Water Tree Influence on Space Charge Distribution and on the Residual Electric Field in Polyethylene Insulation

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Abstract - A computation method of the electric field and ionic space charge density in plane insulations with water trees (using a Comsol Multiphysics software and the thermal step currents \( I_m(t) \) measured with Thermal Step Method) is presented. A parabolic spatial variation of volume charge density, an exponential spatial variation of the electric permittivity \( \varepsilon \) and a linear dependency of \( \varepsilon \) and the temperature coefficient of permittivity \( \alpha_\varepsilon \) with the average water concentration in trees, are considered. For a water tree with a known length, different values of charge density are considered and the electric field and the thermal step currents \( I_A(t) \) are calculated. The currents \( I_A(t) \) and \( I_m(t) \) are compared and the volume of charge density and electric field for which \( I_A(t) \) is identical with \( I_m(t) \) are kept.

Key words: insulation systems, electric field, space charge, water trees

I. INTRODUCTION

One of the main causes of premature breakdown of average and/or high voltage electrical insulation is the existence of local electric fields exceeding the inception values of partial discharges and electrical treeing. The local intensification of the electric field is due to conductor defects (sharp edges, protrusions etc), insulation defects (delamination, cavities etc), electrochemical trees (water, cooper, etc) [1].

In the case of polyethylene insulated power cables, water trees develop either in the vicinity of bulk defects (bow tie trees), or from inner and/or outer semi-conducting layers (vented trees) and they appear under the shape of micro cavities filled with water connected by very thin micro channels [2], [3]. Water treeing leads to ionic space charge formation (corresponding to the salt dissolved in water), inside and outside the treed regions, the quantity depending on the salt concentration in water, on water trees dimensions, frequency of the electric field etc [5], [6].

In previous papers [7]…[9], correlations between the water trees length \( l_a \) and average space charge density \( \rho_v \) have been shown. In the present paper a computation method of the electric field and space charge on the basis of measured thermal step current in insulations with water trees is presented. A Comsol software is used and the dependencies of permittivity \( \varepsilon \) and temperature coefficient of permittivity \( \alpha_\varepsilon \) as a function of their average values (corresponding to polyethylene and water) and average water concentration in trees are taken into consideration.

II. THERMAL STEP METHOD

The thermal step method (TSM) consists in the application of a thermal step \( \Delta T \) (Figure 1) on one face of the tested sample situated between two electrodes [10]. As a consequence, the space charge inside the sample, moves, the induced charges on electrodes are modified, and by connecting the electrodes in short-circuit a current \( I(t) \) appears, having the expression [11]:

\[
I(t) = -C \int_{y_0} \alpha_E(y) E(y) \frac{dT(y,t)}{dt} dy,
\]

where \( \alpha_E \) is the temperature coefficient of permittivity, \( C \) – the sample capacity before the thermal step application, \( E(y) \) – the electric field strength in coordinate point \( y \) (perpendicular measured on the electrodes surfaces), \( T(y,t) \) – the temperature value in coordinate point \( y \) at instant \( t \), \( y_0 \) – a computation quantity depending on the electrode characteristics which is in contact with the liquid which generates the thermal wave.

By measuring the current \( I(t) \) and using equation (1), the values of electric field \( E(y) \) and volume space
charge density \( \rho_c(y) \) can be calculated in each point of the tested sample.

If in the case of homogeneous samples, \( \varepsilon \) and \( \alpha_c \) are known constants, their values are relatively difficult to determine in the case of water treed insulations. On the basis of some experimental data, different variations laws with the \( y \) coordinate have been proposed for \( \varepsilon \): linear, parabolic, exponential etc. [12] ...[14]. In the present paper an exponential variation law of permittivity was considered:

\[
\varepsilon_c(y) = c e^{-\alpha_0 y},
\]

where \( \varepsilon_c(y) \) is the relative permittivity in coordinate point \( y \), and \( c \) and \( d \) are material constants.

The \( \alpha_c \) coefficient values were deduced on the basis of permittivity variation curves of polyethylene and water with temperature between -5 °C and 25 °C [15]...[17]. The obtained values are \( \alpha_{PE} = 4.4 \cdot 10^{-3} \) \( \text{K}^{-1} \) for polyethylene and \( \alpha_{w} = -7.26 \cdot 10^{-3} \) \( \text{K}^{-1} \) for water. For water treed regions a average coefficient \( \alpha_{rw} \) was calculated:

\[
\alpha_{rw} = c_{rw} \alpha_{w} + (1 - c_{rw}) \alpha_{PE},
\]

where \( c_{rw} \) is the average water concentration [18]...[20].

Because the water concentration decreases exponentially from the base towards the front of water trees [19], we considered for \( \alpha_c \) the same kind of variation like permittivity:

\[
\alpha_c(y) = c_1 e^{d_1 y},
\]

where the constants \( c_1 \) and \( d_1 \) are material constants.

III. ELECTRIC FIELD COMPUTATION

Let us consider a flat sample which has the diameter \( d \) and the thickness \( g \), situated between the ground electrode and the thermal diffuser (Fig. 1). It is supposed that from the sample face which is in contact with the thermal diffuser a continuous water tree with the length \( l_e \) has developed, to whom corresponds an ionic space charge layer of volume density \( \rho_c(y) \) and thickness \( l_e(\rho_c, l) \). This charge generates an electric field of intensity \( E \). As the electric field has a plane parallel symmetry, it can be computed in a rectangular domain \( D \) (resulting from the division into sections of the disc with a perpendicular plane on its basis). The domain \( D \) is constituted of 4 sub-domains \( D_1 ... D_4 \) delimited by the boundaries 1...13 (Fig. 2):

- Sub-domain \( D_1 \) – corresponding to the thermal diffuser/sample area, whose thickness \( y_0 \) is experimentally determined and where the electric field in zero;
- Sub-domain \( D_2 \) – corresponding to the water treed region with the length \( l_e \) (\( \varepsilon_c(T,y) = (1+\alpha_c(y)(T - T_0)) e^{-\alpha_0 y} \)) and with a space charge layer with the thickness \( l_e \) and \( \rho_c(y) = \rho_0(1+y^2 + by + c) \);
- Sub-domain \( D_3 \) – corresponding to the region without trees (\( \varepsilon_c(T) = \varepsilon_{PE}(1+\alpha_{PE}(T - T_0)) \)) and with a space charge layer and without space charge;
- Sub-domain \( D_4 \) – corresponding to the region without water trees (\( \varepsilon_c(T) \)) divided into several intervals (\( \Delta T = 5 \text{ ms} \)).

The boundaries conditions are:

- \( V = 0 \) on boundaries 1, 2, 3, 4 and 13,

Considering that \( y_0 \), \( l_e \), \( \rho_0 \), \( a \), \( b \), \( c \), \( d \), \( g \), \( \alpha_{PE} \) and \( \alpha_{rw} \) are known, using the Comsol Multiphysics software, the electric field configuration and temperature in domain \( D \) were determined. Knowing the initials and boundaries conditions for electric potential \( V(y,t) \) and temperature \( T(y,t) \), the Poisson equation for electric field \( \Delta V = -\rho /\varepsilon \) and Fourier equation for temperature \( \gamma c_p \partial T / \partial t = \text{div}(\lambda \text{grad}T) \) where \( \gamma \) is the density, \( c_p \) - specific heat and \( \lambda \) - thermal conductivity, were solved. In all sub domains, an initial temperature of 25 °C was considered. At the instant \( t = 0 \), the temperature on boundary 1 decreases to -5 °C, corresponding to the application of a thermal step \( \Delta T = -30 \) °C. It is considered that the thermal wave acts a time \( t \) \( (t = 5 \text{ s}) \) divided into several intervals (\( \Delta T = 5 \text{ ms} \)).

Fig. 2. Computational domain of the electric field.
- \( \bar{n}E = 0 \) on boundaries 5, 6, 8, 9, 11 and 12,
- \( (\varepsilon E_a)_{z} = (\varepsilon E_a)_{y} \) on boundary 7,
- \( (\varepsilon E_a)_{x} = (\varepsilon E_a)_{y} \) on boundary 10,

where \( \bar{n} \) is the surface normal and \( E_a \) the normal component of \( E \).

The values of the density (\( \gamma \)), thermal conductivity (\( \lambda \)) and specific heat (\( c_p \)) corresponding to the water trees regions have been computed on the basis of the polyethylene and water values, by using a similar equation with (4), for different quantities of average water concentration \( c_{av} \) (Table 1).

**TABLE 1. Values for different average water concentration in polyethylene \( c_{av} \) \( \left( l_s = 227 \ \mu m \right) \).**

<table>
<thead>
<tr>
<th>( c_{av} ) [%]</th>
<th>( \gamma ) [kg/m³]</th>
<th>( \lambda ) [W/mK]</th>
<th>( c_p ) [J/kgK]</th>
<th>( \alpha_{av} \times 10^4 ) [K⁻¹]</th>
<th>( \varepsilon_{av} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>930</td>
<td>0.38</td>
<td>1900</td>
<td>4.4</td>
<td>2.3</td>
</tr>
<tr>
<td>1.5</td>
<td>931.05</td>
<td>0.382</td>
<td>2318.8</td>
<td>3.63</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>931.4</td>
<td>0.384</td>
<td>2337.6</td>
<td>3.24</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Material constants \( c, c_1, d \) and \( d_1 \) are computed from the equations (5) and (6):

\[
e_c \left( y_0 + l_s \right) = \varepsilon_{PE} \int_{y_0}^{y_0 + l_s} \varepsilon_n (y) dy = \varepsilon_{av} l_s \tag{5}
\]

\[
\varepsilon_{av} = c_{av} \varepsilon_{av} + (1 - c_{av}) \varepsilon_{PE},
\int_{y_0}^{y_0 + l_s} \alpha_n (y) dy = \alpha_{av} l_s \tag{6}
\]

where \( l_s \) is the tree length (assumed as continuous), \( c_{av} \) and \( \varepsilon_{av} \) - the average water concentration and the average permittivity of the treed zone, and \( \varepsilon_n \) and \( \varepsilon_{PE} \) - the relative permittivities of water and polyethylene.

The thermal step current corresponding was computed using the relation:

\[
I_c (t) = -\varepsilon S \frac{dE_a}{dt}, \tag{7}
\]

where \( \varepsilon \) is the absolute permittivity of sample, \( S \) - the electrode area, and \( E_a \) - the electric field in the vicinity of measuring electrode (boundary 13, Fig. 2).

IV. EXPERIMENTS

A. Samples

The experiments were made on flat samples having the dimensions 100x100x0.5 mm³, made from LDPE pellets by pressmoulding at \( p = 200 \) bar and \( T = 145 \) °C. In the samples, water trees were developed in an accelerated manner. For electrical measurements, graphite electrodes (40 mm in diameter) have been deposited. For measuring the trees lengths, the samples were cut in slices of 200 μm.

B. Setups

The setup used for water trees development is presented in Fig. 3 [8]. The applied effective 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 - \( \tau = 0...48 \) h. For measuring the dimensions of the water trees, the experimental setup presented in Fig. 4 was used.

V. RESULTS. DISCUSSIONS

A. Thermal step current measurement

The variations of the thermal step currents in samples without and with water trees of the length \( l_s \) (Fig. 5) are presented in Figure 6. It can be observed that the maximum values of thermal step currents \( I_{av,max} \) are higher in water treed samples with respect to virgin samples. For \( l_s = 0, 157 \) and 227 μm, the values of \( I_{av,max} \) are 8.44 and 152 pA respectively. This is due to ionic space charge accumulation in the samples - resulted from the dissociation of NaCl molecules, which is more important in the last samples.
Fig. 5. Water trees developed in LDPE samples ($\tau = 48$ h, $U = 2$ kV, $f = 5$ kHz).

Fig. 6. Thermal step currents $I_{th}(t)$, measured on samples with and without water trees.

B. Computation of thermal step currents and electric field

Considering different values of $\rho_0$ (-4.4...2.7 C/m$^3$) and $l_a$ (267...327 µm), thermal step currents $I_{th}(t)$ for values of $t$ between 0 and 5 s were computed using the Comsol software. The obtained curves $I_{th}(t)$ were compared with the experimental one $I_{th}(t)$ to find the values of $\rho_0$ and $l_a$ for which $I_{th}(t) \approx I_{th}(t)$.

Fig. 7 shows the variation of the maximum values of electric field strength $E$ with $\rho_0$ and $l_a$. It can be seen that $E_{max}$ decreases with the increase of $l_a$ and increases with the increase of $\rho_0$, variations which are similar to the ones obtained in the case of average voltage cables [8].

Fig. 8 shows the time variation of the computed thermal step current $I_{th}(t)$ for different values of the temperature coefficient of permittivity $\alpha_c$. As expected the decrease of $\alpha_c(y)$ in $D_2$ causes a decrease in the thermal step current (curve 2, Fig. 8). This decrease becomes even more important in the case where $\alpha_c$ varies exponentially (curve 3, Fig. 8).

In Fig. 9 the thermal step current $I_{th}(t)$ - measured on a water treed sample - and the thermal step current $I_{th}(t)$ simulated in water treed samples for which it has assumed $l_a = 227$ µm, $l_s = 327$ µm, $y_0 = 0.6$ mm and $\rho_0 = -2.71$ C/m$^3$ and $\alpha_{PE} = 4.4 \cdot 10^{-4}$ K$^{-1}$, or $\rho_0 = -3.35$ C/m$^3$ and $\alpha_{PE} = 4.4 \cdot 10^{-4}$ K$^{-1}$ are presented. It can be observed that the decrease of the values of $\alpha_c$, due to
water penetration inside the samples, leads to the increase of space charge density $\rho_v$ (from - 2.71 C/m$^3$ in the absence of the water trees to - 3.35 C/m$^3$ in their presence).

Electrical field variation vs $y$-coordinate, for different values of $\alpha_c$, in the water treed area is shown in Fig. 10. It is remarked that the $\alpha_c$ decrease in $D_2$ causes an increase in $E$ (curve 2, Fig. 10), and that this increase becomes more important in the case where $\alpha_c$ varies exponentially (curve 3, Fig. 10).

In Figs. 11 and 12 the variations of electric field and volume space charge density (with the $y$ - coordinate), for different values of the average water concentrations are presented. It can be observed that the electric field $E$ and volume space charge density have important variations in the vicinity of the regions from where the water trees develop, and decrease with the $y$-coordinate, as a consequence of the decrease of ion concentration related to water trees [4].

It must be also remarked that the increase of the average water concentration values $c_{\text{av}}$ determines an increase of $E$ and $\rho_v$ values (Figs. 11, 12 and 13). Consequently, the values of residual electric field in the vicinity of samples faces from where water trees develop are relatively important (over 11 kV/mm in the case of a tree with a average water concentration $c_{\text{av}} = 1 \%$), and increases if the water concentration increases (due to the increase of space charge density related to water trees). For example, if the average water concentration in the trees reaches 2.4 $\%$, the value of $E_{\text{max}}$ reaches to 18 kV/mm (enough to initiate an electrical tree [21]).
V. CONCLUSIONS

The computational method presented in this paper evaluates in a good manner the residual electric field in water treed flat samples. The maximum values of the electric field depend on the space charge layer thickness \( l_s \) and on the volume space charge density \( \rho_{v0} \).

The increase of average water concentration determines an increase of the permittivity \( \varepsilon \) and a decrease of the temperature coefficient of permittivity \( \alpha_v \). Therefore the values of the computed current \( I(t) \) decrease. On the other hand, the increase of water content in the trees results in an increase of maximum values of charge density \( \rho_{v0} \) and electric field \( E_{max} \).

In the inception areas of the water trees, the values of the residual electrical field generated by the water trees related ionic space charge may be significant in the case of high average water concentration in water trees (over 18 MV/m for \( c_w = 2.4 \% \)). Therefore, partial discharges and water trees which were initiated when the insulation was in use can develop even after the voltage was stopped.

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REFERENCES