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Numerical Simulation of Charge Accumulation and Transport within Cross-Linked Polyethylene (XLPE) Subjected to High Electrical Stresses

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Abstract

Accumulation of space charge is well identified to be a significant element affecting the performance of high voltage cable insulation system. In the area of polymeric insulation, space charge have been widely investigated under various electric stresses. The aim of this paper is to investigate the charge accumulation and bipolar charge transport within cross-linked polyethylene (XLPE) material through numerical simulation. The simulationestablished in this paper was designed based from previous work proposed by R M Hill and J M Alison. The simulation characterizes the injection, trapping, transport and recombination of electrical charges. The numerical model is driven by three fundamentalcalculations that described the characteristics of space charge which consist of Poisson's, Transport and Continuity equations. In terms of its width, the XLPE sample used for the simulation is uniformly segregated in order to determine the electric field at each division. The electric field in the simulation is determined by using the direct discretization of Poisson's equation. In the simulation, mobile electrons/holes and trapped electrons/holes are considered, while by applying Schottky injection algorithm, the charge is injected into the simulation with holes and electrons are at the anode and cathode respectively. Then different values of applied voltage are considered and preliminary results have shown that the variation of electric field would influence the dynamics and accumulation of space charge within the material.

Keywords: *Space Charge Simulation;Charge Accumulation;Cross-linked Polyethylene*

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1. Introduction

Polyethylene is a kind of a thermoplastic polymer with variable crystalline component. Nowadays, polyethylene have been widely used in various applications depending on the particular type of polyethylene such as from bottles, plastic bags, medical devices and also in electrical application fields. In high voltage equipment, polyethylene have been used as insulation materials such as in high voltage (HV) cables for transmitting and distributing electrical energy. Polyethylene that been used as the insulation are produced by mixing different polymers at different weight ratios in order to determine the best physical and mechanical properties of the final products. Key advantages of using polyethylene compared to traditional insulation which is based on oil impregnated paper that have been published in the literature are that it is environmental friendly (less pollution), oil resistance, rigidity, thermal stability, easily recyclable as well as require less maintenance [1].

The study of charge accumulation within high-density polyethylene (HDPE) [2,3], low-density polyethylene (LDPE) [2,4,5], and cross-linked polyethylene (XLPE) [2,6,7] is becoming more interest nowadays due to the correlation between the degradation of polyethylene-based insulation materials with space charge. Therefore, in terms of reliability, space charge accumulation within an insulation materials becomes a major issue as it will cause a difference in respect to the field within certain regions of the insulation materials [8].

Typically, from time to time, the accumulation of space charge within polyethylene can cause major defects which then lead to degradation of the insulation materials [9]. It was reported in [10], that the charge transport characteristic and space charge accumulation in polyethylene are influenced by the applied voltage. Over the decades, different charge accumulationsimulations such as the simulation proposed by Kaneko et al [11] and Fukuma et al [12] have been studied and developed.

Different models employed different approaches and each has its own features and assumptions. However, the model used for this paper is based from a simple model established from R M Hill and J M Alison work [13]. This work aims to investigate the space charge behaviour by using different values of applied voltage into the bipolar charge transport model.

2. Bipolar Charge Transport Model

Within insulation materials, the conduction current is dictated by developmentof charge carriers which either ions or electronsunder the influence of electric field. The density of the current, J can be represented as:

$$J = \mu n E \tag{1}$$

Where μ represents the mobility of the charge carrier in $m^2V^{-1}s^{-1}$, while n represents the charge carrier density and E represents the local electric field in Vm^{-1} respectively. The unit for J is in AM^{-2}.

The numerical model is driven by three fundamental calculations that described the characteristics of space charge which consist of Poisson's, Transport and Continuity equations. They can be defined as:

Poisson's equation:

$$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\varepsilon} \tag{2}$$

Transport equation:

$$J(x,t) = \mu n(x,t) E(x,t) \tag{3}$$

Continuity equation:

$$\frac{\partial n(x,t)}{\partial t} + \frac{\partial J(x,t)}{\partial x} = s \tag{4}$$

Where ρ is the net charge density in Cm^{-3}, ε is the permittivity in the unit of Fm^{-1}, $\mu$is the charge carrier mobility in m^{2}V^{-1}s^{-1}, E is the local electric field (Vm^{-1}), n is the density of mobile species, J is the current density (Am^{-2}), x is the distance in the direction perpendicular to the electrodes or can be called spatial coordinate (m), s is the source termand t is the time (s).

In terms of its width(Δx), the XLPE sample used for the simulation is uniformly segregated in order to calculate the electric field at each division. The electric field in the simulation is calculated by using the direct discretization of Poisson's equation.In the simulation, the generation of the charge follows the Schottky injection law with holes at the anode and electrons at the cathode:

$$J_e(0,t) = AT^2 exp\left(\frac{ew_{ei}}{kT}\right) exp\left(\frac{e}{kT}\sqrt{\frac{eE(0,t)}{4\pi\varepsilon}}\right) \quad \mathbf{(5)}$$

$$J_h(d,t) = AT^2 exp\left(\frac{ew_{hi}}{kT}\right) exp\left(\frac{e}{kT}\sqrt{\frac{eE(d,t)}{4\pi\varepsilon}}\right) \quad \mathbf{(6)}$$

Where J$_e$(0,t) and J$_h$(d,t) are the current densities injected at the cathode and anode respectively. T=300K is used in the simulation which represent the temperature, A=1.2 x 106 Am^{-1}K^{-2} is the Richardson constant, d is the inter-electrode separation, w$_{ei}$ and w$_{hi}$ are the injection barrier for electrons and holes respectively.

The extraction of the charge at both electrodes can be defined as:

$$J_e(d,t) = \mu_e E(d,t) n_{e\mu}(d,t) \qquad \mathbf{(7)}$$

$$J_h(0,t) = \mu_h E(0,t) n_{h\mu}(0,t) \qquad \mathbf{(8)}$$

Finally, the total current density γ(x,t) can be calculated by using second Maxwell equation as follows:

$$\gamma(x,t) = J(x,t) + \varepsilon \frac{\partial E(x,t)}{\partial t} \qquad \mathbf{(9)}$$

In order to validate the model, the simulation used in this paper is achieved by using the parameters published previously in [14] as providedin Table 1.

Table 1: Parameters used in the simulation

Parameter	Value	Unit
Trapping coefficients		
B$_e$ (electrons)	7.0 x 10-3	s^{-1}
B$_h$ (holes)	7.0 x 10-3	s^{-1}
Recombination coefficients		
S$_0$ et – ht	4.0 x 10-3	m^{-3}C^{-1}s^{-1}
S$_1$ eμ – ht	4.0 x 10-3	m^{-3}C^{-1}s^{-1}
S$_2$ hμ – et	4.0 x 10-3	m^{-3}C^{-1}s^{-1}
S$_3$ eμ – hμ	0	m^{-3}C^{-1}s^{-1}
Mobility		
μe	9.0 x 10-15	m^{2}V^{-1}s^{-1}
μh	9.0 x 10-15	m^{2}V^{-1}s^{-1}
Trap Density		
N$_{0et}$	100.0	Cm^{-3}
N$_{0ht}$	100.0	Cm^{-3}
Barrier height for injection		
W$_{ei}$	1.2	eV
W$_{hi}$	1.2	eV
Other parameters		
Temperature	300	K
Applied DC stress, V	7.5	kV
Time per iteration cycle, dt	0.01	s
XLPE sample thickness, d	150	µm
Number of divisions, m	100	

The simulated charge density and electric field plots on the given parameters in Table 1 are shown in Figure 1 which are similar to the results published in [14]

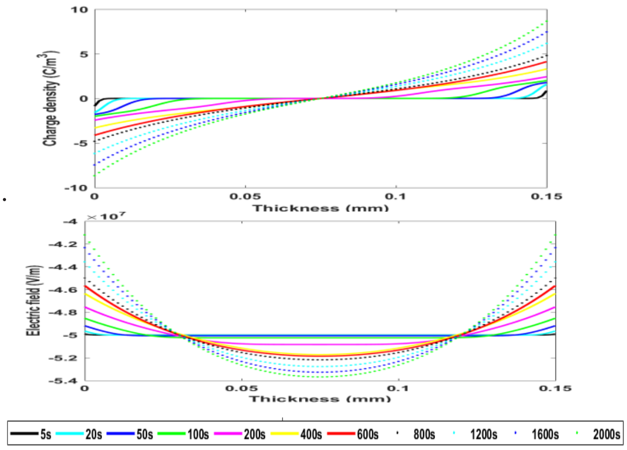


Figure 1: Charge density and electric field plots based on the parameters given in Error! Reference source not found.

3. Simulation Results and Discussion

Space charge is all charged carriers that occur within any dielectric material which can be trapped and migrate under the influence of an external electrical field. Space charge is generated from either electronic injection or ionization of impurities within the dielectric material. The electrical field within dielectric material will be affected due to the presence of space charge. Figure 2 shows the electrical field as a function of thickness of the dielectric sample between the electrodes. The figure illustrates the electrical field with space charge effect and also without space charge effect known as Laplacian field. There are two assumptions have been made in this simulation; firstly, the charge that have been injected into the sample is uniformly distributed along its thickness from the electrode surface. Secondly, it is assumed that there is no charge transportation or charge diffusion taking place outside the space charge field and the thickness is unchanged over the time.

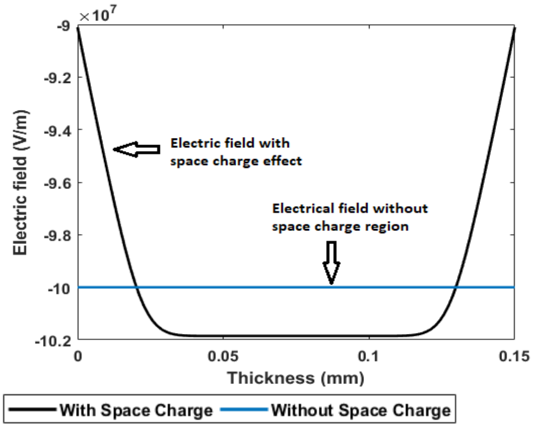
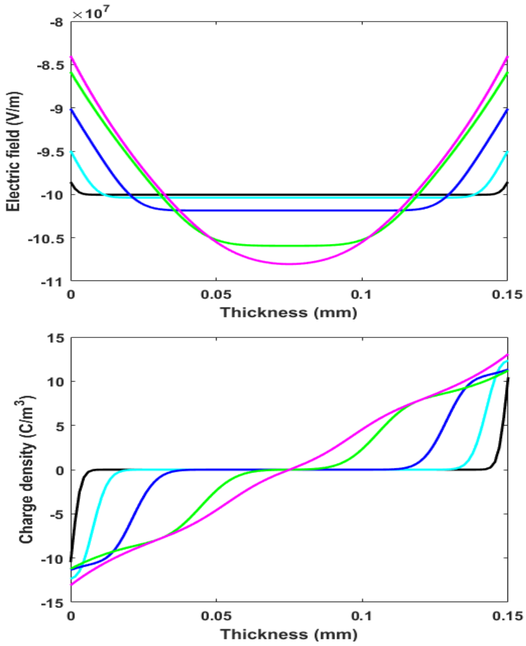
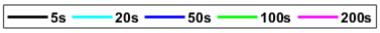


Figure 2: Electric field with and without the effect of space charge at different time under 15kV

In agreement with Poisson’s equation, the electrical field is reduced from Laplacian field at the injecting electrode and increases with the thickness of the sample from the injecting electrode. On the other hand, the electrical field remains constant outside the space charge field even though marginally greater than the Laplacian value in order to maintain the electrical potential value between the electrodes. Over time, the charge accumulation at the electrodes will affect the electrical field of the dielectric materials. The charge carriers will travel from electrodes to the dielectric material and then will be trapped at specific region within the dielectric material. Due to the trapped charges within the material therefore, the electrical field at the specific region will be different from the Laplacian state (absence of space charge). This will cause the electrical field within the specific region exceeds the electrical breakdown strength which would then lead to degradation of the insulating material. Figure 3 shows the electrical field and charge density over the sample thickness over the time from 5s to 200s respectively.

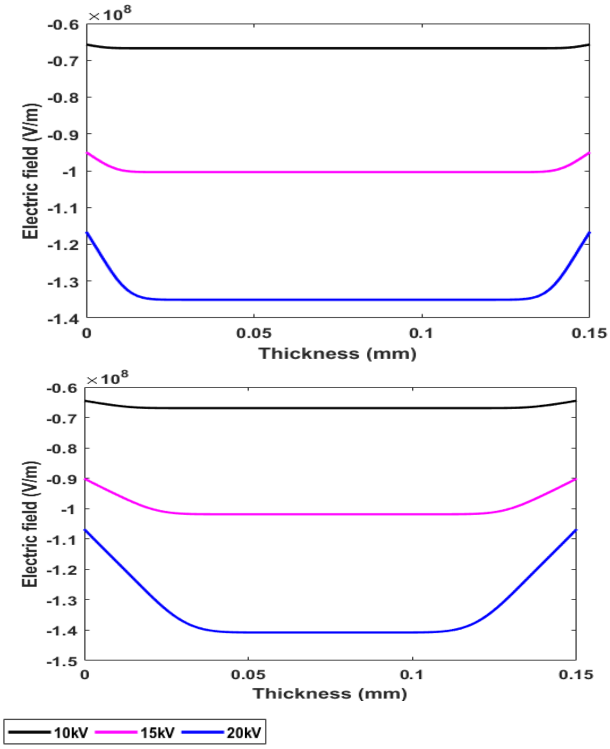




(a) Electric field (b) Charge density

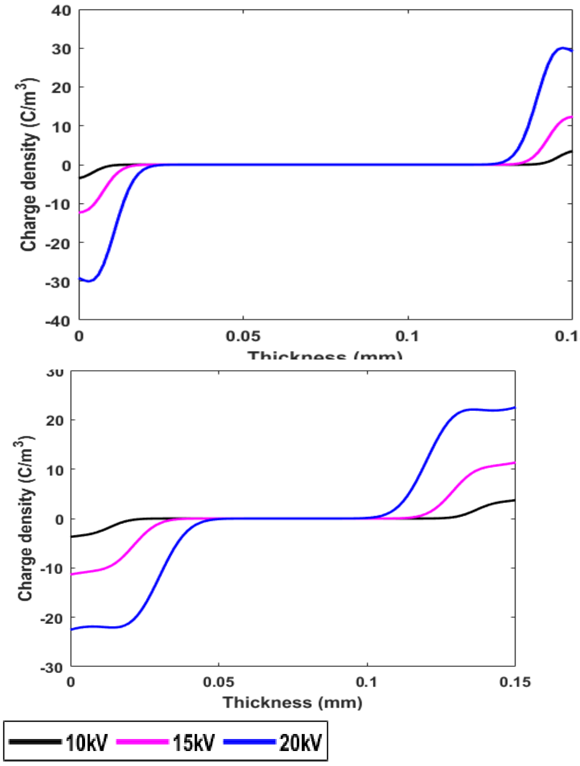
Figure 3. Electric field and charge density under 15kV

The results in Figure 3 show that when the stressing time increase, the amplitude of electric field increase. This is due to the fact that more space charge has accumulated within the dielectric material as the stressing time increases, which leads to the increase of the electrical field. Figure 5 and Figure 4 on the other hand compare electrical field and charge density at different stressing time under different applied voltages.



(a) 20s (b) 50s

Figure 4. Electric field at different time under various applied voltage.



(a) 20s (b) 50s

Figure 5. Charge density at different time under various applied voltage

Figure 4 and Figure 5 indicate that the higher the voltage applied, the higher the electrical field and the charge density produced. The higher the applied voltage means more charge being injected into the dielectric, which would then lead to electric field distortion. In addition, Figure 4 and Figure 5 also show that there are changes in the electric field and charge density as the stressing time become longer i.e. from 20s to 50s. The magnitude of electrical field and charge density at 50s is higher than the magnitude of electrical field and charge density at 20s. This is due to the more charges carriers have been injected into the dielectric materials as the charging time increases.

4. Conclusion

The simulation based on a simple model established from R M Hill and J M Alison work have been developed and explained. The effects of applied voltage within bipolar charge transport in XLPE through a numerical simulation have been examined. The results show that the applied voltage between the two electrodes increases, more charges are injected into the dielectric material. This would increase charge density within the material and perturb the Laplacian electrical field which consequently will affects the electrical performance of any high voltage insulation. The results from the proposed model in this paper has an important significance to investigate and understand the XLPE properties under different applied voltage as an insulation materials within high voltage application.

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