WATER TREES INFLUENCE ON THE POWER CABLES INSULATION BREAKDOWN DURING OPERATION

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Abstract: *In this paper a study regarding the influence of water trees on the values and repartition of the electric field in power cables insulations is presented. Experiments were carried out on flat samples under the circular crown shape, taken from some high voltage cables insulations. In these samples water trees were developed and thermal parameters, water content from treed areas, dimensions and water trees density were measured. Using the dimensions of water trees, water content in treed areas and thermal properties, the electric field computation was done. The results show that the electric field values are strongly modified due to the development of water trees.*

Keywords: *polyethylene, cables insulation, water trees, ionic space charge, electric field computation.*

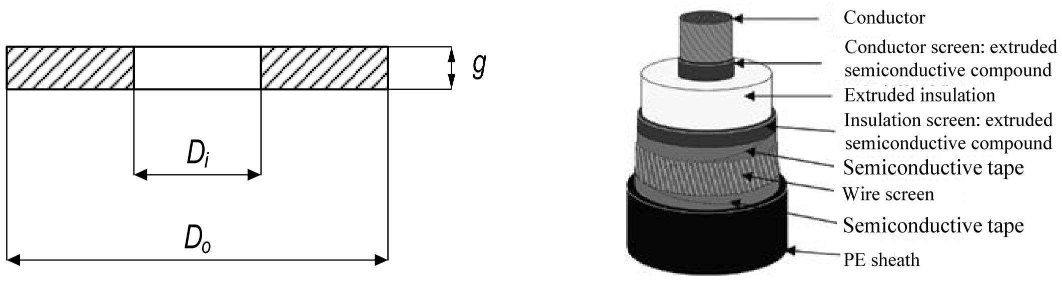
1. INTRODUCTION

During service, the insulation of power cables, are submitted to electrical, thermal, mechanical, environmental stresses etc. that contribute to the initiation and development of certain degradation processes. Under the influence of the electrical field and in the presence of water, in polymeric insulations water trees develop [1-2].

Water trees are water filled micro-cavities linked by very thin channels (of microns order). They appear in regions with intense electrical fields, like the interface insulation/conductor (vented trees) or in the vicinity of cavities and impurities (bow tie trees) and start to develop from the areas where the electrical field is more intense towards the areas where the electrical field is less intense [2]. Studies made on low density polyethylene as well as on cross-linked polyethylene highlight the existence of positive and negative ions, both inside and outside the water trees, thus constituting the ionic space charge [3-5]. The space charge plays an important role in the degradation process by locally intensification the electrical field, facilitating the growth of water trees and causing the appearance of electrical trees, the preliminary phase in insulation breakdown [6-7].

Researches made so far show that the presence of water trees lead to the worsening of the insulations electrical properties where it develop: the decrease of the inception voltage of partial discharges [7], the increase of the water content [8], the electrical field intensification in the vicinity of treed areas [6], a decrease of the breakdown voltage [7] etc. On the other hand, it was shown that, even after the voltage switching off ($V = 0$), the residual electrical field takes important values [6]. The residual electrical field produced by the ionic space charge overlaps the electrical field created by the electrodes whose value may lead to the insulations premature breakdown by inception of electrical trees at the tip of water trees, at lower values than the nominal voltage [9].

In [9] a series of aspects regarding the influence of water trees on the repartition and values of the electrical field, as well as the breakdown voltage, using the Taguchi method [10] or the thermal step method [11] in which the water concentration in the treed area is assumed to be known are presented.



a) b)

Fig. 1. a) Schematic representation of samples; b) High voltage power cable structure.

In the present paper the results of an experimental and theoretical study regarding the influence of water trees on the repartition and values of the electrical field, by taking into account the water concentration in the treed area are presented.

2. EXPERIMENTS

The experiments were carried out on flat circular crown shaped cross linked polyethylene samples, with the inner diameter D_i = 23 mm, the outer diameter D_o = 57 mm and thickness g = 0.5 mm (Fig. 1.a). The samples were sliced from the insulation of a 110 kV high voltage power cable (Fig. 1.b).

The samples, whose inner and outer semi conducting layers were removed, were aged under the combined action of the electrical field and water, with the aim to develop water trees. After ageing, the thermal conductivity, specific heat, water concentration, water trees dimensions and density were determined.

2.1. WATER TREES GROWTH

Water trees were developed for τ = 24…96 h, in electric fields with the strength E = 4 kV/mm and frequency f = 5 kHz, using the setup presented in Fig. 2 [6].

2.2. SPECIFIC HEAT AND THERMAL CONDUCTIVITY

Determination of specific heat was done with a DSC type 131 Evo manufactured by Setaram (France), at T = 30 °C with a growth rate of temperature β = 4 ºC/min (Fig. 3).

For specific heat $c(T)$ and thermal conductivity computation λ were used the relations:

$$c(T) = \frac{HF_s - HF_e}{S(T) \cdot m_s \cdot \frac{\mathrm{d}T}{\mathrm{d}t}}, \quad \lambda = \frac{\sum_{i=1}^{n} \alpha_i \gamma_i c_i}{n} \tag{1}$$

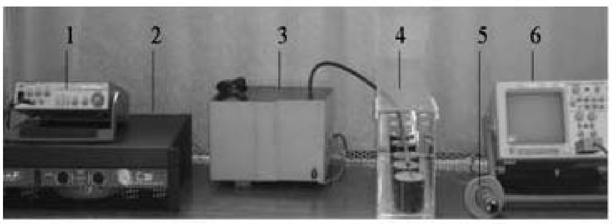


Fig. 2. Setup used for water trees development: 1 – Signal generator, 2 – Amplifier, 3 – Transformer, 4 – Sample holder, 5 – Probe, 6 – HP Scope.

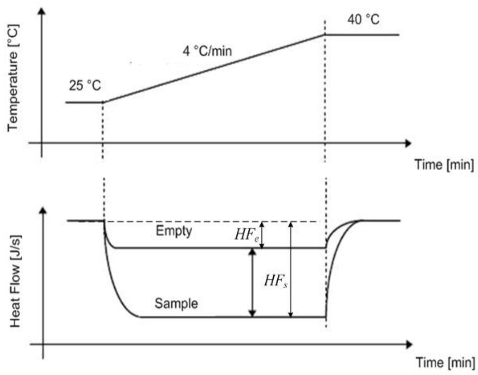


Fig. 3. Variation of temperature in time for determination of heat capacity

where HF_s represents the heat flow inside the sample, HF_e – the heat flow when the crucible (measurement cell) is empty, m_s – sample mass measured in mg, $S(T)$ – sensibility and dT/dt – variation of temperature in time, where α_i, γ_i and c_i represent the thermal diffusivity, the density, the specific heat of sample *i* and *n* – the number of samples [12].

2.3. WATER CONTENT OF TREED AREAS

For water content determination from treed areas (c_a), the initial mass m_i, volume V_i and density $\gamma_i = m_i/V_i$ of each sample *i* and the average values *m*, *V* and γ were determined:

$$m = \frac{\sum_{i=1}^{n} m_i}{n};\ V = \frac{\sum_{i=1}^{n} V_i}{n};\ \gamma = \frac{\sum_{i=1}^{n} \gamma_i}{n}. \tag{2}$$

After the water trees development, treed areas were cut and the new values of mass and density of each sample *i* was determined, using the relations:

$$m_a = \sum_{i=1}^{n} m_{ai};\ \gamma_a = \frac{\sum_{i=1}^{n} \gamma_{ai}}{n} \tag{3}$$

where $m_{ai} = \gamma_a V_i$ represents the treed sample mass before cutting and γ_{ai} – density of treed sample.

The volume occupied by water trees in a sample was computed using the relation:

$$V_a = \frac{\pi D_m^2}{4} L_{max} c_{wtm} A_{es}, \tag{4}$$

where D_m and c_{wtm} represents the average diameter and concentration of trees, L_{max} – the length of greatest tree and A_{es} – the sample area.

Supposing that the sample volume is not modified by water trees formation, the percentage concentration was determined using the relation:

$$c_a = \frac{\gamma_a - \gamma_i}{\gamma_a} \cdot 100 \tag{5}$$

2.4. DIMENSIONS AND DENSITY OF TREES

Water trees dimensions were carried out using the setup presented in Fig. 4, for each value of ageing time τ more slices from tested sample were cut and the total number of trees N_w, length L_k and diameter D_k of each sample were determined.

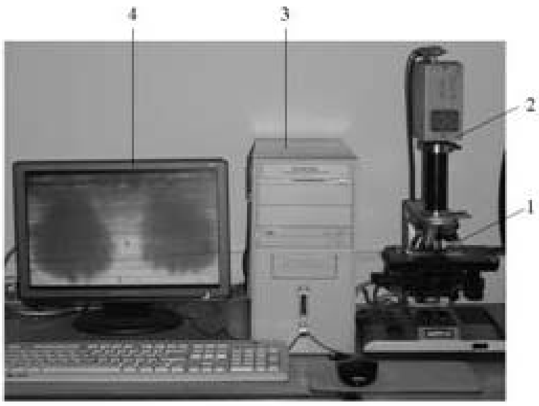


Fig. 4. Measurement of water trees dimensions:
1 - Sample; 2 - Video Camera; 3 - PC; 4 - Monitor.

The average diameter D_m, length L_m and trees density c_{wtm} were computed using the relations:

$$L_m = \frac{1}{N_w}\sum_{k=1}^{N_w} L_k \; ; D_m = \frac{1}{N_w}\sum_{k=1}^{N_w} D_k \; ; c_{wtm} = \frac{N_w}{2\pi r_i n_r} \; , \tag{6}$$

where n_r represents the number of taken slices.

3. ELECTRIC FIELD COMPUTATION

3.1. INSULATION AT NOMINAL VOLTAGE U_N

Let us consider the insulation of a cable having the length greater than the diameter where a continuous water tree of length l_a was developed containing a space charge layer of thickness l_s ($l_s \geq l_a$) in the vicinity of the inner semiconductor (Fig. 1.b).

The computation domain D (Fig. 5) is divided in three sub-domains: D_1 (of variable permittivity $\varepsilon_1(r) = ce^{-dr}$), bounded by cylindrical surfaces S_1 (of radius r_1) and S_2 (of radius $r_1 + l_a$), D_2 (of permittivity $\varepsilon_2(r) = 2.2\,\varepsilon_0$), bounded by surfaces S_2 and S_3 (of radius $r_1 + l_s$) and D_3 (of variable permittivity $\varepsilon_3(r) = 2.2\,\varepsilon_0$), bounded by cylindrical surfaces S_3 and S_4 (of radius r_2). Sub-domains D_1 and D_2 contain a charge layer of variable density $\rho_v(r) = \rho_{v0}(ar^2 + br + e)$, the expressions of ρ_{v0}, a, b and e were presented in [6].

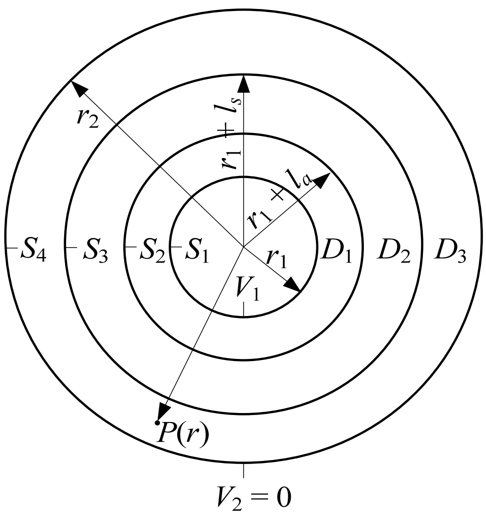


Fig. 5. Electric field computation domain for cable insulation.

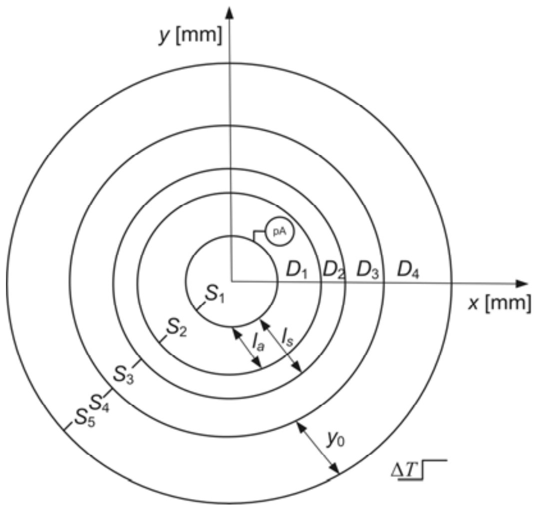


Fig. 6. Computation domain for residual electric field.

For computations the following values were considered: l_a = 500 μm, l_s = 1000 μm, ρ_{v0} = 0.1 C/m^3 and $V_1 = U_n$ =110 kV.

The potential $V(P)$ and the electric field $E(P)$ in a point $P \in D_{1,2,3}$ were computed with the equations $\Delta V = -\rho_v/\varepsilon$ and $E = -\mathrm{d}V/\mathrm{d}r$.

The boundary conditions are:

$$\begin{aligned} &V_1(P) = V_2(P),\ P \in S_2 \\ &\frac{\mathrm{d}V_1(P)}{\mathrm{d}r} = \frac{\mathrm{d}V_2(P)}{\mathrm{d}r},\ P \in S_2 \\ &V_2(P) = V_3(P),\ P \in S_3 \\ &\frac{\mathrm{d}V_2(P)}{\mathrm{d}r} = \frac{\mathrm{d}V_3(P)}{\mathrm{d}r},\ P \in S_3, \end{aligned} \tag{7}$$

where $V_1(P)$, $V_2(P)$ and $V_3(P)$ represents the potential values in points $P \in S_{2,3}$ [6].

3.2. RESIDUAL ELECTRIC FIELD COMPUTATION (V = 0)

Residual electric field is computed using the experimental thermal step current measured by Thermal Step Method [11]. It is considered that in cylindrical insulation of a cable (delimited by cylindrical surfaces of radii r_i and r_e and generator $G >> r_e$) were developed – from inner surface – continuous trees (under the shape of cylindrical shell of thickness l_a) and an ionic space charge layer with the same shape and thickness $l_s > l_a$. As the electric field has a radial symmetry, for the computation it was considered a flat domain D, constituted from 4 sub-domains $D_{1…4}$ delimited by the surfaces $S_1…S_5$ (Fig. 6).

- sub-domain D_1 (delimited by surfaces S_1 and S_2) - corresponding to the water treed region of length l_a ($\varepsilon_r(r, T) = (1+\alpha_\varepsilon(T - T_0))\cdot c\mathrm{e}^{-dr}$) ($T_0$ - the temperature of the insulation before applying the thermal step and α_ε – permittivity variation factor with the temperature). This region is supposed to contain a space charge layer of thickness l_a and of density $\rho_v(r) = \rho_{v0}(ar^2+br+e)$;
- sub-domain D_2 (delimited by surfaces S_2 and S_3) – corresponding to the region placed in front of water trees and which contains a space charge layer of thickness $l_s - l_a$ and of density $\rho_v(r) = \rho_{v0}(ar^2+br+e)$;
- sub-domain D_3 (delimited by surfaces S_3 and S_4) – corresponding to the region without water trees and without space charge ($\varepsilon_r(T) = \varepsilon_{r\mathrm{PE}}(1+\alpha_\varepsilon(T - T_0))$);
- sub-domain D_4 (delimited by surfaces S_4 and S_5) - corresponding to the region thermal diffuser/sample of thickness y_0, where the electric field is null.

The computation of the electric field and the temperature is done with the Comsol Multiphysics software, considering that y_0, l_a, l_s, a, b, e, $\alpha_{\varepsilon\mathrm{PE}}$, $\alpha_{\varepsilon w}$, c, c_1 d, d_1 and g as known and the Poisson $\Delta V = -\rho_v/\varepsilon$ and Fourier ($\gamma c \partial T/\partial t = \mathrm{div}(\lambda \mathrm{grad} T)$) equations, where ρ_v represents the ionic space density, ε – absolute permittivity, γ – density, c – specific heat and λ – thermal conductivity of material. The imposed boundary conditions are:

- $V(r) = 0$ on S_1, S_4 and S_5
- $\overline{n}(\overline{D_1} - \overline{D_2}) = 0$ on S_2 and S_3
- $T(r, t) = T_1$ on S_1 and $T(r, t) = T_5$ on S_5.

where n represents the normal unit vector, $\overline{D}$ is the electric displacement, T_1 and T_5 – the temperatures values on the semiconductor layers surfaces (Fig. 5).

The material constants c and d from the expression of permittivity corresponding to D_1 ($\varepsilon_r(r) = c\mathrm{e}^{-dr}$) were determined with the expressions:

$$\varepsilon_r(r_i + l_a) = \varepsilon_{r\mathrm{PE}};\ \int_{r_i}^{r_i+l_a} \varepsilon_r(r)\mathrm{d}r = \varepsilon_{rm} l_a;\ \varepsilon_{rm} = c_a \varepsilon_{rm} + (1 - c_a)\varepsilon_{r\mathrm{PE}}, \tag{8}$$

where c_a is the average water concentration in the water trees, ε_{rm} and ε_{rPE} - the relative permittivity of water and polyethylene and ε_{rm} - the average permittivity in treed region (sub-domain D_1).

The values of α_ε were deduced on the basis of the permittivity variation curves for water and polyethylene at temperatures between T_5 = -5 °C and T_1 = 25 °C [13]. It was obtained $\alpha_{\varepsilon PE} = 4.4\cdot10^{-4}$ K^{-1} for polyethylene and $\alpha_{\varepsilon w} = -7.26\cdot10^{-3}$ K^{-1} for water. Because the relative permittivity decreases exponentially with r from S_1 and S_2, a variation law similar to the permittivity was considered for α_ε:

$$\alpha_\varepsilon(r) = c_1 e^{-d_1 r}, \qquad (9)$$

the values of c_1 and d_1 have been obtained from the expressions:

$$\alpha_\varepsilon(r_i + l_a) = \alpha_{\varepsilon PE}\,;\ \int_{r_i}^{r_i+l_a} \alpha_\varepsilon(r)\mathrm{d}r = \alpha_{\varepsilon m} l_a\,;\ \alpha_{\varepsilon m} = c_a \alpha_{\varepsilon w} + (1 - c_a)\alpha_{\varepsilon PE}\,. \qquad (10)$$

4. RESULTS AND DISCUSSIONS

4.1. WATER TREES DEVELOPMENT

In Fig. 7 and Table 1 different development time of water trees for E = 4 kV/mm and f = 5 kHz are presented. It can be seen that, with the ageing time increase τ, the dimensions and density of trees increase. This is due to the ions penetration resulted by salt dissociation from water (under the electric field action), on one hand, and increase of water content worn by the ions in their displacement, on the other hand [14].

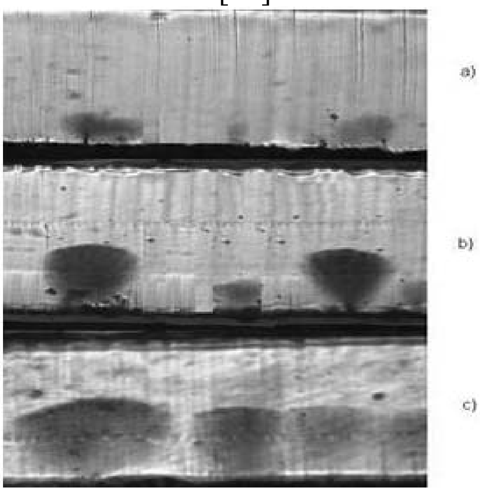


Fig. 7. Water trees in XLPE samples for *τ* = 48 h (a), *τ* = 72 h (b) and *τ* = 96 h (c) (*E* = = 4 kV/mm, *f* = 5 kHz).

Table 1 Dimensions and density of water trees

Ageing time [h]	L_m [μm]	D_m [μm]	c_{wtm} [wt/mm^2]
30	84.1	62	2.5
65	136.8	77	5

Table 2 Diffusivity, specific heat and thermal conductivity values

Sample	τ [h]	α [m^2/s]	c [J/kgK]	λ [W/mK]	L_{max} [μm]	c_a [%]
Un-treed	0	0.149	2067	0.3	-	0
Treed	30	0.15	2170	0.32	200	0.72

4.2. THERMAL DIFFUSIVITY, SPECIFIC HEAT AND THERMAL CONDUCTIVITY

The values of thermal diffusivity α, specific heat *c* and thermal conductivity λ are presented in Table 2. Values of α, *c* and λ are closer to the values obtained by other authors [15-16] and are greater on the treed samples relative to the un-treed ones. This is explained by the fact that, with the increase of ageing time τ the water content from treed areas increases and λ and *c* values reach to the values for water ones [17].

4.3. WATER CONTENT

Values obtained on treed samples after τ = 30 h are presented in Table 2. For an easier computation, was supposed that un-treed sample do not contain water, although it was shown [7] the water existence in a small concentration (about 0.01 %), appeared during fabrication, due to water cooling. The obtained values for τ = 30 h are relative small, but increase with water trees development.

4.4. ELECTRIC FIELD COMPUTATION

Electric field computation was done in the following conditions: l_a = 500 µm, l_s = 1000 µm, ρ_{v0} = 0.1 C/m^3 (Fig. 8) and the results are presented in figure 8. It can be seen that water trees determine an important variation of the electric field in front of them (in coordinate points $r_1 + l_a$, curve 2, Fig. 8). Electric field value in these points is 5.3 MV/m, 43 % greater than in the absence of water trees. Space charge increases at its turn the electric field values (curve 3, Fig. 8). Also, even after the voltage switching off, the electric field doesn't drop to zero, being 1.3 MV/m. This value of the electric field (closer to the necessary one for water trees inception (3 MV/m)) makes easier degradation processes continuation, even in the voltage absence, by new water trees appearance and electrical trees inception in front of them, which lead to premature breakdown of cable insulation.

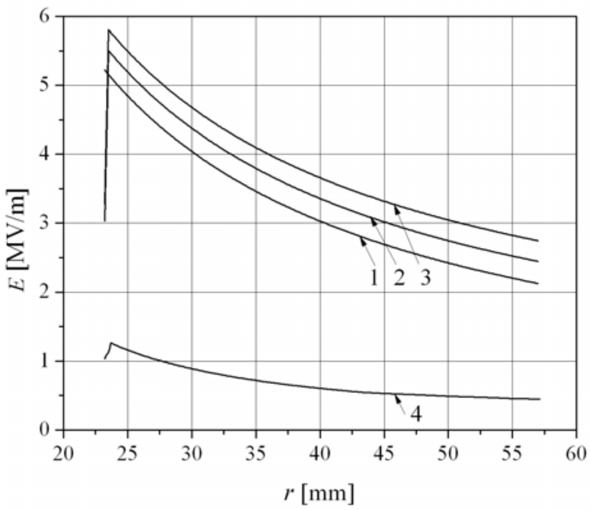


Figure 8. Variation of electric field *E* with the *r* coordinate in the absence of water trees (1), presence of a water tree (2), water tree and space charge (*V* = 110 kV) (3) and water tree and space charge (*V* = 0) (4) (l_a = 500 µm, l_s = 1000 µm, ρ_{v0} = 0.106 C/m^3).

5. CONCLUSIONS

The increase of the samples ageing time in the presence of water leads to an increase of water trees dimensions (L_m, D_m) and average concentrations (c_{wtm}).
Water trees development determines an increase of the thermal properties values of the treed areas. The presence of water trees determines a change of the electric field repartition, more important when dimensions, concentration and water content increase.

The residual electric field values (for $U = 0$) are still higher and make easier the electrical ageing processes (inception of electrical trees) and premature breakdown of cable insulations.

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