

**DIELECTRIC PROPERTIES OF POLYETHYLENE SUBJECTED TO  
ELECTRIC FIELD IN THE PRESENCE OF WATER**

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**Abstract**

*One of the most important characteristic of polyethylene used for power cables insulation is the low water permeability. Experimentally, it was shown that, under the action of a time variable electric field, water can penetrate inside the polyethylene insulation, causing the appearance the so called water trees.*

*In this paper, an experimental study regarding the modification of dielectric properties of polyethylene subjected to the electric field action in the presence of water is presented. Experiments on two sample types (needle-plane and flat samples), made of low density polyethylene were made. In order to reduce the test duration, electric fields (over 4 kV/mm) and frequency (3-5 kHz) superior to those from service were used.*

*For some ageing time values the water trees dimensions, electrical strength in power frequencies electric fields (50 Hz) and permittivity and conductivity components (for frequencies between 1 mHz and 1 MHz) were determined. The results show that, water trees development leads to the electrical strength decrease and permittivity, conductivity and loss factor increase. Finally, it is shown that the dielectric properties variation are most important at lower frequencies and the water penetration under the electric field action facilitates the premature breakdown of cable insulations.*

**Key words:** polyethylene, water trees, dielectric spectroscopy, permittivity, electrical conductivity

## 1. INTRODUCTION

Replacement of paper and oil power cables insulations with the polyethylene ones (low and high density) represented a true revolution in electric power transmission. Indeed, polyethylene is easy to manufacture, dielectric properties are very good, low water permeability (almost 0) and maintenance costs. Due to low water permeability of polyethylene, many medium voltage cables were not provided with polyvinyl chloride jacket (with low water permeability) (Bartnikas and Srivastava, 2003).

In the 70's was shown that, if the materials are subjected to an electric field, water (which contains always salts) penetrates inside them, leading to the initiation of so called "water trees" (diffuse areas made from micro-cavities filled with water connected by very thin channels) (Dissado and Fothergill, 1992). Water trees development is facilitated by the existence of conductor, screen and insulation defects (Steennis and Kreuger, 1990) and contributes to the local enhancement of the electric field (Notingher et al., 1995, Notingher et al., 2009) and to the worsening of dielectric properties (increase of permittivity and conductivity (Nakamura and Kawai, 2001), increase of loss factor (Kuschel et al., 1995) and to a decrease of the insulations breakdown voltage (Hai, 2006, Radu, 1997).

Dielectric properties modifications were shown, especially, in measurements made in DC (Ciuprina et al., 1997, Stancu, 2008) at power and/or high frequencies (Steennis and Dissado, 1990) and less at

lower frequencies (Medjoub et al., 2008, Parpal et al., 2007). Or, the presence and the volumes of the treed areas can be highlighted at low frequencies, as a consequence of direct dependency between permittivity, conductivity and loss factor, water-PE interface area and average ions concentration inside insulations.

In this paper, different measurements are made, on one hand, in DC (absorption/resorption currents, conductivity) and, on the other hand, in AC (for frequencies between  $1.5 \cdot 10^{-3}$  and  $10^4$  Hz), and a direct relationship between the complex permittivity and electrical conductivity components and water trees dimensions is obtained.

## 2. ABSORPTION/RESORPTION CURRENTS

When a voltage step  $U_0$  is applied to the plates of surface  $A$  of a non ideal flat capacitor (containing a dielectric of thickness  $d$ , of conductivity  $\sigma \neq 0$  and of permittivity  $\epsilon$ ), the capacitor absorbs a time-dependent current of intensity  $i_1(t)$ , which is the sum of four components (Fig. 1):

$$i_1(t) = i_i(t) + i_p(t) + i_{ss}(t) + i_c(t), \quad (1)$$

where  $i_i(t)$  is the intensity of the current corresponding to the charging of the capacitor with vacuum dielectric,  $i_p(t)$  is the intensity of the polarization current,  $i_{ss}(t)$  is the intensity of the current associated to space charge,  $i_c(t)$  is the intensity of the conduction current.

The component  $i_i(t) = \epsilon_0 A \partial E / \partial t$  corresponds to the charging current of the capacitor without dielectric ( $\epsilon = \epsilon_0$ ), and reaches zero almost instantly. Consequently, the raising portion of the  $i_1(t)$  curve (Fig. 1) is not recorded in usual measurements.

The component  $i_p(t)$  corresponds to the polarization of the dielectric contained by the capacitor, i.e. to very localized displacements of a significant number of bounded charges (particles or particle groups belonging to the molecules of the dielectric), which return to their initial positions when the voltage is switched off. The polarization current  $i_p(t)$  comes down to zero progressively after the application of the dc voltage  $U_0$ .

The component  $i_{ss}(t)$  corresponds to the space charge from the dielectric bulk, which is generated during manufacturing (broken molecules a.s.o.) and during service (thermal, electrical, mechanical, irradiative degradation a.s.o.), by carrier injection at sharp conducting edges a.s.o. The charge carriers are trapped in deep or shallow traps and can move more or less within the dielectric (some of them being able to reach the electrodes).

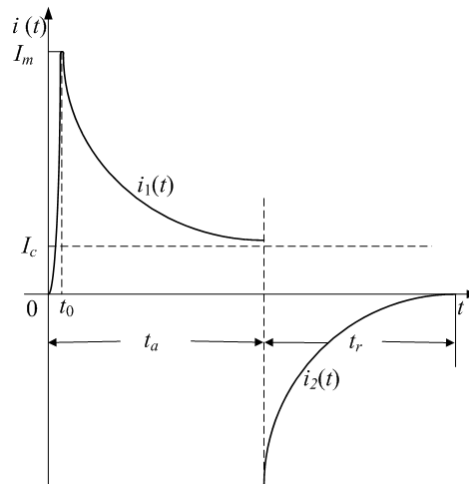


**Fig. 1.** Current evolution  $i(t)$  versus time ( $t$ ), after application of a voltage step ( $i_1(t)$ ) and after voltage switch off ( $i_2(t)$ ).

As these carriers either got re-trapped (mostly at interfaces between homogeneous regions of the dielectric) or reach the electrodes (thus decreasing their concentration), the current  $i_{ss}(t)$  drops to zero after a certain time.

The conduction current  $i_c(t) = I_c = A \cdot \sigma \cdot U_0 / d$  (Fig. 1) is due to electron, hole and ion convection. The concentration of each carrier species depends, among others, on the chemical nature and on the physical structure of the dielectric, which leads either to major electronic or ionic conduction (Bartnikas and Srivastava, 2003). This component of the measured current is time-independent (from voltage switch on to voltage switch off) and allows determining experimentally the electric conductivity (or resistivity) of the dielectric.

In the case of samples with high water content (as water treed samples), an index polarization is defined (Notingham et al., 2009):

$$k_p = \frac{i_{160}}{i_{1600}}, \quad (2)$$

where  $i_{160}$  is the value of  $i_1(t)$  measured after  $t = 60$  s and  $i_{1600}$  – the value of  $i_1(t)$  measured after  $t = 600$  s after the application of the voltage  $U_0$ .

### 3. DIELECTRIC SPECTROSCOPY

Dielectric spectroscopy method consists in the application of an ac voltage to the sample placed between two armatures:

$$u(t) = U_1 \cos \omega t = \text{Re}(\underline{U} \exp(j\omega t)) \quad (3)$$

where  $U_1$  represents the voltage amplitude and  $\omega = 2\pi f$  – the angular frequency of electric field. Application of  $u(t)$  causes apparition of a current  $i(t)$  at the same frequency. In addition there will generally be a phase shift between current and voltage described by the phase  $\varphi$ :

$$i(t) = I_1(\cos \omega t + \varphi) = \text{Re}(\underline{I} \exp(j\omega t) + \varphi) \quad (4)$$

where  $\underline{U} = U' + jU''$ ,  $U' = U_1$ ,  $U'' = 0$ ,  $\underline{I} = I' + jI''$ ,  $I' = I_1 \cos \varphi$ ,  $I'' = I_1 \sin \varphi$  and  $j = \sqrt{-1}$ .

The impedance  $\underline{Z}(\omega)$  is the ratio between voltage and current:

$$\underline{Z}(\omega) = \frac{\underline{U}}{\underline{I}}. \quad (5)$$

Taking the impedance  $\underline{Z}(\omega)$  as a pure capacitive one,

$$\underline{Z}(\omega) = \frac{1}{j\omega \epsilon_0 \epsilon_r C} \quad (6)$$

the relative complex permittivity  $\underline{\epsilon}_r = \epsilon_r' - j\epsilon_r''$  is computed, its components  $\epsilon_r'$  and  $\epsilon_r''$  and loss factor  $\text{tg} \delta = \epsilon_r''(\omega) / \epsilon_r'(\omega)$ . In relation (6)  $C$  represents the condenser capacity having as dielectric the studied sample.

## 4. EXPERIMENTS

### 4.1. Samples. Setups

The experiments were made on flat samples having the dimensions  $100 \times 1000.5 \text{ mm}^3$ , made from LDPE pellets by pressmoulding at  $p = 200 \text{ bar}$  and  $T = 145 \text{ }^\circ\text{C}$ . In the samples, water trees (with different lengths  $l_a$ ) were developed in an accelerated manner.

To measure the dimensions and the concentrations of water trees, from each treed sample five slices with  $g = 0.2 \text{ mm}$  thickness were taken, the dimensions and the concentration of trees from each slice were measured and the average dimensions were computed using the expressions:

$$\begin{aligned} L_m &= \sum_{i=1}^5 L_i \\ D_m &= \sum_{i=1}^5 D_i \\ c_{wtm} &= \sum_{i=1}^5 c_{wti} \end{aligned} \quad (7)$$

where  $L_i$ ,  $D_i$  and respectively  $c_{wti}$  – represent the length, diameter and trees concentration corresponding to each slice  $i$ .

The setup used for water trees development is presented in Figure 2 (Stancu, 2008). The applied voltage was  $U = 2$  kV, the frequency  $f = 5$  kHz, the NaCl concentration in water  $c = 0.1$  mol/l, and the duration of voltage application  $\tau = 0...144$  h. The experimental setup presented in Figure 3 was used for measuring the dimensions and concentrations of water trees (Notingher et al., 2009).

The absorption/resorption currents were measured with the setup presented in Figure 4 (for  $U_0 = 1000$  V) and for measurement of permittivity components ( $\epsilon_r'$  and  $\epsilon_r''$ ), complex conductivity ( $\sigma'$  and  $\sigma''$ ) and loss factor ( $\tan \delta$ ) a NOVOCONTROL dielectric spectrometer for frequencies between  $1.5 \cdot 10^{-3}$  si  $10^4$  Hz was used (Fig. 5).

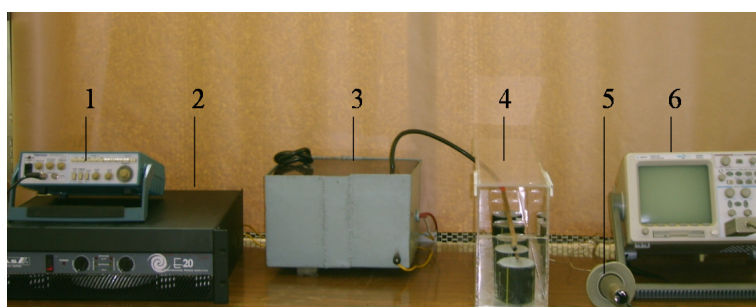


**Fig. 2.** Setup used for water trees development:

1 – Generator , 2 – Amplifier, 3 – Transformer,  
4 – Sample holder, 5 – Probe, 6 – HP Scope.

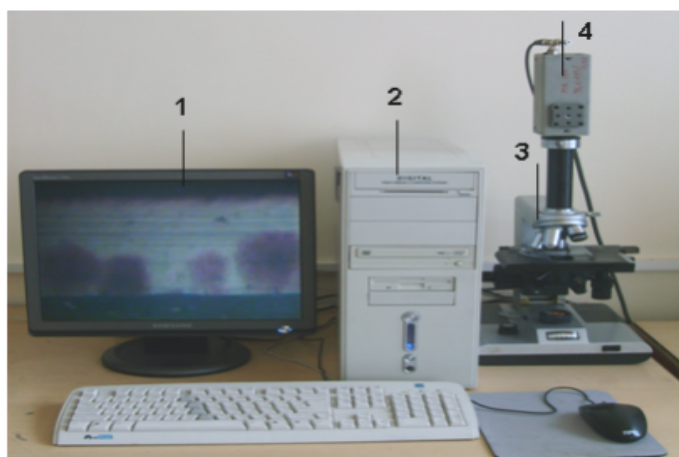


**Fig. 3.** Setup used for measuring the dimensions

of the water trees: (1) – Monitor, (2) – PC,  
(3) – Microscope, (4) – Camera.

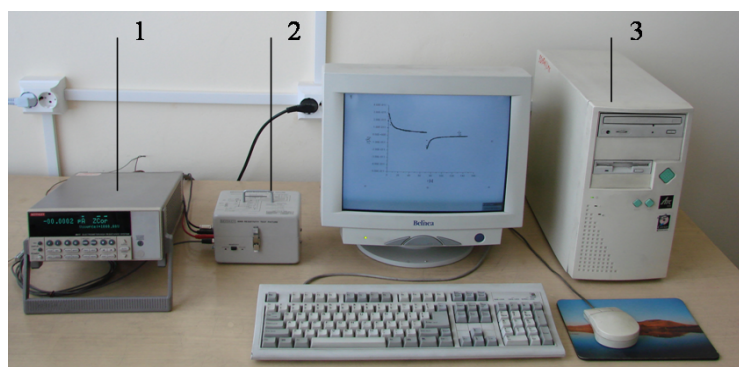


**Fig. 4.** Setup used for measurement of absorption/resorption currents:  
1 – Keithley 6517, 2 – 8009 Keithley cell, 3 – PC.

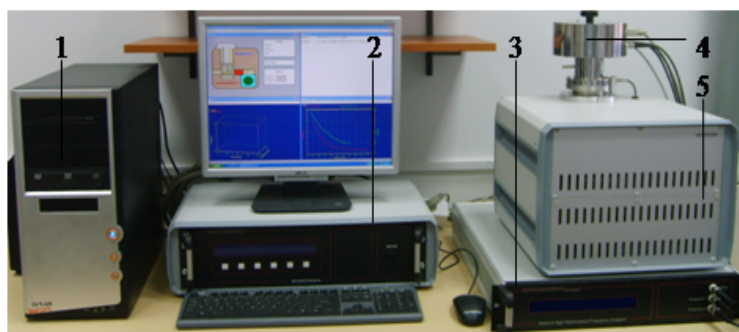


**Fig. 5.** NOVOCONTROL dielectric spectrometer for impedance measurement: 1 – PC, 2 – Central unit, 3 – Control unit, 4 – Sample cell, 5 – Temperature control system.

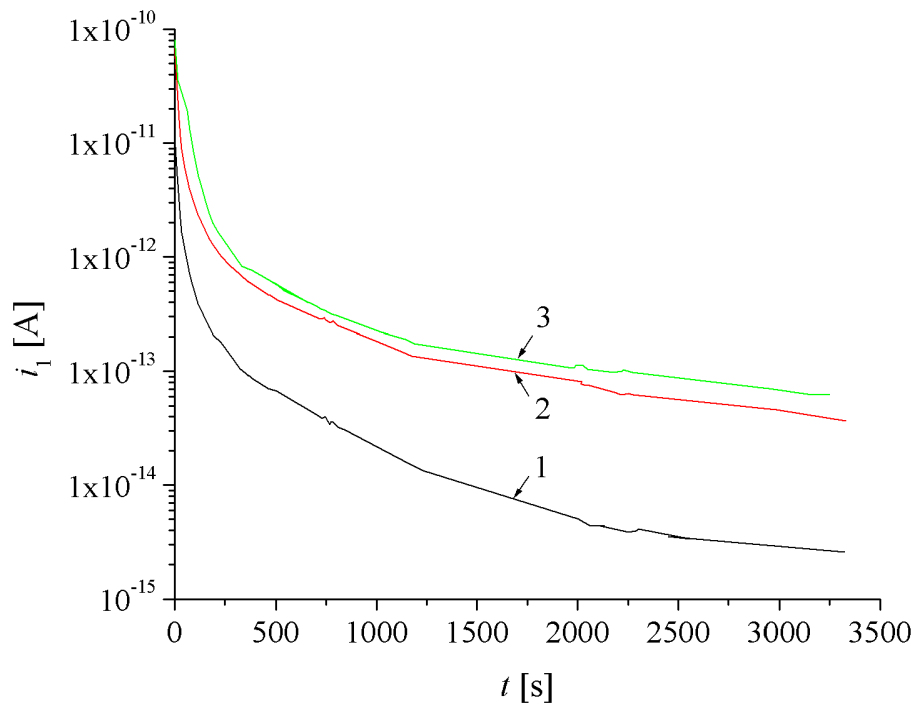
## 5. RESULTS

In Figure 6 the variation of absorption currents in time measured on virgin LDPE samples and subjected to electric field in the presence of water during  $\tau = 24$  and respectively 48 h are presented. It can be seen that the electric field and water presence lead to the increase of absorption currents values and this effect is more important when  $\tau$  is higher (Fig. 6, curve 2).

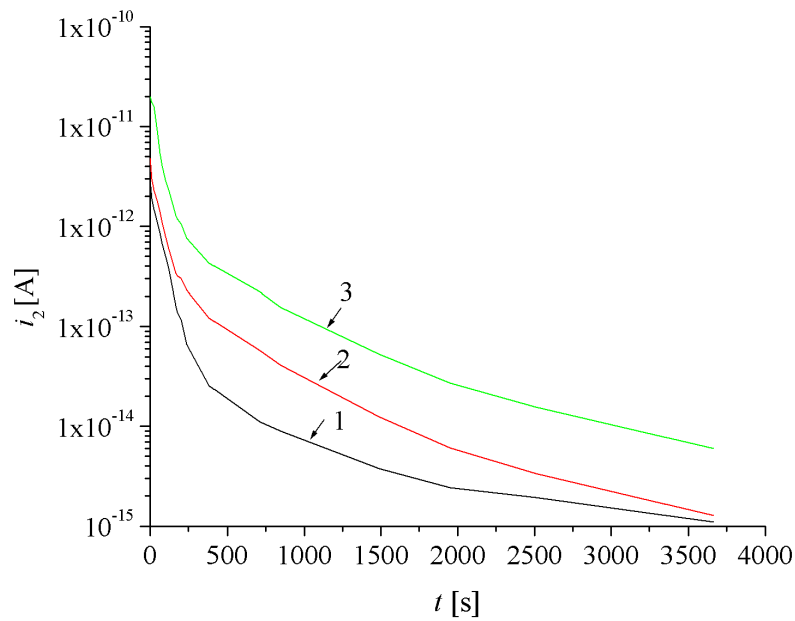
On the other hand, increasing the stress time  $\tau$ , the average dimensions ( $L_m$  and  $D_m$ ) and concentrations of water trees increase also (Table 1).

**Table 1.** Maximum values of absorption currents and of dimensions and concentrations of water trees.

| <i>Stress time <math>\tau</math> [h]</i> | <i><math>i_{lmax}</math><br/>[pA]</i> | <i><math>L_m</math><br/>[<math>\mu m</math>]</i> | <i><math>D_m</math><br/>[<math>\mu m</math>]</i> | <i><math>c_{wtm}</math><br/>[wt/mm<sup>2</sup>]</i> |
|------------------------------------------|---------------------------------------|--------------------------------------------------|--------------------------------------------------|-----------------------------------------------------|
| 0                                        | 2                                     | -                                                | -                                                | -                                                   |
| 24                                       | 6                                     | 157                                              | 145                                              | 2                                                   |
| 48                                       | 20                                    | 212                                              | 184                                              | 8                                                   |



a)



b)

**Fig. 6.** Variation of absorption  $i_1(t)$  (a) and resorption currents  $i_2(t)$  (b) in time for virgin LDPE samples (1) and electrical aged during  $\tau = 24$  h (2) and  $\tau = 48$  h (3).

**Table 2.** Index polarisation values  $k_p$   
for different ageing time  $\tau$

| <i>Strees time</i><br>$\tau [h]$ | $k_p$ |
|----------------------------------|-------|
| 0                                | 1.1   |
| 24                               | 2.5   |
| 48                               | 3.3   |

This enhancement of absorption currents (especially, the maximum values of  $i_{1max}$ , Table 1) and trees dimensions can be explained by water and  $Na^+$  si  $Cl^-$  ions penetration in polyethylene, which leads to the increase of polarisation and space charge components of absorption currents (Meyer, 1983, Notingher et al., 2007).

Index polarization  $k_p$  for different values of ageing time  $\tau$  is presented in Table 2. It can be seen that, with the increase of  $\tau$ , the values of  $k_p$  increase, which confirms the increase of water content inside the samples (Busoi et al., 2008).

Variations of dc electric conductivity  $\sigma_0$  in time on untreed and treed samples are presented in Figure 7. Their values were computed with the expression:

$$\sigma_0(t) = \frac{i_1(t) - i_2(t)}{U_0} \cdot \frac{d}{A} \quad (8)$$

where  $d$  is the sample thickness and  $A = \frac{\pi D^2}{4}$  - upper armature area of sample cell (with diameter  $D$ ).

The increase of ageing time  $\tau$ , respectively water trees development leads to the enhancement of electric conductivity (with almost one size order), which confirms the conductive nature of water trees (Dissado, Fothergill, 1992).

Variation of real permittivity component  $\epsilon_r'$  with frequency on virgin LDPE and treed samples is presented in Figure 8. The increase of ageing time  $\tau$  respectively water trees dimensions (Table 1) leads to the enhancement of  $\epsilon_r'$ . This increase is more important in low frequency range and is due to the increase of dipoles concentration as a consequence of water penetration and interfacial polarisation (by ionic charge dissociation at polyethylene-water interfaces).

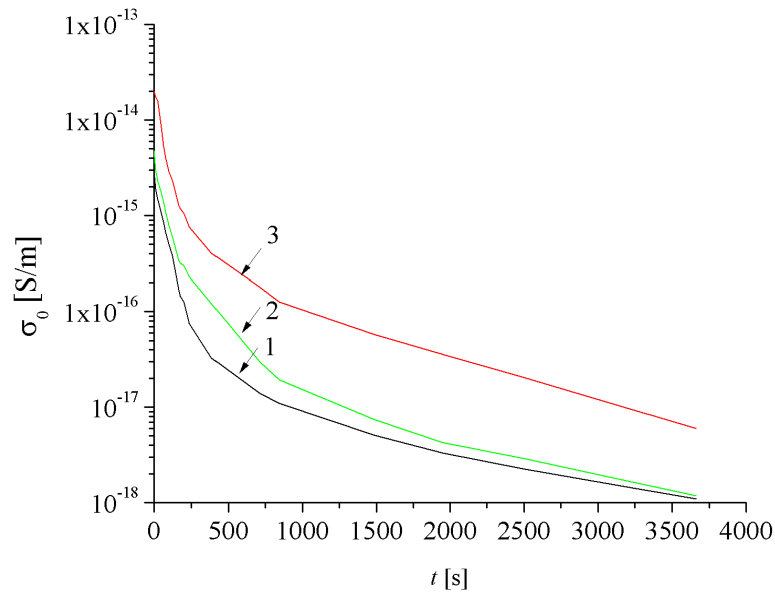


**Fig. 7.** Conductivity dependence  $\sigma_0$  on time  $t$  of LDPE samples for different values of  $\tau$  : 0 h (1), 24 h (2) and 48 h (3).

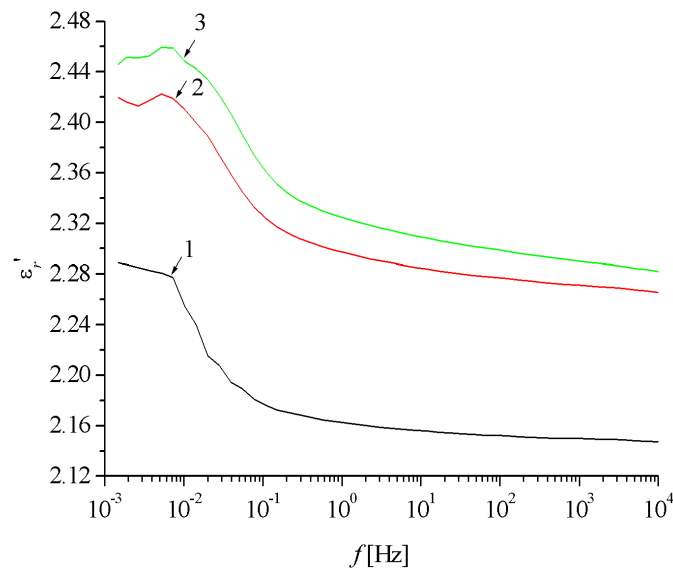


**Fig. 8.** Variation of real component of permittivity  $\epsilon_r'$  with frequency  $f$  for virgin LDPE samples (1) and electrical aged during  $\tau = 48$  h (2) and 144 h (3).

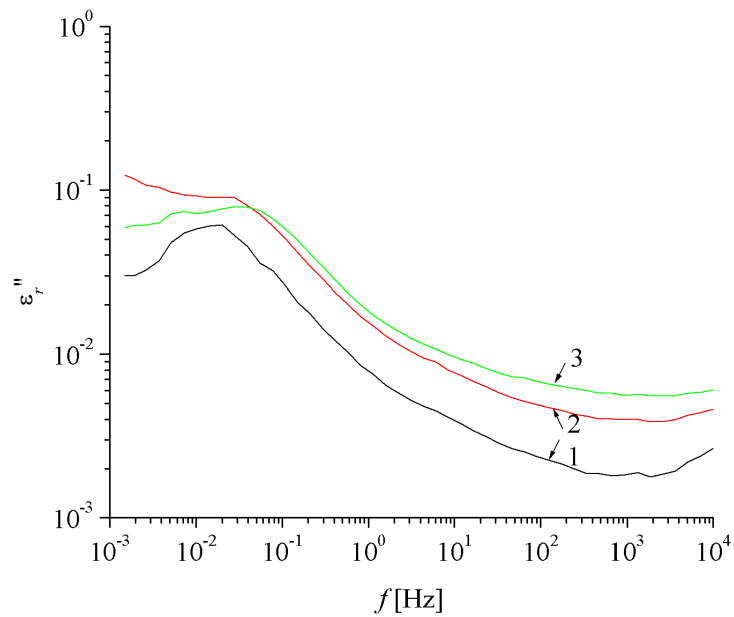


**Fig. 9.** Variation of imaginary component of permittivity  $\epsilon_r''$  with frequency  $f$  for virgin LDPE samples (1) and electrical aged during  $\tau = 48$  h (2) and 144 h (3).

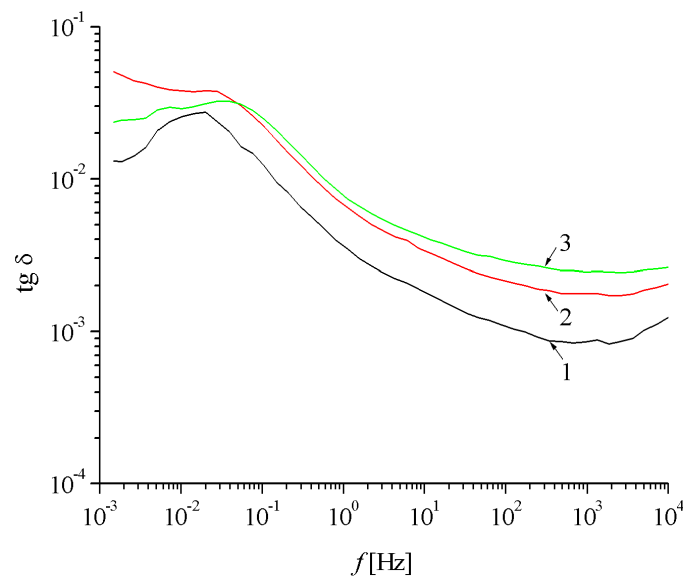


**Fig. 10.** Variation of loss factor  $\text{tg } \delta$  with frequency  $f$  for virgin (1) and electrical aged LDPE samples during  $\tau = 48$  h (2) and 144 h (3).

Figures 9 and 10 present variations of imaginary component of permittivity  $\epsilon_r''$  and loss factor  $\tan \delta$  with frequency for virgin and treed samples.

An increase of  $\epsilon_r''$  and  $\tan \delta$  with decrease of frequency, especially in low frequency range ( $10^{-2}$  Hz) is observed. Also, a peak apparition can be seen (Jonscher, 1996). This can be explained by the dispersion phenomenon at low frequency (Hong et al., 2009), by increase of ions mobilities, ions displacement inside and between clusters due to water penetration (Dissado et al., 1984) a.s.o. On the other hand,  $\epsilon_r''$  si  $\tan \delta$  have higher values in treed samples for higher ageing time (curves 2 and 3, Figs. 9 and 10). This is due to interfacial polarisation and ionic conduction enhancement, following to water penetration inside the samples.

In Figures 11 and 12 the variations of real and imaginary component of electric conductivity  $\sigma'$  and  $\sigma''$  with frequency  $f$  in virgin and electrical aged samples in the presence of electric field and water are presented. An increase of those values in treed samples is observed, according to the results presented in Figure 1 (obtained for dc conductivity).

The real component of complex conductivity ( $\sigma'(\omega) = \sigma'(f)$ ) can be written as : a constant or dc component ( $\sigma_0$ ) and other dependent of frequency or ac component ( $\sigma_a(f)$ ), respectively :

$$\sigma'(f) = \sigma_0 + \sigma_a(f). \quad (9)$$

In the case of frequencies higher than  $10^{-3}$  Hz,  $\sigma_a \gg \sigma_0$  and  $\sigma'(f)$  can be determined using the empirical relation:

$$\sigma'(f) = af^n, \quad (10)$$

where  $a$  and  $n$  are material constants.

For very low frequency values, respectively if  $f \rightarrow 0$ , then  $\sigma_a \rightarrow 0$  and  $\sigma'(f) \rightarrow \sigma_0$ . Also, relation (9) can be written as:

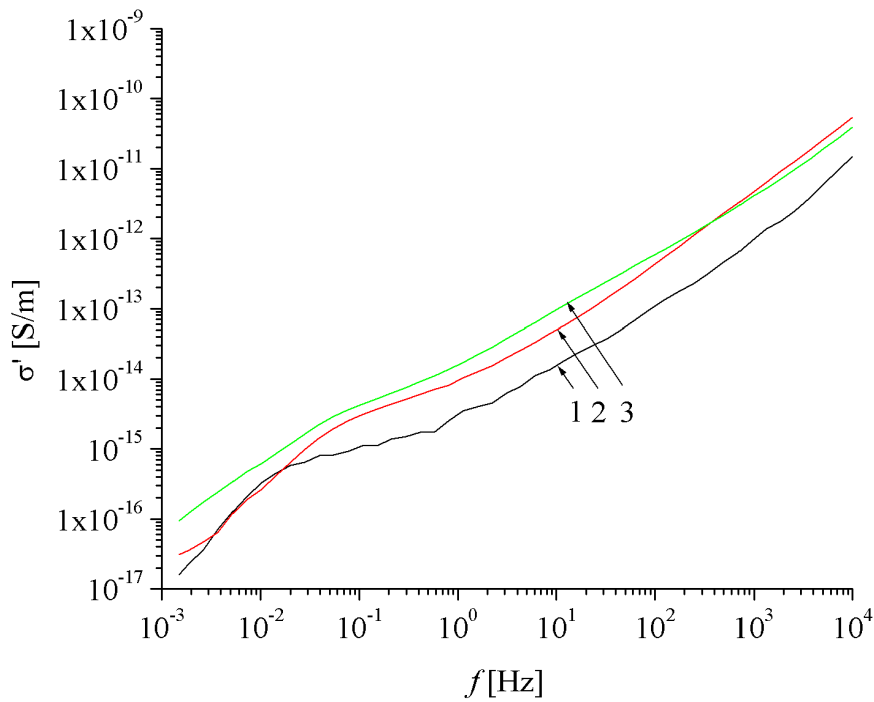


**Fig. 11.** Variation of real component of conductivity  $\sigma'$  with frequency  $f$  for virgin LDPE samples (1) and electrical aged during  $\tau = 48$  h (2) and  $\tau = 144$  h (3).

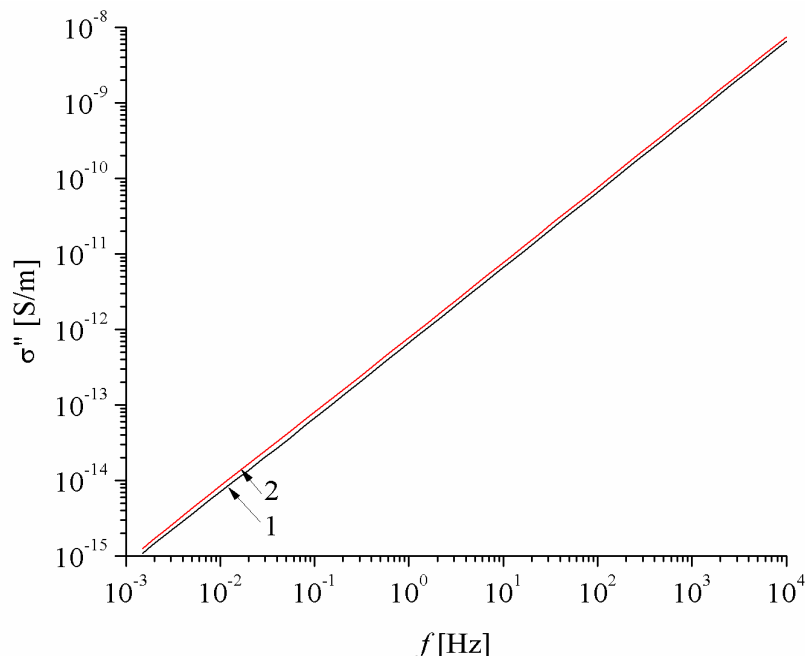


**Fig. 12.** Variation of imaginary component of electric conductivity  $\sigma''$  with frequency  $f$  for virgin LDPE samples (1) and electrical aged during  $\tau = 48$  h (2).

$$\sigma'(f) = \sigma_0 + af^n. \quad (11)$$

In the case of electrically aged polyethylene samples in the presence of salt water for 48 h,  $\sigma'(f)$  can be written as:

$$\sigma'(f) = \sigma_0 + af^{0.86}. \quad (12)$$

It must be remarked that the increase of conductivities, in dc, but also in ac, leads to a decrease in the breakdown strength, respectively the breakdown occurs at lower voltages (Radu, 1997).

## 6. CONCLUSIONS

The presence of time variable electric field and water which contain ions of some salts ((NaCl, CuSO<sub>4</sub>, AgNO<sub>3</sub>) leads to water penetration inside the samples and water trees formation.

Dimensions and water trees concentrations depend on the ageing time  $\tau$ .

Increase of the ageing time  $\tau$  determines a decrease of dielectric properties of samples, respectively an increase of absorption/resorption currents, complex permittivity components  $\epsilon_r'$  si  $\epsilon_r''$ , loss factor  $\text{tg}\delta$ , DC conductivity ( $\sigma_0$ ) and AC complex conductivity components.

Increase of electric conductivities ( $\sigma_0$  and  $\sigma_a$ ) and dielectric losses ( $\epsilon_r''$  and  $\text{tg}\delta$ ) lead to the decrease of breakdown strength in samples and in medium voltage power cables polyethylene insulations.

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