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Effect of hydrostatic pressure on the space charge distribution in power cable materials

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Abstract. — The performance of high-voltage cables with synthetic insulation is highly dependent on the appearance of a space charge under AC or DC stress. The presence of this charge plays a very important role in aging and polymer breakdown phenomena. For submarine power cables, the pressure $P$ for the immersion depth of the cables is now considered. We then study the effect this has on the space charge distribution, as a function of the amplitude of the stressed applied, DC voltage, temperature and hydrostatic pressure. Preliminary results obtained with cross-linked polyethylene are given.

1. Introduction.

The performance of high-voltage cables with synthetic insulation is highly dependent on the appearance of a space charge under AC or DC stress [1, 2]. This space charge is generated either by injecting carriers (electrons or holes) or by induced polarization (orientation of permanent dipoles, formation of induced dipoles or displacement of charges over short or long distances).

The presence of this space charge distorts the electric field in the insulating material nonuniformly relative to the applied electric potential, and consequently plays a very important role in aging and polymer breakdown phenomena. Thus the need to study the variation of this space charge under the insulator utilization conditions.

For submarine power cables, the pressure $P$ for the immersion depth of the cables is now considered. We then study the pressure effect on the space charge distribution in the insulators, as a function of the amplitude of the stresses applied, which are electrical (DC voltage), thermal (temperature) and mechanical (hydrostatic pressure).

Preliminary results obtained with cross-linked polyethylene show that the residual electric field and the space charge are not uniformly distributed through the material, and are subject to change under the effect of pressure. The formation of homocharges and heterocharges in the vicinity of the electrodes also changes.

The FIRELEC prize was awarded to Béatrice Garros for this work.
2. Experimental apparatus.

2.1 PROCESSING OF MATERIAL UNDER PRESSURE. — The samples of XLPE come in the form of plates, 1.5 mm thick, with semiconductor electrodes on either side of the insulation, of the same kind used in the cables. We bonded a guard ring on each side to avoid any edge effects, and thereby were able to operate on the same samples (Fig. 1).

![Cross-section of electrodes-sample set-up](image)

To work under the same initial conditions on all samples and to eliminate all spurious surface charges before undertaking any laboratory operations, the samples are first debiased at a temperature of 70 °C for about 12 h, during which time the electric state of the material can be considered stable under the given experimental pressure conditions. It was verified that, after this treatment, the samples contained no charges with the thermal step method, explained in section 2.2. They are then subjected to a DC voltage.

These samples were submitted to electrical and thermal conditions under pressure with a special cell [3] consisting of electrodes with Rogowski section (Fig. 2). The assembly is mounted in a teflon cylinder, used as a heat screen and electrical insulator. This is then placed in an experimental chamber at high pressure, consisting of a metal cylinder lying on a horizontal axis (external length 75 cm, external diameter 50 cm, useful volume 9 500 cm³) and closed by two caps at its ends. One cap is designed to provide high voltage, heating and temperature measurement. The other cap, carrying a capillary tube for gas outlet and inlet into of the pressure chamber, is equipped with the electrical passages for supplying the high voltage relays and the breakdown detection system.

The maximum pressure obtained with this device is 1 500 bar, in a gas transmission medium (nitrogen). The pressure generator consists of a two-stage membrane-type compressor (1 000 and 3 000 bar).

A voltage up to 100 kV is brought into the experiment chamber through two special cone-shaped sapphire passages encased in epoxy resin (Araldite).

2.2 CHARGE DISTRIBUTION MEASUREMENT. — Among the methods of space charge measurement [4-9], the one currently adopted, in our laboratory, is the thermal wave method conceived
by Toureille [2, 10]. The principle can be described briefly as follows. A thermal step $\Delta T$ is applied to one of sample sides, across an insulator to create a current response due to the thermal expansion of the sample.

The experiment consist to put the sample in a cooling container where the temperature is at $-10^\circ\text{C}$. Then we inject a warm liquid (at $20^\circ\text{C}$) in a radiator (see inset in Fig. 3) to create the thermal step, so the current response will be measured by the current meter which is linked to an analog-to-digital converter card for storing the data in the computer.

If we remember that the thicknesswise diffusion of the heat in the sample appears in the form of a thermal wave or plane propagating at a certain velocity, we can establish the expression for the current, representing the local movements of the charges, in the following external circuit:

$$I(t) = A \int_0^L \rho(x) f(x, t) \, dx \quad \text{with} \quad A = \frac{2 \alpha S \Delta T_0}{WLD}$$

where $t =$ times, $a = a_D - a_r$, $a_r =$ coefficient of permittivity variation with temperature, $a_D =$ coefficient of expansion for the material, $S =$ active surface area of the sample, $\Delta T_0 =$ temperature step, $W = \mu C/\lambda$ ($\mu$ being the specific mass of the material, $C$ its specific heat per unit mass, and $\lambda$ the heat conductivity), $D =$ sample thickness, $L =$ abscissa of the cold source, $x =$ depth of penetration of the heat, $\rho(x) =$ equation density of the space charge at distance $x$ and $f(x, t) =$ dimensionless function deduced from the heat cohesion and from the heat wave propagation velocity.

Starting with this expression, we can establish the relations between the measured current and the charge densities or electrical field in the material by a deconvolution method, which can be solved by classical numerical methods developed in another paper [10, 11].
3. Experimental results.

The electric field and charge distributions in the material were deduced from the measured current on plates of cross-linked polyethylene prepared by the Câbles-Pirelli company. The mean thickness of the plates was 1.5 mm. Each had been subjected to a 30 kV DC bias voltage at temperatures of 30 °C and 70 °C, for a period of 24 h, at pressures of $P = 50$, 150 and 300 bar (corresponding to depths of 500, 1 500 and 3 000 m).

In order to be able to keep the charges in the positions that they initially acquired under the combined effects of the electric field and of the pressure, these samples were kept in a temperature-controlled chamber at 0 °C, at which temperature the charges are considered to be frozen, before their distribution was measured, at atmospheric pressure.

Figures 4 and 5 show the electric field and space charge distributions in the XLPE samples, for 50, 150 and 300 bar. Figures 6 and 7 show the effect of the temperature on the space charge distribution at 30 kV, at 50 bar and 300 bar.

4. Discussion.

The above results prompt us to make the following remarks.

1) The electric field distribution of figure 4 shows that the maximum field amplitude increases with the pressure, from 0.5 kV/mm at 50 bar to 0.8 kV/mm at 300 bar.

The electric field value is not constant along the sample thickness. This is due to the existence of a nonuniform density of charges that create a local field capable of reinforcing or decreasing the initial electric stress.
**Electric field**

\[ E \text{(kV/mm)} \]

**Space charge**

\[ \rho \text{(C/m}^3\text{)} \]

**Fig. 4.** — Field distributions along the PR sample thickness (1.5 mm) for different pressures: 50, 150, 300 bar. Polarization voltage = 30 kV. Temperature = 70°C.

**Fig. 5.** — Space charge distributions along the PR sample thickness (1.5 mm) for different pressures 50, 150, 300 bar. Polarization voltage = 30 kV. Temperature = 70°C.
Fig. 6. — Space charge distributions along the PR sample thickness (1.5 mm) for different temperatures: 30, 70 °C. Polarization voltage = 30 kV. Pressure = 50 bar.

Fig. 7. — Space charge distributions along the PR sample thickness (1.5 mm) for different temperatures: 30, 70 °C. Polarization voltage = 30 kV. Pressure = 300 bar.
2) As far as the space charge distribution in the material is concerned, the shape of the curve in figure 5 shows that, as the pressure $P$ increases, the space charge density also increases, which is probably evidence of a purely electronic phenomenon.

This is confirmed by the presence of the quantity of positive charges located in the center of the material. It may then be thought that these charges exhibit much less mobility than the negative charges (electrons) near the anode. There are slightly more negative charges than positive.

Moreover, as the pressure rises, double injections at the electrodes are promoted.

That is, at 50 bar, we observe the presence of heterocharges in the vicinity of the anode and homocharges in the vicinity of the cathode, probably stemming from an injection of negative charges (electrons). At 150 and 300 bar, homocharges accumulate in the vicinity of the electrodes: at the anode, this phenomenon might be explained by electron rejection.

The effect of the temperature, illustrated in figures 6 and 7, tends to support this hypothesis. At 30 °C, there are more space charges stored in the material than at 70 °C.

This can be explained by the fact that, since the electrons have relatively greater mobility at the higher temperature, they circulate more easily, while the charges will be more easily trapped at 30 °C.

5. Conclusion.

The results obtained with the heat wave method show that, qualitatively, when a DC electric field is applied, the pressure has a significant effect on the quantity of charges involved and on their spatial distribution.

These new findings will allow us to improve our understanding of the phenomena involved in the materials used in submarine power cables (polarity reversals, aging, dielectric strength under pressure).

Finally, to gain a better theoretical understanding of the pressure effect on the DC voltage strength and aging of polyethylenes, the space charges distribution has to be studied thoroughly as a function of certain additional parameters such as the short-circuit time or the amplitude of the applied electric field. These additional findings may make it possible to determine the origin and type of charges from the kinetic variation of the charges with time and to reach a better understanding of the breakdown phenomenon in solid insulators under pressure.

References


