Calculation and Measurement of Space Charge in MV-size Extruded Cables Systems under Load Conditions

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Abstract: A load current in dc high voltage cables results in a temperature drop across the insulation and hence a radial distribution of the insulation conductivity is found. Direct consequence is an accumulation of space charge in the bulk of the insulation, that may significantly affect its reliability.
This phenomenon was modeled in terms of the macroscopic properties of the cable insulation and a numerical procedure was developed for the calculation of the time-dependent space charge and electric field in extruded-type cables.
Results of calculations were compared to those of space charge measurements performed on MV-size XLPE cables at different values for the temperature drop. The analysis of the results indicates that the space charge induced by the temperature drop is measurable and that its magnitude and location can be reasonably well estimated by means of the proposed numerical procedure.
Moreover, different space charge accumulation mechanisms could be distinguished taking into account the knowledge obtained of the space charge distribution induced by the temperature drop.

INTRODUCTION

From basic electromagnetic field theory it follows that space charge accumulates within the insulation of dc cables when and where a conductivity gradient is found in the presence of an electric field [1]. The conductivity is a function of temperature and, to a lesser degree, of the electric field. Therefore, a conductivity gradient is present in the cable insulation when the temperature and/or the electric field distribution are not uniform. In practice, both conditions are true for loaded dc cables and hence space charge is expected to accumulate.
Nevertheless, there is only little experimental evidence of this phenomenon, e.g. [2-4]. The main reasons for this are:
- The amount of charge is rather small, in the order of a few hundreds of mC/m^3 for XLPE-insulated cables under typical stress conditions [1].
- The charge is distributed through the entire insulation bulk. Such a "flat" distribution of charge is detected by the measuring system only if the frequency range of the measuring system is sufficiently broad [6]. For instance, for a 1-mm thick XLPE sample, the lower cut-off frequency of the measuring system should not be higher than 300 kHz.
- The charge distribution takes a certain time to reach a quasi-steady state. This time depends on the value of the insulation conductivity and can be as long as several weeks for tests done at room temperature and at moderate fields.
In addition, other mechanisms exist for the accumulation of space charge. In particular charge injection from the electrodes has been shown to be significant when the temperature and the applied field are sufficiently high [5, 7].
In this paper, the results of space charge measurements are presented on MV-size cables with a temperature drop applied across the insulation. Experimental results are discussed and compared to the simulations using a numerical procedure which calculates the dynamic space charge distribution induced by the non-uniform conductivity of the insulation.

MACROSCOPIC MODEL

The system to be studied consists of the cable insulation, which is generally in non-ohmic contact with the electrodes. This is modeled by considering an equivalent insulation in ohmic contact with the electrodes. The conductivity of the equivalent insulation is derived by fitting the conductivity function with the experimental results derived from conduction current measurements [8]. The conduction current measurements were performed on the cable insulation in contact with semicon electrodes. In this way, the equivalent insulation includes the effect that the electrodes have on the conduction process.

Physical model

The following three equations describe the electrical behavior of a non-homogeneous weakly conductive material:

$$\vec{j} = \sigma \cdot \vec{E} \qquad \text{Ohm's law} \qquad (1)$$

$$\rho = \nabla \cdot \left(\varepsilon_0 \cdot \varepsilon_r \cdot \vec{E}\right) \qquad \text{Gauss' law} \qquad (2)$$

$$\nabla \cdot \vec{j} = -\frac{\partial \rho}{\partial t} \qquad \text{current continuity} \qquad (3)$$

where j is the current density, E is the electric field and ρ the space charge density. By combining these three equations, the space charge is given by:

$$\rho = -\frac{\varepsilon_0 \cdot \varepsilon_r}{\sigma} \cdot \frac{\partial \rho}{\partial t} + \vec{j} \cdot \nabla \left(\frac{\varepsilon_0 \cdot \varepsilon_r}{\sigma} \right) \tag{4}$$

Equation (4) shows that when the current density is non-zero, space charge accumulates if the conductivity σ or the relative permittivity ε_r are not uniform across the insulation.

The permittivity of the insulation is considered constant within the range of temperatures and fields adopted in this work.

On the other hand, the conductivity is to be considered a function of both temperature and electric field. The following empirical equation was used for taking into account the field and temperature dependency of conductivity:

$$\sigma(T,E) = \sigma_{ref} \cdot \left(\frac{E}{E_{ref}} \right)^{\nu} \cdot \exp\left[\alpha \cdot \left(T - T_{ref} \right) \right] \tag{5}$$

where σ_{ref} is the conductivity at temperature T_{ref} and at an electric field E_{ref}, whereas ν and α are constants.

Model implementation

The model was implemented by means of a numerical procedure assuming the radial space charge distribution is the same along the whole cable, independently on the axial position and on the angular position. Therefore, a one dimensional configuration was used.

The insulation is divided into 201 annulus-shaped partitions of thickness Δr (see Figure 1). Each partition is characterized by the following quantities, which are in general a function of time t and radius r: temperature $T(t, r)$, electric field $E(t,r)$, current density $J(t,r)$, space charge density $\rho(t,r)$ and conductivity $\sigma(T(t,r),E(t,r))$.

The above specified quantities are assumed to be constant within each partition and within a time interval Δt.

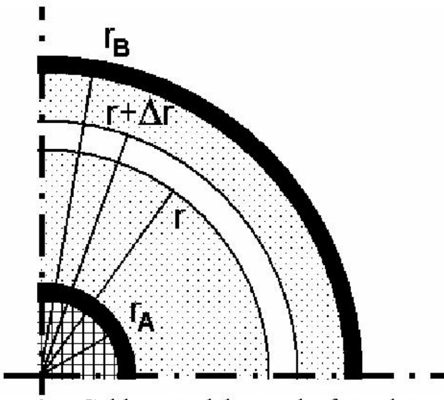
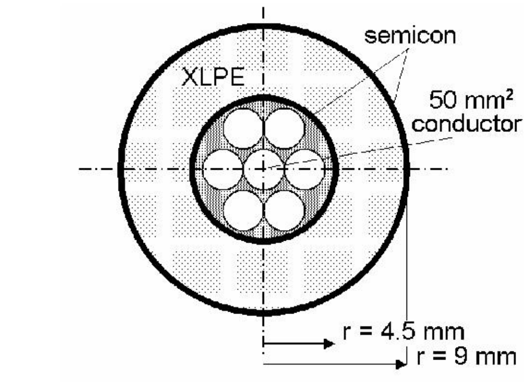


Figure 1: Cable model used for the numerical procedure. r_A = inner semicon, r_B = outer semicon.



(4)

Figure 2: Cross-section of the MV-size XLPE cable.

After all quantities for the initial conditions have been calculated, the time is increased by an exponentially increasing time step Δt and the quantities are recalculated. This is repeated until the time has reached a predefined value or the calculation has converged toward a solution.

The calculation was considered converged if the divergence of the current density was smaller than a predefined error. In fact, when the divergence of the current density is zero, the actual electric field has reached a purely resistively-distributed state.

TEST SPECIMENS, TEST SET-UP AND TEST PROCEDURE

Space charge measurements were performed on 7-m long MV-size XLPE cables, with an insulation thickness of 4.5 mm. In Figure 2, a cross-section of a MV-size cable is shown. In order to expel volatile cross-linking by-products, all cables were thermally treated at 80 °C for 20 days before any testing. Tests were performed at different temperature conditions and at different values of the applied dc voltage. A temperature drop was realized across the insulation by inducing a current in the test specimen that was arranged in a loop. The temperature was measured on a dummy loop with the same characteristics as the test specimen. Four temperature sensors were placed on the dummy loop, two at the conductor and two at the outer semicon.

Measurements started only after all sensors had indicated that the temperature had reached a stable value. The Pulsed ElectroAcoustic (PEA) method was used to measure the dynamic space charge distributions.

RESULTS

Positive space charge was measured within the insulation bulk of the studied cables in the presence of a temperature gradient. For a given applied field, this charge increases with the temperature drop, whereas, for a given temperature distribution, the amount of charge increases with the applied electric field. This is shown in Figure 3, where the maximum value of the measured space charge is reported for different temperatures and for different values of the applied voltage.

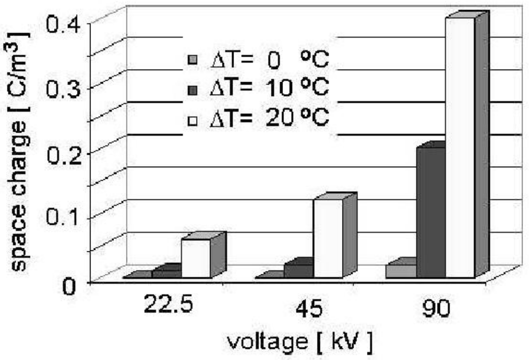


Figure 3: Maximum value of the accumulated space charge in cable specimens after 5.6 hrs of polarization.

In addition, hetero-charge was detected near the inner semicon for temperature drops of 10°C and 20°C. Figure 4 shows the charge profiles measured when a voltage of 90 kV and a temperature drop of 20°C are applied. The calculated space charge patterns are shown in Figure 5. A gaussian filter was applied to the calculated data, in order to reproduce patterns of the same type as the measured patterns. Figure 5 shows that the model correctly predicts accumulation of positive space charge in the insulation bulk due to the presence of the temperature gradient. However, the maximum of the calculated space charge distribution is slightly underestimated and no hetero-charge near the inner semicon is indicated (compare Figures 4 and 5). On the other hand, the fact that most of the charge accumulates in the first 10^4 s of polarization is acceptably estimated by the model. This is shown in Figures 6 and 7, where the charge evolution in time is shown at specific locations of the cable insulation.

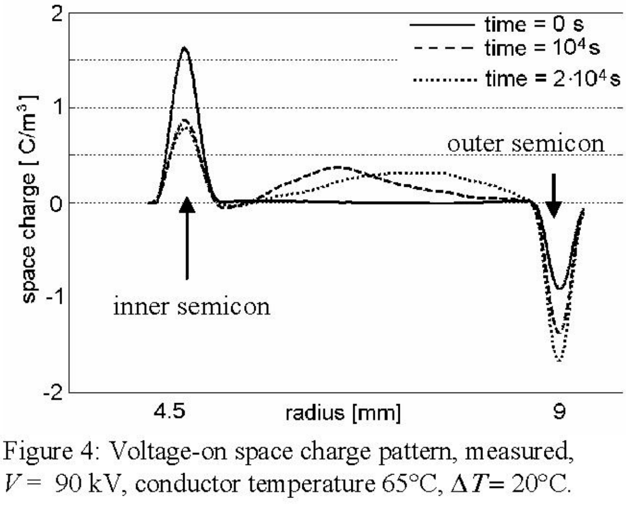


Figure 4: Voltage-on space charge pattern, measured, V = 90 kV, conductor temperature 65°C, ΔT= 20°C.

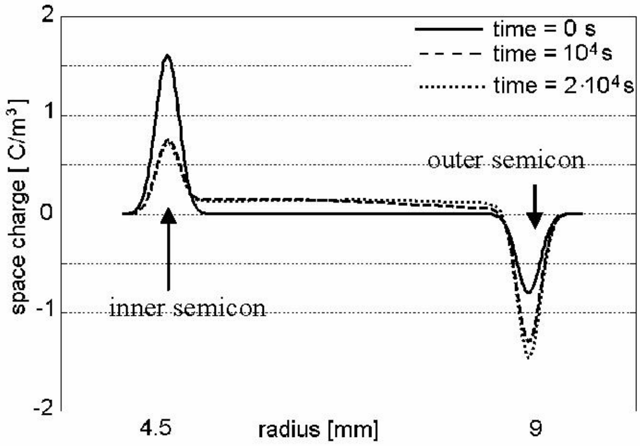


Figure 5: Voltage-on space charge pattern, calculated, V = 90 kV, conductor temperature 65°C, ΔT= 20°C.

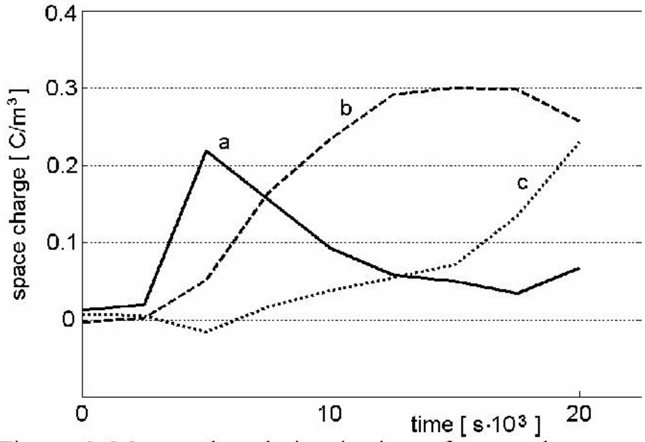


Figure 6: Measured evolution in time of space charge density at specific locations, V = 90 kV, conductor temperature 65°C, ΔT= 20°C.
a) near inner semicon; b) in the middle of the insulation; c) near the outer semicon.

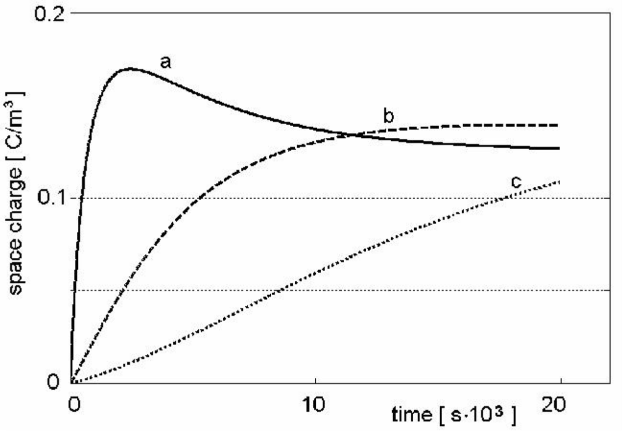


Figure 7: Calculated evolution in time of space charge density at specific locations, V = 90 kV, conductor temperature 65°C, ΔT= 20°C.
a) near inner semicon; b) in the middle of the insulation; c) near the outer semicon.

DISCUSSION

Recently, it has been shown that injection mechanisms play a role in the accumulation of charge in samples in which a temperature drop exists, when the maximum electric field exceeds the threshold for space charge accumulation [2, 3, 5-7]. Therefore, a discrimination is necessary between the extent of space charge accumulation due to the temperature gradient and that due to charge injection from the electrodes. For this purpose, space charge measurements were also carried out on MV-size cables under *isothermal* conditions. Under this particular condition, only charge due to injection at the electrodes can be detected. In Figure 8, the space charge patterns measured under isothermal conditions are shown.

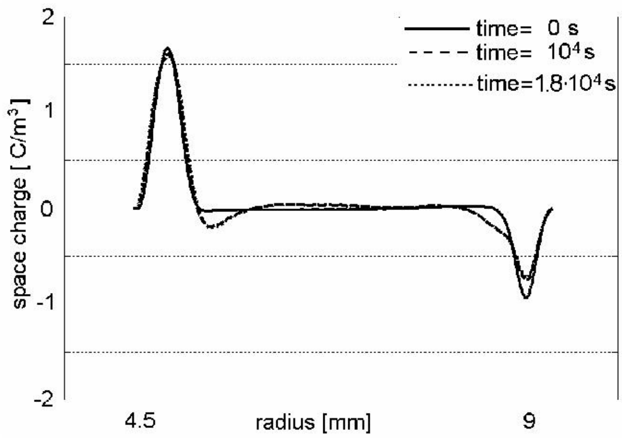


Figure 8: Voltage-on space charge pattern, measured, V = 90 kV, T = 65°C, isothermal.

The figure indicates that under isothermal conditions less charge accumulates in the insulation bulk if compared to the situation in which the temperature drop is applied. This indicates that, for the studied cables under test voltage up to 90 kV (i.e. up to a field of 20 kV/mm), the dominant accumulation mechanism most probably is due to the temperature drop. One has to be careful in drawing too strong conclusions because the conditions at the outer semicon are different for both situations. In case of the temperature drop, the outer semicon temperature was 45°C and for the isothermal situation the temperature was 65°C.

At the outer semicon, negative homo-charge is present, whereas negative hetero-charge is present at the inner semicon (see Figure 8). It can be speculated that the hetero-charge is caused by the blocking properties of the semicon electrode. Negative charge is injected at the earth electrode and, after migration through the insulation, is blocked in front of the HV electrode. In the space charge pattern measured at a temperature drop, this phenomenon is less evident, since injection now plays a minor role if compared to temperature drop induced accumulation.

CONCLUSION

A physical model has been presented, which describes the dynamic space charge behavior in dc cables when a temperature drop is present across the insulation. Results of space charge measurements performed on MV-size XLPE cables have been quite well reproduced by the proposed model. Measurements have also shown accumulation of charge which could not be correlated to the temperature gradient. This has been attributed to the injection and blocking properties of the semicon electrodes. In this framework, the model can be a useful tool for the identification of different space charge accumulation mechanisms.

Acknowledgement

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REFERENCES

[1] R. Coelho, "Charges in non homogeneous dielectrics", Proc. IEEE Conf. Electr. Insul. Diel. Phen., pp. 1-10, 1997.

[2] K. R. Bambery, R. J. Fleming, J. T. Holboll, "Space charge profiles in low density polyethylene samples containing a permittivity/conductivity gradient", J. Phys. D Appl. Phys., 34, pp.3071-3074, 2001.

[3] S. Trætteberg, E. Ildstad, R. Hegeberg, "Space charge formation in XLPE caused by temperature gradient and DC voltage reversal", Proc. Nord. Insul. Symp, pp. 111-114, 2005.

[4] J. T. Holbøll, M. Henriksen, J. Hjerrild, "Space charge build-up in XLPE-cable with temperature gradient", Proc. IEEE Conf. Electr. Insul. Diel. Phen., pp. 157–160, 2000.

[5] D. Fabiani, G. C. Montanari, R. Bodega, P. H. F. Morshuis, C. Laurent, L. A. Dissado, "The effect of temperature gradient on space charge and electric field distribution of HVDC cable models", Proc. IEEE Int. Conf. Prop. App. Diel. Mat., pp.65-68, 2006.

[6] P. H. F. Morshuis, M. Jeroense, "Space charge measurements on impregnated paper: a review of the PEA method and a discussion of the results", IEEE Electr. Insul. Mag., Vol.13 No.3, pp.26-35, 1997.

[7] L. A. Dissado, C. Laurent, G. C. Montanari, P. H. F. Morshuis, "Demonstrating a threshold for trapped space charge accumulation in solid dielectrics under DC field", IEEE Trans. on Diel. Electr. Insul., Vol. 12, No 3, pp. 612-620, 2005.

[8] R. Bodega, G. C. Montanari, P. H. F. Morshuis, "Conduction current measurements on XLPE and EPR insulation", Proc. IEEE Conf. Electr. Insul. Diel. Phen., pp. 101-105, 2004.