

Study of Electric Field Distortion in Dielectrics due to Streamer Discharge Activity

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The continuous streamer discharge activity caused by the degradation and failure of solid insulation systems leads to charge accumulation in the dielectric and distortion of the electric field. This paper presents an analysis of charge accumulation and electric field distribution on the surface of a dielectric due to continuous corona discharge activity with numerical analysis techniques. The results of discharge current and surface charge measurements are also presented.

Index Terms—Partial discharge, numerical method, corona discharge, high-voltage

I. INTRODUCTION

Advances in numerical analysis hardware and software technologies have recently led to an increase in numerical analysis studies aimed at validating discharge and insulation degradation phenomena caused by unexpected failures during the operation of high-voltage systems [1,2]. The degradation of insulation systems under AC and DC voltage conditions causes partial discharge as described by Townsend and streamer theory [3,4]. This continuous discharge activity accumulates charges inside and outside the dielectric, distorting the electric field and leading to insulation degradation [2]. In this paper, the discharge phenomenon caused by electric field changes in a needle-plate structure is simulated based on the fluid diffusion equation. The changes in the surface charge density of the dielectric and the electric field in the region where electron diffusion and recombination occur are calculated using the finite element method (FEM). Electrodes and dielectrics are designed with the same structure, and an instrumentation system measures the surface charge density and discharge current of the dielectric under a time-varying electric field. The simulation results are then validated by comparing the discharge current waveform, surface charge density, and surface electric field.

II. NUMERICAL ANALYSIS AND EXPERIMENTAL METHODS

A. Charge Transport Model

Fig. 1 shows the geometry of an axisymmetric 2D model to simulate the dielectric properties of the discharge phenomenon. The corona discharge characteristics are derived by the fluid diffusion equation and Poisson's equation as shown in (1) and (2), respectively [1].

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (w_i n_i - D_i \nabla n_i) = R_i \quad (1)$$

$$\nabla \cdot (\epsilon_r \epsilon_0 E) = \rho \quad (2)$$

where n_i denotes the charge carrier density, w_i is the drift velocity, D_i represent the diffusion coefficient, and R_i is the reaction rate. Table I also shows the setup variables for solid and gas conditions to simulate the movement of charge above the threshold. Calculate the charge that accumulates on a dielectric surface over time under AC voltage conditions and simulate the distribution of the electric field.

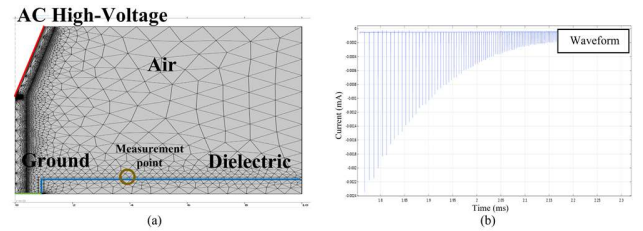


Fig. 1. Corona discharge (a) 2D-axisymmetric modeling, (b) discharge current

TABLE I
SETTINGS AND PARAMETERS

Condition	Parameter	Value	Unit
Setting	Secondary electron emission coefficient	0.004	
	Surface emission	$1 \cdot E^5$	$1/\text{cm}^3$
	Voltage	$2500 \cdot \sin(2 \cdot \pi \cdot 60 \cdot t) \cdot (t/(t+0.1))$	V
	Gap distance	7	mm
Gas (Air)	Pressure	1	atm
	Relative permittivity	1	
	Electron-ion recombination coefficient	$1 \cdot E^{-7}$	cm^3/s
	Ion-ion recombination coefficient	$1 \cdot E^{-7}$	cm^3/s
	Electric conductivity	$1 \cdot E^{-12}$	S/m
	Electron diffusion coefficient	0.18	m^2/s
	Positive ion diffusion coefficient	0.01	m^2/s
	Negative ion diffusion coefficient	0.01	m^2/s
	Initial electron density	$1 \cdot E^5$	$1/\text{cm}^3$
	Initial positive ion density	$1 \cdot E^5$	$1/\text{cm}^3$
	Initial negative ion density	$1 \cdot E^5$	$1/\text{cm}^3$
Solid (FR4)	Relative permittivity	4.5	

B. Experimental Method

Fig. 2 shows the test setup. The AC generator and voltage divider use high-voltage test equipment. The streamer discharge current is measured at a sampling rate of 250 MS/s through an impedance matching resistor at the bottom of the discharge chamber. In addition, a 2 mm diameter hole is drilled in the center of a 25 mm square FR4 plate to measure the dielectric surface potential due to the continuous activity of the corona discharge with a non-contact electrostatic meter.

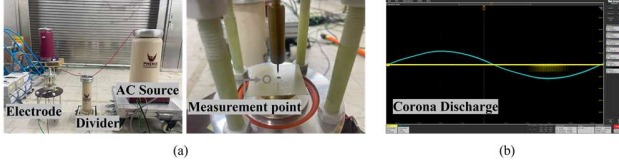


Fig. 2. Dielectric-gas discharge test (a) test equipment, (b) corona waveform

III. RESULTS AND DISCUSSION

Fig. 3 shows the simulation and test results of the negative discharge current in a time-varying electric field. The rise time, from when the current starts to rise to when it reaches its peak, is 14 ns in the simulation and 10 ns in the experiment. This difference is likely due to the insufficient sampling rate in the experiment and the fact that the simulation calculates the total current on the electrode surface while the experiment measures the current discharged to the ground electrode.

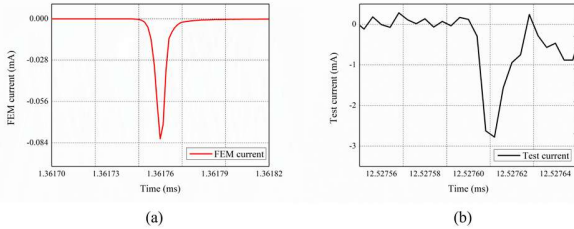


Fig. 3. Negative discharge current (a) FEM result, (b) test result

Fig. 4 shows the simulation results for the dielectric surface measurement points for one cycle (16.67 ms) of 60 Hz AC voltage. Fig. 4 (a) shows the AC streamer discharge current. Since the discharge mechanisms are different between positive and negative polarity conditions, it is necessary to change the analysis conditions and perform a continuous time-division analysis to analyze the time response. Fig. 4 (b) and (c) show the potential and electric field distributions at the measurement points over time based on the simulation. Irregular electric fields may occur due to the distortion of the electric field caused by the discharge. Fig. 4 (d) shows the dielectric surface charge density over time when positive and negative streamer discharges occur. It can be seen that the dielectric surface charge density repeatedly accumulates and discharges positive charges. When the surface was monitored with a non-contact electrostatic meter, a dominant positive charge was also observed. Under AC discharge conditions, a polarized voltage is continuously applied to the dielectric surface, which can

distort the electric field by accumulating space charge within the dielectric and accelerate degradation. Increasing the amount of discharge will further enhance these effects.

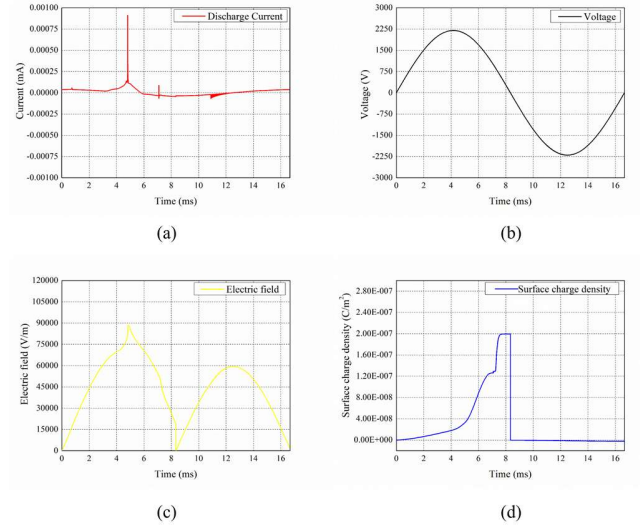


Fig. 4. FEM results under AC discharge condition (a) discharge current, (b) potential at the measurement point, (c) electric field at the measurement point, (d) surface charge density

IV. CONCLUSION

This paper presents a numerical analysis method to study the effect of charge diffusion by AC corona discharge on dielectric surfaces. Discharge activity causes irregular charge accumulation in the dielectric, and prolonged exposure to this condition leads to problems such as leakage and insulation breakdown. Analyzing and identifying these problems in advance is expected to improve the reliability and stability of high-voltage equipment operation.

V. ACKNOWLEDGMENT

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