Simulation of Space Charge in XLPE under AC Electric Field

Zhe Xu, Dongxin He, Tao Zhang and Wenjie Geng

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Zhe Xu
Shandong Provincial Key laboratory of UHV Transmission Technology and Equipment
School of Electrical Engineering
Shandong University
Jinan,China
xuzhebm@163.com

Dongxin He
Shandong Provincial Key laboratory of UHV Transmission Technology and Equipment
School of Electrical Engineering
Shandong University
Jinan,China
hdx@sdu.edu.cn

Tao Zhang
Shandong Provincial Key laboratory of UHV Transmission Technology and Equipment
School of Electrical Engineering
Shandong University
Jinan,China
zhangtao_1229@163.com

Wenjie Geng
Shandong Provincial Key laboratory of UHV Transmission Technology and Equipment
School of Electrical Engineering
Shandong University
Jinan,China
gwj@mail.sdu.edu.cn

***Abstract*—The dynamic behavior of the space charge in the crosslinked polyethylene insulation is one of the important reasons for the initiation of the aging of electrical branches in ac cables. In this paper, a bipolar charge model is established to numerically simulate the dynamic behavior of space charge in each AC cycle and the accumulation of space charge under long-term stress. Space charge under AC stress can be divided into two types: periodic charge and aperiodic charge. Space charge density and electric field are influenced by each other. It is found that the periodic charge at the electrode interface changes with the polarity and intensity of the electric field, and the accumulation rate is relatively slow. The aperiodic charge has a multi-period accumulation effect, which causes a certain degree of distortion of the electric field near the two electrodes. Compared with periodic charge, aperiodic charge has a more significant effect on cable insulation performance.**

Keywords—crosslinked polyethylene, space charge, AC electric field

I. INTRODUCTION

With the development of urbanization, crosslinked polyethylene insulated cables are widely used in power transmission and distribution systems. To prevent the occurrence of cable faults, it is particularly important to explore the generation and development mechanism of cable insulation faults and aging. Studies have shown that electrical tree aging is the main form of crosslinked polyethylene insulation aging [1]. The space charges are injected and extracted at the interface, and the recombination, trapping and other dynamic behaviors are carried out in the insulating, which damage the microstructure of the polymer insulation material and are the main factors causing the electrical tree [2]. Under DC voltage, a large amount of space charges are captured by the insulation internal traps and accumulate in the insulation. The accumulation of space charges will cause the distortion of the electric field in the insulation, leading to the aging and breakdown of materials. Under AC voltage, it is difficult to cause the accumulation of charges due to the alternating electric field, but the breakdown field strength is far lower than that is under DC field. Therefore, it is necessary to study the influence of dynamic behavior characteristics of space charge on the formation of electrical tree under AC voltage.

Due to the difficulty of space charge testing, there are few studies on cable AC space charge, but researchers have confirmed from different angles that space charge plays a significant role in the aging of insulating materials under AC electric field. Through electroluminescence(EL) experiments, FBaudoin found that the EL intensity under AC electric field was greater than that under DC electric field with the same amplitude and the EL intensity was closely related to the dynamic behaviors such as space charge migration and recombination [3]. This shows that under the AC field, the alternating positive and negative electric fields make the space charges of the two electrodes continuously inject and extract, and there is a large amount of recombination between the opposite polar charges. In this process, a large amount of energy released causes the cable insulation degradation, making the initial voltage of the electrical tree under the AC field far less than that of the DC field [4]. Some researchers also believe that due to the asymmetry of the movement of positive and negative polar space charges, the accumulation of negative space charges exists in the alternating field of the polymer, which mainly occurs near the electrodes and distorts the electric field near the interface to a certain extent [5]. Therefore, the electrical tree branch of the DC electric field usually starts far away from the electrodes, while the electrical tree branch under the AC electric field generally starts at the electrodes interface [6]. However, current studies focus on the effect of the behavior of space charge on the microstructure of the material, or the distortion of the electric field caused by the accumulation of space charge. These studies lack a fundamental detailed description of the dynamic behavior characteristics of positive and negative charges inside the insulating material under the AC electric field based on the coupling mechanism between charge and electric field.

The bipolar charge transfer model, which considers the processes of charge injection, extraction, recombination, trapping, de-trapping and migration, is widely used to simulate the dynamic characteristics of space charge in polymer materials [7]. Under the DC electric field, the bipolar charge transfer model is highly consistent with the experimental results, so the researchers conducted a comprehensive and in-depth study on the dynamic behavior of space charge through the model simulation [8-10]. G. Chen compared the simulation results of the model with experimental data to verify its applicability in AC electric field [11]. Through this simulation model, researchers explained the causes of space charge accumulation under AC field from different perspectives [11-12].

In this paper, a bipolar charge transfer model is established to simulate the dynamic behavior of space charge in crosslinked polyethylene insulating material under AC electric field. Considering the coupling effect between space charge and electric field intensity and the influence of periodic charge and multi-period accumulation on the model, the accumulation rule of positive and negative space charge with pressurization time is studied.

II. MODEL DESCRIPTION

A. *Bipolar Charge Transfer Model*

The bipolar charge transfer model describes the dynamic behavior of space charge in insulating materials under electric field. It is assumed that the free charges are injected from two electrodes, and the amount of injected charges are related to the electric field. The process from the electrode metal into the insulation follows the Schottky rule:

$$J = AT^2 \exp(-\frac{\psi_{e,h}}{kT}) \exp(\frac{e}{kT}\sqrt{\frac{eE}{4\pi\varepsilon_0\varepsilon_r}}), \qquad (1)$$

Where A is the Richardson constant; T is the temperature; Ψ are the injection barrier heights for electrons and holes; k is the Boltzmann constant; e is the elementary electronic charge; E is the electric field; ε_0 is the vacuum dielectric constant; ε_r is the relative permittivity.

There are two ways to extract space charge: one is that space charges do not need to overcome any potential barrier from insulation to opposite metal electrode; the other is that electrons and holes need to overcome an interface potential barrier to flow out from insulation to electrode. The first way is adopted here, which satisfies the following formula:

$$J = e\mu_{e/h} n_{e/h} E , \qquad (2)$$

Where μ is the mobility; n is the charge density.

The bipolar charge transfer model assumes that there are free electrons, free holes, bound electrons and bound holes in the insulating material. Free electrons and free holes migrate and diffuse under electric field stress. As the defects in polymer materials will form a lot of traps in the medium, free electrons and free holes will be captured by the traps, forming bound electrons and bound holes in the process of movement. At the same time, the bound electrons and the bound holes are excited by the energy to de-trap. The heteropolar charge will recombine, of which the bound electron or bound hole will return to the trap which has not yet captured the charge. Fig.1 shows the behavior of bipolar charge in materials.

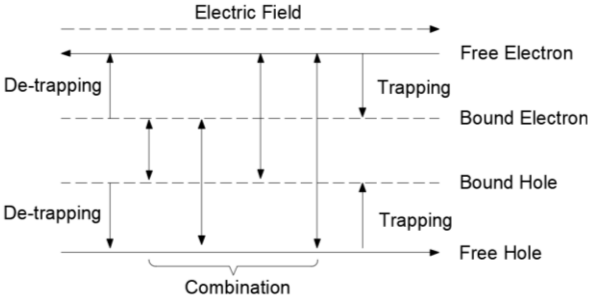


Fig. 1. Schematic diagram of bipolar charge behavior.

The charge transfer in insulating materials can be described by three equations: transport equation, current continuity equation and Poisson equation. If the model is simplified to one-dimensional spatial structure, the equation is as follows:

Transport equation:

$$J_{e/h} = \mu_{e/h} n_{e/h} E(x,t) = v_{e/h} n_{e/h} , \qquad (3)$$

Poisson equation:

$$\nabla^2 V = \frac{\partial^2 V(x,t)}{\partial x^2} = -\frac{\rho(x,t)}{\varepsilon_0 \varepsilon_r}, \qquad (4)$$

$$E = -\nabla V , \qquad (5)$$

Current continuity equation:

$$\frac{\partial n_a(x,t)}{\partial t} + \frac{\partial j_a(x,t)}{\partial x} = s_a(x,t) , \qquad (6)$$

where ν is the rate of charge transfer; ρ(x) is the total charge density of four charges at position x; n_a is the charge density in the delamination; j_a is the current density of free electrons and free holes. The s_a on the right side of the current continuity equation is the source term, indicating that only the changes in the respective densities caused by the interaction between the four space charges are considered, excluding the changes in the space charge density due to migration.

B. *Periodic Charge at Electrode Interface*

When testing the AC space charge of the cable body, the researchers found that there are two kinds of space charge forms: periodic charge and aperiodic charge[13]. Under the action of electric potential, the periodic polarized charges with opposite polarity appear at the interface of the two electrodes. In the production process of XLPE, due to the uneven process of high-temperature crosslinking and cooling crystallization, a density uneven area will be formed in the cable insulation, and the charges that change with the electric field will also be formed at the interface of the uneven area. The amount of charges is as follows:

$$\sigma = \varepsilon_0 \varepsilon_r E + \int_0^d \frac{z}{d} \rho(z) dz , \qquad (7)$$

Where d is the insulation thickness of the cable, z is the radial distance from the charge to the inner semiconducting. When the applied potential is removed, the periodic charge will disappear immediately.

C. *Parameter Setting of Simulation Model*

In different studies, the selection of parameters varies greatly. Select the parameters with higher frequency of use and set the parameters symmetrically as follows:

TABLE I. MODEL RELATED PARAMETERS

Parameter	Value
$\psi_{e,h}$ / eV (injection barrier heights)	1.2,1.2
$\psi_{et,ht}$ / eV (de-trapping barrier heights)	0.95，0.95
$\mu_{e,h}$ / $(m^2V^{-1}s^{-1})$ (mobilities)	2×10^{-12}, 2×10^{-12}
R_{eh} / $(m^3s^{-1}\,C^{-1})$ (recombination coefficients for free electrons and free holes)	0
$R_{eht,eth,etht}$ / $(m^3s^{-1}\,C^{-1})$ (recombination coefficients for free electron and bound hole, bound electron and free hole, bound electron and bound hole)	1×10^{-5}
$B_{e,h}$ / (s^{-1}) (trapping coefficients)	0.01，0.01
$n_{0et,0ht}$ / $(C\,m^{-3})$ (trap density)	3, 3
v/ (s^{-1}) (de-trapping rate)	6×10^{12}
ε_r (relative permittivity)	2.3

The bipolar charge model is solved by COMSOL Multiphysics. The film crosslinked polyethylene sample is simplified to a one-dimensional model with a thickness of 100μm. The applied voltage used in the simulation is $V=V_p\sin(2\pi f)$. The frequency is 1Hz and the peak value of voltage is 10kV. Symmetrical parameters and asymmetrical parameters are set respectively. The simulation step size is 0.01s and the simulation time is 120s. The variation rules of space charge density in one voltage period and space charge density accumulated in multiple periods are obtained.

III. SIMULATION RESULTS

The model is grounded at 0μm and a sinusoidal ac voltage is applied at 100μm with a peak value of 10kV and a frequency of 1Hz. The parameters of the free electrons and the free holes are symmetric. Considering the periodic charge at the interface, the model assumes that the polymer in the insulator is uniform and the periodic charge only exists at the electrode interface.

Fig.2 shows the evolution of space charge density with phase in the first second throughout the material. The amplitude and polarity of periodic charge change periodically with the phase of AC voltage. The density of space charge is the largest at 105° and 291°. When the voltage is zero, the periodic charge dissipates rapidly and the density is basically zero, so it is difficult to form accumulation even if the voltage is applied for a long time. The density of aperiodic charge is smaller than that of periodic charge, but it can be seen from Fig2 that the maximum value of negative space charge is larger than that of positive space charge at 0μm, and the maximum value of negative space charge is smaller than that of positive space charge at 100μm. This indicates that there are negative aperiodic charges at 0μm and positive aperiodic charges at 100μm. The existence of space charges will change the original electric field. Fig3 shows the effect of space charge on the electric field. It can be seen that the space charge weakens the electric field near the two electrodes when the voltage is positive half wave from Fig.3(a). However, the additional electric field generated by space charge will increase the original electric field when the voltage is negative half wave in Fig.3(b).

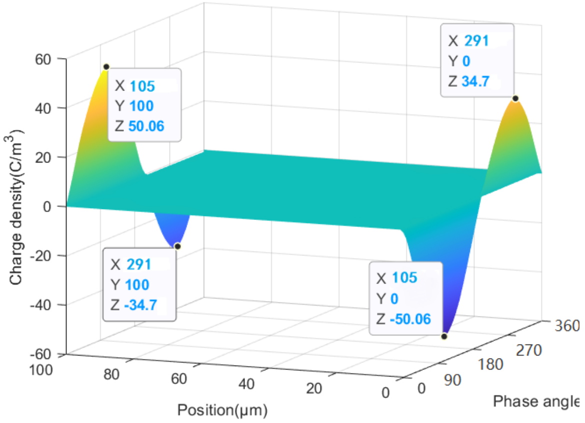
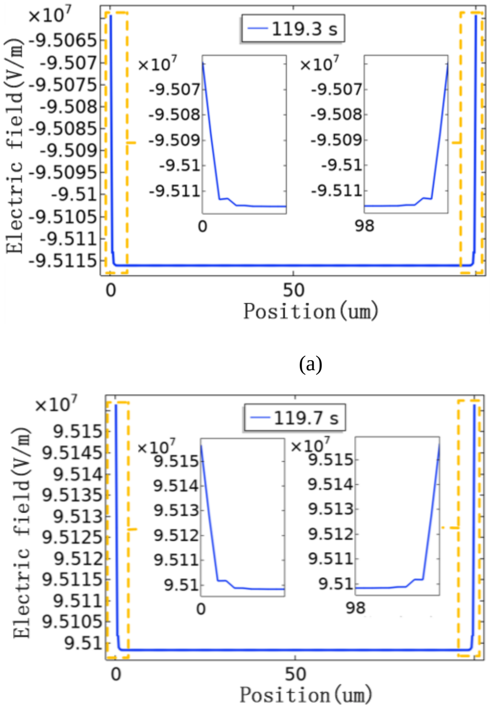


Fig. 2. The evolution of space charge density with phase in the first period of simulation.



(a)

(b)

Fig. 3. Effect of space charge on electric field strength when the parameters are symmetric: (a) Positive half wave of voltage; (b) Negative half wave of voltage.

The distortion of electric field intensity will also affect the space charge injection and migration. When the electric field intensity increases, the amount of charge injection increases and the migration speed accelerates. When the electric field intensity is weakened, the amount of charge injection decreases, and the migration speed slows down. The space charge density and electric field strength influence each other continuously in the process of simulation.

In order to see the evolution of aperiodic charge more clearly, a method called the all-phase average is employed, which is to average the space charge waveforms of 32 symmetrical phases uniformly. The periodic interface charge will be filtered out in the average process, so that the aperiodic charge will appear.

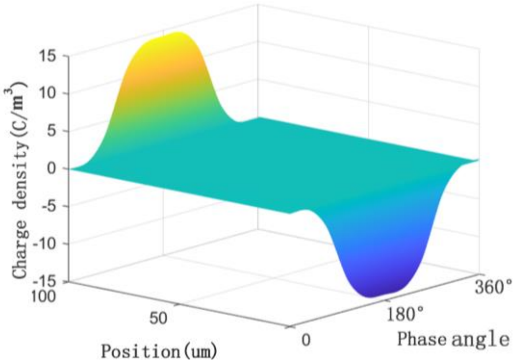


Fig. 4. The evolution of the density of the aperiodic space charges with phase in the first second at each position of the material when the parameters are symmetric.

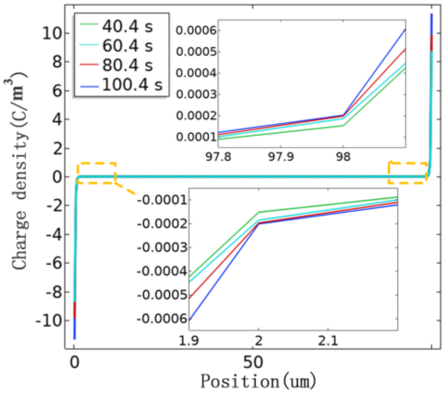


Fig. 5. The accumulation of aperiodic space charges in multicycle.

Fig.4 shows the rule that the density of aperiodic space charge changes with phase in the first second. Take the grounding electrode as an example, the density of negative space charge near 0μm gradually increases when the voltage is positive half wave. However, when the phase is more than 90 degrees, the free electrons injected into the electrode gradually decrease, move to the inside and be trapped, so the growth rate of negative charge near the electrode begins to slow down. When the voltage is negative half wave, the free holes are injected, the free electrons are extracted, and the holes are compounded with the trapped electrons. Therefore, the negative space charges near the electrode gradually decrease to zero, and the positive space charges begin to increase. At the end of a period, a small number of free electrons migrate to the interior and are captured by traps, which are not combined with holes. Therefore, a small number of free electrons remain, leading to the multi periods accumulation effect. Fig.5 shows the evolution of the aperiodic charge density accumulated in multicycle. Negative charges are accumulated near 0μm and positive charges are accumulated near 100μm.

According to the actual situation of XLPE cable, keep the free hole's mobility and injection barrier, increase the free electron's mobility to 2.1×10^{-12}, reduce the free electron's injection barrier to 1.198eV, and carry out multi periods simulation. Fig. 6 shows the accumulation of aperiodic space charges for multiple periods.

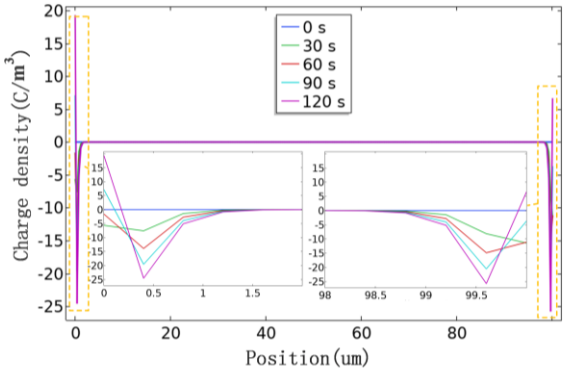
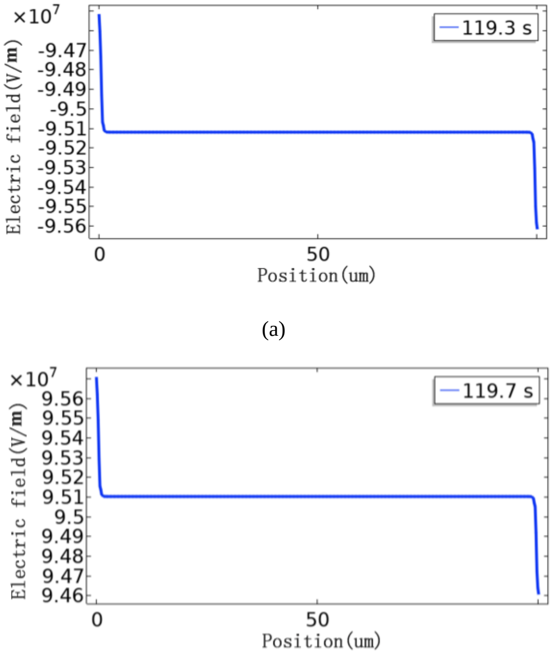


Fig. 6. The accumulation process of aperiodic space charges with multible periods when the parameters are asymmetric.



(a)

(b)

Fig. 7. Effect of space charge on electric field when the parameters are asymmetric: (a) Positive half wave of voltage; (b) Negative half wave of voltage.

During the AC stress process, free electrons can penetrate deeper into the material than free holes. So negative charges gradually migrate to the inside. Negative polarity space charges accumulate near the two electrodes. However, due to the alternation of the electric field, the migration distance of charges is limited, and the density of space charges in the middle of the material is almost zero. The reasons for negative charge accumulation may be as follows: There are more free electrons injected than free holes; The motion characteristics of positive and negative charges are asymmetrical and the mobility of free electrons is a little higher; The number of free electrons injected in negative half wave is more than that extracted in positive half wave.

When negative charges are accumulated near the two electrodes, the effect of space charge on electric field is different from that of symmetry parameter. Fig.7 shows the change of electric field caused by space charge with asymmetric parameters. When the voltage is positive half wave, the electric field of the grounding electrode is weakened and that of the potential electrode is enhanced as shown in Fig.7(a). When the voltage is negative half wave, the electric field of the grounding electrode is enhanced and that of the upper electrode is weakened as shown in Fig.7(b). Similarly, the electric field intensity and space charge density will also affect each other.

IV. CONCLUSION

The space charge of XLPE under AC electric field was simulated by bipolar transfer charge model considering periodic charge. When the AC stress is applied, there are two forms of charge, periodic charge and aperiodic charge, in the crosslinked polyethylene film material.

The rule of space charge density changing with phase in a voltage period is obtained by applying AC stress to the model. In order to see the aperiodic space charge density more clearly, the method called the all-phase average is used to filter the periodic charge, and the simulation results of aperiodic space charge density are obtained. Carry out multi-period simulation to obtain the accumulation rule of space charge density with pressurization time. Set asymmetric parameters to explore the accumulation of positive and negative charges.

Due to the alternation of the electric field, the accumulation of space charge under the AC electric field is much less than under the DC electric field. However, with the increase of simulation time, negative aperiodic charge will gradually accumulate near the electrode, which will distort the electric field distribution. Compared with periodic charge, aperiodic charge has a significant effect on cable insulation, which can be used as a characteristic parameter to reflect aging state.

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