Study of Charge Dynamic and Breakdown Phenomenon in Insulating Materials Using a Bipolar Charge Transport Model

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ABSTRACT

In insulating materials, the accumulation of space charge is regarded as the main source of dielectric breakdown, which depends on their electrical lifetime. Within this work, a bipolar transport charge model is presented to study the phenomenon of electrical breakdown in low density polyethylene used for electrical insulation. Therefore, the sample thickness effect is observed on the charge dynamic and particular interest in the external current density is developed in the dielectric breakdown of the insulator, as a first witness. Distribution of the electric field is displayed by model results besides the net charge density in the insulator before and during the breakdown phenomenon. In fact, these distributions are highly related to the development of the external current density which reflects the breakdown phenomenon.

1-Introduction

Widely used in diverse electric apparatus, insulating polymers have been known for their outstanding thermal and mechanical properties, such as for electrical cables. One of the key polymers, used as insulator, is low-density polyethylene (LDPE) for electrical transport [1, 2]. It is observed though, that high level of damage to the electrical system, particularly under high voltage (DC), is experienced through the presence of the space charges in polymeric insulating material [3, 4]. Concerning these issues, various space charge measurement techniques have been developed in an attempt to comprehend and address their consequences on the electrical properties, for instance, as conduction mechanism and electrical breakdown [5, 6].

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In the prior years, for the space charge dynamics' better comprehension, theoretical simulation and modelling have been unified [7-12]. Within this study, numerical results are presented, as undertaken by our model, which interest the effect of sample thickness on the electrical breakdown of the insulator. These results show that the decrease of the sample thickness intensifies the electric field's distortion which guides the electrical breakdown of the insulator. We show also an estimation of the electrical lifetime of the sample which is highly affected by the sample thickness. It is to be noted that all the details pertaining to our model were given in our preceding works where we showed, under high dc applied voltage, an original result concerning the space charge packets' apparition on the profiles of net charge density and conduction current [12, 13]. In addition, we provided in a previous study an experimental validation proving that our model reproduces qualitatively and quantitatively the various applied voltages and the evolutions of the external current [14].

2- Hypothesis/Model equations

2-1- Hypothesis

Under DC applied voltage, polyethylene film inserted between two electrodes was considered. While contact electrode-polyethylene is supposedly perfect, the current density injected is understood through the Schottky model. Assumed to be plane infinite, the sample is used by admitting that all physical mechanisms perform chiefly in the thickness direction. The polyethylene itself is under unvarying temperature conditions.

The transporters would have effective constant mobility. Based on the work of Meunier et al [15, 16] it is presumed that, in the majority of the polyethylene, deep and shallow traps are dispersed in between the electrodes. In the transport mechanism, the contribution of shallow traps is merely based on their very weak residence time. Contributing to the charge accumulations are the deep traps, virtually supplying an infinite residence time. Finally, it is assumed that the sample comprises space charges' initial density.

2-2- Equations of the model

In this study, the transport, continuity, and Poisson equations are regrouped by the physical model.

The Poisson's equation is given as follows:

$$grad\,(V(x,t)) = -\,E(x,t) \tag{1}$$

$$\frac{\partial^2 V(x,t)}{\partial x^2} + \frac{\rho(x,t)}{\varepsilon} = 0 \qquad 0 < x < D \tag{2}$$

Here, $\rho\,(x, t,)$ $E\,(x, t)$, *and* $V\,(x, t)$, *are* the net charge density, the electric field and the local potential.

The initial condition concerning polyethylene free of additive is:

$$\rho(x,0) \approx 0 \tag{3}$$

The boundary conditions are:

$$\Delta V = V_C - V_A \tag{4}$$

$$V(0, t > 0) = V_C \tag{5}$$

$$V(D, t > 0) = V_A \tag{6}$$

$$\int_0^D E dx = \Delta V \tag{7}$$

The continuity equation and the source terms are written as under:

$$\frac{\partial \rho_{(e,h)\mu}(x,t)}{\partial t} + \frac{\partial j_{(e,h)}(x,t)}{\partial x} = S_{t(e,h)}(x,t) + S_{r(e,h)}(x,t) + S_{dtp(e,h)}(x,t) \tag{8}$$

$$S_{t(e,h)}(x,t) = B_{(e,h)}\ \rho_{(e,h)t}(x,t) \times \left(1 - \frac{\rho_{(e,h)t}(x,t)}{d\rho_{(e,h)t}}\right) \tag{9}$$

$$S_r(x,t) = S_{r(e\mu,\,ht)}(x,t) + S_{r(et,\,h\mu)}(x,t) + S_{r(et,\,ht)}(x,t) \tag{10}$$

$$S_{dtp(e,h)}(x,t) = \pm D_{dt(e,t)}\,\rho_{(e,t)} \tag{11}$$

with:

$$D_{dt(e,t)} = \nu \exp\left(-\frac{e w_{d(e,h)}}{kT}\right) \tag{12}$$

For the trapping coefficient (B), signs (-) relates to mobile charges' disappearance while (+) shows trapped charges' appearance. For the coefficient of de-trapping (D_{dt}), signs (-) and (+) link to the trapped charges' disappearance and the mobile charges' appearance, correspondingly.

Following is the transport equation:

$$j_{(e,h)}(x,t) = \mu_{e,h}\ \rho_{(e,h)\mu}(x,t)\ E(x,t) \tag{13}$$

The density's net charge ρ(x,t) locally consists of trapped and mobile electrons and holes:

$$\rho(x,t) = \rho_{h\mu}(x,t) + \rho_{ht}(x,t) - \rho_{e\mu}(x,t) - \rho_{et}(x,t) \tag{14}$$

According to Schottky law, the injected charges' boundary conditions are:

$$j_e(0,t) = A T^2 exp(-\frac{w_{ei}}{kT})\ exp(\frac{e}{kT}\sqrt{\frac{e\left|E(0,t)\right|}{4\pi\varepsilon}}) \tag{15}$$

$$j_h(D,t) = A T^2 exp(-\frac{w_{hi}}{kT})\ exp(\frac{e}{kT}\sqrt{\frac{e\left|E(D,t)\right|}{4\pi\varepsilon}}) \tag{16}$$

For the mobile carriers, the local conduction current is:

$$j_{e\mu,h\mu}(x,t) = (\mu_e \ \rho_{e\mu}(x,t) + \mu_h \ \rho_{h\mu}(x,t))E(x,t) \tag{17}$$

The instant local displacement current density is:

$$j_d(x,t) = \varepsilon \frac{\partial E(x,t)}{\partial t} \tag{18}$$

Obtained by numerical integration, the external total current density is:

$$J(t) = \int_0^D (j_{e\mu,h\mu}(x,t) + j_d(x,t))\ dx \tag{19}$$

The following equation is always satisfied according to the stationary boundary equation (7):

$$\int_0^D j_d(x,t)\ dx = 0 \tag{20}$$

3- Results and Discussion

All figures are obtained under 75 kV dc applied voltage. Figure 1(a) indicates the evolution of the external current in LDPE sample of 160 μm thickness. It is noted that as an outcome of high voltage application, the external current surges gradually until reaching a steady state. This evolution arises at the occurrence of the charge packet phenomenon [13]. The external current reaches a higher value as the electron-hole charge packets begin to recombine. Hence, electric field distortion is brought about by the charge packet phenomenon: the electric field surges at the electrode-insulation interface and reduces in the mid of the sample [13]. Theoretically, the distortion of the electric field is already prospected in an attempt to obey equation 7's physical condition.

At a steady state and at fixed applied voltage, the local as well as the entire contribution of the displacement current vanishes, as can be deduced, respectively from equations (18) and (20).

So, at steady state, the external current is equivalent to the integral of the conduction current over the thickness of polyethylene. As the sample thickness decreases (figure 1(b)), the injection becomes more significant and the value of the external current at steady state (conduction current density) is more important. Certainly, at steady state and in accordance with the figures 1(a, b), the external current density value is enhanced from 5.7 10^{-5} $A.m^{-2}$ to 9.2 10^{-5} $A.m^{-2}$. As a result, when the sample thickness diminishes, the conduction process in the sample becomes more distinct that in turn, can threaten to their breakdown and to the lessening of its electrical lifetime.

Figure 2(a) indicates the temporal evolution of the external current density for an LDPE of 151 μm thickness which embodies the threshold rate of breakdown thickness. The progress is similar qualitatively, as seen in the prior experimental works [17]. Undeniably, the external current density rises progressively from the beginning of voltage application till the time it reaches a stable state, until an abrupt increase transpires, indicating the electrical post breakdown process of the sample. In relation to the profile of figure 2(a), it can be concluded that beginning from 400 s, all traps are filled while all charges that are injected add to the external current density, hence, it can be observed that the concept of a like-avalanche current amplification that arrives at 2 10^{-4} $A.m^{-2}$. It is deduced that the noted aspect stems from the intensification pertaining to interfacial electric field becoming essential and the charge densities (injected) getting significant, leading to condition processes' augmentation in the sample. In addition, the strengthening of the mobile charges' injection adds to the augmentation of local charges density, causing the enhancement of the local field in minor volumes of the polyethylene.

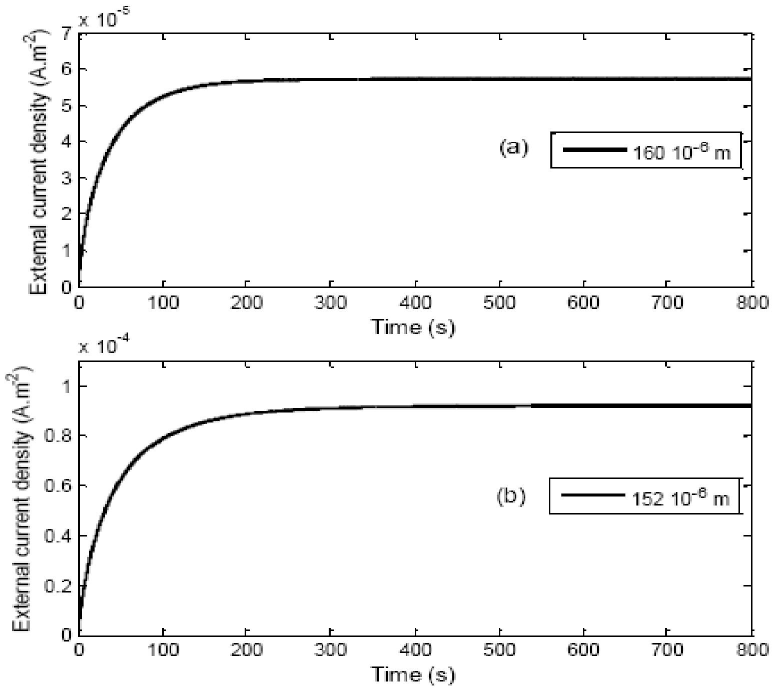

Fig. 1. Temporal evolution of the external current density (a) 160 µm thickness (b) 152 µm thickness.

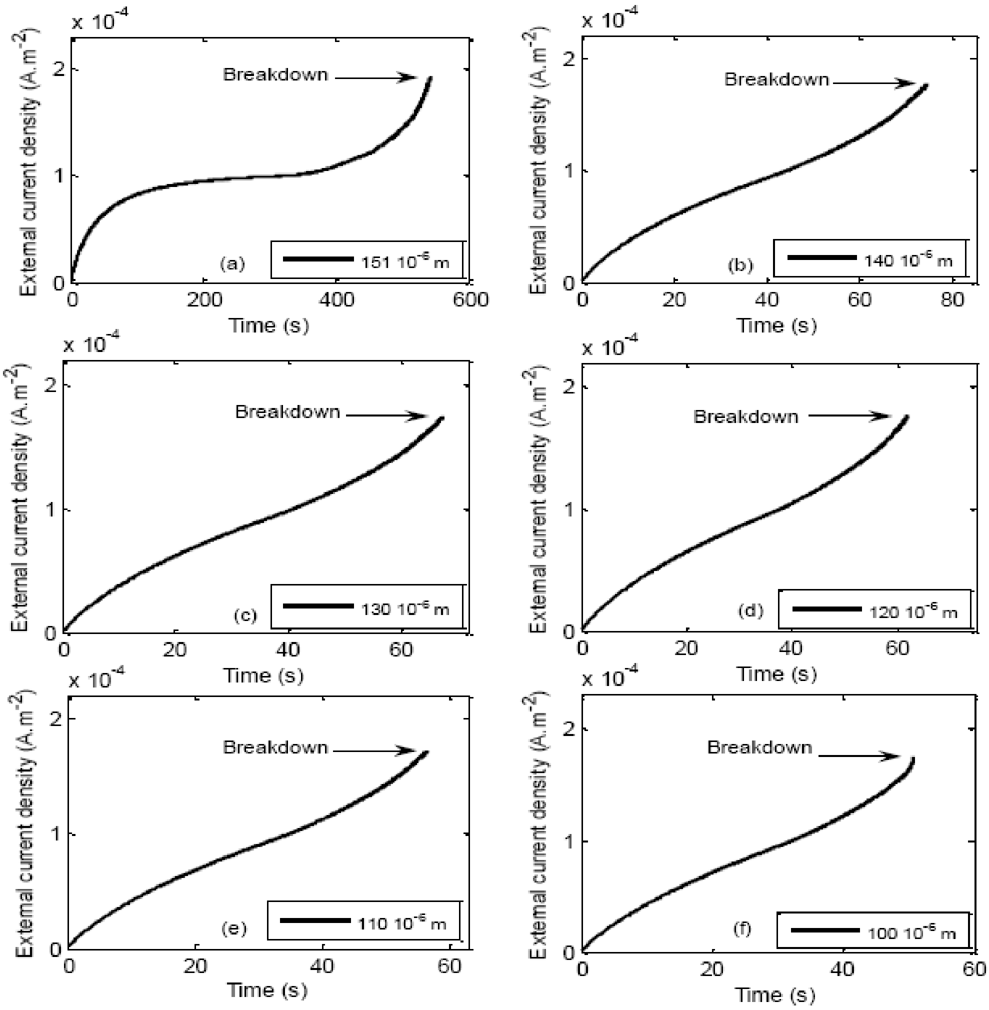

Fig. 2. Temporal evolution of the external current density (a) 151 µm thickness, (b) 140 µm thickness, (c) 130 µm thickness, (d) 120 µm thickness, (e) 110 µm thickness, (f) 100 µm thickness.

The conduction amplification, as well as enhancement of the local field, indicate post-breakdown while also leading to the material's effective breakdown. The novels mentioned results are observed on figures 2(b)-(f) which indicate the temporal evolutions of the external current density for thicknesses of 140 10^{-6} m, 130 10^{-6} m, 120 10^{-6} m, 110 10^{-6} m and 100 10^{-6} m, respectively. In the given examples, the electrical breakdown of the sample can be incurred after 75 s, 67 s, 62 s, 56 s and 51 s for thicknesses of 140 10^{-6} m, 130 10^{-6} m, 120 10^{-6} m, 110 10^{-6} m and 100 10^{-6} m, correspondingly. In the results portrayed by the model, it can be deduced as a logical conclusion that as the sample thickness decreases, the breakdown phenomenon establishment makes an appearance early.

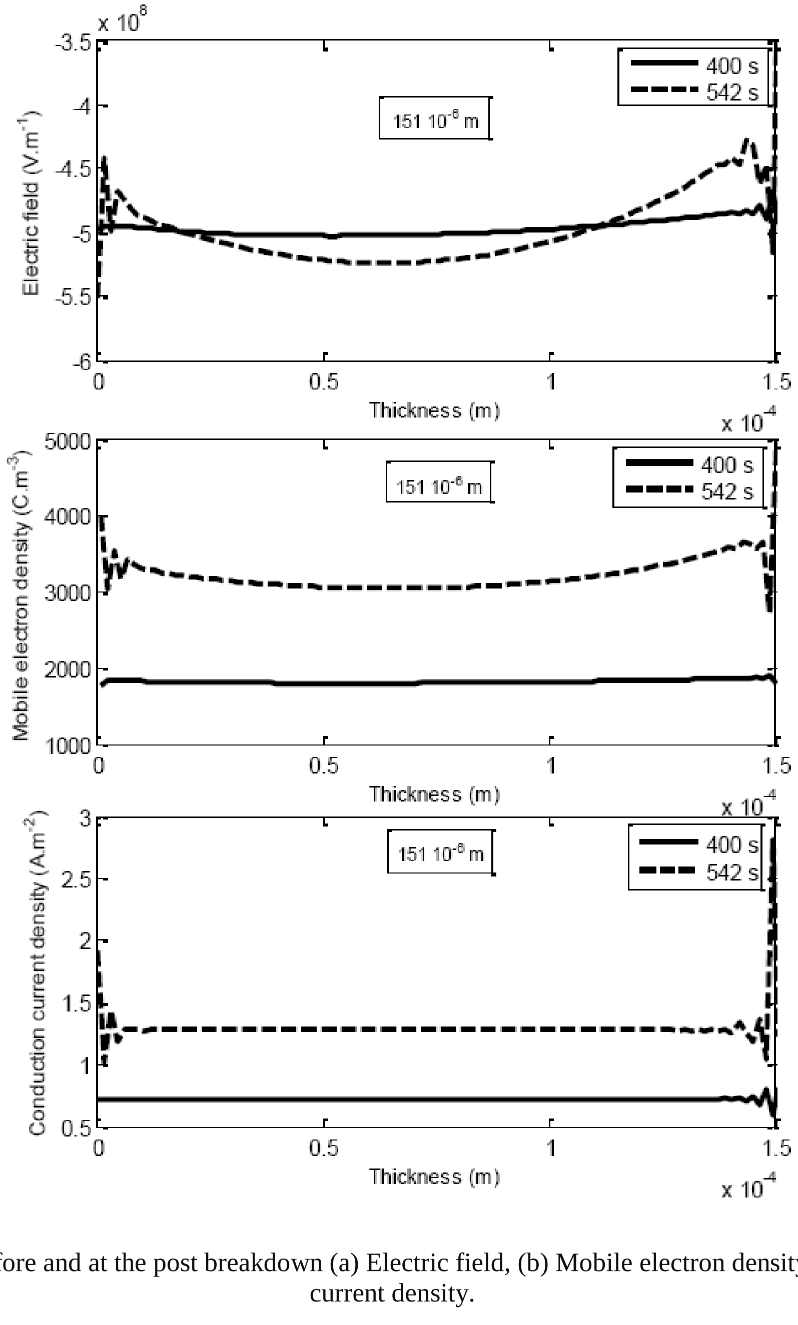

Fig. 3. Profiles before and at the post breakdown (a) Electric field, (b) Mobile electron density, (c) Conduction current density.

To comprehend the abrupt increase of the current better, we illustrate on figures 3(a)-(c) the profiles of the electric field distributions, the mobile electron density, besides the conduction current in the polyethylene. These profiles are computed for the example of 151 10^{-6} m, pre and post-breakdown for the corresponding instants 400 s and 542 s. Figure 3(a) illustrates that at 542 s, the electric field's absolute value at the cathode increases until reaching a maximum of about 5.5 108 $V.m^{-1}$. In figure 3(b), we can see that the injected density rate pertaining to mobile electrons jumps from 1800 $C.m^{-3}$ to 4000 $C.m^{-3}$ between 400 and 542 s. Since the external current is dependent on mobile charges, it can be observed in figure 2(a) that an abrupt increase is seen as a result of the jump mentioned. A more elaborate conductive character of the sample can be seen in figure 3(c) where the conduction current density jumps from 0.7 $A.m^{-2}$ at 400 s to 1.9 $A.m^{-2}$ at 542 s.

In an attempt to estimate the electrical lifetime pertaining to the sample, figure 4 plots the lifetime against the sample thickness, and the conclusion reached is that as the thickness increases, the electrical lifetime of the sample simultaneously rises. It is clearly shown that the augmentation of the thickness allows an improvement in the electrical lifetime of the insulator and while allowing it to avoid the relevant electrical breakdown. So, this study enables in predicting the electrical lifetime of the insulator.

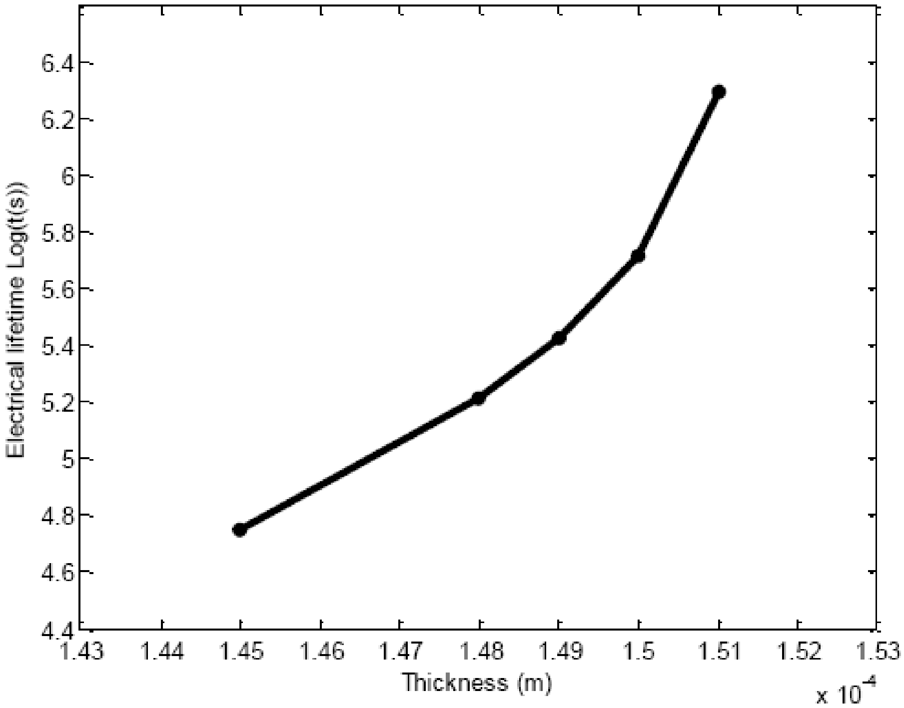

Fig. 4. Dependence of LDPE electrical lifetime on sample thickness.

4- Conclusion

Within this study, a model in relation to bipolar charge transport is presented in order to study the post-breakdown and the electrical lifetime of polyethylene insulator under dc applied voltages. We are particularly interested in the effect of the sample thickness on the external current which provides evidence as to the sample post breakdown. This model indicates that as the thickness decreases, the value of the external current at steady state becomes increasingly important. Therefore, the intensity of the conduction process in relation to the insulator rises, which in turn, is proved by the increase of the conduction current density. When the thickness decreases further, the charge injection in the sample intensifies more and more which threatens the lessening of the electrical lifetime and the post-breakdown which is manifested by a rapid increase on the external current density's profile. In our knowledge, these results have not been obtained ever before in breakdown modeling.

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Nomenclature

E	Dielectric permittivity ($A.s.V^{-1}.m^{-1}$)
ρ	Net charge density ($C.m^{-3}$)
E	Electric field ($V.m^{-1}$)
V	Local potential (V)
$\rho_{(e\mu,h\mu)}$	Density of mobile carriers ($C.m^{-3}$)
μ	Carrier's mobility ($m^2.V^{-1}.s^{-1}$)
D	Dielectric thickness (m)
V_A	Potential at the anode (V)
V_C	Potential at the cathode (V)
$j_{(e,h)}$	Charge flux of mobile carriers (V.m)
$j_e(0,t)$	Flux of electrons at the cathode (V.m)
$j_h(D,t)$	Flux of holes at the anode (V.m)
$\rho_{(et,ht)}$	Density of trapped carriers ($C.m^{-3}$)
$B_{(e,h)}$	Trapping coefficients (s^{-1})
$S_{r(e,h)}$	Recombination source terms ($m^3.C^{-1}$)
$S_{t(e,h)}$	Trapping source terms ($m^3.C^{-1}$)
$S_{dt(e,h)}$	Detrapping source terms ($m^3.C^{-1}$)
$S_{(et\ (or)\ e\mu,\ h\mu (or)\ ht)}$	Recombination coefficients ($m^3.C^{-1}$)
$w_{(de,dh)}$	Carrier's detrapping (eV)
$w_{(ei,hi)}$	Carrier's injection barrier (eV)
A	Richardson constant ($A.m^{-1}.K^{-2}$)
T	Temperature (K)
v	The frequency of attempt to escape (s^{-1})
$D_{dt(e,h)}$	Detrapping coefficients (s^{-1})

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