Charge Transport Simulation in Single-layer Oil-paper Insulation

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This paper proposed a simulation method for the charge transport in single-layer oil-paper insulation. The method of transient upstream finite element method (FEM) is derived in order to calculate the time variation of charge densities in medium. The numerical simulation of charge transport in single-layer oil-paper insulation is realized by applying transient upstream FEM to the transport equations of bipolar charges. With reasonable micro parameter, charge transport in an experimental object is simulated. The simulation results are consistent with the experimental data. This paper provides an exploratory research to the simulation of charge phenomenon in oil-paper, and has guiding significance to the design of oil-paper insulation.

***Index Terms*—oil-paper insulation, space charge, transport, transient upstream FEM.**

I. Introduction

THE OIL-PAPER insulation in converter transformer usually works under direct current (DC) electric field. Under this condition, space charge in the insulation is more likely to accumulate, compared with alternating current (AC) condition. The presence and transport of space charges in oil-paper may cause distortion of electric field, which will lead to degradation, and even breakdown of insulator.

Although a large number of experiments have been conducted, and qualitative regularity is obtained [1], the numerical simulation of space charge transport in oil-paper insulation still needs more investigations.

To study the electric field distortion of insulation in DC cables, recent researches on the simulation of space charge transport mainly focus on polymeric materials such as polyethylene [2-4]. Different numerical models of charge transport in these materials are built basing on experimental data. These models are based on the Poisson equation and current continuity equation. Among these models, the bipolar charge transport model proposed by Roy is wildly accepted [2]. Because of the symmetrical structure of cables, most of these models were based on one-dimensional analysis, which do not fit for oil-paper insulation.

To simulate the time variation of charge densities in the medium under the effect of electric field, transient upstream finite element method (FEM) is derived. Furthermore, the numerical simulation model of charge transport in single-layer oil-paper insulation is established by applying transient upstream FEM to the transport equations of bipolar charge. By setting reasonable micro parameter in the equations, simulation results consistent with the experimental data are reached.

II. Method of Transient Upstream FEM

After injected form the electrodes, space charges will migrate in the medium under the electric force. The transport of space charges must satisfy the Poisson equation and current continuity equation. When considering both positive and negative space charges, the main system of equations describing the field is shown as follows:

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

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

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

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

where

ε dielectric permittivity (F/m)
ρ absolute values of space charge densities (C/m^3);
$\boldsymbol{J}$ current densities formed by space charge transport (A/m^2);
φ electric potential (V);
μ ion mobility (m^{2}V^{-1}s^{-1});
R_{ion} recombination coefficient;
e electric charge of electron;
superscript $^+$ and $^-$ represent positive and negative separately

The mobility direction vectors of positive and negative space charges are defined as follows,

$$\boldsymbol{V}^{+}(t) = -\mu^{+} \nabla \varphi(t) \tag{5}$$

$$\boldsymbol{V}^{-}(t) = \mu^{-} \nabla \varphi(t) \tag{6}$$

In order to solve the equations above, and obtain the space charge densities of each point at each time, the region to be solved is meshed and upstream FEM is used. This method approximates the first-order derivative term of charge density at a node by the derivative in its upper stream element and can avoid unstable iterative solutions. Besides, it can be applied to 2D and even 3D models of different shapes. For each node, the upstream element is defined as the triangular element with ion mobility direction vector facing this node.

Combing (1) ~ (6), rate equations are obtained as (7), which reflects the changes of bipolar charge densities with time.

$$\frac{\partial \rho^{+(-)}(t)}{\partial t} = -\boldsymbol{V}^{+(-)}(t) \cdot \nabla \rho^{+(-)}(t) - \frac{\mu^{+(-)}}{\varepsilon} \rho^{+(-)}(t) \rho(t) - (\frac{R_{ion}}{e}) \rho^{+}(t) \rho^{-}(t) \tag{7}$$

Discretizing (7) into time domain, the bipolar space charge densities at time $t = t_{n+1}$ can be calculated with the result at previous time step t_n, using the following equation.

$$\frac{\rho_i^{+(-)}(t_{n+1})-\rho_i^{+(-)}(t_n)}{t_{n+1}-t_n}=-\boldsymbol{V}_i^{+(-)}(t_n)\cdot\nabla\rho_\Delta{}^{+(-)}(t_n)$$
$$-\frac{\mu^{+(-)}}{\varepsilon}\rho_i^{+(-)}(t_n)\rho_i(t_n)-\frac{R_{ion}}{e}\rho_i^{+}(t_n)\rho_i^{-}(t_n) \quad (8)$$

where i, j, and m represent the nodes of the upstream element of node i, and $\nabla\rho_\Delta$ is the first-order differential operator of charge density within the element. $\nabla\rho_\Delta$ is approximated as a linear function of coordinates inside the element.

Hence, if $\rho^{+(-)}(t_n)$ of each node and $\rho^{+(-)}(t_{n+1})$ of nodes at the surface of electrodes are given, then $\rho^{+(-)}(t_{n+1})$ of every node can be obtained by solving (8) with their upstream element.

By solving (8) with the initial charge density, the charge distribution in the space at each time step can be obtained.

III. Numerical Model of Charge Transport in Oil-Paper Insulation

The flowchart of charge transport simulation in oil-paper insulation using transient upstream FEM is as follows. In the initial time step, it is assumed that no space charge existing in the insulation.

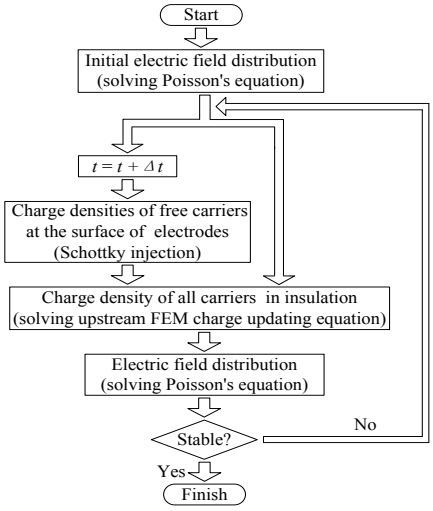

Fig. 1. Calculation flowchart of charge transport

A. Charge injection

When the energy of carriers exceeds corresponding barriers at the surface of electrodes, carriers will escape from the electrodes and inject into the medium. Referring to the bipolar charge transport model of low-density polyethylene LDPE, the carrier injection is assumed to be of the Schottky type as described in [2].

B. Transport model of carriers

In oil-paper insulation, the main electronic carriers are electrons (negative) and holes (positive). Besides, there also exist some stationary traps because of the physical or chemical defects. These traps will capture free electronic carriers and therefore restrict the charge transport. Considering the effect of traps, there are four kinds of electronic carriers, namely free electrons, free holes, trapped electrons, and trapped holes. To take all the four kinds of electronic carriers in to consideration, (8) is modified as (9), which is called convection equation.

$$\frac{\rho_{ai}(t_{n+1})-\rho_{ai}(t_n)}{t_{n+1}-t_n}=-\boldsymbol{V}_{ai}(t_n)\cdot\nabla\rho_{a\Delta}(t_n)$$
$$-\frac{k_a}{\varepsilon}\rho_{ai}(t_n)\rho_i(t_n)+S_{ai}(t_n) \quad (9)$$

where, a represents the type of electronic carriers, which are $e\mu$—free electrons; et—free holes; $h\mu$—trapped electrons; ht—trapped holes. S_a is the source term which represents the trapping and recombination processes.

The formula to calculate the source terms for the four types of carriers are given in [3]. Hence, the transport of carriers in oil-paper insulation will be obtained by applying transient upstream FEM to (9).

IV. Application

Using the method proposed, simulation model of experimental object in [4] is built, as shown in Fig.2. The simulated net charge densities at t = 600s are also shown in Fig. 2. The experimental and the filtered simulation results with the surface charges at different time are plotted in Fig. 3.

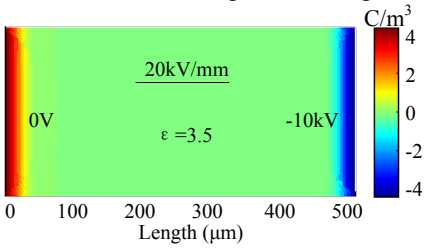

Fig. 2. Simulated net charge density at t = 600s

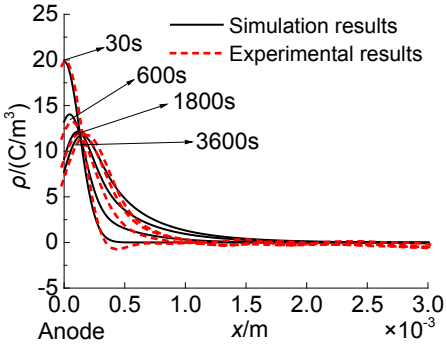

Fig. 3. Simulated net charge densities at different time near the anode.

V. References

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