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# Considerations on diverse physical phenomena leading to return voltage on insulators

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**Abstract**— A brief short circuit is not sufficient to relax the entire spectrum of the stress accumulated in an insulator during a long time polarization. Following neutralization, a return voltage appears. This phenomenon is used as a routine characterization tool in some areas of electrical engineering. Several experimental results are detailed here supporting the interest of this electrostatic technique as a laboratory characterization tool. For instance, the sensitivity of this technique may be applied to follow the ageing of cables for the aircraft industry, as well as to monitor interfacial polarization build-up at high temperature on polarized alumina plates. It has also been used to demonstrate a photoelectret effect on polyimide films, which is described.

We analyze here the diverse physical processes that may be responsible for return voltage: slow dipolar relaxation processes, interfacial polarization, heterogeneous conductivity and injected space charge motion.

**Index Terms**—Dielectric measurement, surface potential, cable insulation, Electrostatics, photoconductivity, electrets

## I. INTRODUCTION

Reporting his pioneering 1837 experiments, Faraday remarked: “if after having been charged for some time, as fifteen or twenty minutes, it [a spherical capacitor filled with a dielectric substance] was suddenly and perfectly discharged (...), then the apparatus being left to itself, would gradually recover a charge” [1]. This was the first reported observation of the return voltage. Forty years later, using the superposition principle, Hopkinson established a model of this delayed dielectric response [2].

The “return voltage method” is nowadays in common use in industry to monitor the ageing of HV transformers and cables. The voltage signal may be correlated to water uptake and degradation of impregnated insulations [3-6]. Return voltage is also a laboratory tool, used as a complement to classical surface potential decay measurements for dielectric material characterization [7-9]. Charge, neutralization and measurement may be performed without any contact with the surface, using corona discharge and electrostatic probes.

Return –or recovery- voltage is a consequence of internal constraints in the dielectric which cannot be removed by short-time neutralization. Several mechanisms involved in this process have been discussed in the scientific literature, but, to our knowledge, most of it is focused on modeling industrial machines insulation, using networks of capacitors and resistances. We try to present here a more complete

physical description of the various processes which may account for the voltage return.

We consider the typical laboratory experiment described figure 1. An insulating slab of permittivity  $\epsilon$  and thickness  $L$  is deposited on a grounded electrode. Its top and bottom surfaces may be metallized or not. The voltage at the upper surface is assumed to be measured by a feedback electrostatic voltmeter, or deduced from measurements performed by a grounded field meter located at a large distance from the slab (compared to its thickness), so that a zero-field boundary condition may be assumed in air above the insulator upper surface. The insulator is charged at a voltage  $V_0$  at  $t = -t_n$ , then it is briefly short-circuited at  $t = 0$ . Its surface return voltage will then be recorded in open circuit, during a much longer period of time.

The duration of the charging or discharging processes may be assumed to be negligible compared to  $t_n$ . This may be practically realized using a corona discharge with a point-to-grid setup, the grid potential being set at the required charging voltage. It may also be done by a short-duration contact, especially if the upper surface is metallized. The charging phase may be implemented by maintaining a polarization at a constant voltage, or by leaving the insulator in open circuit. In this last case, potential decay may be recorded until neutralization is performed for a surface voltage value  $V_n$ , according to figure 2.

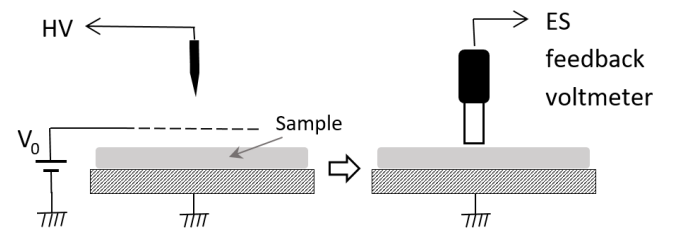


Fig. 1. Corona charge deposit and voltage measurement

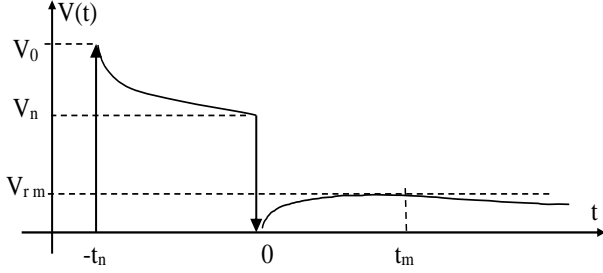


Fig. 2. Potential decay and return experiment.

## II. THEORY OF LINEAR RESPONSE

Most disordered insulating materials exhibit a slow component of their dielectric relaxation response, which may have several physical causes, as long-range molecular motions in polymers, or internal charge motion leading to interfacial polarization. Assuming these to be linear with the electric field, the insulator response may be described by a dielectric function [10]. The voltage at the upper surface depends on the amount of charge density deposited on the surface per unit area  $q(t)$  from the beginning of the experiment as follows:

$$V(t) = \frac{L}{\epsilon} \int_{-\infty}^t q(\tau) \Phi(t - \tau) d\tau \quad (1)$$

The value of the permittivity  $\epsilon$  considered here includes the fast polarization processes while the dielectric function includes the slow ones. This delimitation is arbitrary, and depends on the experimental parameters.

The dielectric function  $\Phi(t)$  is a property of the material, which may be derived from the surface potential decay rate after deposition of a pulse of charge. Considering that the surface has been charged at  $t = 0$  by a deposit of charge density  $q_0$  inducing the surface potential  $V_0$ , we may write that  $q(t) = q_0 \Gamma_0(t)$ ,  $\Gamma_0(t)$  being the Heaviside function centered on 0. Equation (2) may then be derived, for  $t \neq 0$  from equation (1):

$$\frac{dV(t)}{dt} = \frac{Lq_0}{\epsilon} \Phi(t) = V_0 \Phi(t) \quad (2)$$

The validity of equation (1) implies that  $\Phi(t)$  incorporates a Dirac function  $\delta_0(t)$  centered on 0, so that  $V(t = 0^+) = Lq_0/\epsilon$ . For  $t > 0$ ,  $\Phi(t)$  has to be negative.

Charging the insulator at  $t = -t_n$  and neutralizing at  $t=0$  the insulator surface at the potential  $V_n$ , the return voltage will be, using the superposition principle:

$$\frac{dV(t)}{dt} = V_0 \Phi(t + t_n) - V_n \Phi(t) \quad (3)$$

Considering a homogeneous insulator described by a constant permittivity  $\epsilon$  and a non-zero conductivity  $\sigma$ , it behaves as a simple parallel RC circuit and no return voltage will be observed. In this case  $\Phi$  is a decreasing exponential function, and from (3) it may also be deduced that  $dV/dt=0$ . However, on most disordered materials, dielectric functions are following time power laws [11]:

$$\frac{\Phi(t)}{\Phi(t_0)} = \left(\frac{t}{t_0}\right)^{-n} \text{ for } t \neq 0 \quad (4)$$

$t_0$  arbitrary time reference  
 $n$  characteristic exponent of the material ( $n < 1$ )

In this case,  $\Phi(t)$  decreases (in absolute terms) faster than an exponential at short times, and the second term of equation (3) predominates for small values of  $t$ , thus leading to a voltage return of the same sign than the initial potential.

The assumption of linearity may be quite easily verified, since from the dielectric function deduced from the voltage decay measurement, it is easy to use equation (3) to predict the shape of the return voltage that should be obtained.

It must be underlined that the return voltage, after a maximum value reached for  $\phi_E(t)/\phi_E(t - t_n) = V_n/V_0$ , will slowly decrease to zero. For large time values, the voltage decay will be the same than for an initial charge deposit inducing the potential  $V_0 - V_n$ .

For a dielectric function following equation (4), the time to reach the maximum voltage may be computed:

$$t_m = \frac{t_n}{1 - \left(\frac{V_n}{V_0}\right)^{\frac{1}{n}}} \quad (5)$$

Many experiments at moderate fields (below 1 to 10 kV/mm at ambient temperature, depending on the material and interface) on polar or composite insulating materials may be described by this linear model considering a dielectric function (see for instance [12]). However, it is often more convenient to use of a discrete array of RC cells with different time constants accounting for the distribution of relaxation times included in the dielectric function. This kind of modelling has been in use for a long time to assess the ageing of power transformers or cables [3-6].

Both ways of modelling are equivalent and empirical, since they may incorporate a large variety of relaxation phenomena. Among them, interfacial (or Maxwell-Wagner) polarization has a particular importance concerning return voltage measurements. For this reason, it will be treated in a separate section.

## III. INTERFACIAL POLARIZATION

Most insulating materials commonly used in modern systems are composites, designed to optimize mechanical, electrical, thermal properties. They may be organized as multilayered systems or as a dispersion of fillers in the material bulk. A homogeneous material (at the macro scale) may also be organized at the microscale in domains, with different levels of crystallinity. Different values of conductivity may thus be found in these different phases. As a result, the capacitive potential distribution (involved at short times or high frequencies) may differ from the resistive one. In this case the material will exhibit a return voltage after a long-time polarization followed by a brief short-circuit.

Since it may be related to long distance charge motion, the spectrum of interfacial polarization may have a broad extension in very low frequencies. That is the reason why this

phenomenon often prevails for time domain experiments like potential decay and return measurements.

The success of the return voltage method (RVM) to monitor ageing in transformers is linked to the strong interfacial polarization that may appear in a layered insulation made of oil impregnated paper and paperboard [6].

An elementary representation of interfacial polarization may be given using a two-cell RC model (figure 3).

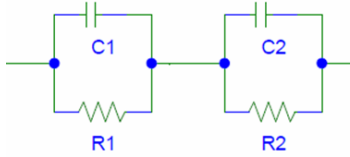


Fig. 3. Two-cell RC model.

It may be shown that, for a short-time neutralization after a long DC poling time at  $V_0$ , a voltage return will appear on this circuit, with always the same sign as the poling voltage, according to equation (6).

$$\frac{V(t)}{V_0} = \frac{R_2 C_2 - R_1 C_1}{(R_1 + R_2)(C_1 + C_2)} \left( e^{-\frac{t}{R_2 C_2}} - e^{-\frac{t}{R_1 C_1}} \right) \quad (6)$$

If the time constant of one cell is much higher than the other, for instance  $R_2 C_2 \gg R_1 C_1$ , the return voltage will be high, and its maximum value is obtained assuming at the same time  $R_2 \gg R_1$  and  $C_2 \gg C_1$ . In this case, it may even tend towards the poling value.

To our knowledge, interfacial polarization is the physical phenomenon that leads to the highest return voltage signal. Therefore the return voltage method does not only concern complex industrial installations but may also be used as a laboratory characterization tool since many small scale insulations may exhibit interfacial polarization.

For instance, we have found large values of return voltage, up to 20% of the applied polarization, using an electrostatic probe to characterize the ageing of short (10 cm) aircraft cable samples, insulated with a polyimide/PFA/PTFE wrapped tape [13].

We have reported [14] even larger return voltage, up to 30 % of the applied polarization, on polycrystalline alumina plates (figure 4) polarized above 100°C, even though the applied field was moderate (figure 5). Space charge measurements by thermal step method did not allow to measure any significant internal space charge for these combinations of temperature and fields.

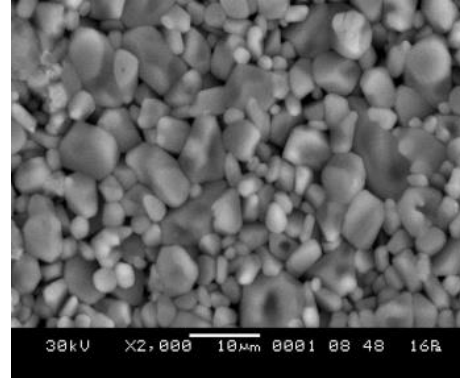


Fig. 4. SEM photograph of the alumina plates surface [14]

A simulation has been done using the RC model given figure 3 to reproduce these return voltage measurements on alumina plates. The cell with a high RC value may in this case represent the grain boundaries, whereas the other represents the bulk. The high value of the return voltage may then be due to a temporary charge accumulation at the grain boundaries.

Results are given figure 6, for two different values of  $R_1$ . Simulation A may be assumed to represent the return voltage at 100°C, while simulation B represents the response at 150°C. It is assumed that heating at 150°C reduces the value of  $R_1$  compared to its value at 100°C, without affecting the other parameters.

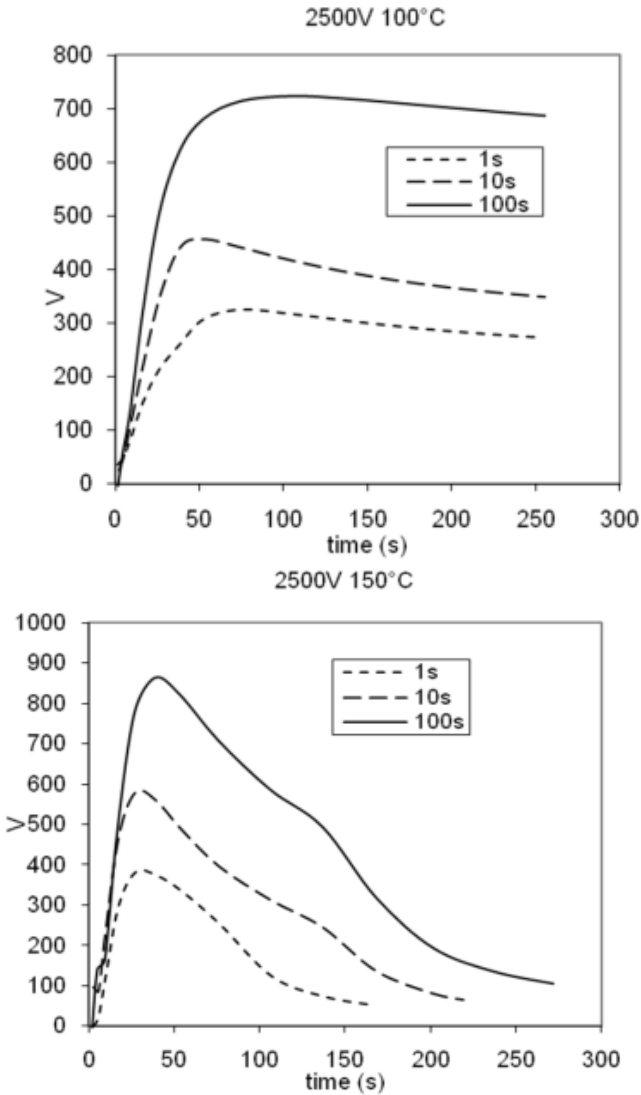


Fig. 5. Return voltage measurements on 1mm-thick polycrystalline Al<sub>2</sub>O<sub>3</sub> slabs previously polarized at 2500V (during 1s, 10s, 100s). [14].

The increase of the voltage with the charging time is due to the time constant (64s in our simulation) necessary to switch from the initially mainly capacitive current to a purely resistive current.

This model is too primitive to account precisely for the results, but it provides a good qualitative explanation. For a precise description, simulating the power law character of the dielectric response, which appears when the time dependence of the decay/return is analyzed, a network of RC cells with different time constants may empirically fit the system behavior. A complete model should however incorporate field non-linearity, which is important in this system. This complexity is a quite common behavior of insulators, due to non-linear activation mechanisms, as Schottky or Poole-Frenkel, and to dynamical charge trapping and detrapping phenomena.

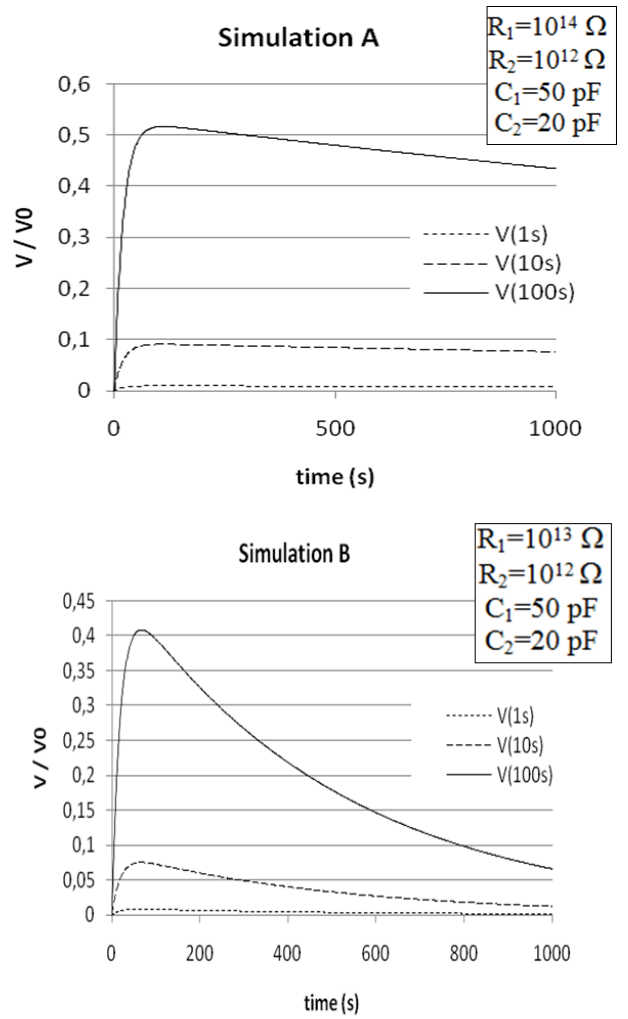


Fig. 6. Simulated return voltage using the two-cell RC model.

#### IV. INJECTED SPACE CHARGE

The voltage decay due to the injection of a charge deposited on an insulating surface has been extensively studied, with various hypotheses on the injection process, charge mobility and trapping in the material [9]. Calculations of the voltage return after neutralization have been performed by Coelho in several works [7][8]. This section provides an extended view of these models, and a calculation for a unipolar space-charge limited current distribution which has never been published before.

##### A. General theory

Assuming a null field at the upper surface, using the Poisson equation, the surface potential due to the internal charge distribution with volume density  $\rho(x)$  just before neutralization may be written:

$$V_n = \frac{1}{\epsilon} \int_0^L x \rho(x) dx = \frac{q_0 \bar{x}}{\epsilon} \quad (7)$$

The surface potential is proportional to the integrated surface charge density  $q_0$  multiplied by the mean distance  $\bar{x}$  of the charge to the ground.

When the insulator surface is neutralized, the average field inside becomes zero. A zero-field plane appears in the bulk (shown as a dotted line figure 7). The charge injected beyond this plane continues its drift, whereas the rest comes back to the injecting surface.

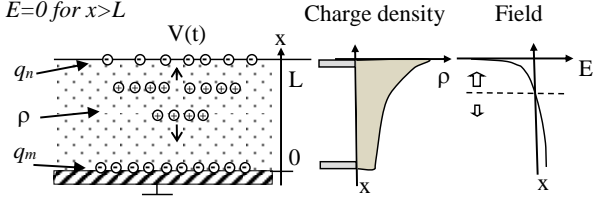


Fig. 7. Charge distribution and field in the insulator after surface neutralization.

The neutralization surface charge is  $q_n = -q_0 \bar{x}/L$ . Using Gauss theorem between the zero-field plane and the upper surface, the surface density of the charge located in the region where the field has been inverted by the neutralization is then  $q_0 \bar{x}/L$ , while the charge density beyond the zero-field plane (including the charge already neutralized at the ground electrode) is  $q_0 (1 - \bar{x})/L$ .

We may describe the charge motion by a mobility  $\mu$ , which may be depending on field and time (to include progressive trapping). Then we may describe the charge transport on both sides of the zero-field plane as the motion of charged sheets, each of them having the same charge density (figure 8). The amount of charge separating each of them from the zero-field plane remains constant during this motion, together with its driving field and its drift speed. The sheets speed increases however with their initial distance to the zero-field plane, as illustrated by figure 8.

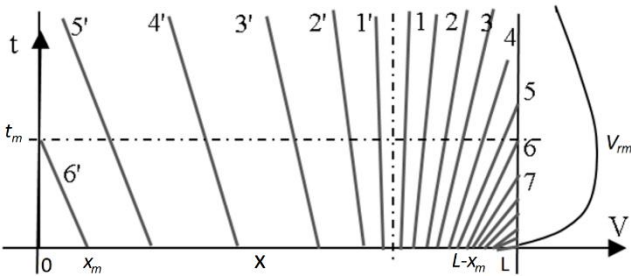


Fig. 8. Charge sheets motion on both sides of the zero-field plane (left and center of the figure) during the voltage return experiment (voltage shown on the right). Charge sheets are numbered according to the distance to the zero field plane (dotted line), N and N' referring to charges subjected to the same absolute value of the field.

For an homogeneous insulator, two charged sheets driven by the same field on both sides of the zero-field plane (for instance 3 and 3' on figure 8) have exact opposite influences on the surface voltage during their drift. The calculation of the return voltage may be done by only considering the charge sheets deprived from any counterpart on the other side of the insulator.

In the example of figure 8, most of the injected space charge remained on the injecting surface (right) side of the zero-field plane. The charge sheets located on the right side with  $N > 6$  are initially moving with no counterparts on the left side. In this case, the sign of the return voltage is the same than the initial potential before neutralisation.

However, after a given time  $t_m$ , more charge will be present on the left part, because of the longest path available for their charges motion, and the return voltage will begin to decrease. The internal charge distribution will in the end vanish, and the return voltage tends asymptotically to zero, since the surface charge of the insulator will also tend to zero with the return of the whole charge distribution located right of the zero field plane to the surface.

At  $t_m$  the return voltage reaches its maximum value. A particular feature at this moment is that the value of the field  $E_m$  in the vicinity of the injecting surface is exactly opposite to its value near the ground electrode ( $E_m = E(L^-) = -E(0^+)$ ). All the charges still present in the distribution at  $t_m$  were initially located between  $x_m$  and  $L - x_m$ , with  $x_m = E_m \mu t_m$  and were subjected to fields weaker than  $E_m$ , in absolute terms, while the other charges have been eliminated by fields higher than  $E_m$ .

From the situation at  $t_m$ , the space charge may be divided into three components:

- the charge remaining in the volume at  $t_m$ , that was located initially at an abscissa  $x_m < x < L - x_m$ , has not contributed to the return voltage buildup until its maximum, since the motion before  $t_m$  of each sheet has been compensated by the motion of another one on the other side of the zero-field plane.
- the charge returned to the ground, that was located initially at an abscissa  $x < x_m$
- the charge returned to the injecting surface, that was located initially at an abscissa  $x > L - x_m$ .

The maximum return voltage  $V_{rm}$  at  $t_m$  is then equal to the voltage return due to the motion of the charge returned to the injecting surface at  $t_m$ , minus the voltage drop due to the motion of the charge returned to the ground:

$$V_{rm} = \frac{1}{\epsilon} \int_{L-x_m}^L (L-x) \rho(x) dx - \frac{1}{\epsilon} \int_0^{x_m} x \rho(x) dx \quad (8)$$

Changing the variable in the first term:

$$V_{rm} = \frac{1}{\epsilon} \int_0^{x_m} x [\rho(L-x) - \rho(x)] dx \quad (9)$$

Considering  $\overline{L-x_r}$  the mean distance to the surface of the charges returned to the surface and  $\overline{x_g}$  the mean distance to the ground of the charges returned to the ground at  $t_m$ :

$$V_{rm} = \frac{q_r \overline{L-x_r}}{\epsilon} - \frac{q_g \overline{x_g}}{\epsilon} \quad (10)$$

A space charge in a briefly neutralized insulator may induce a return voltage only if its distribution is asymmetric. An anomalous return voltage may appear if  $q_g \overline{x_g} > q_r \overline{L-x_r}$ , which means that most of the charges of the initial distribution are closer to the ground electrode.

It must be underlined that the return voltage due to space charge motion has quite different features than what has been described in the previous sections. This phenomenon is strongly nonlinear, the possibility of an anomalous voltage being one feature of this nonlinearity. However, the competition between both sides of the zero-field plane will greatly reduce the maximum possible return voltage. This will be shown in next section for a particular charge distribution.

### B. Exact calculation for unipolar space-charge limited current (SCLC) charge distribution

We assume unipolar injection of the maximum possible charge (from the surface, in the steady state regime) in a trap-free insulator. This occurs when the internal space charge reduces the field at the injecting surface to zero. This configuration corresponds to the well-known space-charge limited current [15].

Assuming a steady state regime to be reached, a uniform current density flows in the insulator:

$$j = \mu\rho E = \mu\varepsilon E \frac{dE}{dx} = \frac{1}{2}\mu\varepsilon \frac{dE^2}{dx} \quad (11)$$

This implies that the spatial dependence of the field follows a square root law, and taking into account the boundary condition  $E(L) = 0$ :

$$E = -\left(\frac{2j}{\mu\varepsilon}(L-x)\right)^{\frac{1}{2}} \quad (12)$$

The negative solution of (12) has been chosen, corresponding to the case of a positive injected charge. The internal charge distribution is then:

$$\rho = \varepsilon \frac{dE}{dx} = \left(\frac{2\mu}{j\varepsilon}(L-x)\right)^{-\frac{1}{2}} \quad (13)$$

It may be related to the applied voltage by considering that:

$$V_0 = -\int_0^L E dx = \left(-\frac{8j}{9\mu\varepsilon}\right)^{\frac{1}{2}} L^{\frac{3}{2}} \quad (14)$$

so that, eliminating  $j$  between (13) and (14):

$$\rho = \frac{3\varepsilon}{4L^2} V_0 \left(1 - \frac{x}{L}\right)^{-\frac{1}{2}} \quad (15)$$

This equation is the charge distribution corresponding to the classical SCLC problem in a trap-free insulator [15]. Let us now assume that the neutralization occurs immediately after the charging period ( $V_n = V_0$ ). The field inside the insulator immediately after neutralization is given by adding the field  $V_0/L$  produced by the neutralization charge to the integration of (15):

$$E(x) = -\frac{1}{\varepsilon} \int_x^L \rho dx + \frac{V_0}{L} = \frac{V_0}{L} \left[ \frac{3}{2} \left(1 - \frac{x}{L}\right)^{\frac{1}{2}} - 1 \right] \quad (16)$$

The abscissa of the zero-field plane is thus  $x_0 = 5L/9$ .

The demarcation abscissa  $x_m$  defined above is a solution of the equation  $E(x) = -E(L-x)$ :

$$\left(1 - \frac{x_m}{L}\right)^{\frac{1}{2}} + \left(\frac{x_m}{L}\right)^{\frac{1}{2}} = \frac{4}{3} \quad (17)$$

$$\frac{x_m}{L} = \frac{1}{2} - \frac{4}{9\sqrt{2}} \quad (18)$$

The maximum of the return voltage may be found by combining (9) and (15):

$$V_{rm} = \frac{3}{4L^2} V_0 \int_0^{x_m} x \left[ \left(\frac{x}{L}\right)^{-\frac{1}{2}} - \left(1 - \frac{x}{L}\right)^{-\frac{1}{2}} \right] dx \quad (19)$$

An integration by parts leads to:

$$\frac{V_{rm}}{V_0} = \frac{3}{2} \left[ \frac{x}{L} \left( \left(\frac{x}{L}\right)^{\frac{1}{2}} + \left(1 - \frac{x}{L}\right)^{\frac{1}{2}} \right) \right]_0^{x_m} - \frac{3}{2L} \int_0^{x_m} \left[ \left(\frac{x}{L}\right)^{\frac{1}{2}} + \left(1 - \frac{x}{L}\right)^{\frac{1}{2}} \right] dx \quad (20)$$

Taking into account (17):

$$\frac{V_{rm}}{V_0} = 2 \frac{x_m}{L} - \left[ \left(\frac{x_m}{L}\right)^{\frac{3}{2}} - \left(1 - \frac{x_m}{L}\right)^{\frac{3}{2}} + 1 \right] \quad (21)$$

Which may be slightly simplified in:

$$\frac{V_{rm}}{V_0} = \frac{2}{3} \frac{x_m}{L} - \left(\frac{x_m}{L}\right)^{\frac{1}{2}} + \frac{1}{3} \quad (22)$$

The numerical value of the relative maximum return voltage deduced from (21) is then:

$$\frac{V_{rm}}{V_0} = \frac{2}{3} \left(1 - \frac{4}{9\sqrt{2}}\right) - \left(\frac{1}{2} - \frac{4}{9\sqrt{2}}\right)^{\frac{1}{2}} \approx 0,026$$

The interest of this result is to show that the return voltage value is quite low, less than 3% for the maximum possible injected charge in steady state, compared to what is possible to obtain in a heterogeneous insulator by interfacial polarization, or by heterogeneous conductivity (see below). Moreover, concerning neutralization after a delay allowing surface potential decay, the return voltage will be less important, because the space charge density will tend towards a larger uniformity during the decay than the SCLC profile.

That may explain why it is difficult to present experimental results showing clear evidence of a return voltage due to an injected space charge only. The signal due to this component is usually quite faint, and often appears at high field as a transient and irregular phenomenon. For most materials, it should be hidden behind the higher value of the dipolar or Maxwell-Wagner component.

Anomalous return voltage would be a valuable signal for strong space charge effects, and prebreakdown events. However, it requires a charge distribution centroid closer to the ground electrode than to the injecting electrode, which is

rare, and may be produced by a non-equilibrium situation rather than DC poling in quasi state. Some interesting results of anomalous voltage return on polyethylene films were presented by Coelho a long time ago [7], but not reported elsewhere since (figure 9).

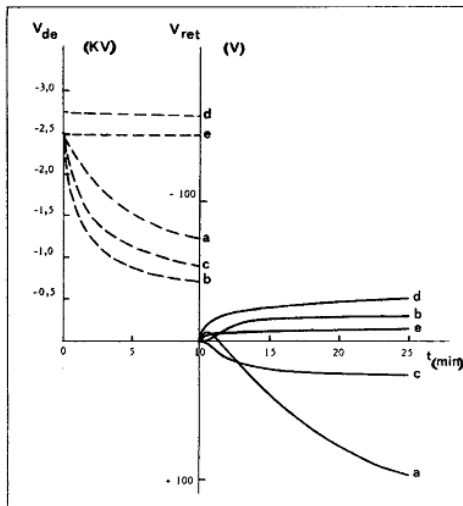


Fig. 9. Anomalous return voltage on polyethylene [7].

## V. HETEROGENEOUS CONDUCTIVITY

A homogeneous insulator may be subjected to a gradient of temperature, light, humidity, or any other parameter able to activate charge carriers motion and thus lead to a heterogeneous conductivity in the bulk of the material. This phenomenon has been studied in the past with a special focus on HVDC cables [16], where the inner conductor may be heated at a much higher temperature than the ambient. A strong temperature gradient appears in high field areas of the cable, which produces a high conductivity gradient.

As a result, an inner space charge distribution may build up, which will not be neutralized instantly when the insulator is short-circuited and may therefore induce a return voltage.

We describe here another experiment, which has been performed in our laboratory, involving a gradient of photoconductivity [17]. Polyimide films were positively charged by corona, and then exposed to two circular light dots coming from pipes canalizing the light emitted by a blue and a white LED (figure 10a). This exposure led to a decrease in potential in the corresponding areas (figure 10b), due to the photoconductivity of the films when irradiated with wavelengths below 550 nm.

The central area of the film surface was then neutralized using a negative corona charge deposit. In the darkness, the potential in this area remains steadily close to zero (figure 10c), while exposure to sunlight or to a white lamp illumination progressively leads to a significant voltage return in the areas illuminated before neutralization (figure 10d).

This is a consequence of the absorption of the wavelengths responsible for polyimide photoconductivity, which leads to a conductivity gradient, and consequently to an inner space

charge. Switching off the illumination freezes charge motion. Neutralizing the surface will then provide the necessary negative surface charge density to bring back the surface voltage to zero, but does not neutralize the inner charge distribution. It will be split by a zero-field plane above which the field is inverted. However, it is assumed to remain steadily trapped. As long as the sample is kept in the dark, this photoelectret may last during a quite long time (days) without vanishing. Applying another illumination of the surface then induces a larger conductivity in the inverted field zone than in the lower part of the sample, due to light absorption. As a result, a return voltage appears, due to the progressive compensation of the negative surface charge by a fraction of the internal positive charge.

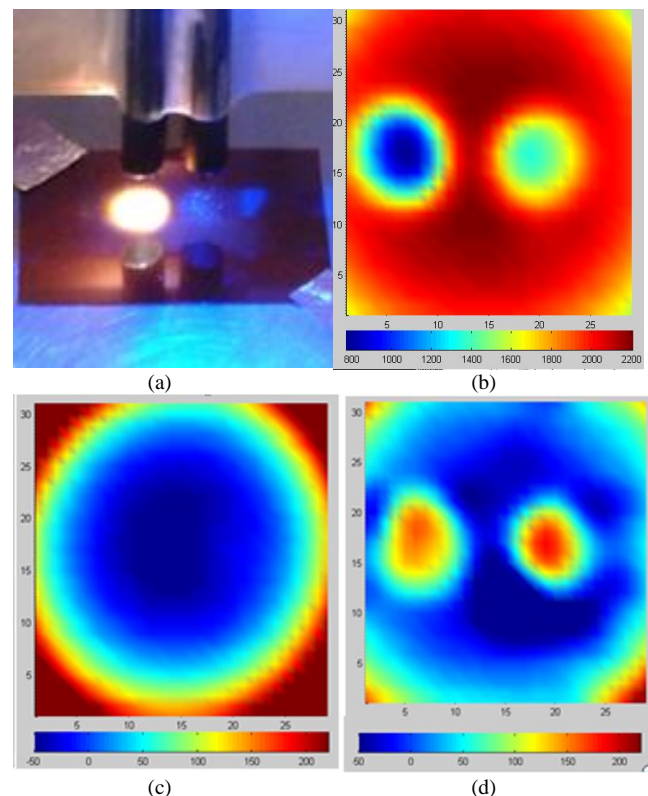


Fig. 10. Voltage return on a photoelectret induced in polyimide [17]. (a) Experimental setup applying light dots from white and blue LED (b) Potential mapping with an electrostatic feedback probe after 2000V charging and 120s exposure to white (left) and blue (right) LED light (c) Surface neutralization of the main central area of the sample (d) Return voltage after an additional 1h lamp illumination. Potential maps are 16mm x 16mm. Unit for the color scale is Volt.

The internal distribution of the charge may be adjusted by choosing the experimental parameters, its mean depth increasing with the exposure time, and its broadness depending on the light color, the absorption in the material being higher, and hence the photoconductivity gradient steeper for the blue light than for the white.

The use of light to produce a photoelectret has been known since a long time [18][19]. However, to our knowledge, the link between this space charge buildup due to heterogeneous conductivity and voltage return has not been reported elsewhere than in [17], where more details on this experiment and models may be found.



## VI. CONCLUSION

Field or potential measurements are sensitive to the geometrical distribution of the charge, rather to its motion. This feature is the strong point of this kind of measurements in the field of electrostatics, providing a better sensitivity as well as a greater noise immunity than measurements based on current intensity measurements. This is the main reason why, in addition to their important practical industrial interest to monitor ageing in transformers and cables, return voltage measurements may provide an interesting laboratory characterization tool.

A general conclusion that may be drawn from the different configurations and mechanisms examined here is that the measurement of high values of the return voltage signal requires a situation where the insulator may be divided in layers with quite different conductivities. This may be a consequence of the composite character of the material, inducing interfacial polarization or, in a homogeneous material, of a gradient of an activation parameter, as temperature, or light for a photoconductive material.

The signal produced by space charge motion away from the zero-plane field after external neutralization is much fainter, and probably much transient than the relaxation of interfacial polarization. However, given the importance of space charge phenomena in the ageing of the insulations, return voltage measurements remains an interesting way to investigate them, as well as to contribute to fundamental studies on charge mobility and trapping in insulators, which has not been fully explored.

## REFERENCES

- [1] M. Faraday, *Experimental researches in electricity*, note n°1234, Phil. Trans. Roy. Soc. London, 1838.
- [2] J. Hopkinson, "Residual charge of the Leyden jar. Dielectric properties of different glasses", *Phil. Trans. Roy. Soc. London* Vol. 167, pp. 599-626, 1877.
- [3] R. Patsch, D. Kamenka, and J. Menzel, "Return voltage measurements Diagnostic interpretations based on the dielectric time constants", *Materials Science-Poland* Vol. 27 , n°4, pp. 1157-1169, 2009.
- [4] Z.Á. Tamus, Á. Szirmai, and B Németh, "Comparison of Voltage Response and Return Voltage Measurements of a Transformer Insulation Model", *5. 19th International Symposium on High Voltage Engineering*, pp. 23 - 28, Pilsen, August 2015.
- [5] B. Nemeth, G. Csepes and R. Cselko, "Applicability of the Dielectric Response Methods for Diagnostics of Power Transformers by Application of Return Voltage Measurement", *2018 IEEE 2nd International Conference on Dielectrics (ICD)*, pp. 1-6, Budapest, 2018
- [6] R. Patsch, "Return Voltage Measurements – a Promising Tool for the Diagnosis of the Insulation Condition of Power Transformers", *IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, pp.1-4, Athens, 2018.
- [7] R. Coelho, "Surface potential decay and return voltage buildup. Applications to the understanding of the electrical transport in insulating films". In *Proc.5<sup>th</sup> Int. Conf. DMMA*, pp. 33-36, Canterbury, 1988.
- [8] R. Coelho, P. Jestin, L. Levy, and D. Sarrail, "On the return-voltage buildup in insulating materials". *IEEE Trans. Elec. Insul.*, no 6, pp. 683-690, 1987.
- [9] P. Molinié, "Measuring and modeling transient insulator response to charging: the contribution of surface potential studies", *IEEE Trans. Dielectrics and El. Ins.*, Vol. 12, n°5, pp. 939-950, 2005.
- [10] B. Gross, "On discharge voltage and return voltage curves for absorptive capacitors", *Physical Review*, Vol. 62, pp. 383-387, 1942.
- [11] A. K. Jonscher, *Dielectric relaxation in solids*. London: Chelsea Dielectrics Press, 1983.
- [12] P. Molinié, M. Goldman, and J Gatellet, "Surface potential decay on corona-charged epoxy samples due to polarization processes", *Journal of Physics D: Applied Physics*, Vol. 28 , n°8, pp. 1601-10, 1995.
- [13] P. Molinié and M. Karadjian, "Application de techniques électrostatiques à la caractérisation non destructive du vieillissement de câbles basse tension", *Proceedings of the 11th SFE Conference*, Grenoble, August 2018.
- [14] P. Molinié, S. Agnel, and J. Castellon, "Investigations on charge accumulation and relaxation in polycrystalline Al<sub>2</sub>O<sub>3</sub>", *10th Int. Conf. on Conduction and Breakdown in Solid Dielectrics*, Potsdam, July 2010.
- [15] N. F. Mott and R. Gurney W., *Electronic Processes in Ionic Crystals*. Oxford University Press, New York, 1940.
- [16] D. Fabiani et al., "HVDC Cable Design and Space Charge Accumulation. Part 3: Effect of Temperature Gradient", *IEEE Electrical Insulation Magazine*, vol. 24, no. 2, pp. 5-14, 2008
- [17] V. Griseri and P. Molinié, "Space charge buildup and dissipation in charged polyimide films exposed to visible light". In *Proc. IEEE 1<sup>st</sup> Int. Conf. on Dielectrics*, pp. 42-45, Montpellier, 2016.
- [18] J. K. Quamara., P. K. C. Pillai, and B. L. Sharma. "The photoelectret state in Kapton polyimide film. I. The effect of polarizing temperature, field and time". *Acta Polymerica* Vol. 33, n° 8, pp. 501-3, 1982.
- [19] J. K. Quamara., R. P. Bhardwaj, P. K. C. Pillai, and B. L. Sharma. "The photoelectret state in Kapton polyimide film. II. The effect of intensity of illumination and the autophotoelectret state". *Acta Polymerica*, Vol. 34, n° 6, pp. 355-358, 1983.