ACCUMULATION AND EFFECTS OF SPACE CHARGE IN DIRECT CURRENT CABLE JOINTS. PART I: MODEL AND METHODS FOR SPACE CHARGE DENSITY COMPUTATION

LUCIAN VIOREL TARANU, PETRU V. NOTINGHER, CRISTINA STANCU

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Part I of this paper presents a cylindrical two-layer insulation model and two methods (A and B) for determining the space charge density in the insulation (dual insulation) of dc cable joints. The method A is based on the material parameters (electrical conductivity and permittivity) and the method B - on electroacoustic pulses. The values of the electrical conductivity for different temperatures and electric fields are computed using some experimental results and equations specific to each material. The equations used to compute the electrical conductivity, the electrical field and the superficial space charge densities at the interfaces between the joint's insulation layers are also presented. Finally, the values and the variations of the electrical conductivity with the electric field and temperature are presented and analyzed.

1. INTRODUCTION

Due to the remarkable advantages that dc power transmission has, compared to that in ac, (higher energy transmission capacity, lower conductor losses, no electromagnetic interference and skin effect, low corona effect losses, reduced magnetic field, lower impact on the environment, etc.), over the last few years there have been considerable developments (in Europe, Asia and North America) of networks of polymeric insulated cables that can operate at very high voltages (from 500 kV currently and up to 800 or even 1100 kV) in the near future [1, 2]. Since the sections of high voltage cables have reduced lengths (1 ... 10 km), for the transmission of energy over long distances several sections are required, connected together with joints [2]. In the last decade, great efforts have been made to develop joints with extruded polymeric insulation materials, such as XLPE, EPDM, EPR, silicone rubber etc. (Fig. 1, [3]).

On the other hand, consumer demand for the quality of energy provided by the energy suppliers has considerably increased. The availability of an energy supply system is one of the key factors in establishing a power supply, and the availability values required today are very high: a domestic user in the EU requires a 99.98 % availability, whilst an industrial one requires 99.996 % [4]. An ideal power supply is that which is always available, with the voltage and frequency within acceptable limits and with a pure sinusoidal voltage wave [1].

The most obvious electric power failures are power outages (power interruptions from a few seconds to several hours) and voltage dips (where the voltage reaches a low value for short duration (from 10 ms to 60 s)) [4]. Obviously, long-term interruptions are a problem for all consumers, but many operations are very sensitive even at very short interruptions: continuous flow processes (paper industry etc.), successive and continuous operations, or in many stages (semiconductor industry etc.), data processing (stock exchanges, value exchanges etc.) etc. The statistics made in last year's shows that joints are responsible for 52 % of premature removal from operation of transmission and distribution lines of electricity (Fig. 2, [5]).

Premature failure of the joint is due, especially, to the degradation of the insulation [6], generated by the intensification of the thermal, electrical and mechanical stresses during operation. This intensification is due to manufacturing defects (peeling of insulation layers, cavities, impurities etc.), partial discharges, charge injection from electrodes, separation of space charge in the bulk and at the interfaces of insulation layers, local increases of temperature etc. The accumulation of space charge in the volume of the insulation is due to the byproducts resulted from the technological processes of their manufacture, charge injection from electrodes, chemical degradation (fracture of the molecules) of the insulation, development of electric and water trees etc., and has as a main effect the local intensification of the electric field during the operation of the joint and, of course, of the residual electric field (after the power-off of the cable lines of which the joints are a part of). Or, the increases of the residual electric field values could be extremely hazardous for dc joints operating at high and extremely high voltages.
charge density determination are described. Also here, the variations of the electrical conductivity for different temperatures and electric fields are shown and analyzed.

The results regarding the superficial charge density are presented and discussed in Part II.

2. COMPUTATION OF THE CHARGE DENSITY

2.1. METHOD A

2.1.1. ELECTRIC FIELD AND CHARGE DENSITY

Because the electrical conductivity depends on the electric field, the computation of the field is needed. The computation of the electric field \( E \) and surface charge density \( \rho_s \) were performed in a cylindrical domain \( D = D_1 \cup D_2 \), consisting of subdomains \( D_1 \) (of thickness \( g_1 \), relative permittivity \( \varepsilon_{r1} \) and dc conductivity \( \sigma_{dc1} \)) delimited by the surfaces \( S_1 \) (of radius \( r_1 \)) and \( S_{12} \) (of radius \( r_{12} = r_1 + g_1 \)) and \( D_2 \) (of thickness \( g_2 \), relative permittivity \( \varepsilon_{r2} \) and conductivity \( \sigma_{dc2} \)) delimited by the surfaces \( S_{12} \) and \( S_2 \) (of radius \( r_2 = r_1 + g_1 + g_2 \)) (Fig. 3). All the cylindrical surfaces \( S_{11}, S_{12}, S_2 \) have the same generator of length \( l \), higher than their radii. A value of potential \( V_1 \) has been assigned to \( S_1 \), whilst a value \( V_2 = 0 \) (ground potential) has been set on \( S_2 \).

2.1.2. EQUATIONS

Considering the domain \( D \) linear, isotropic and inhomogeneous, respectively

\[
\vec{D}(P) = \varepsilon(P)\vec{E}(P), \quad P \in D,
\]

\[
\vec{J}(P) = \sigma(P)\vec{E}(P), \quad P \in D,
\]

and the electrostatic generalized field regime, the following equations were used:

- Electric flux law:

\[
\text{div} \vec{D}(P) = \rho_v(P), \quad P \in D,
\]

- Charge conservation law:

\[
\text{div} \vec{J}(P) + \frac{\partial \rho_v(P)}{\partial t} = 0, \quad P \in D,
\]

- Potential theorem:

\[
\vec{E}(P) = -\text{grad}V(P), \quad P \in D
\]

where \( \vec{D}(P) \) represents the electric induction, \( \vec{E}(P) \) – electric field, \( \vec{J}(P) \) – electric current density, \( \rho_v(P) \) – volume charge density, \( V(P) \) – electric potential, \( \varepsilon(P) \) – electrical permittivity and \( \sigma(P) \) – electrical conductivity in a point \( P \in D \) at time \( t \).

2.1.3. BOUNDARY CONDITIONS

On the surfaces \( S_1 \) and \( S_2 \) Dirichlet conditions were imposed at each time \( t \):

\[
V(M) = V_1, \quad M \in S_1,
\]

\[
V(M) = V_2, \quad M \in S_2.
\]

On the discontinuity surface \( S_{12} \) the following conditions were imposed at each time \( t \):

On the other hand, as polymeric materials used for the joints have different physical and electrical properties (electrical conductivity and permittivity), during cable operation, at the insulator-insulator interfaces superficial space charge of density \( \rho_s \) is separated [7, 8]. Using an analytical expression of \( \rho_s \), several researchers have tried to determine its values at the interfaces between layers of cross-linked polyethylene (XLPE) and ethylene-propylene-diene-monomer rubber (EPDM) or ethylene-propylene rubber (EPR) [9, 10].

During operation, new charge carriers appear, the space charge density increases, both inside the homogeneous areas and at the interfaces between them. Unlike the operation in ac, in dc the space charge accumulates continuously, producing a supplementary electric field that exceeds the field corresponding to the voltage at which the cable operates [11]. The accumulation of space charge is, also, closely linked to the quality of the interface between the two insulating materials (surface roughness [12] etc.), influenced by the technological parameters (pressure, temperature) of joint manufacture [13]. Therefore, in some areas of joint insulation (near the interfaces between heterogeneous areas, in cavities etc.) the electric field greatly intensifies, reaching values several times higher than those existing in the absence of charge. As a result, there is an increase in partial discharges and a reduction in the inception voltage of the electrical and water trees, and, respectively, insulation breakdown.


In previous works [2, 24–26], the influence of the properties of the insulation components of a joint on the accumulation of space charge at the interface was analyzed, and the electric field distribution was calculated.

In this paper, for the computation of the superficial charge density accumulated at the interface of a joint cable model layers two methods are presented. The first one (A) uses an equation that includes the material parameters (the electrical permittivity and conductivity) and the second one (B) is based on the use of some electroacoustic pulses. In Part I, only the methods and equations used for space
where \( \bar{n}_{12} \) is the normal versor on \( S_{12} \), \( \rho_s(M) \) represents the surface charge density in a point \( M \in S_{12} \) at time \( t \), \( \varepsilon_{11} = \varepsilon_{12} = \varepsilon_0 \) and \( \varepsilon_0 \) is the vacuum permittivity.

### 2.1.4. INITIAL CONDITIONS

It is considered that, at the moment of applying the voltage \( t = 0 \), there is no electric charge on the discontinuity surface \( S_{12} \), respectively that:

\[
\rho_s(M) \bigg|_{t=0} = 0, \quad M \in S_{12},
\]

### 2.1.5. MATERIAL PROPERTIES

To initialize the computation of the electric field, the values of dc conductivity \( \sigma_{dc} \) and relative permittivity \( \varepsilon_r \) are needed. The electrical conductivity was determined by experiments at various voltages between 1 kV and 20 kV (denoted by \( \sigma_A \) for EPR and \( \sigma_B \) for XLPE, the values presented in [10, 27]) and the real part of complex relative permittivity (denoted by \( \varepsilon_A \) for EPR and \( \varepsilon_B \) for XLPE) was measured at 50 Hz, with values presented in Table 1.

The values of \( \varepsilon_r \) were considered independent on the thermodynamic temperature \( T \) and on the electric field \( E \). For the conductivity it was considered that the influence of \( T \) and \( E \) cannot be neglected, respectively that \( \sigma \) has an expression of the following form [30]:

\[
\sigma(E, T) = A_T(T) f_E(E),
\]

where \( A = \prod_i f_{C_i}(C_i) \), and \( f_{C_i}, f_E \) and \( f_T \) are dependent functions on the charge carriers concentrations \( C_i \), on \( E \) and, respectively, on \( T \).

In this paper it was considered that the values of \( C_i \) are constant in regards to \( E \) and \( T \) and \( \sigma \) was computed in \( D_1 \) with equation

\[
\sigma_A(E, T) = A_A \exp\left(-\frac{E_a A}{kT}\sinh((a_A T + b_A) \ln E)\right),
\]

proposed by the authors, for EPR, in [10], and in \( D_2 \) with the equation

\[
\sigma_B(E, T) = A_B \exp\left(-\frac{E_a B}{kT}\sinh((a_B T + b_B) \ln E)\right),
\]

proposed by the authors, for XLPE, in [27], where \( \sigma_{a,b} \) represent the conductivity in a point, \( E_{a,b} \) – activation energies, \( a_{a,b} \) and \( b_{a,b} \) and \( a_A \) – material constants for EPR (A) and XLPE (B) (Table 1), \( T \) – temperature (measured in K), \( T = 0 + 273.15 \) and \( k = 1.3810^{-23} \) J/K – the Boltzmann’s constant.

### 2.1.6. CHARGE DENSITY

The value of the surface charge density \( \rho_s(t) \), separated at the instant \( t \) after applying the voltage \( U = V_1 - V_2 \) at the \( S_{12} \) interface, has been calculated with the equation [8]:

\[
\rho_{s,cal}(t) = \varepsilon_B E_2(\eta_2, t) - \varepsilon_A E_1(\eta_1, t),
\]

where \( E_{1,2}(\eta_1, \eta_2, t) \) represents the values of the electric field on the \( S_{12} \) interface at instant \( t \).

### 2.1.7. ELECTRIC FIELD

Considering that the material parameters \( \varepsilon_A \) and \( \sigma_A \) are constant in \( D_1 \) and that, at instant \( t = 0 \), at the \( S_{12} \) interface there is no electric charge (respectively, \( \rho_s(0) = 0 \)), using equations (1), (3) and (5), the electric field expressions (15) – in \( D_1 \) and (16) – in \( D_2 \) – have been obtained.

\[
E_1(t) = \frac{U}{r} \exp\left(-\frac{\varepsilon_A \ln \frac{n_2}{n_1} + \varepsilon_B \ln \frac{n_2}{n_1}}{\eta_1} \right) e^{-t/\tau},
\]

\[
E_2(t) = \frac{U}{r} \exp\left(-\frac{\varepsilon_A \ln \frac{n_2}{n_1} + \varepsilon_B \ln \frac{n_2}{n_1}}{\eta_1} \right) e^{-t/\tau} + \frac{\sigma_B}{\varepsilon_A \ln \frac{n_2}{n_1} + \varepsilon_B \ln \frac{n_2}{n_1}}.
\]

With the equations (15) and (16) the values of the electric field \( E(t) \) can be calculated in any point from \( D_1 \) and with (14) – the charge density at the interface \( S_{12} \) (\( \rho_s(t) \)).

As \( \sigma \) depends on \( E \) (respectively, on \( r \)), analytical expressions of the electrical field cannot be obtained, and the computation of its values was performed using a
numerical method, utilizing the COMSOL Multiphysics® software. The equations (15) and (16) were used to initiate the numerical calculation program of the electric field.

2.2. METHOD B

Method B uses some electroacoustic pulses that allow measuring a volume space charge density \( \rho_v \). The volume density of space charge in our models was measured using a pulsed electroacoustic (PEA) space charge measuring setup at the Laboratory of Innovation Technology (LIT), University of Bologna [29], in the absence and in the presence of various dc voltages (under 100 kV), on cylindrical samples described in subparagraph 3.1 of the paper. The PEA signal has been acquired at different time instants (faster in the beginning – approx. 1 second apart – and slower – approx. 1 minute apart – at about 1 hour of measurement time) on an oscilloscope controlled with an application using the LABVIEW software. The PEA measurement results (the volume density of space charge, \( \rho_v \)) were elaborated from the acquired signal using a deconvolution and calibration procedure for cylindrical samples using a GUI application in the MATLAB software.

Knowing the experimental values of \( \rho_v \), the values of \( \rho_s \) (respectively, \( \rho_{s,exp} \)) were determined with the equation:

\[
\rho_{s,exp} = \left( \frac{\int_0^1 \rho_v(r) r \, dr}{r_a + r_b} \right)
\]

where \( r_a \) and \( r_b \) represent the radii of cylindrical surfaces very close to each other, located at an equal distance on both sides of the \( S_{12} \) interface.

3. EXPERIMENTS

The dc electrical conductivity \( \sigma_{dc} \) and relative permittivity \( \varepsilon_r \) were determined experimentally on flat samples of EPR (of average thickness \( g_1 = 0.484 \) mm) and XLPE (of average thickness \( g_2 = 0.304 \) mm). The computation of \( \sigma \) values for different values of the temperature and electric field was done on the cylindrical joint model presented in subparagraph 2.1.1, with a geometry close to that of the cylindrical samples.

The cylindrical samples have the conductor from aluminum strands (with a diameter of 14 mm), a layer of semiconductor from carbon black (CB) polyethylene (of thickness 0.7÷1 mm), a layer of ethylene-propylene rubber \( S_1 \) (EPR) (of thickness 3.3÷3.7 mm) and a layer of cross-linked polyethylene \( S_2 \) (XLPE) (of thickness 1÷1.2 mm) (Fig. 4). All samples were manufactured at ICME ECAB SA Bucharest, and the manufacturing method is presented in [28].

The manufacturing and conditioning procedures used for the flat samples are presented in [10] for EPR and in [27] for XLPE. The measurement of the \( \varepsilon_r \) values was performed using a Novocontrol impedance analyzer at the Politehnica University of Bucharest (UPB) and for the electrical conductivity a Keithley electrometer connected to a setup at LIT was used (at variable temperatures and electric fields [10]).

Based on the conductivity variation curves obtained at 3 temperatures (30, 50 and 70 °C) and 4 values of the electric field (5, 10, 15 and 20 MV/m) ([10, 27]) and equations (12) and (13), using the Matlab software (with the \textit{fsolve} function from the \textit{Optimization Toolbox} package) the \( E_{a,b}, A_{a,b}, a_{a,b}, b_{a,b} \) and \( \alpha_A \) constants were calculated (Table 1).

4. RESULTS

Introducing these values in equations (12) and (13), the values of the electrical conductivity for different temperatures up to 90 °C and electric field values were computed. A part of the results are presented in Figs. 5–8.
probably, to the decrease with \( r \) for the electric field \( E \).

Also, the conductivity is found to increase in both layers as
the applied voltage increases from 25 to 100 kV, having
values roughly two times higher in EPR and four times
higher in XLPE at \( U = 100 \) kV from \( U = 25 \) kV (Fig. 6).

![Image](https://example.com/image1.png)

**Fig. 7** Variation of the electrical conductivity with time in EPR at the
interface \( \Sigma_{12} \), for \( \theta = 60 ^\circ \) C (1), 80 ^\circ \) C (2) and 90 ^\circ \) C (3)
(Voltage On, \( U = 50 \) kV).

![Image](https://example.com/image2.png)

**Fig. 8** Variation of the electrical conductivity with time in XLPE at the
interface \( \Sigma_{12} \), for \( \theta = 60 ^\circ \) C (1), 80 ^\circ \) C (2) and 90 ^\circ \) C (3)
(Voltage On, \( U = 50 \) kV).

Immediately after applying the voltage, at the points in
EPR adjacent to the \( \Sigma_{12} \) interface there is an important
increase in the electrical conductivity (Fig. 7), followed by
a reduction of its values to the steady state. In the case of
XLPE, in the first seconds there is a pronounced increase in
conductivity (Fig. 8), followed by a slow increase when its
values stabilize. This is due, most likely, to the increases
with time of the electric field values.

When the temperature increases from 60 to 90 \(^\circ\) C, the
electrical conductivity at the points adjacent to the \( \Sigma_{12} \)
interface increases (Figs. 7 and 8). For example, for \( t = 60 \)
s, \( \sigma \) increases 6 times in EPR and 3.5 times in XLPE (Figs.
7 and 8). These increases of \( \sigma \), highlighted in equations
(12) – (13), are due to the temperature rise of the values
of the own energies of charge carriers [7].

For the calculation of the electric field \( E(t) \) and the
superficial charge density \( (\rho_{\text{cal}}) \) at the interfaces of samples
at instant \( t \), the values of the conductivity determined at that
instant \( (\sigma(t)) \) will be used. The values of \( E \) and \( \rho_{\text{cal}} \) will be
presented in the Part II of the paper.

5. CONCLUSIONS

The cylindrical two-layer insulation models of joints
allow to calculate the space charge density at the interfaces
of dc cable joints.

As space charge density depends on the electric field and
material properties (electric conductivity and permittivity)
values, the electric field and the electric conductivity were
calculated and their variations with temperature was shown.

Increasing the temperature and the electric field leads to
a considerable increase (with approx. 3 – 4 orders of
magnitude) in the electrical conductivity of the insulating
layers. As the variations with temperature for the
permittivity are less important than those of the
conductivity, the increase of the conductivity leads to a
significant increase of the superficial charge density, and,
thus, of the electric field in the cable joints (see Part II).

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