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Conductivity Measurements and Space Charge Inference in Polymeric-insulated HVDC Model Cables

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Abstract: The general objective of this work is to obtain a better understanding of polymeric-insulated HVDC cable characteristics, especially related with conduction current and space charge features. It goes with the building of a model of conductivity vs. field and temperature in order to forecast field distribution in cables. Conduction current was measured in miniature of HVDC power cables with construction 1.5mm polymer insulation thickness, 0.7mm inner semiconductor, 0.15mm outer semiconductor and conductor diameter of 1.4mm. Current measurements were performed with applied voltage varying from 2kV to 30kV and temperature in the range from 30°C to 90°C. The time of polarization (voltage applied) and depolarization (short-circuit) were 1h/1h.

The results show that there is not a single conduction mechanism for all applied fields and in the all temperature range. The conductivity is clearly non-linear at voltages above about 10kV (field at inner semicon of 10kV/mm), the threshold being dependent on temperature. With the increase in thermal and electrical stresses, transient currents appear characteristic of processes with massive charge injection at the electrode and therefore the treatment of transport based on a homogeneous conductivity is no longer a sufficient hypothesis.

Index Terms — HVDC Cables, polymeric insulation, XLPE, conduction current, conductivity, space charge

I. INTRODUCTION

In the last 20 years, research has been done for design and development of insulating material, especially polymers, for HVDC cables. The space charge features and conductivity of the insulation versus field and temperature are important topics as they drive the field distribution within the insulation of the cable and therefore directly impact on the design of the cable. The non-linear character of conductivity and its strong temperature dependency bring strong redistribution of the electric field, which in turn manifests by space charge build-up in the cable. One of the processes whereby space charge settles in the material is linked to these conductivity gradients.

To provide an interpretation of space charge profile measurements, it is therefore important to know about the dependencies of conductivity vs. field and temperature. The purpose of the work presented in this paper is to obtain the conductivity characteristics of HVDC model cables as function of temperature and voltage by conduction current measurement.

II. THEORY

In a general way, the current density is the current flowing through the cross-section of a conductor, which consists of the amount of transferred charge per unit time (second). Since the transferred charge is equal to density of charge (ρ) with velocity (v) at the cross-section in time, then current density (J) is equal to quantity of charge with proper velocity. Charge velocity depends on electric field (E) through a proportional coefficient which is charge mobility (μ). So based on Ohm's Law this relation can be expressed by equation below:

$$J = \rho \cdot v = \rho \cdot \mu \cdot E \quad (1)$$

and relation with conductivity (σ),

$$\sigma = \rho \cdot \mu = \sum n_i q_i \mu_i \quad (2)$$

There are few assumptions about relation between conductivity and temperature [1] that; “temperature influences the concentration of charge carriers and their mobility; the carriers transport is thermally activated; the carriers are located in potential wells that limit their mobility”.

From these assumptions, due to a change in temperature, conductivity can be changed since the mobility also changes depending on temperature. Therefore, based on Arrhenius equation, the relation between conductivity and temperature (T) through thermal activation (ϕ) is given by:

$$\sigma = \sigma_0 \exp\left(-\frac{\phi}{k_B T}\right) \quad (3)$$

where σ_0 is the reference value of conductivity, k_B is Boltzmann's constant (8.62×10^{-5} eV/K), and T is temperature in K. Therefore, conductivity depends on electric field and temperature, which for polymeric insulations has been modeled using several expressions [1, 2].

To provide an analytical model of the conduction as a function electric field and temperature, we considered the

expression for high-field ionic conduction, a relevant mechanism in HVDC polymeric-insulated cables [1-4]:

$$\sigma(E, T) = A \exp\left(-\frac{\phi}{k_B T}\right) \frac{\sinh(B|E|)}{|E|} \quad (4)$$

where A and B are constants.

III. EXPERIMENTAL

A. Materials

Samples from model cables, called minicable were considered in this research. Minicables are special cables that were manufactured for research purposes. With their reduced size – see Fig.1, these cables can reduce the cost of production, transportation and testing. Related with the research, especially for measurement of conductivity and space charge, with their geometry, (conductor diameter of 1.4 mm, diameter of outer insulation 5.8 mm), applied voltage is moderate: with this geometry, voltages (in kV) represent roughly maximum electric field (in kV/mm) at the inner semiconductor (SC). These cables have 3 layers from conductor: inner SC, polymer insulation and outer SC.

B. Set-up and procedure

Prior to conductivity measurements, the cables were thermally treated for 2 days at 60°C. Cables were peeled and prepared in 4 layers structure from conductor, inner SC, insulation, outer SC and aluminum foil. Cables were prepared for 3 cell set-up, as depicted in Fig. 2, where side cells act as ground protection to block the surface current. The active length of cable during current measurement was 20 cm.

The experiments were performed at 30°C to 90°C in steps of 10°C. The conduction current were measured under 2kV, 4kV, 6kV, 8kV, 10kV, 13kV, 16kV, 19kV, 22kV, 25kV and 30kV, but at 80°C and 90°C, measurement were achieved only up to 22kV, since at these temperatures, the insulation strength could be affected. The oven temperature was stabilized to the desired temperature, and then measurements were performed with duration 1 hour for voltage ON and 1 hour for voltage OFF, for all voltage levels. Then, for each temperature, full measurements required duration more than 22 hours including transition process. Since the measurement needed long duration with various voltage levels, a different sample was used for every temperature level.

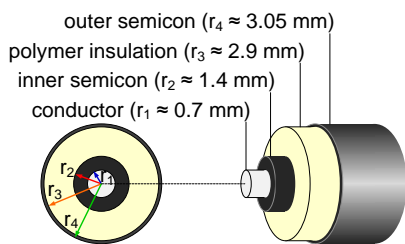


Figure 1. Sample cable section

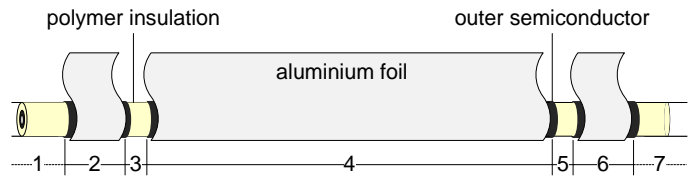


Figure 2. Cable set-up in 4 layer structure: 1&7 = 350mm, 2&6 = 30mm, 3&5 = 10mm, 4 = 200mm

IV. RESULTS AND DISCUSSION

For the results, conduction currents vs. field and temperature were obtained after 1 hour measurement assuming it is a steady current. For cases where noisy currents were measured, averaging over reliable data points was achieved. The obtained field-current characteristics are shown in Fig. 3.

From 1h current measurement, it is clearly seen that under constant electric stress (considering applied voltage) and temperature, for most of measurements there is a transient current regime, as discussed below. It must be stressed that 1h polarization is not enough to reach a steady state current, especially at low temperature/low field.

From these results, as example for 30°C as shown in Fig. 4, it can be seen that there are transient currents after the voltage application, with in many instances a peak in the transient current. The shapes of current transients for all temperatures/fields follow the general 4 curves depicted in Fig. 5. The curves are classified depending on time to peak of the current. The below pictures may appear as a combination of continuously decaying curve (C) and some transient composed of a peak in current followed by a slow decrease to steady state. There are cases where the minimum in current is at short time, not in the steady state (schematized by curve A). The most classical shape in transient current is as curve C. One of the reasons for this is the build-up of orientation polarization in the material.

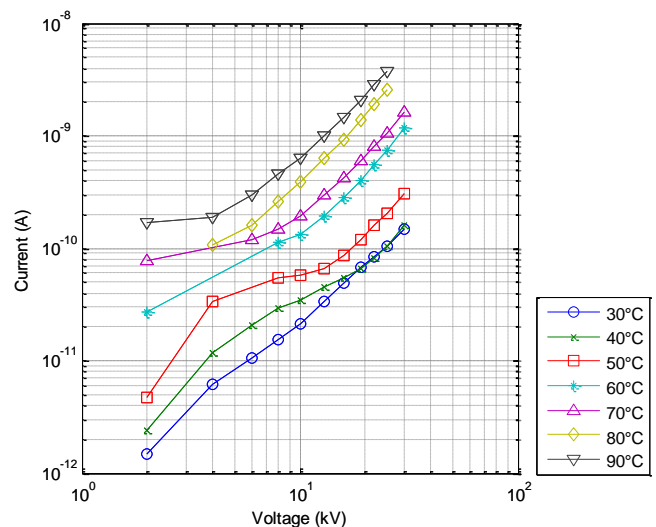


Figure 3. Conduction current results on mini-cables as a function of field for different temperatures.

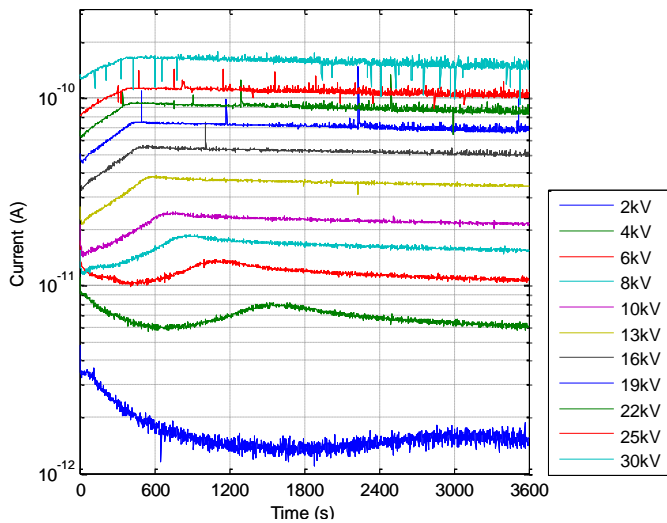


Figure 4. Transient current results at 30°C on mini-cable

When dipole orientation changes with time, the time-dependent bound-charge density creates a polarization current. So total transient current is composed of a conduction current (being constant or not in time) plus this transient polarization current. Normally charging and discharging polarization currents are symmetrical: this is a criterion to identify the process. Even if polyethylene is a non-polar material, there are some residues in it that are polar groups.

Let us now consider transport contributions to current. Theoretically, if at time = 0, there is no charges in the insulation, then the current must be increasing in time (at short time), owing to the fact that the external current in the circuit is the average over volume of the transport current. However, not often such transient features are seen, because they can be compensated by the above described polarization current. Once charges have been injected, they move through the insulation and the space-averaged transport current increases. When the front of charges reaches the opposite electrode, the current evolves (slow decrease) towards steady state.

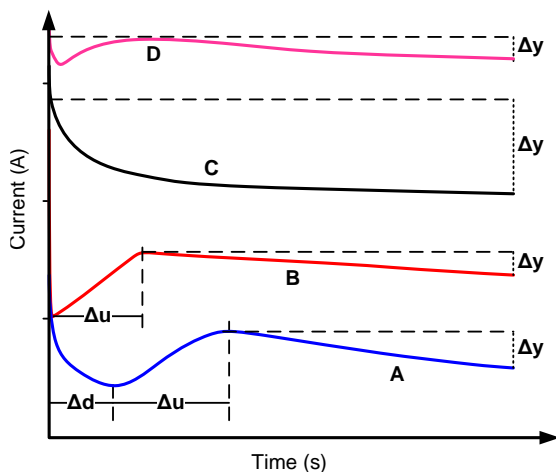


Figure 5. Curve models of current measurement results

We can reasonably suppose that the 4 typical curves described in Fig. 5 are a superposition, of these two basic mechanisms, the relative amplitudes being varying along with the characteristic times.

We consider curves can be described by the following features: i/ time of current to decrease due to polarization process (Δd), ii/ time of current to increase (Δu) to reach the peak current; and iii/ current decrease from peak to quasi-steady state (Δy). Curve A shows the two time constants. In curve B, Δu is very fast ($\Delta u_B \ll \Delta u_A$), then only Δd is seen. In curve C not only Δu but also prediction that Δd is too fast ($\Delta d_C \ll \Delta d_A$), then the peak current is not seen. For curve D, besides Δd is very fast, we observed another current peak.

Consider just the transient current peak. There can be several reasons for the appearance of this process:

- 1) Due to injection and transport of charges through the insulation – in that case, the carrier transit time would be measured;
- 2) A specific case of 1) associated with a front of charges observed by space charge measurements in the same samples like shown in Fig. 6. However, the transient front of charges is slower in PEA: 30min to 1h at RT (which seems not consistent with data presented here); slower with increasing voltage, not faster like in the current results.
- 3) Due to an association of field dependent conductivity and divergent field (cylindrical geometry) where current transient could correspond to the equilibration of the field distribution, in this case then one need to compute conductivity in voltage and temperature variation.

In respect to hypothesis 1), we consider the time to peak of conduction current. The voltage and temperature variations of the time to current peak are shown in Fig. 7. From this transit times, we have estimated the velocity of the front of charges and then the mobility of carriers from the average field, see (1) and (2). The obtained values of mobility are in the same range as those given by other authors (Seanor, Davies, Tanaka and Calderwood) in Ref. [5], i.e. $5.86 \times 10^{-13} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ to $2.82 \times 10^{-13} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ for varying voltage at 30°C, and $1.65 \times 10^{-11} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ to $2 \times 10^{-11} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$, for varying voltage at 60°C.

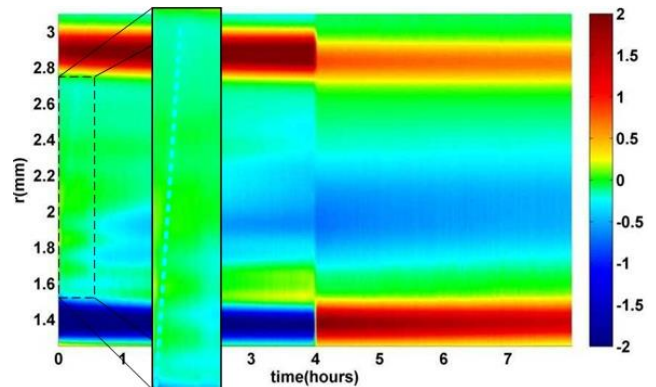


Figure 6. Charge density distribution measurement on minicable by pulsed electroacoustic method under -30kV with a thermal gradient of 12°C (72 / 60°C at in/out-SC)

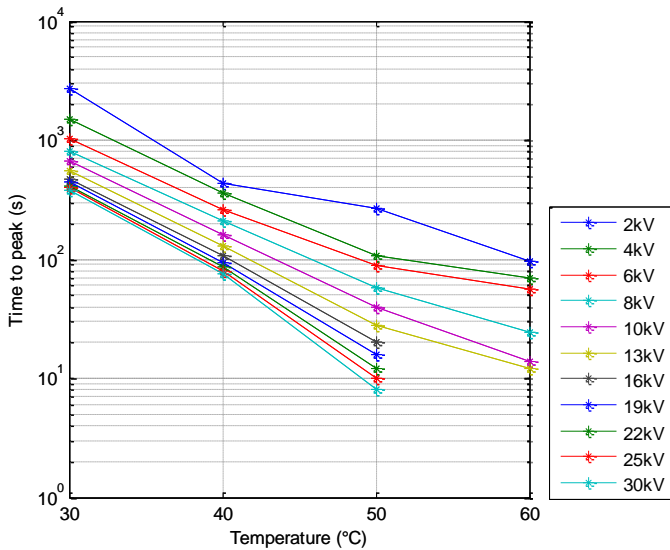


Figure 7. Time to peak of current vs. temperature

Thermal activation energy of Arrhenius-equation (3) was obtained by plotting the conduction current vs. reciprocal temperature in K, cf. Fig. 8. Linear fit to the data provided a thermal activation energy of 0.57 eV in average (for data under different voltages). Data at different fields were fitted to (4) to obtain a parameterized equation of conductivity as:

$$\sigma(E, T) = 31.85 \exp\left(-\frac{0.57}{k_B T}\right) \frac{\sinh(9.1 \times 10^{-8} |E|)}{|E|} \quad (5)$$

where the field is in V/m, and conductivity in $\Omega^{-1} \cdot \text{m}^{-1}$. Equation (5) is relevant to high-field ionic conduction as well as to hopping conduction, cf. [6] and references therein. So, at the present stage, it is not possible to identify the actual transport mechanism.

Fig. 8 shows a superposition of measured and fitted current using (5). The conductivity becomes clearly non-linear in field beyond an apparent threshold of about 13kV/mm. The non-linear feature of conductivity can constitute an advantage for the design of cables, as it contributes to field grading along the cable radius: In condition of conductivity gradient as in cables, it tends to homogenize the field and to balance out the stress inversion process associated with the temperature gradient, i.e. field at the outer SC becoming higher than that at the inner SC of the cable [4]. The activation energy obtained in the present work is rather on the lower range compared to literature data on XLPE. For example, Hestad et al. [7] measured activation energies close to 1.5eV using the same principle as herein, working with XLPE-insulated MV cables. The low activation energy of conductivity is an objective for the insulation of HVDC cables as the stress inversion process is strengthened when high conductivity gradient along the cable radius is present [4].

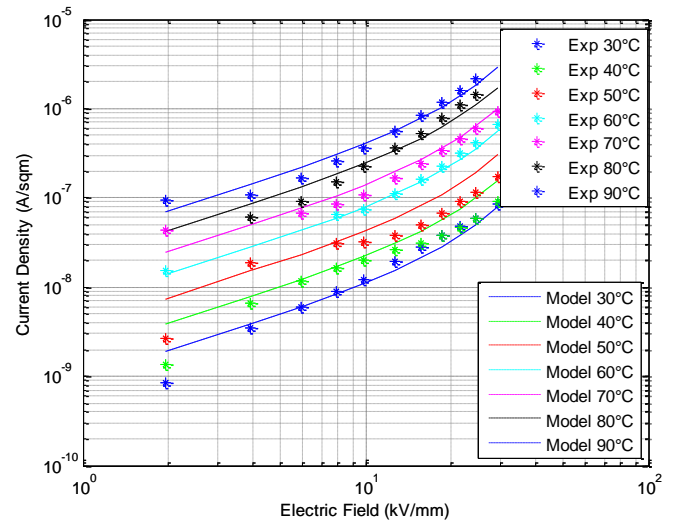


Figure 8. Fit of conduction current data to the model

V. CONCLUSIONS

Conduction currents were measured on polymeric-insulated HVDC model mini-cables. Results revealed transient currents, with shape depending on field and temperature. Besides decaying transient due to polarization processes, a peak in current was observed, time to peak decreasing with increasing field or temperature. This feature presumably arises from the injection of charges and their transit through the insulation. However, it seems not related to the front of charge shown in space charge measurements. The thermal activation energy for conductivity was estimated to 0.57 eV, and a functional dependence of conductivity vs. field and temperature has been obtained. From the modeling, conductivity threshold can be identified at about 13kV/mm. Work is in progress to compare measured and predicted space charge and field profile within the cables under thermal gradient.

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