Simulation on Electric Field Affected by Space Charge in Oil-paper Insulation System Under Polarity Reversal

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The distribution of electric field in oil-paper insulation system is influenced by space charge. In this paper, a new method based on Schottky emission and transient upstream finite element method (FEM) is proposed to solve the carrier transport equations. The simulation of charge motion characteristics in single oil-paper insulation considering electrode implantation barrier, carrier mobility, trap coefficient and carrier recombination coefficient is carried out. The simulation results coincide with experiment. Moreover, the charge movement and electric field distribution under polarity reversal operation condition are calculated and the effect of micro parameters is studied. The distributions of space charges and total electric field at every time step after polarity reversal are worked out. It can be concluded that the electric field has a great distortion near electrodes at the instant of voltage reversal. This method can provide more accurate consulting values for the design of insulation in the high voltage DC converter transformer.

***Index Terms*—oil-paper insulation, polarity reversal, space charge characteristic, transient upstream FEM**

I. Introduction

OIL-PAPER MEDIUM is the main insulation in convert transformer, hence it sustains alternating current (AC) and direct current (DC), as well as polarity reversal voltage. In the circumstance of DC, space charges in oil-paper insulation tends to transport and accumulate, which will strengthen or weaken the original electric field. Especially under the polarity reversal, the space charge distribution will make a real difference to the breakdown of insulation.

Most studies about space charge focus on experiments [1]. The PEA method proposed by Takada is widely accepted and experiments focusing on polyethylene material were carried out based on this. Whereas this method can't figure out the influence of micro parameters in material on charge characteristic.

In the aspect of numerical simulation, models represented by bipolar charge transport model based on the Poisson's equation and current continuity equation were put forward [2]. The numerical calculation under compound and polarity reversal voltage was realized. However, charge distribution was not taken into consideration or roughly calculated in these studies, which leaded to imprecise results.

In this paper, the transient upstream finite element method (FEM) is proposed to simulate the space charge characteristics. The bipolar charge transport model and Schottky emission are introduced to the established numerical model [3]. The time variation of charge densities under DC voltage is calculated and characteristic of electric field under the polarity reversal is studied in single oil-paper insulation.

II. Mathematical Model and method

The transport of space charge and transient electric field satisfy the Poisson's equation and current continuity equation, which are described as follows:

$$\nabla \cdot [-\varepsilon \nabla \varphi(t)] = \rho(t) \tag{1}$$

$$J^{+(-)}(t) = -\mu^{+(-)} \rho^{+(-)}(t) \nabla \varphi(t) \tag{2}$$

$$\partial \rho^{+}(t) / \partial t + \nabla \cdot \boldsymbol{J}^{+}(t) = -(R_{ion} / e) \rho^{+}(t) \rho^{-}(t) \tag{3}$$

$$\partial \rho^{-}(t) / \partial t + \nabla \cdot \boldsymbol{J}^{-}(t) = -(R_{ion} / e) \rho^{+}(t) \rho^{-}(t) \tag{4}$$

$$\rho(t) = \rho^{+}(t) - \rho^{-}(t) \tag{5}$$

$$J(t) = J^{+}(t) + J^{-}(t) \tag{6}$$

where ε is the dielectric permittivity (F/m), ρ is space charge densities (C/m^3), $\boldsymbol{J}$ is the current densities formed by space charge transport (A/m^2), φ is the electric potential (V), μ is the ion mobility (m^{2}V^{-1}s^{-1}), R_{ion} *is* the recombination coefficient, e is the electric charge of electron.

A. Schottky Injection

According to the trap theory in literature [4], there exist four kind of carriers: free electrons, free holes, trapped electrons, and trapped holes. As to carrier generation at the surfaces of electrodes, the Schottky emission theory is introduced and the boundary conditions for the injected carriers are as follows:

$$J\ (t) = AT^2 \exp(-\frac{e\omega_i}{kT}) \exp(\frac{e}{kT}\sqrt{\frac{e|E(t)|}{4\pi\varepsilon}}) \tag{7}$$

where $J(t)$ is the fluxes of electrons at cathode or holes at anode. T is the temperature in K, A is the Richardson constant set as 1.2×10^6 A/(m^{2}K^2), ω_i is the injection barrier for electrons or holes, k is the Boltzmann constant, $E(t)$ is the electric field intensity at cathode or anode.

B. The transient upstream FEM

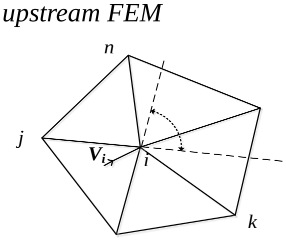


Fig. 1. The judgment of upstream finite element

The region is meshed into a series of triangles. For the node i, as is shown in Fig. 1, element *ijm* is defined as the upstream finite element if the direction of $\boldsymbol{V_i}$ (ion mobility) is in between the dash lines. Therefore, the charge density of i can be obtained from the other two nodes in the element.

Through discretizing (3), (4)into time domain, the charge density of i at t_{n+1} can be calculated in the upstream finite element if charge densities of all three nodes at the previous time step t_n have been known. It can be described as follow:

$$\frac{\rho_{ai}(t_{n+1})-\rho_{ai}(t_n)}{t_{n+1}-t_n}=-\boldsymbol{V}_{ai}(t_n)\cdot\nabla\rho_{a\Delta}(t_n) - \frac{\mu_a}{\varepsilon}\rho_{ai}(t_n)\rho_i(t_n)+S_{ai}(t_n) \quad (8)$$

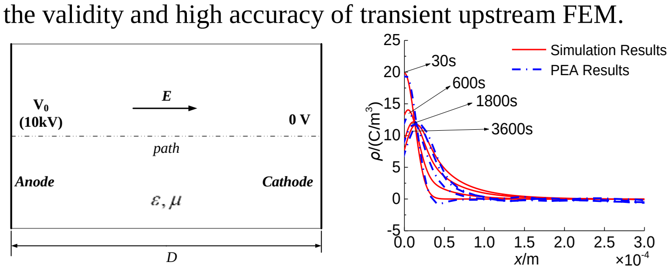
where S_{ai} is the source term that represents the trapping and recombination processes, $\nabla\rho_{a\Delta}$ is the first-order differential operator of carrier charge density within the upstream element of node i.

III. Simulation Results and Analysis

TABLE I
PARAMETER SET IN OIL-PAPER MATERIAL

Parameters	Value
Mobility	
μ_e (electrons)	1×10^{-14}m^{2}V^{-1}s^{-1}
μ_h (holes)	1×10^{-14}m^{2}V^{-1}s^{-1}
Trapping coefficients	
B_e (electrons)	5×10^{-3}s^{-1}
B_h (holes)	5×10^{-3}s^{-1}
Trap density	
N_{et0} (electrons)	100Cm^{-3}
N_{ht0} (holes)	100Cm^{-3}
Recombination coefficients	
$S_{e\mu,ht}$(free electrons/trapped holes)	5×10^{-2}m^{-3}C^{-1}s^{-1}
$S_{et,h\mu}$ (trapped electrons/free holes)	5×10^{-2}m^{-3}C^{-1}s^{-1}
Barrier height for Schottky injection	
ω_{ei}(electrons)	1.1eV
ω_{hi} (holes)	1.1eV
Temperature (T)	20°C (293.2K)
Sample thickness (D)	500μm
Relative dielectric constant (ε)	3.5

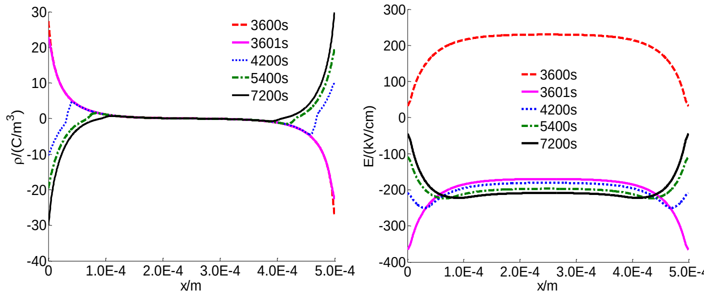
The single oil-paper model is established for simulation as Fig. 2.a. The micro parameters in the medium is set as Table I. The charge density distribution near the anode is shown in Fig.1.b. It can be concluded that the simulation results at different time agree well with the experiment, which verifies the validity and high accuracy of transient upstream FEM.



a. The single oil-paper model b. The results at different time

Fig. 2. Comparison of the transformed simulation results with PEA results

The same model is applied to study the characteristic of polarity reversal. The polarity of voltage is reversed from positive to negative at 3600s, when the charge density and electric field distribution have reached steady. The simulation results after polarity reversal on the defined path, as is shown in Fig.2.a, are demonstrated in Fig. 3.



a. Net charge distributions b. Electric field distributions

Fig. 3. Simulation results under polarity reversal at different time

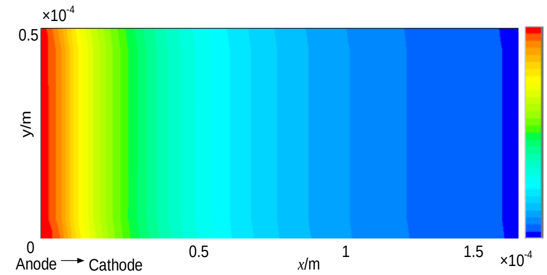


Fig. 4. The electric field distribution at the instant of polarity reversal (kV/cm)

The charge and electric field distribution in steady state after reversal (7200s) is approximately symmetrical with that before reversal (3600s). At the instant of reversal, the electric field strength near the electrodes reaches to the maximum value due to the additional effect of heterocharges accumulation, which results in the enhance of Schottky injection. The net charge density near the electrodes decreases because of charge recombination, as is shown in Fig. 3.a. After reversal, the electric field in the center of medium decreases in initial time and then increases. With the dynamic variations of charge density, the electric field strength near the electrodes become lower and reaches steady about 3600s after reversal.

IV. Conclusion

A new numerical method, transient upstream FEM, is proposed in this paper to calculate the accurate charge distribution and electric field in single oil-paper insulation under the polarity reversal condition. The injection, transport, trapping and recombination of charges are considered based on Schottky emission and trap theory. The simulation results indicate the proposed method is consistent with experiment. Compared with previous methods, the transient upstream FEM has better applicability and can output abundant data, which will provide more precise preferences for insulation design.

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