Behavior of the DC cable joints interface subjected to high electric field and temperature

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ABSTRACT

In this paper, the electric field computation in electro-kinetic stationary and quasi-stationary regime in a joint model is done. The joint model consists of 2 dielectrics (PE and EPDM). The conductivity and permittivity at different temperatures are experimentally determined. The superficial charge density near the interface is calculated, at different temperatures and applied voltage values.

The results show a significant increase of the electric field near the interface. This increase is more important as the temperature and charge density increase.

The charge density and electric field values increase in time. This phenomenon is dangerous for DC cables and accessories.

KEYWORDS

Electric field, temperature, superficial charge, interface, joints.

INTRODUCTION

Nowadays, many projects regarding the increasing electricity transmission capacity at long distance by installing DC lines are ongoing. Among this: DC line between Romania and Turkey, under the Black Sea (400 kV), DC line between France and Spain 64 km (320 kV, 2000 MW) and others. Because the interconnection is achieved over great distances, this means long distances between the generating and the distribution system of electricity as well as the limited length of the cable section. Because of that, more cable sections connected by joints are used. The „classic" structure of a joint is shown in Figure 1.

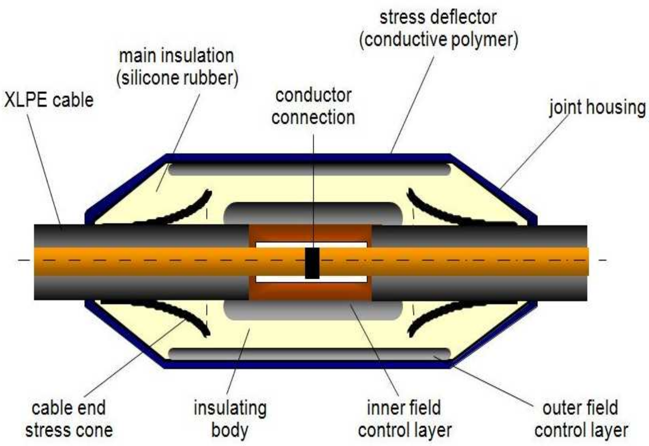

Fig. 1: Structure of a joint [1]

Each of these materials presents its properties (permittivity and conductivity), making possible the appearance of the interfacial polarization [2], at the interface between them. This phenomenon is described by the Maxwell-Wagner-Sillars model (MWS) [3]. On the other hand, an additional space charge layer is formed [4]. The result is an electric field which overlaps the one given by Laplace field [5].

Therefore, the electric field can have values large enough, over the charge injection threshold field in the polyethylene insulation (10-20 kV/mm) [6]. Also, partial discharges can occur and may lead to degradation and failure of the joint.

Because of this, the joints are known as the most vulnerable components in a power transmission line, especially in DC fields.

The values of the electric field depend on the permittivity and the conductivity of the insulating materials, which also depend on the temperature, the electric field and the space charge [7-8].

The computation of the electric field and space charge, in DC cable insulation and accessories has been the subject for many researches in the last few years.

So, Xu [9] calculated the electric field in LDPE and XLPE flat samples subjected to a DC voltage of 10 kV, in the presence of space charge. It was assumed, however, that the temperature is constant through the insulation. The accumulated space charge density, at the XLPE/EPR samples interface subjected to a DC voltage of 20 kV for 3 hours, was calculated by Le Roy [10]. In this case, the temperature is constant in each point of the insulation, also. The calculating model for the accumulated space charge density at the interface is complex, even if it is one-dimensional and it depends of the chemical structure of materials by considering the density of traps. The electric field, in 2D, in medium voltage cable joints, in the absence of space charge and temperature gradient, was calculated by Illias & co. [11].

In this paper the electric field distribution considering a joint model consisting of a cylindrical conductor and two insulating layers (A-B section, Figure 2) is determined. The insulating layers are: polyethylene (PE) and ethylene propylene diene monomer rubber (EPDM).

Dielectric permittivity and conductivity are experimentally determined on flat samples for different temperatures between 30 and 80 ºC. The charge density ρ_s which is accumulated at the PE/EPDM interface (Figure 2) and the values of the electric field for different voltage and temperature values in stationary and quasi-stationary (time variable) electro kinetic regime are calculated using Comsol Multiphysics software.

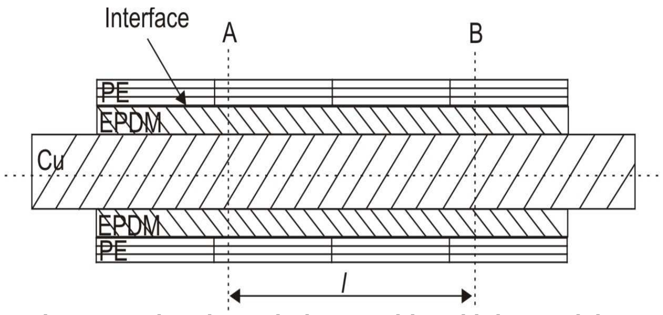

Fig. 2: Section through the considered joint model

ELECTRIC CHARGE AT THE INTERFACE

Applying a DC voltage, U, on a system consisting of two or more dielectric, interfacial polarization and superficial charge will appear, at the interface between the two dielectrics.

Considering MWS model [2], time variation of surface charge density ρ_s (t) is given by:

$$\rho_s(t) = \frac{\varepsilon_1\sigma_{\mathrm{dc}2} - \varepsilon_2\sigma_{\mathrm{dc}1}}{\sigma_{\mathrm{dc}1}g_2 + \sigma_{\mathrm{dc}2}g_1} U\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \qquad [1]$$

where g_1 and g_2 represent the thickness of each dielectric, σ_{dc1} and σ_{dc2} – the conductivity, ε_1 and ε_2 represent electric permittivity for each dielectric and τ is the relaxation time:

$$\tau = \frac{g_1\varepsilon_2 + g_2\varepsilon_1}{g_1\sigma_2 + g_2\sigma_1} \qquad [2]$$

EXPERIMENTS

Samples

In order to measure the electrical permittivity and conductivity, PE and EPDM flat samples, with 150x150 mm^2 surface and thickness g_1 = 0.7 mm for EPDM and g_2 = 0.5 mm for PE were used. The polyethylene samples were manufactured (at the Université Montpellier 2) of grains supplied by Borealis by pressing at T = 160 º C and pressure p = 200 bar, for 10 minutes. EPDM samples (manufactured and supplied by CABLEL Romania) were obtained from pressed pellets at T = 180 °C and p = 200 bar pressure for 10 minutes.

Determination of electrical permittivity and conductivity

Variations with the temperature of the conductivity σ_{ac} and permittivity ε_r were obtained by dielectric spectroscopy method [12, 13] on PE and EPDM samples. The measurements were performed in the frequency range 1 MHz ... 10 mHz at a temperature between 30 and 80 ºC.

The permittivity and conductivity values at the frequency f = 50 Hz were considered for numerical calculations. The DC conductivity σ_{dc} (T) (f ~ 0) was estimated by extrapolating the graphics σ_{ac} (T). The results were verified by measuring the dc conductivity σ_{dcm} at T = 30 ° C, for both PE and EPDM. The measurements were performed with a Keithley 6517 electrometer [14].

ELECTRIC FIELD COMPUTATION MODEL

The electric field computation is done in the cylindrical domain $D = D_1 \cup D_2$ (Figure 3a), consisting of sub domain D_1 (corresponding to EPDM insulation layer) and D_2 (corresponding to PE insulation layer). The sub domain D is bounded by the cylindrical surfaces S_1 (of radius is r_1) and S_2 (of radius $r_1 + g$). The length l is longer than $r_1 + g$. The permittivity and the conductivity of the dielectric 1 are ε_{r1} and σ_1 ($\sigma_1 = \sigma_{dcEPDM}$), and the permittivity and the conductivity of the dielectric 2 are ε_{r2} and σ_2 ($\sigma_2 = \sigma_{dcPE}$).

The potential of the surface S_1 is V_1 = 72 kV (potential of the conductor) and the surface S_2 has the potential V_2 = 0 (ground potential).

Because $l >> r_1 + g$, the problem has an axial symmetry, so that the electric field strength does not vary along the z axis. The problem can therefore be reduced to 2D (Figure 3b).

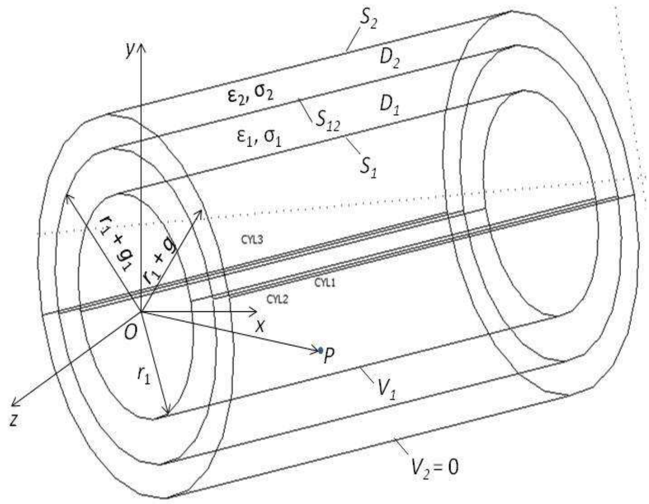

Fig. 3a: 3D computation domain of the electric field

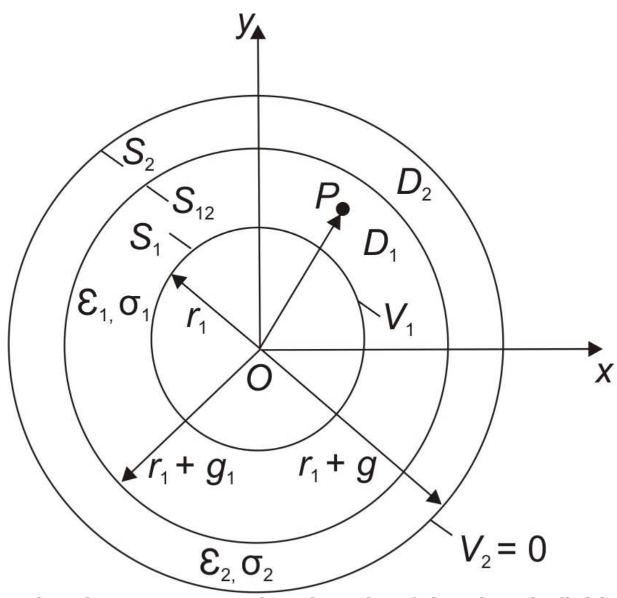

Fig. 3b: 2D computation domain of the electric field

Close and Return

Equations

Electro kinetic stationary regime

$$\overline{J} = \sigma \overline{E}$$ - Electrical conduction law

$$\overline{D} = \varepsilon \overline{E}$$ - The connection law between $\overline{D}$ and $\overline{E}$

$$\overline{E} = -\mathrm{grad}V$$ - Electrostatic potential theorem

where V represents the electric potential, $\overline{D}$ is the electric induction, $\overline{J}$ represents the electric field density, σ – the electric conductivity, ε is the relative electric permittivity and $\overline{E}$ represents the electric field strength.

Electro kinetic quasi-stationary regime

The charge conservation law is added to the above equations:

$$\mathrm{div}\overline{J} + \frac{\partial \rho_s}{\partial t} = 0$$

where ρ_s is the accumulated surface charge density on the surfaces S_{12} and S_{23}.

Boundary conditions

- Dirichlet conditions were imposed on the S_1 and S_2 surfaces:

$$V(P,t) = V_1, \quad P \in S_1, \quad t \in [0,\infty]$$
$$V(P,t) = 0, \quad P \in S_2, \quad t \in [0,\infty]$$

- On the discontinuity surface S_{12} the following condition was imposed:

$$\mathrm{div}_s \overline{D} = \overline{n}_{12}\left(\overline{D}_2 - \overline{D}_1\right) = \rho_s, \; P \in \text{ on } S_{12},\; t \in [0, \infty]$$

Material properties

The values of the electrical conductivity and permittivity on PE and EPDM samples are shown in Table 1.

Table 1 Values of electrical conductivity and permittivity on PE and EPDM samples

Material	T [ºC]	σ_{dc} [S/m]	$\varepsilon_{r50\ Hz}$
PE	30	$9.86 \cdot 10^{-17}$	2.21
	40	10^{-16}	2.20
	50	$1.1 \cdot 10^{-16}$	2.18
	60	$1.57 \cdot 10^{-16}$	2.17
	70	$2.32 \cdot 10^{-16}$	2.16
	80	$5.13 \cdot 10^{-16}$	2.10
EPDM	30	$9.1 \cdot 10^{-15}$	3.19
	40	$2.04 \cdot 10^{-14}$	3.16
	50	$3.43 \cdot 10^{-14}$	3.13
	60	$4.35 \cdot 10^{-14}$	3.11
	70	$1.62 \cdot 10^{-13}$	3.09
	80	$1.02 \cdot 10^{-12}$	3.08

RESULTS AND DISCUSSIONS

Electrical conductivity and permittivity

Figure 4 shows the variation of electric conductivity σ_{dc} measured on PE and EPDM flat samples at T = 30 ... 80 ° C, at frequency f = 50 Hz and voltage U_a = 1 V RMS. Both PE and EPDM electric conductivity increases with temperature for frequency f = 50 Hz (Figures 4 and 5). The increase of conductivity with the temperature is resulting from the relation $\sigma(T) = C\exp(-w_a / kT)$, where w_a is the activation energy and k is the Boltzmann constant.

From Figure 5 it can be seen that the permittivity decreases with the temperature. This decrease is relatively low and indicates a reduced dependence of permittivity with temperature. This behavior is specific to polar dielectrics. Both, permittivity and conductivity values measured on PE and EPDM samples at f = 50 Hz, are very close to those presented in [15] (ε_r = 2.3, σ = 10^{-15} – 10^{-16} S/m – for PE and ε_r = 2.7, σ = 10^{-12} S/m – for EPDM).

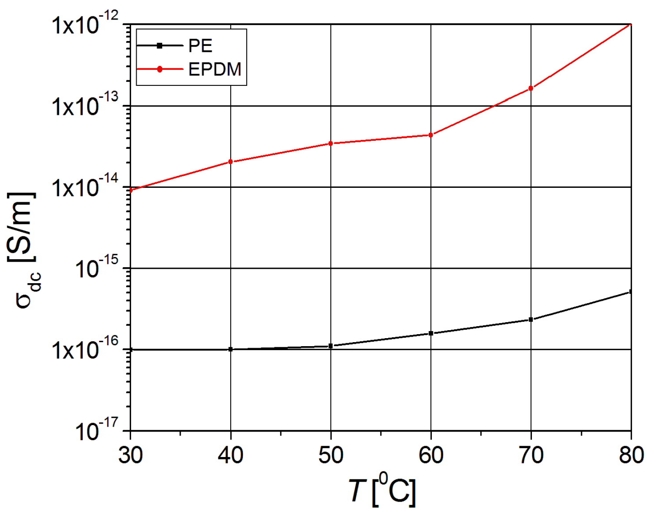

Fig. 4: Variation of electrical conductivity σ_{dc} with temperature

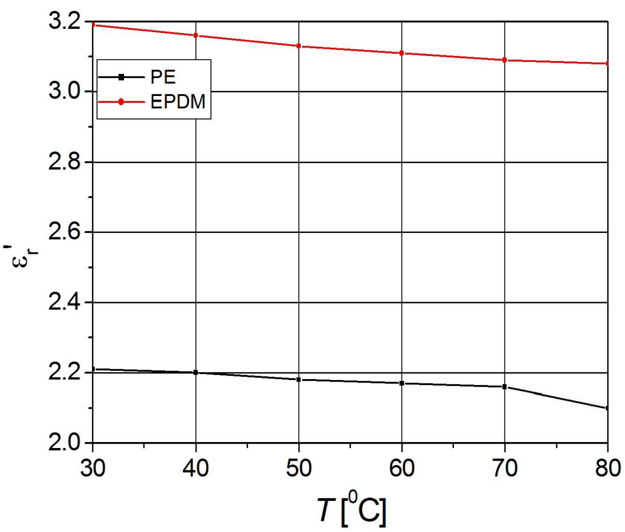

Fig. 5: Variation of the the electrical permittivity ε_r' with temperature (f = 50 Hz)

Superficial charge density

The values of the superficial charge density ρ_s (calculated with equation (1)) for temperatures between 30 and 80 °C, at frequency f = 50 Hz and voltages of 72 kV, 123 kV and 145 kV are shown in Table 2. These values were chosen in agreement with the ABB standards and with the corresponding voltages at which the high voltage accessories cables are operate.

It can be noticed that the superficial charge for both PE and EPDM is relatively low, of the order mC/m^2. On the other hand, the superficial charge density is not significantly influenced by the temperature and voltage.

Table 2 Calculated values of superficial charge density accumulated at the PE/EPDM interface

T [ºC]	ρ_{s72} [C/m^2]	ρ_{s123} [C/m^2]	ρ_{s145} [C/m^2]
30	0.002731	0.004665	0.0055
40	0.002765	0.004723	0.005568
50	0.002753	0.004703	0.005544
60	0.002737	0.004676	0.005513
70	0.002591	0.004426	0.005218
80	0.002672	0.004565	0.005382

Electric field computation

Electric field values were obtained using Comsol Multiphysics software, in the computation domain presented in the figure 3b. Computation domain is divided in 26560 triangular elements.

Electro kinetic stationary regime

a. Influence of the superficial charge

In Fgure 6 the variation of the electric field with coordinate r in the absence and presence of the charge accumulated at the PE/EPDM interface is presented. It is found that for low values of surface charge density, the electric field (green curve) is less disturbed to the field in the absence of the charge. For a greater charge density value (Table 2) the electric field is strongly perturbed (red curve). The existence of a positive charge at the PE/EPDM interface leads to an increase of the electric field (with over 90 % from the field in the absence of the charge) at the interface ($\forall x \in$ [0...1.2 mm], y = 0.7 mm).

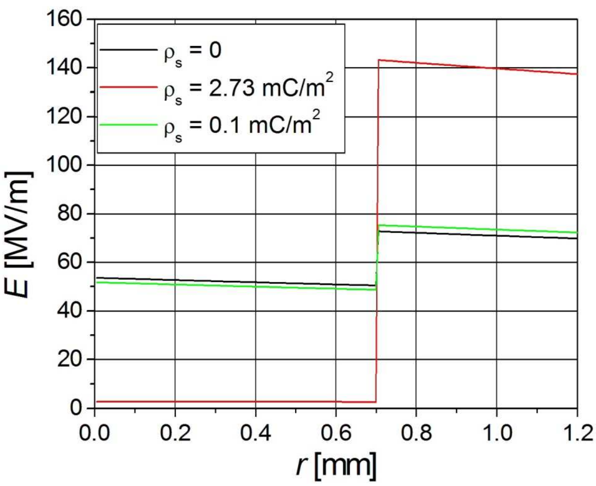

Fig. 6: Variation of the electric field with coordinate *r* in the absence and presence of the surface charge ρ_s (*x* = 0, *y* – variable, *T* = 30 ºC)

b. Influence of the temperature

In Figures 7 and 8 the variation of the potential V and electric field strength with r coordinate for different values of the temperature is presented. For T = 30 ºC and 50 º C (Figure 6, black and red curves) the potential shows a pronounced decrease from the high potential electrode (r = r_1) toward to the interface area (r = 0.7 mm). For T = 80 ºC, the values of the potential show a small decrease before the interface area (r = 0.7 mm). On the other hand, the electric field increases with the temperature near the interface (Figure 8).

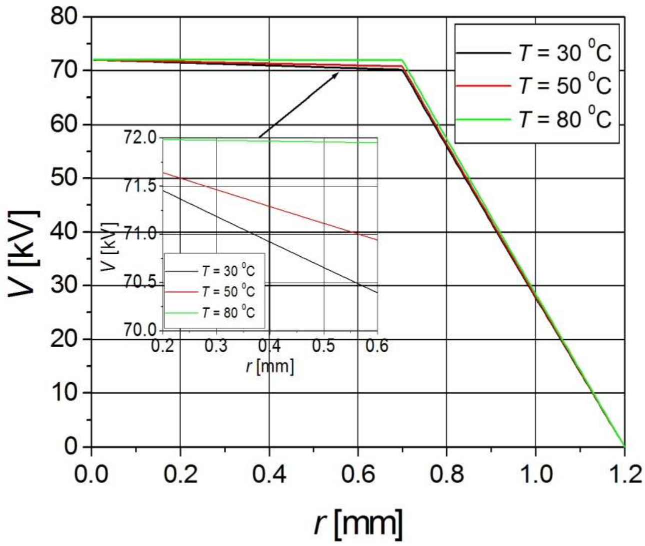

Fig. 7: Variation of the potential with coordinate *r* in presence of the superficial charge ρ_s (*x* = 0, *y* – variable, ρ_s = 2.73 mC/m^2)

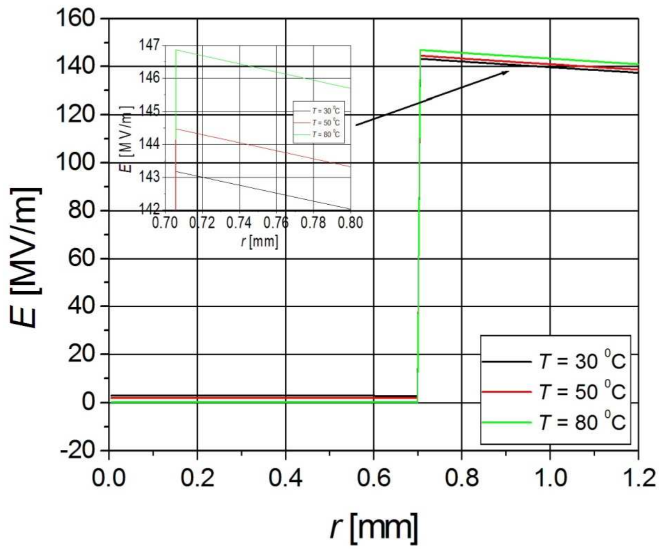

Fig. 8: Variation of the electric field strength with coordinate *r* in presence of the superficial charge ρ_s (*x* = 0, *y* – variable, ρ_s = 2.73 mC/m^2)

Electro kinetic quasi-stationary regime

According to IEC 60840 and IEC 62067, the operating temperature of the conductor is 70ºC. Because the operating temperature of the cable accessories is considered equal or greater than that of cable, it is considered that the joint studied in the present work operates, also, at 70ºC.

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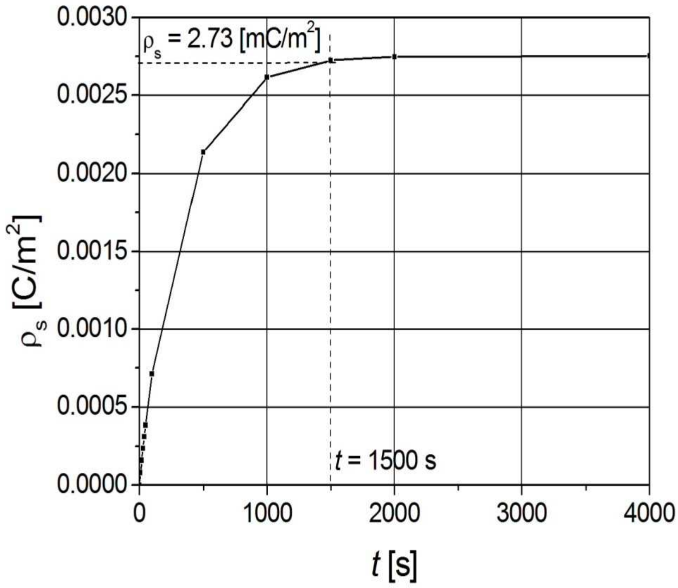

Fig. 9: Variation of charge density ρ_s with time (*x* = 0, *y* = 0.7 mm, *T* = 70 ºC)

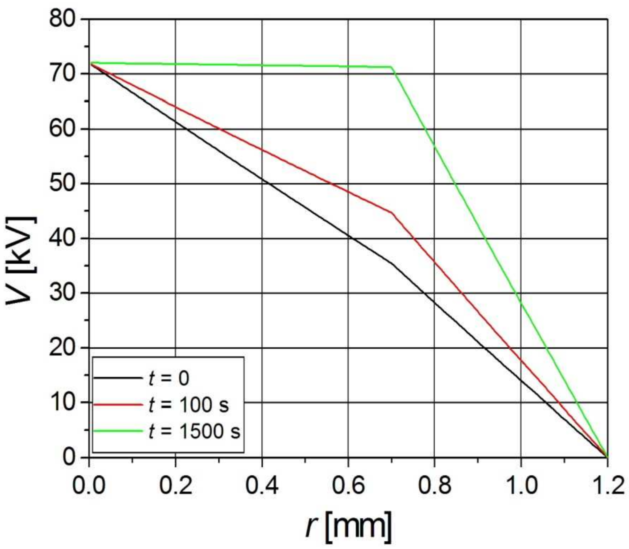

Fig. 10: Variation of potential with coordinate *r* at different instant *t* (*x* = 0, *y* – variable, *T* = 70 ºC)

Figure 9 presents the variation of superficial charge density ρ_s in time. It was found that superficial charge accumulates with the increase of the voltage time application. In order to achieve the calculated value ρ_s = 2.7 mC/m^2 (Table 2) the voltage should be applied at least 0.5 h. After 1 hour the charge density remains constant over time.

Figures 10 and 11 show the variation of the potential *V* and the electric field strength *E* with coordinate *r.* It is found that if the voltage application time increases, the slope of the potential became less sudden. On the other hand, with increasing the voltage application time the electric field increases, near the interface, twice to those at *t* = 0.

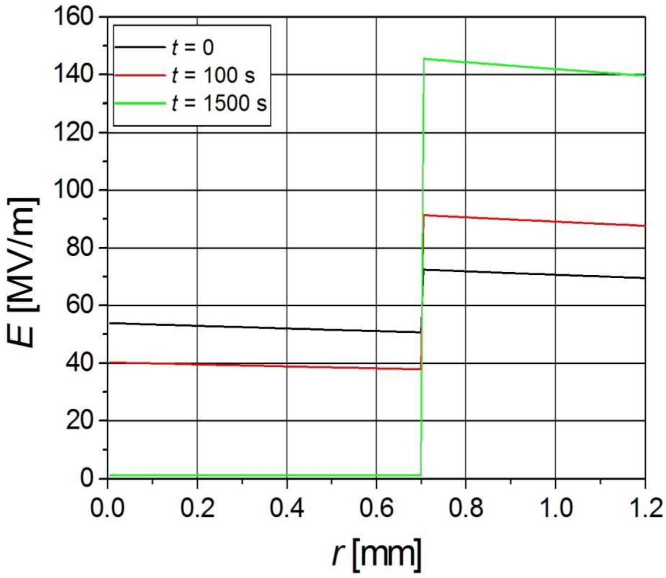

Fig.11: Variation of the electric field with coordinate *r* at different instant *t* (*x* = 0, *y* – variable, *T* = 70 ºC)

CONCLUSIONS

Charge accumulated at the interface of two dielectrics produce a perturbation of the electric field distribution. This perturbation is more important as the charge density value is higher.

The electric field and potential increase with the temperature, near the interface.

The electric field near the interface increases with the voltage application time. This phenomenon is dangerous especially for DC cables.

Experimental determination of the charge density at the interface in order to validate the model for computation of ρ_s, will be presented in a forthcoming paper.

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