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INFLUENCE OF THE SURFACE DEFECTS ON THE ABSORPTION/RESORPTION CURRENTS IN POLYETHYLENE INSULATIONS

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Defectele existente pe suprafețele sau în interiorul izolațiilor cablurilor de medie şi înaltă tensiune determină o intensificare a câmpului electric în vecinatatea acestora. Aceasta conduce la reducerea valorilor tensiunii de apariție a descărcărilor parțiale şi a arborescențelor electrice şi de apă, respectiv la intensificarea proceselor de degradare şi la reducerea duratei de viață.

În lucrarea de față este prezentat un studiu experimental cu privire la influența defectelor de suprafață asupra curenților de absorbție/resorbție şi a rezistivității de volum în polietilena de joasă densitate şi reticulată. Experimentele au fost efectuate pe eşantioane fără şi cu defecte cu diferite raze de curbură şi adâncimi, obținute prin presarea eşantioanelor cu hârtie abrazivă. O parte din eşantioane au fost supuse acțiunii câmpului electric în prezența unei soluții de NaCl (E = 4 kV/mm si f = 5 kHz), după care s-au măsurat curenții de absorbție/resorbție.

Rezultatele obținute arată că valorile curenților de absorbție/resorbție şi ale rezistivității de volum sunt influențate de densitatea şi dimensiunile defectelor.

The defects on the surfaces or inside of medium and high voltage cables' insulations determine a local increase of the electric field in their vicinities. This leads to the reduction of the partial discharges and electrical and water trees inception voltages, respectively to the intensification of the degradation processes and insulations lifetime reduction.

In this paper, an experimental study regarding the surface defects influence on the absorption/resorption currents and the volume resistivity of low density and crosslinked polyethylene is presented. The experiments were made on samples without and with defects having different curvature radii and depths, obtained by pressing the samples with abrasive paper. Some of the samples have been submitted to the alternative electric field stresses and in the presence of the NaCl solution (E = 4 kV/mm and f = 5 kHz) and the absorption/resorption currents values have been measured.

The results show that the absorption/resorption currents values and the average volume resistivity of the samples are influenced by the density and dimensions of the defects.

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1. Introduction

The defects represent one of the most important causes of premature degradation of power cables insulations. These can occur, during the cable fabrication (protrusions of semiconductor layers, cavities with gas or water, conductive impurities etc), but also during their operation.

The existence of voids has been emphasized using optical/electrical microscopy [1]… [3]. It has been shown that the concentration of voids *c* depends on the insulation cooling method during the fabrication process: $c_d = 10^6$ voids/mm^3 in the case of water cooling and $c_d = 10^3$ voids/mm^3 - in the case of nitrogen cooling. All defects determine a local increase of the electric field, leading to the reduction of partial discharge, electrical and water trees inception voltage values [4], [5].

In the dielectric of a plane capacitor whose plate has a protuberance of needle hyperbolic shape of the radius r_0, situated at the distance *a* from the other plate, the maximum value of the electric field strength $E_{\max}$ (at the needle tip) is given by the equation:

$$E_{\max} = \frac{2U_0\sqrt{1+r_0/a}}{r_0 \ln\left[\dfrac{2a+r_0+2a\sqrt{1+r_0/a}}{r_0}\right]}, \tag{1}$$

where U_0 is the applied voltage to the capacitor [6].

For $U_0 = 5$ kV, $r_0 = 10$ µm and $a = 1$ mm, it results $E_{max} = 166$ kV/mm. In the case of a needle with $r_0 = 5$ µm, this value rises up to the 300 kV/mm. By consequence, the existence of such defects leads to the important local intensifications of the electric field *E*, which produce intensifications of the conduction and electrical polarization process and apparition of some water trees at the lower values of the applied voltage [7].

On the other hand, the intensification of the conduction and electrical polarization process determines an increase of the absorption/resorption currents. The absorption current $i_1(t)$ appears when a step voltage U_0 is applied to a capacitor (with electrodes of surface *A* and the dielectric of thickness *g*, electrical conductivity σ and permittivity ε) (Fig. 1):

$$i_1(t) = i_i(t) + i_p(t) + i_{sc}(t) + i_c(t), \tag{2}$$

where $i_i(t)$ is the charging current of the capacitor with vacuum dielectric, $i_p(t)$ is

the polarization current, $i_{sc}(t)$ is the space charge current and $i_c(t)$ is the conduction current [8].

The current $i_i(t) = \varepsilon_0 A\partial E/\partial t$ is due to the charging of vacuum dielectric capacitor ($\varepsilon = \varepsilon_0$) and decreases to zero very quickly.

The component $i_p(t)$ is given by the dielectric polarization phenomena that consist in very small motions of a large number of attached charges. When the applied voltage is reduced to zero, these charges return to their initial positions.

The current $i_{sc}(t)$ corresponds to the movement of the existing space charge in the dielectric volume. This charge is generated during the technological processes (macromolecules' fractures etc.), degradation processes during operation (thermal, electric, mechanic and radiation etc.), charge injection at the surfaces of the metallic small radius curvature electrodes and protuberances etc. In a certain time depending on dielectric properties, the currents $i_p(t)$ and $i_{sc}(t)$ become zero.

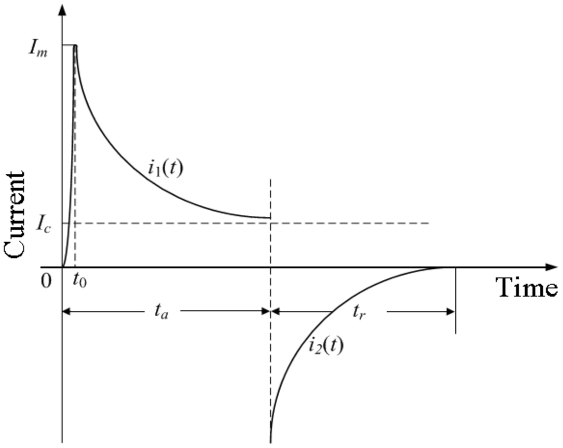


Fig. 1. Time variation of the current in a capacitor dielectric for a step applied voltage U_0 ($i_1(t)$) and after the supply disconnection and electrode short-circuit ($i_2(t)$)

Generally, the conduction current $i_c(t) = I_c = A\cdot\sigma\cdot U_0/g$ is given by the convection of electrons, ions and molecular ions. This component is unchanged in time (from the start moment of applied voltage until its turn off) and allows the determination of the electrical resistivity of dielectric.

When the voltage supply is turned off ($U_0 = 0$) and the plates of capacitor are connected in short-circuit, the discharge of the capacitor begins and the dielectric is passed by a transitory current $i_2(t)$ (Fig.1):

$$i_2(t) = i_d(t) + i_{dp}(t) + i'_{sc}(t)\,, \tag{3}$$

where $i_d(t)$ is the discharge current of the vacuum dielectric capacitor, $i_{dp}(t)$ – depolarization current and $i'_{sc}(t)$– the current that corresponds to the dielectric space charge.

In [9] and [10] the defects' influence on the water trees development was presented. In this paper, the influence of the surface defects of polyethylene insulations on the absorption/resorption currents is analyzed.

2. Experiments

The samples having the dimensions 100x100x0.5 mm^3 have been realized from low density polyethylene (LDPE) and crosslinked polyethylene (XLPE) pellets, supplied by Borealis Group (Belgium), by heat pressing (at the pressure p_m = 200 bar and the temperature T = 140 – 180 °C) [11].

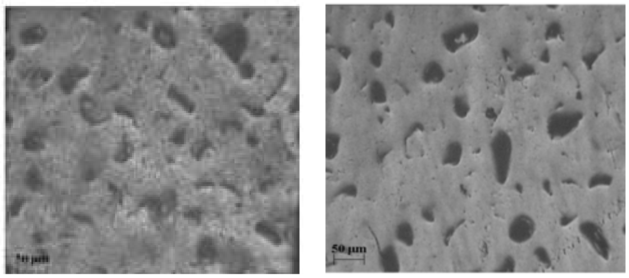
On one surface of the samples, superficial defects with different dimensions and were produced, by covering the samples with P240 abrasive paper and pressing them (for a time t_p = 2 minutes) with a Carver press (at the pressure p = 2…22 MPa). Many sample types were realized: A0 (without defects), A1 (p = 2 MPa), A2 (p = 11 MPa) and A3 (p = 22 MPa) - from LDPE - and B0 (without defects), B1 (p = 2 MPa), B2 (p = 11 MPa) and B3 (p = 22 MPa) - from XLPE.

Absorption/resorption currents have been measured on samples with and without defects for applied voltage U_0 = 1 kV, during t = 2 h, in the presence of a NaCl solution. The used experimental setup is presented in [11].

3. Results

3.1. Defects concentration

In Figure 2, the surface of a LDPE sample pressed at p = 22 MPa and for t_p = 2 minutes is presented. The defects areas and concentrations are depending on the abrasive paper granulation and the values of parameters p and t_p [9].



a) b)

Fig. 2. Surface of a LDPE (a) and XLPE (b) pressed sample (p = 22 MPa, t_p = 2 minutes)

To determine the defects concentration for each sample, 5 square regions (i) with 1 mm side were delimited (Fig. 3). In each region (i = 1...5) the defects number n_{di} was determined with the setup presented in Figure 4. Average number n_{dm} and average defects concentration c_{dm} were calculated with the equations:

$$n_{dm} = \frac{\sum_{i=1}^{5} n_{di}}{5} \tag{5}$$

$$c_{dm} = \frac{n_{dm}}{S}, \tag{6}$$

where $S = 1\ \text{mm}^2$ is the area of each region.

The average values of defects concentration c_{dm} for different values of pressure are presented in Table 1. The values of c_{dm} increase with the pressure, because the dimensions of abrasive paper grains are different. When the pressure increases, the grains with smaller radius (A, Fig.5) produce the defects, too.

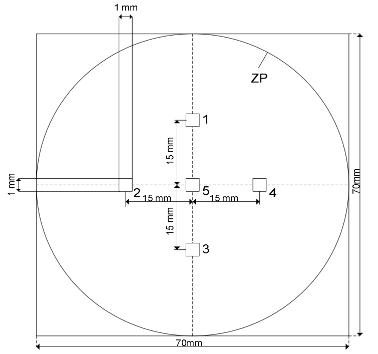


Fig. 3. Determination of superficial defects (ZP = pressed region).

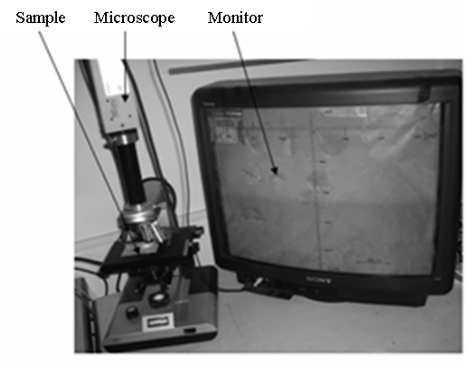


Fig. 4. Experimental setup for defects visualization.

Table 1

Values of the average defects concentration (c_{dm}), maximum absorption current ($I_{\max}$), conduction current (I_c) and volume resistivity (ρ_v) measured at 3500 s after the voltage application for LDPE samples without (A0) and with defects (A1, A2, A3)

Sample	p [MPa]	c_{dm} [def/mm^2]	$I_{\max}$ [pA]	I_c [pA]	ρ_v [Ωm]
A0	-	-	1.76	0.08	$8.3\cdot10^{16}$
A1	2	46.6	5.54	0.11	$7.85\cdot10^{16}$
A2	11	62.6	6.3	0.16	$3.29\cdot10^{16}$
A3	22	72	7.84	0.29	$1.79\cdot10^{16}$

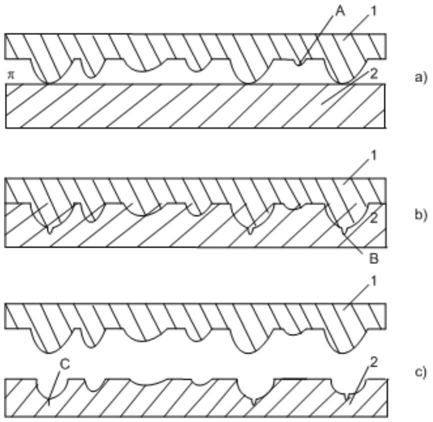


Fig. 5. Defects generation before (a), during (b) and after the pressing (c); 1 – Abrasive paper, 2 – Sample

3.2. Absorption/resorption currents

3.2.1. Unaged samples

In Figure 6 (curves 1 and 2), the absorption/resorption currents variations obtained on LDPE samples without (A0 samples) and with (A3 samples) defects are presented. The shapes of absorption/resorption currents curves are not changed by the production of defects, but the maximum values of the currents ($I_{\max}$) increase and the resistivity decrease in the case of samples with defects (Table 1 and Fig. 7, curves 1 and 2).

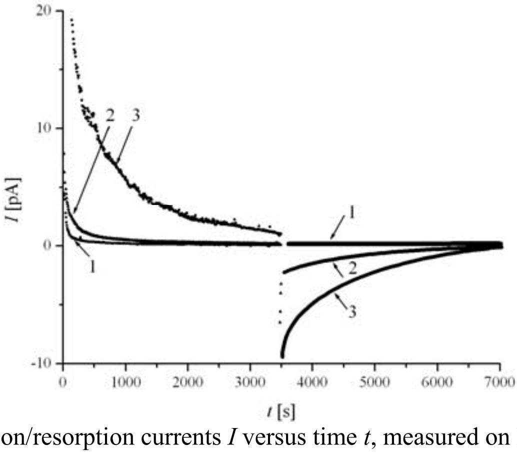


Fig. 6. Absorption/resorption currents I versus time t, measured on LDPE samples A0 (1), A3 (2) and A3 aged forτ = 48 h (3) (U_a = 2 kV, f_c = 5 kHz, c = 0.1 mol/l, U_0 = 1 kV)

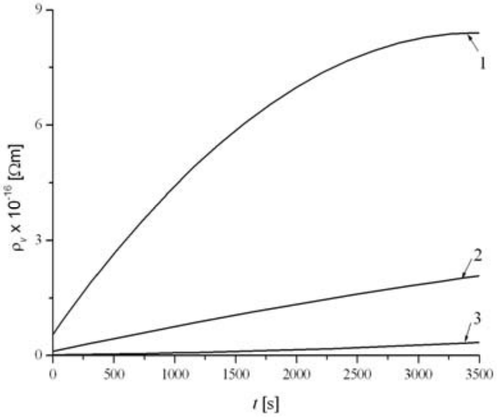


Fig. 7. Volume resistivity ρ_v versus time t, measured on LDPE samples: (1) A0, (2) A3 and A3 aged for $\tau = 48$ h (3) ($U_a = 2$ kV, $f_c = 5$ kHz, $c = 0.1$ mol/l, $U_0 = 1$ kV)

In the case of XLPE samples, the same variations of the currents and volume resistivity are obtained (Table 2 and Figs. 8 and 9). This is due to the break (by pressing) of the macromolecules chains and by the new space charge generation.

On the other hand, the increase of the pressure leads to the increase of the small radius defects concentration (A, Fig. 5) and even to the apparition of microcracks in the samples (B and C, Fig. 5). Consequently, the maximum electric field intensity values increase and, the polarization and space charge components of absorption currents increase, too.

Table 2

Values of the average defects concentration (c_{dm}), maximum absorption current ($I_{\max}$), conduction current (I_c) and volume resistivity (ρ_v) measured at 3500 s after the voltage application

Sample	p [MPa]	c_{dm} [def/mm^2]	$I_{\max}$ [pA]	I_c [pA]	ρ_v [Ωm]
B0	-	-	1.6	0.006	$2.7 \cdot 10^{17}$
B3	22	66.2	6.89	0.1	$0.48 \cdot 10^{17}$

3.2.2. Aged samples

Groups of five measure cells containing A3 LDPE samples [11] with superficial defects realized with P240 abrasive paper ($t_p = 2$ min, $p = 22$ MPa) were submitted, for $\tau = 48$ hours, to electric field stress ($U_a = 2$ kV, $f_c = 5$ kHz) in the presence of NaCl water solution ($c = 0.1$ mol/l).

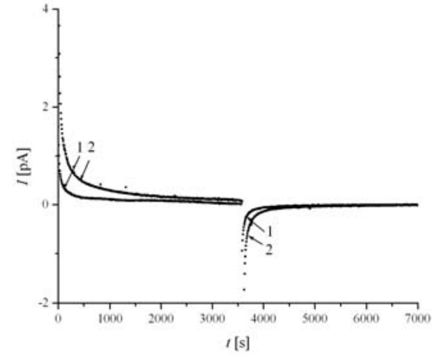


Fig. 8. Absorption/resorption currents *I* versus time *t*, measured on XLPE samples B0 (1) and B3 (2) (U_0 = 1 kV).

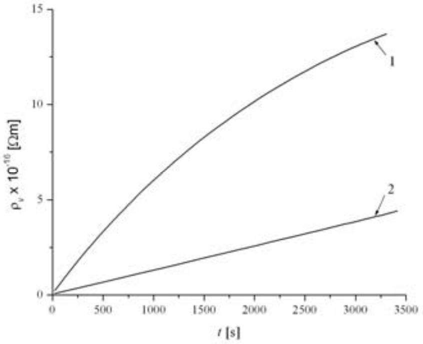


Fig. 9. Volume resistivity ρ_v versus time *t*, measured on XLPE samples B0 (1) and B3 (2) (U_0 = 1 kV).

The variation of absorption/resorption currents measured at U_0 = 1 kV (in unaged (A3) and aged (A3a) samples) as a function of time is presented in Figure 6, curve 3. The current curves shapes are not modified by the ageing process, but maximum values of absorption/resorption currents increase and volume resistivity values decrease, respectively (Table 3 and Fig.7, curve 3). The increase of absorption/resorption currents values can be explained by water and Na^+ and Cl^- ions penetration in the samples, phenomenon which leads to the increase of polarization i_p and space charge i_{sc} components of the currents [11].

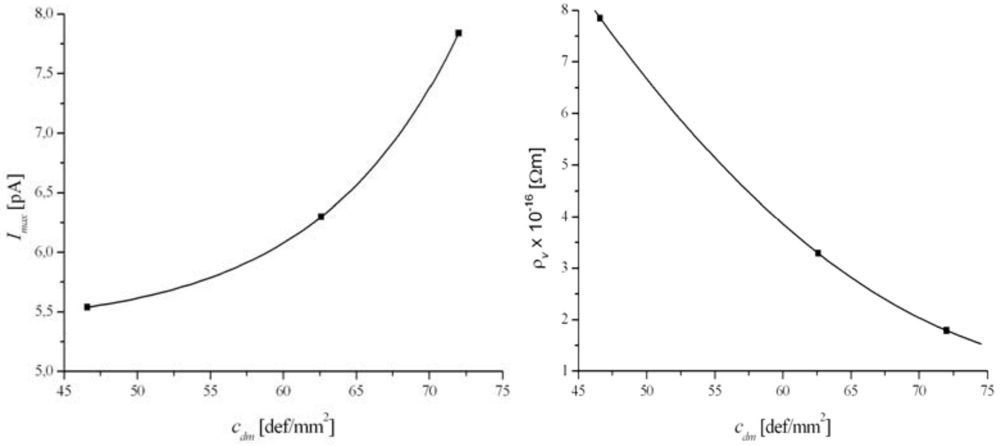
The NaCl solution fills the superficial defects, leading to the formation of "water needles" with high conductivity. Due to the electric field produced by water needles, the water molecules and the ions from the samples lead to the water trees formation. As a consequence, the electric dipoles and the charge carriers' concentrations in the treed regions of the samples increase.

The variations of maximum values of absorption/resorption currents $I_{\max}$ and volume resistivity ρ_v with the defects concentration are presented in Figure 10. It can be seen that, for aged LDPE samples, $I_{\max}$ values increase and the resistivity values ρ_v decrease with the increase of samples defects concentration c_{dm}.

Table 3

Values of the average defects concentration (c_{dm}), maximum absorption current ($I_{\max}$), conduction current (I_c), polarization index (k_p) and volume resistivity (ρ_v) measured at 3500 s after the voltage application for LDPE samples unaged (A3) and aged (A3a)

Sample	p [MPa]	c_{dm} [def/mm^2]	$I_{\max}$ [pA]	I_c [pA]	k_p	ρ_v [Ωm]
A3	22	72	7.84	0.29	4.26	$1.79 \cdot 10^{16}$
A3a	22	72	65.6	1.01	3.17	$3.1 \cdot 10^{15}$



(a) (b)

Fig.10. Variation of $I_{\max}$ (a) and ρ_v (b) with c_{dm} on unaged LDPE samples (P240, t_p = 2 min, U_0 = 1 k V).

These behaviors are due to the increase - with the increase of the defects concentration - of the contact surface between the electrolyte and the samples (Fig. 5). On the other hand, due to the formation of defects with smaller radii, many regions with high electric field appear (Eq. (1)). These phenomena make easy the ions and water molecules penetration inside the samples, the increase of i_p and i_{sc} components of absorption currents and the decrease of the electrical resistivity, respectively.

The electrical ageing in the presence of water determines a reduction of polarization index values k_p (Table 3), but these values are higher than the admissible limit accepted value k_{pl} ($k_{pl} = 1.5$) for a normally operation of electrical equipments [7] ($k_p = i_1(60)/i_1(600)$ – currents measured after 60, respectively 600 seconds). This reduction is due to the increase of polarization (i_p) and space charge (i_{sc}) components of absorption currents (by Na^+ and Cl^- ions penetration) and becomes very important for the samples submitted to electric field stress in the presence of water for long time, respectively, for samples with big water trees.

4. Conclusions

Production of superficial defects determines an increase of local values of the electric field. Consequently, the maximum values of absorption/resorption currents increase and the volume resistivity of the sample decrease.

The defects concentration has smaller values in XLPE samples than in LDPE. Consequently, the absorption/resorption currents have smaller values in XLPE as in LDPE.

Samples electrical ageing in the presence of water leads to the increase of absorption and resorption currents values and to the decrease of volume resistivity, too.

The increase of the defects (by pressing) and ions (by water trees formation) concentrations lead to the decrease of electrical resistivity of all tested samples.

The polarization index values decrease in the case of electrical aged samples. This is due to water and Na^+ and Cl^- ions penetration, water trees development, respectively.

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