discharge system consists of a high voltage electrode, main conductor and floating electrode. The floating electrode is placed around main conductor, lightning impulse voltage was applied to the high voltage electrode. To analyze the corona discharge behavior, we investigated the electric field analysis at very small gap with charge continuity equations including charge continuity equations including charge continuity equations with ionization (positively charged ion-free electron), dissociation (ion-ion), charge recombination (ion-ion and positively charged ion-free electron) and electron attachment combined with Poisson's equation in air insulating using 2D space dimension.

Numerical Analysis for Corona Discharge Behavior
The behaviors of free electron (ρ_e), positively charged ion (ρ_+) and negatively charged ion (ρ_-) can be calculated by using hydrodynamic drift-diffusion equations derived from the continuity equation. These governing equations is presented as follows [1-4]:

$$\frac{\partial \rho_+}{\partial t} + \nabla \cdot (\rho_+ \mu_+ \vec{E}) = -G_I(|E|) + D(|E|) + \frac{\rho_+ \rho_- \rho_{+,-}}{q} + \frac{\rho_+ \rho_e \rho_{+,e}}{q} \quad (1)$$

$$\frac{\partial \rho_-}{\partial t} + \nabla \cdot (\rho_- \mu_- \vec{E}) = -D(|E|) - \frac{\rho_+ \rho_- R_{+,-}}{q} + \frac{\rho_e}{\tau_a} \quad (2)$$

$$\frac{\partial \rho_e}{\partial t} + \nabla \cdot (-D_e \nabla_{\rho e} \rho_e \mu_e \vec{E}) = -I(|E|) - \frac{\rho_+ \rho_- R_{+,e}}{q} - \frac{\rho_e}{\tau_a} \quad (3)$$

Where the subscripts ρ_+, ρ_- and ρ_e denote positively charged ion, negatively charged ion and electron, respectively; ε is the dielectric permittivity; $I(|E|)$ is the molecular ionization; $D(|E|)$is the ionic dissociation source; R is the recombination rate; q is the electronic charge; τ_a is the electron attachment time constant. μ_-, μ_+ and μ_e denote mobility of negatively charged ion, positively charged ion and free electron.

The continuity equation is coupled with Poisson's equation, it is employed in air insulation. The current density within insulation are as follows:

$$-\nabla \cdot (\varepsilon_r \nabla V) = \rho_+ + \rho_- + \rho_e \quad (4)$$

$$\vec{J} = \left(\sigma + \varepsilon_0 \varepsilon_r \frac{\partial}{\partial t}\right) E + J_e \quad (5)$$

Where ε_r relative permittivity of air insulation; $\vec{E}$ and $\vec{J}$ are electric field and current density within air insulation.

To consider the electron emission for the surface of each electrode, the charge generation on the surface of each electrode assumed to be given by a dominant process among candidates of field emission each electron to insulation air expressed in equations as follows:

$$J_{FE} = \frac{e^3|\vec{E}|^2}{8\pi h \emptyset_D} \exp\left(-\frac{8\pi\sqrt{2m}\emptyset_D^{\frac{3}{2}}}{3he|\vec{E}|}\right) \quad (6)$$

Where J_{FE} is emitted current density due to the influence of the applied electric field, h is Planck's constant, e is the magnitude of electronic charge (1.602×10^{-9} C), $|\vec{E}|$ is the local electric field, $\emptyset_D=\emptyset_w-\chi$ is effective barrier height. When $\emptyset_w$ is the work function and χ is the electron affinity of the air insulation, respectively. Note that the effective barrier height of aluminum is 4~5 eV [5], [6].

Lightning voltage 1.2/50 μs is applied. The double exponential expression is an analytical representation of the pulse waveform as follows:

$$V(t) = V_1[\mathrm{Exp}(-t/\tau_2) - \mathrm{Exp}(-t/\tau_1)] \quad (7)$$

with τ_2=1.443T_t, τ_1=0.2T_f, V_1=$V_m$exp $(t_f/1.443T_t)$, where

where T_f and T_t are virtual front time and time of 50% voltage.

The following Table 1 describes the significance of various abbreviations and acronyms used throughout the paper.

Symbol	Meaning
ρ_+, ρ_-, ρ_e	Positive ion, negative ion and free electron
I	Ionization term
D	Dissociation term
R	Recombination term
τa	Electron attachment
$\mu-$, $\mu+$, μe	Mobility of positive, negative ion and free electron
$\vec{E}$	Electric field
$\vec{J}$	Current density
JFE	Current density by field emission
h	Planck's constant
e	Magnitude of electronic charge
$\emptyset w$	Work function
χ	Electron affinity

Simulation Model Geometry

Figure 1 shows computer aided design representation of the numerical model geometry in COMSOL Multiphysics 2D model. The distance between the main conductor and high voltage electrode is 0.5 mm. The floating electrode is placed around main conductor, the height of main conductor is 0.05 mm. The gap distance between main conductor and floating electrode is 5 μs. The applied voltage to the high voltage electrode is 300 kV positive standard lightning impulse voltage. In this research work, we considered the corona discharge behavior with presence of floating electrode at 0.5 mm short electrode gap system.

Numerical Analysis Results

Figure 2 shows result of numerical model analysis to simulate the local electric field distribution in air insulation under 300 kV impulse voltage as a function of time step. For simulation model without floating electrode, the electric field is formed at sharp tip ranges from 3.1 to 8.8×10⁶ [kV/mm]. On the other hands, a high electric field with the presence of floating electrode is distributed between main conductor and floating electrode. The electric field is formed at sharp tip of floating electrode about 2 $\times10^6$ [kV/mm] at t 0.1 [μs] and about 8.9$\times10^6$ kV/mm at 1.2 [μs], around floating electrode is about 1.48 $\times10^6$ [kV/mm] at 0.1 μs and about 4.05 $\times10^6$ [kV/mm] at 1.2 [μs]. Meaning that first corona discharge with presence of floating electrode is likely to incept between main conductor and floating electrode and then sharp tip of floating electrode due to concentrated strong electric field.

Figure 3 (a) and (b) shown positive ion and negative ion density with presence of floating electrode obtained from Equation (1)-(2) including ionization, dissociation, recombination. The results revealed that when the high electric field is formed between high voltage electrode and main conductor, positive ion, negative ion and free electron are generated in the gap between main conductor and floating electrode caused by ionization process in neutral air insulation. Figure 3 (a) shows electron density at the sharp tip of floating electrode as a function of time. The positive ion and electron density increases with increasing time step. In other words, both densities increase with increasing time step gradually until t = 6 $\times10^{-7}$ [s], and then both densities increase drastically from t = 6 $\times10^{-7}$ [s] to t = 1.2 $\times10^{-6}$ [s]. Meaning that the corona discharge occurs at the sharp tip of floating electrode by induced high electric field formation.

Figure 4 shows behavior of negative and positive ion density. When electric field is not applied between high electrode and main conductor, the positively charged ion and negatively charged ion are in a stable state as a neutral molecule, it is because air insulation have many neutral ion pairs. Whereas, the external energy is applied larger than the bonding energy of neutral ion pairs in air insulation, and then neutral ions are detached from each other. In other words, the around of floating electrode seem to create a non-uniform electric field with a large electric field enhancement due to ionization under positive impulse voltage.

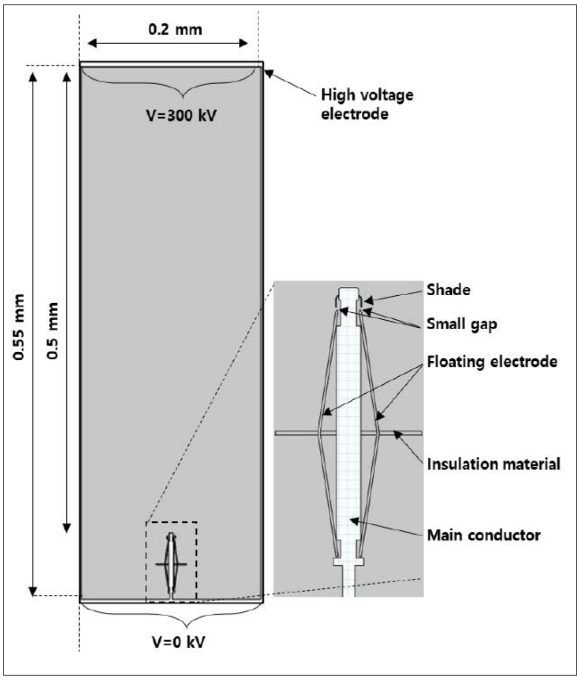

Figure 1: Computer Aided Design Representation of the Minimized Numerical Model Geometry

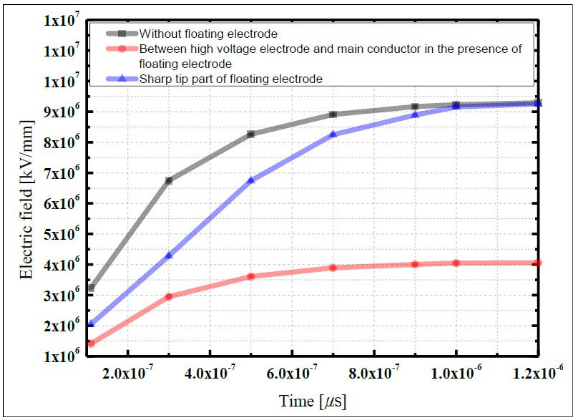

Figure 2: Electric Field Level as a Function of Time Step

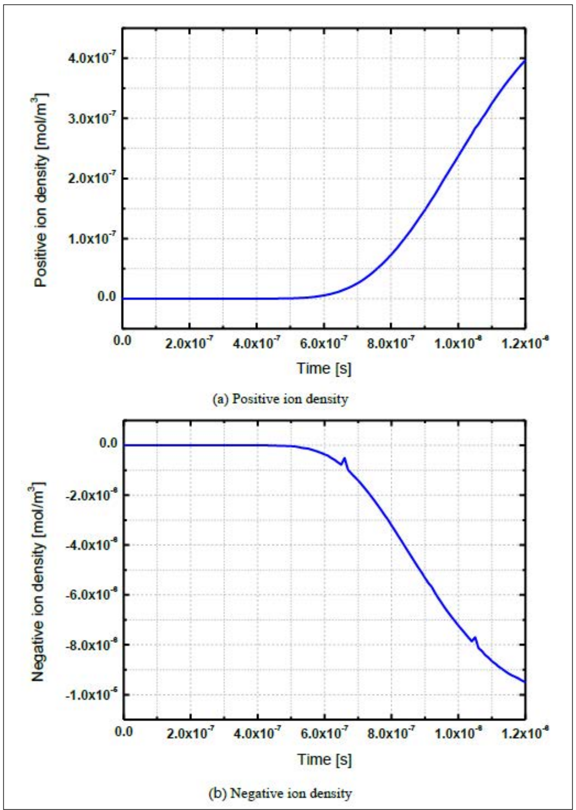

Figure 3: Electric Field Level as a Function of Time Step

Figure 5 (a)-(d) shown free electron density with presence of floating electrode obtained from Equation (3) and (6). The free electron density is calculated from field emission and molecular ionization by high electric field. The peak value of electric field is formed between main conductor and floating electrode, and then excessive ionization process is accelerated after 0.6 [μs]. Meaning that the presence of floating electrode creates a non-uniform electric field distribution with a large field enhancement, causing ionization to initiate corona discharge. From above results, first corona discharge with presence of floating electrode is likely to incept between main conductor and floating electrode and then sharp tip of floating electrode due to concentrated strong electric field.

Discussion

The generated process of positive, negative ion and free electron is illustrated in Figure 6. In the case of low external electric field, the bonding energy between free electron and positively charged ion in air insulation is larger than that of external electric field. Therefore, a lot of neutral molecules remaining in air. Whereas, in high external electric field where collisions occur between neutral molecules and then free electrons accelerated in the high electric field. The newly generated free electron from the surface of floating electrode and air insulation can play a role as the new electron avalanches under a high electric field. Some of these secondary electrons will again strike the air insulation, producing tertiary electron. The possibility of early corona discharge caused by the presence of floating electrode was reviewed in view point of lightning protection rod. In the case of positive strike occurrence, the surface of the main conductor is induced negative charge, floating electrode is positive charged. The electric field between main conductor and floating electrode is distorted caused by the presence of floating electrode, ionized free electron emitted from sharp tip of floating electrode under high electric field. Thus, floating electrode might be possible that the electric field concentration occurs at the sharp tip of floating electrode and it could be starting point of a corona discharge inception. However, above discussion is just one possibility review in view point of lightning protection rod. Further work is needed on real size model simulation and experiment for validation from the above our research work [1-8].

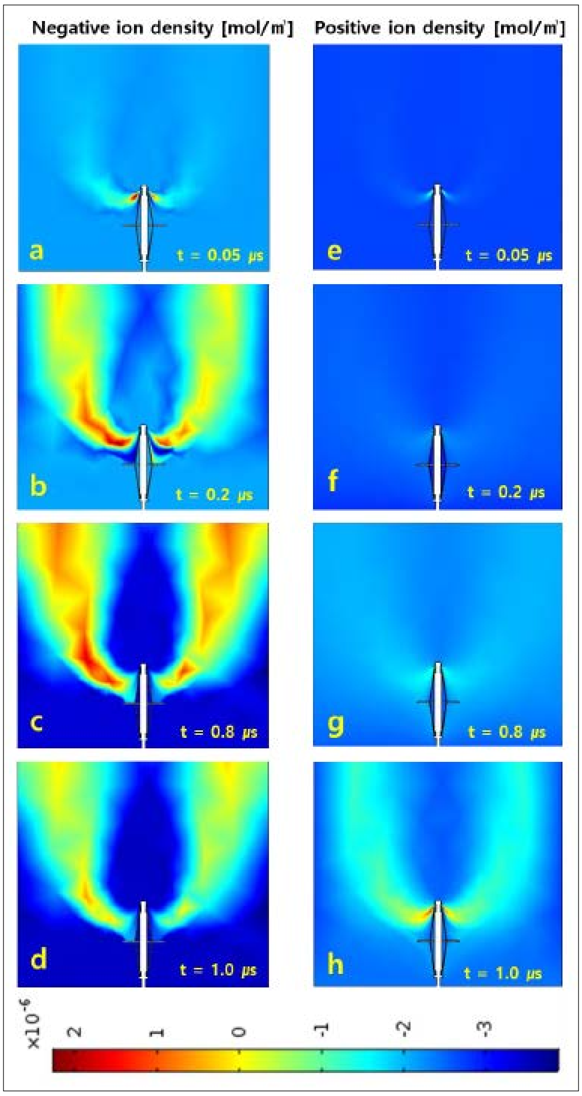

Figure 4: Behavior of Negative and Positive Ion Density as a Function of Time under 300 kV Positive Standard Lightning Impulse Voltage (a-d is negative ion density, e-h is positive ion density)

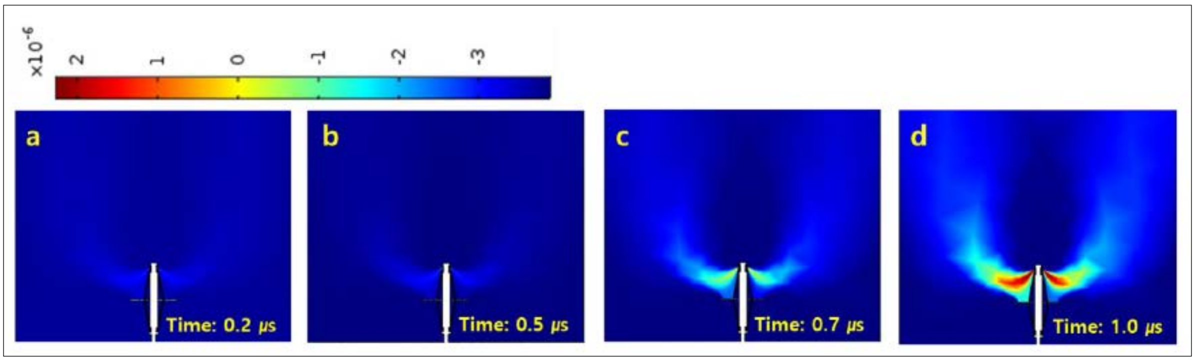

Figure 5: Free Electron Density [mol/m3] as a Function of Time under 300 kV Positive Impulse Voltage

Conclusion

This paper focused on numerical simulation analysis for corona discharge behavior in the presence of floating electrode. To analyze the corona discharge behavior, 0.5 mm very short electrode gap system is adopted as one of the basic research works. The finite element method is fully coupled with charge continuity equations including positive, negative ion and free electron. The results obtained from this research are summarized as follows.

- The high electric field is distributed between main conductors and floating electrode, and then the electric field is concentrated at sharp tip of floating electrode.
- Positive, negative ion and free electron are generated in the gap between main conductor and floating electrode caused by ionization process, positive and negative ion densities increase drastically from after t = 0.6 μs.
- The presence of floating electrode seems to create a non-uniform electric field distribution causing, causing initial corona discharge by emitting free electron at the sharp tip part of floating electrode.
- Further research work is needed on real size simulation model and experiment results to verify our simulation results.

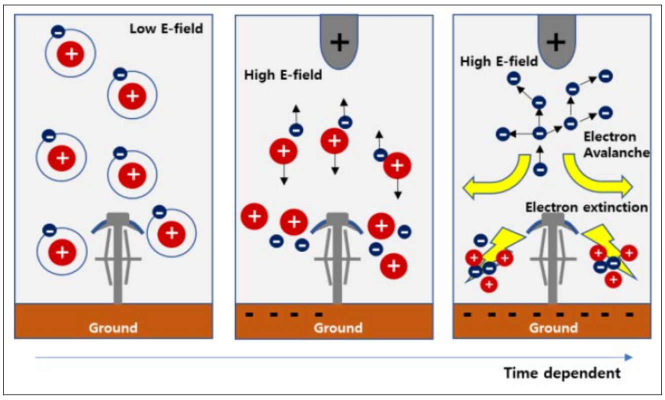

Figure 6: Schematic of Molecular Ionization by Electric Field

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