Simulation on Dynamic Space Charge Behaviour in LDPE under Temperature Gradient

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ABSTRACT

The research for the space charge and electric field distributions of polyethylene under HVDC stress and temperature gradient has a high theory and engineering values. In this paper, a numerical model to describe the process of space charge transport in Low Density Polyethylene (LDPE) is established, which includes injection, trapping and recombination. Based on the numerical model, the space charge behaviours in LDPE under different temperatures gradient are studied. The results show that the electric field at low temperature area of sample increases with the increase of the temperature gradient.

KEYWORDS

Low density polyethylene, Space charge distribution, Numerical simulation, Temperature gradient, etc.

INTRODUCTION

With the extension of power system, the increase of transmission power and transmission distance, some problems have occurred in AC transmission system. HVDC transmission with low-cost, low losses, convenient power connections and without reactive power losses is relatively easy to control and regulate. So HVDC power cables are mostly used to transport electrical power over long distances[1]. However, there are some pressing technical issues in the research of HVDC power cables due to its DC characteristics. It is generally known that the electric field distribution in the cable insulation under AC is determined by its dielectric constant, which is almost independent of temperature. While the electric field distribution under DC is determined by its resistance and the distribution of space charge, and the field distribution is closely related to the temperature and applied voltage[2]. Due to the Joule heat caused by the current in the HVDC cable conductor, the temperature gradient appears in the cable insulation, which may make the insulation resistance distribute in gradient and the electric field increase from inside to outside. This change intensifies the space charge accumulation and the field distortion on the outside of the insulation, which not only affects the long-term stability seriously but also causes the early damage when a power failure or the reversal of polarity happens to a cable[3]. The charge accumulation and the field distortion in DC cable are the biggest barrier to application in high voltage. Therefore, the research on the distribution of space charge and electric field in polyethylene under HVDC and temperature gradient is of great theoretical value and engineering significance.

In this paper, combining with the reported research results, research in the past is often concentrated on space charge distribution and the aging or breakdown of materials under constant temperature and DC stress[4-5]. Later, the space charge measurement in LDPE films under temperature gradient has been studied in detail by the domestic research group of WuKai, who got an outstanding achievement[6-10]. Space charge profiles and field distributions in the cable bulk are mainly studied through experiments. Only LDPE films can be measured as a result of the restrictions imposed by the experimental conditions, but not the actual insulation thickness of cable. Moreover, the charge distribution gotten by experiments are the distribution of net space charge in LDPE, which could not factually reflect the source and transport process of space charge in film. To better explain the behavior of space charge and the field distortion occurring in the experiments theoretically, in this paper, the High Runge-Kutta, LU and FDM methods are applied to numerically analyze the transport process of space charge in one dimensional polyethylene under different temperature gradients. Through the model, the relationships between the space charge distribution and temperature as well as time are obtained, and these provide references to the further study on the behavior of space charge in the coaxial cable.

SIMULATION METHOD

Finite difference method is firstly to subdivide the successive domain with a finite number of discrete points. These discrete points are called grid nodes. Secondly, the difference quotients of function are used to approximate the partial derivatives at each discrete point so that the determining solution of partial differential equations is transformed into a set of corresponding differential equations. Finally, according to the differential equations, the function values (namely, discrete solutions) at discrete points can be solved.

Simulation model

The model built in this paper introduces the foreign ion transport model based on a bipolar charge transport model which was proposed by Alison and Hill in 1994[11]. The basis concept of simulation model is that establish a one-dimensional coordinate along the sample depth. By applying the FDM method to the sample, the thickness d, as shown in figure 1, is divided into elements (segments) called the finite element mesh. The elements are linked by nodes (2-N). An arbitrary element denoted (i) having a length $\Delta x_i=x_{i+1}-x_i$ is chosen and then isolated from the grid of elements. As the grid sizes are all evenly spaced, so $\Delta x_i=\Delta x=h_i$. The initial electric field at arbitrary element can be obtained by Poisson equation after given the distribution of initial charge density. Then the variations of the trapped and the mobile charge densities at the next time $\triangle t$ can be obtained through the current continuity equation, thereby the distribution information of the space charge at arbitrary element can be known. According to this process, the distributions of space charge with different polarities and different states at any time can be solved by iteration.

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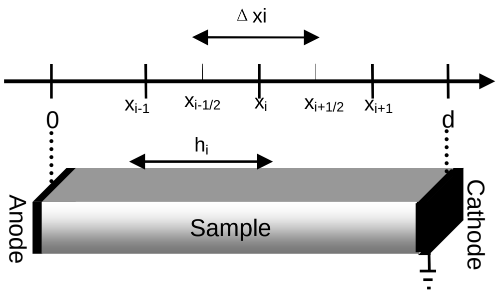

Fig.1: Schematic of the diagram of discretization in a LDPE sample

Interface charge injection process

In this model, the boundary conditions for the injected charges follow the Schottky law when the electric field is not so high:

$$j_e(0,t) = AT^2 \exp\left(-\frac{w_{ei}}{kT}\right) \exp\left[\frac{e}{kT}\sqrt{\frac{eE(0,t)}{4\pi\varepsilon_0}}\right]$$
$$j_h(d,t) = AT^2 \exp\left(-\frac{w_{hi}}{kT}\right) \exp\left[\frac{e}{kT}\sqrt{\frac{eE(d,t)}{4\pi\varepsilon_0}}\right] \qquad [1]$$

Where $j_e(0,t)$ and $j_h(d,t)$ are the fluxes of electrons and holes at the cathode and anode, respectively. T is the temperature, k is the Boltzmann constant, A is the Richardson constant, w_{ei} and w_{hi} are the injection barriers for electrons and holes.

Carrier transport process in LDPE

In order to describe the space charge transport process in LDPE accurately, the quantity of charge at the electrodes in this model is thought to be variable instead of the assumption in the model built by Alison and Hill, and foreign ion charge transport model is also proposed based on the model built by Alison and Hill. The charge injected from the electrodes will gradually move into the sample under DC stress. Meanwhile, impurities can be dissociated into positive and negative ions when the thermal energy of impurities exceeds the dissociation barrier. The positive and negative ions will move towards the electrodes with opposite polarity when the energy of ions exceeds the migration barrier. Therefore, the transport process of charge in LDPE in one dimensional coordinate can be described by the following equations, namely.

The transport equation is written in the following way:

$$j = \left(\mu_h n_{h\mu} + \mu_e n_{e\mu} + \mu_{ion+} n_{\mu+} + \mu_{ion-} n_{\mu-}\right) E(x,t)$$
$$= v_h n_{h\mu} + v_e n_{e\mu} + v_{ion+} n_{\mu+} + v_{ion-} n_{\mu-} \qquad [2]$$

Continuity and transport equations. The continuity equations with source terms are as follows:

$$\frac{\partial n_a(x,t)}{\partial t} + \frac{\partial j_a(x,t)}{\partial x} = s_a(x,t)$$
$$s(x,t) = s_{t(e,h)}(x,t) + s_{\mu(e,h)}(x,t) + s_\mu(x,t) + s_t(x,t) \qquad [3]$$

Poisson equation. The Poisson equation, the initial and the boundary conditions are given as follows:

$$\frac{\partial^2 V(x,t)}{\partial x^2} + \frac{n_T(x,t)}{\varepsilon_r \varepsilon_0} = 0 \quad 0 < x < d$$
$$grad(V(x,t)) = -E(x,t) \qquad [4]$$
$$n_T(x,t) = n_{h\mu}(x,t) + n_{ht}(x,t) - n_{e\mu}(x,t) - n_{et}(x,t) + \ldots$$
$$+ n_{ion+}(x,t) - n_{ion-}(x,t)$$

Initial condition: $n_T(x,t)=0$ [5]

Boundary conditions: V(0, t>0)=V, V(0, t>0)=0 [6]

Here subscript 'a' represents the electron, hole, positive ion and negative ion. n is the carrier density. μ is the mobility of carriers. v is the migration rate of carriers. $s_a(x,t)$ represents the trapping source terms of electrons, holes or ions and the recombination source terms of electrons, holes or ions. The source terms of carriers is represented by the following set equations.

$$s_{e\mu} = -s_1 n_{\mu e}(x) n_{th}(x) - B_e n_{\mu e}(x)\left[1 - \frac{n_{te}(x)}{dpe}\right]$$

$$s_{h\mu} = -s_2 n_{te}(x) n_{\mu h}(x) - B_h n_{\mu h}(x)\left[1 - \frac{n_{th}(x)}{dph}\right]$$

$$s_{et} = -s_2 n_{\mu h}(x) n_{te}(x) - s_0 n_{th}(x) n_{te}(x) + B_e n_{\mu e}\left(1 - \frac{n_{te}}{dpe}\right)$$

$$s_{ht} = -s_1 n_{\mu e}(x) n_{th}(x) - s_0 n_{th}(x) n_{te}(x) + B_h n_{\mu h}\left(1 - \frac{n_{th}}{dph}\right)$$

$$s_{\mu-} = -\xi_1 n_{t+}(x) \cdot n_{\mu-}(x) - \xi_3 \cdot n_{\mu+}(x) \cdot n_{\mu-}(x) -$$
$$b_{\mu-}(x) + d_{t-}(x) + D_d \cdot N_0(x)$$

$$s_{\mu+} = -\xi_2 n_{t-}(x) \cdot n_{\mu+}(x) - \xi_3 \cdot n_{\mu+}(x) \cdot n_{\mu-}(x) - b_{\mu+}(x)$$
$$+ d_{t+}(x) + D_d \cdot N_0(x)$$

$$s_{t-} = -\xi_2 n_{\mu+}(x) \cdot n_{t-}(x) - \xi_0 \cdot n_{t+}(x) \cdot n_{t-}(x) + b_{\mu-}(x)$$
$$- d_{t-}(x)$$

$$s_{t+} = -\xi_1 n_{t+}(x) \cdot n_{\mu-}(x) - \xi_0 \cdot n_{t+}(x) \cdot n_{t-}(x) + b_{\mu+}(x)$$
$$- d_{t+}(x)$$

$$b_{\mu+} = B_+ \cdot n_{\mu+} \cdot \left(1 - \frac{n_{t+}}{n_{ot+}}\right)$$

$$b_{\mu-} = B_- \cdot n_{\mu-} \cdot \left(1 - \frac{n_{t-}}{n_{ot-}}\right)$$

$$d_{t+} = \nu \cdot \exp\left(-\frac{\Delta U_{t+}}{kT}\right) \cdot n_{t+}$$

$$d_{t-} = \nu \cdot \exp\left(-\frac{\Delta U_{t-}}{kT}\right) \cdot n_{t-}$$

[7]

Where s_0, s_1, s_2 are the recombination coefficients. B_e, B_h are the trapping coefficients for electrons and holes respectively. *dpe* and *dph* are, respectively, the trapping densities for electrons and holes. And

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$n_{\mu e}$, $n_{\mu h}$, n_{te}, n_{th}, $n_{\mu +}$, $n_{\mu -}$, n_{t+}, n_{t-} are the mobile electron, the mobile hole, the trapped electron, the trapped hole, the mobile positive ion, the mobile negative ion, the trapped positive ion and the trapped negative ion densities, respectively. $b_{\mu +}$, $b_{\mu -}$ are the trapping quantities of the mobile positive ion and the mobile negative ion. d_{t+}, d_{t-} are the detrapping quantities of the trapped positive ion and the trapped negative ion.

Simulation parameters

Table 1 gives a list of these values for the model.

Table 1 The main parameters used in the model

Parameter	Assigned value
Sample thickness, *d*	300um
Barriers height	
The injection barriers for electrons, w_{ei}	1.2 eV
The injection barriers for holes, w_{hi}	1.2eV
Recombination coefficients	
S_0 trapped electron/trapped hole	4×10^{-3} $m^3 C^{-1} s^{-1}$
S_1 mobile electron/trapped hole	4×10^{-3} $m^3 C^{-1} s^{-1}$
S_2 trapped electron/mobile hole	4×10^{-3} $m^3 C^{-1} s^{-1}$
S_3 mobile electron/mobile hole	0
ξ_0 trapped positive ion/trapped negative ion	4×10^{-3} $m^3 C^{-1} s^{-1}$
ξ_1 trapped positive ion/mobile negative ion	4×10^{-3} $m^3 C^{-1} s^{-1}$
ξ_2 mobile positive ion/trapped negative ion	4×10^{-3} $m^3 C^{-1} s^{-1}$
ξ_3 mobile positive ion/mobile negative ion	4×10^{-3} $m^3 C^{-1} s^{-1}$
Trapping coefficients	
B_e electrons	$0.01 s^{-1}$
B_h holes	$0.01 s^{-1}$
Trap densities	
dpe for electrons	$100 C m^{-3}$
dph for holes	$100 C m^{-3}$
Ionic dissociation	
Impurity density, N_0	$2.5\times10^{19} m^3$
Ionic unit charge, *q*	2e
Ionic tapping	
Section modulus for positive ion, *B+*	$0.15 s^{-1}$
Section modulus for negative ion, *B-*	$0.1 s^{-1}$
n_{ot+} for positive ion	$100 C m^{-3}$
n_{ot-} for negative ion	$100 C m^{-3}$

Method validation

The results of the model are obtained for a 300 μm thick LDPE film. The film is assumed to be clamped between two electrodes. Figure 2 and 3 show the density of simulated and experimental space charge within the sample for DC applied voltage of 3kV under 20□.

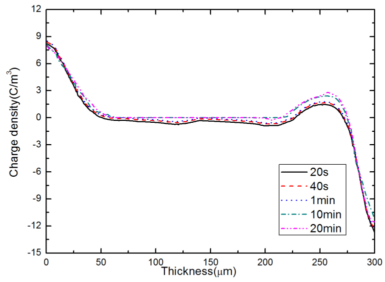

Fig.2: Simulated charge density profiles at different times under 3kV dc stress.

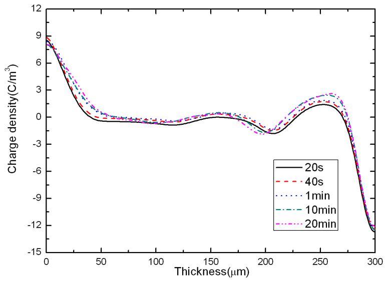

Fig.3: Experimented charge density profiles at different times under 3kV dc stress.

As shown in figure 2 and 3, the space charge distributes dispersively within the sample under low DC stress, and a certain amount of hetero charges appear near the both electrodes, which is mainly caused by dissociative processes under electric field effect. It is worth noting that the results of this simulation are in good agreement with the experimental results.

SIMULATION RESULTS IN LDPE FILMS AND DISCUSSION

Space charge distribution characteristic under different temperature gradients

Based on thermal conductive equation, the simulation researches under different temperature gradients were achieved by changing the temperature setting at both electrodes. Space charge profiles and field distributions in LDPE films were simulated under different temperature (ΔT=10-30℃), and DC stress of 30kV/mm within 20 minutes.

Figure 4 shows the space charge profiles of the LDPE sample under DC stress of 30kV/mm, with different temperature differences(ΔT=10-30℃) across the sample bulk. Here, x=0 represents anode electrode (i.e. low temperature side), and x=d represents cathode electrode (i.e. high temperature side).

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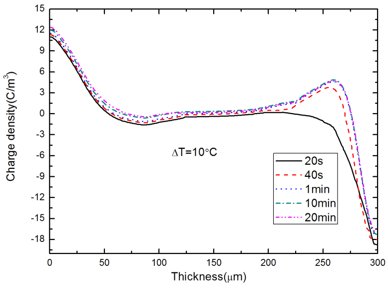
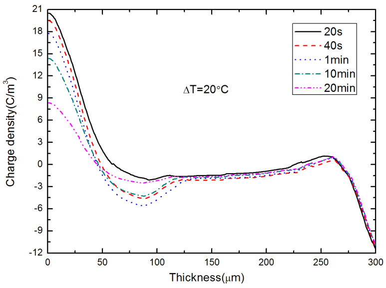
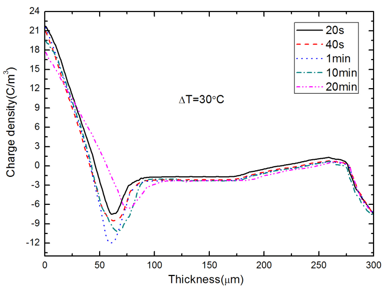


(a) ΔT=10℃



(b) ΔT=20℃



(c) ΔT=30℃

Fig.4: Space charge profiles in LDPE with average stress 30kV/mm under different temperature differences

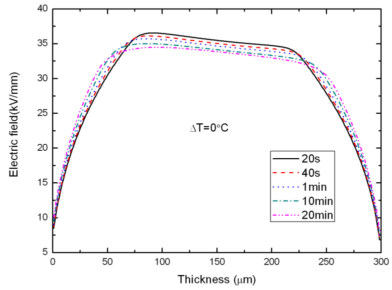
It can be seen from Figure 4 that under ΔT =10℃, the increase of time results in the less hetero charges near the anode. However, the hetero charges near the anode increase first, and then decrease with the increase of time under 20℃ and 30℃. Furthermore, the higher the temperature difference the more the decrease of the hetero charges. At the same time, under the same time, the increase of temperature difference results in the more interface charges at the anode and the less interface charges at the cathode, but the more hetero charges near the anode and the less hetero charges near the cathode.

As conduction band with narrow gap and forbidden band with lots of localized states in LDPE insulation, charge carriers are easily be trapped to form space charges as they travel a little distance under electrical field. The space charges are divided into homo-charges and hetero-charges. The homo-charges are mainly injected into the insulation through both electrodes, while the hetero-charges are primarily formed through the thermal dissociation of impurities under electrical field. These space charges may cause local electrical field distortion, leading to the change of dielectric performance[12]. The cable insulation is inevitably doped in the actual manufacturing process with kinds of impurities, such as antioxidant, anti-aging agent and cross-linking agent, etc. The thermal dissociation of these impurities may occur under electrical field, causing the growing accumulation of hetero-charges and the increasing electrical field near the low temperature side of cable insulation[13-14].

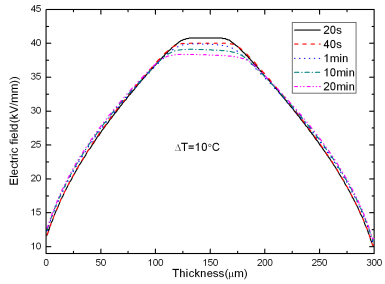
The informed research shows that the increasing temperature can not only improve the mobility of charge carriers in the polymer, but also can reduce the charge injecting barriers near the electrodes so as to strengthen the Schottky effect and thermionic emission. Therefore, the charge injecting barrier near the cathode is reduced with the increasing temperature gradient. The reduced barrier increases the quantity of the injecting negative charge and makes the charges move to the anode quickly, which reduces the quantity of charge near the cathode. On the other hand, with lower temperature near the anode, the trapped charges are difficult to detrap and charge accumulation occurs, which strengthens the electrical field near the anode. Meanwhile, the quantity of charge near the anode is gradually increasing with time, which strengthens the electrical field and reduces the charge injecting barrier near the anode. The injecting positive charge recombines with the hetero-charges accumulating near the anode, so the quantity of the injecting charge begins to reduce.

Electric field distribution characteristic under different temperature gradients

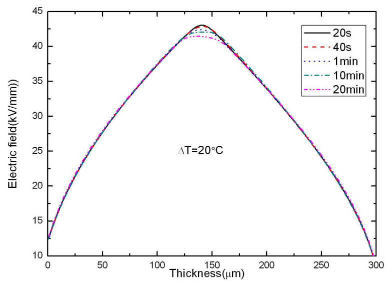
Figure 5 shows the electric field distribution characteristic under different temperature gradients in LDPE. It can be seen from Figure 5 that the increase of the temperature difference results in the larger maximum electric field near the anode. When the temperature gradient is 30℃, the maximal electric field can reach 46kV/mm in LDPE films, which is 1.53 times of the applied electric field. At the same time, the increase of time results in the smaller the maximum electric field near the anode. Furthermore, the higher the temperature difference the more the decrease of the maximum electric field. Because of the temperature character of insulation resistance is negative, the increase of temperature results in the less insulation resistance[15]. So the insulation resistance increases gradually from the high temperature side to the low temperature side. Owning to the electrical conductivity is inversely proportional to the resistance distribution under DC stress, the direct consequence is the electrical conductivity near the anode is less than that near the cathode. The carriers will gradually accumulate near the anode when they are transported to the low temperature side, for which the electrical conductivity near the anode is low. Consequently, the electric field increases higher with the poling time. It is well known that the increase of temperature will increase carrier mobility in the sample bulk, decrease injection barrier of charges and aggravate Schottky effect or thermal electron emission at electrode. And subsequently, the decrease of negative hetero charges near the anode lead to the decrease of the electric field.



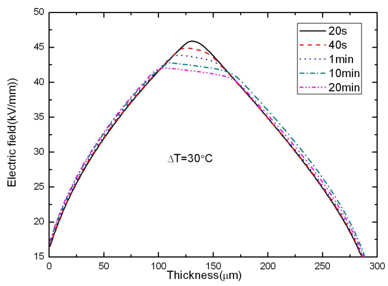
(a) ΔT=0℃



(b) ΔT=10℃



(c) ΔT=20℃



(d) ΔT=30℃

Fig.5: Electric field profiles in LDPE with average stress 30kV/mm under different temperature differences

CONCLUSIONS

Numerical model for studying dynamic space charge behavior in LDPE was established. It is worth noting that the results of this simulation are in good agreement with the experimental results.

The increase of temperature difference results in the more interface charges at the anode and the less interface charges at the cathode. At the same time, the accumulation of negative hetero charges near the anode will aggravate Schottky effect. And subsequently, the increase of time results in the smaller electric field near the anode. At the same time, under the same time, the higher the temperature difference the more the decrease of the maximum electric field.

When the temperature gradient is 30℃, the maximal electric field can reach 46kV/mm in LDPE films, which is 1.53 times of the applied electric field.

Acknowledgments

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REFERENCES

[1] Tu Demin, 2001, "A survey of development in HV DC XLPE cable", Journal of Electrical & Electronic Education. vol. 23 (2), 5-10(in Chinese).

[2] Zhang Ping, 2004, "Design on the insulation of the DC cable", High Voltage Engineering. vol. 30(8), 20-21, 24(in Chinese).

[3] Tu Demin, Liu Wenbin, 1987, "Theory of dielectric breakdown caused by space charge effects and study of the charge emission shield", Journal of Xi'an Jiaotong University. vol. 21(4), 1-11(in Chinese).

[4] L E G C, BLAISE G, 1992, "Breakdown phenomena related to trapping/detrapping processes in wide band gap insulator", IEEE Trans on EI. vol. 27(3), 472-481.

[5] LOTTE F, CONGEDO M, 2007, "A review of classification algorithms for EEG-based brain-computer interfaces", Journal of Neural Engineering. vol. 4(2), R1-R13.

[6] Wu K, Zhu Q, 2011, "Effect of Temperature Gradient on Space Charge Distribution in Oil Impregnated Papers", High Voltage Engineering. vol. 37(4), 823-827(in Chinese).

[7] Chen X, Wang X, 2011, "Space Charge Accumulation and Stress Distortion in Polyethylene Under High DC Voltage and Temperature Gradient", Transactions of China Electrotechnical Society. vol. 26(3): 13-19(in Chinese).

[8] Chen X, Wang X, 2010, "Temperature Gradient Effect on Distortion of DC Electrical Field in Polyethylene", Journal of Xi'an Jiaotong University. vol. 44(4): 62-65, 124(in Chinese).

[9] Chen X, Wang X, 2010, "Space Charge Measurement in LDPE Films Under Temperature Gradient and DC Stress", IEEE Trans on DEI vol. 17(6): 1796-1805.

[10] Chen X, Wang X, 2010, "Effect of Temperature Gradient on Space Charge Waveform in Pulsed Electroacoustic Method", Acta Physica Sinica. vol. 59(10): 7327-7332(in Chinese).

[11] Alison J M and Hill R, 1994, "A model for bipolar charge transport, trapping and recombination in

degassed crosslinked polyethene", Appl Phys. vol. 27(6): 1291-9.

[12] Ie da M, 1987, "Carrier injection, space charge and electrical breakdown in insulation polymers", IEEE Trans on DEl. vol. 22(3): 261-267.

[13] Tanaka Y, Chen G, 2003, "Effect of additives on morphology and space charge accumulation in low density polyethylene", IEEE Trans on DEl. vol. 10(1): 148-154.

[14] Maeno Y, Hirai N, 2005, "Effects of crosslinking byproducts on space charge formation in crosslinked polyethylene", IEEE Trans on DEl. vol. 12(1): 90-97.

[15] Zhang B. 2004, "Design on the Insulation of the DC Cable", High Voltage Engineering. vol. 30(8): 20-21, 24(in Chinese).