INFLUENCE OF THE AGEING STATE OF INSULATION SYSTEMS ON ABSORPTION/RESORPTION CURRENTS

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Polymer and insulation systems degradation leads to an increase of the concentration of charge carriers trapped in deep and shallow traps, i.e. of the volume charge density. Consequently, the amplitudes and the shapes of absorption/resorption currents are altered after normal or incidental ageing. In this work are analyzed the nature and the shape of the absorption/resorption currents, as well as the contribution of its different components, with a focus on those corresponding to space charge. Experimental results obtained on samples before ageing and after accelerated thermal and electrical ageing are presented. It is observed that, after water tree ageing, the volume space charge density increases, also leading to a modification of the absorption/resorption currents. Eventually, the possibility of assessing the ageing state of the samples using the absorption/resorption currents is analyzed.

1. INTRODUCTION

When a voltage step U_0 is applied to the plates of surface A of a non ideal flat capacitor (containing a dielectric of thickness g, of conductivity $\sigma \neq 0$ and of permittivity ε), the capacitor absorbs a time-dependent current of intensity $i_1(t)$, which is the sum of four components (Fig. 1)

$$i_1(t) = i_i(t) + i_p(t) + i_{ss}(t) + i_c(t),\qquad(1)$$

where: $i_i(t)$ is the intensity of the current corresponding to the charging of the capacitor having the vacuum as dielectric; $i_p(t)$ is the intensity of the polarization current; $i_{ss}(t)$ is the intensity of the current associated to space charge; $i_c(t)$ is the intensity of the conduction current.

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The component $i_i(t) = \varepsilon_0 A \partial E / \partial t$ corresponds to the charging current of the capacitor without dielectric ($\varepsilon = \varepsilon_0$), and reaches zero almost instantly. Consequently, the raising portion of the $i_1(t)$ curve (Fig. 1) is not recorded in usual measurements.
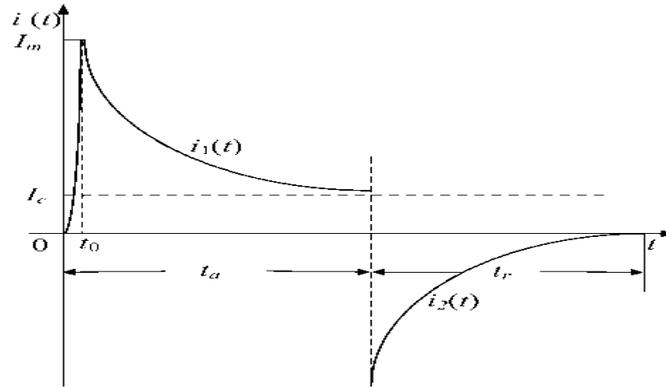

Fig. 1 – Current evolution versus time (t) after application of a voltage step ($i_1(t)$) and after voltage switch off ($i_2(t)$).

The component $i_p(t)$ corresponds to the polarization of the dielectric contained by the capacitor, *i.e.* to very localized displacements of a significant number of bounded charges (particles or particle groups belonging to the molecules of the dielectric), which return to their initial positions when the voltage is switched off. The polarization current $i_p(t)$ comes down to zero progressively after the application of the dc voltage U_0. The component $i_{ss}(t)$ corresponds to the space charge from the dielectric bulk, which is generated during manufacturing (broken molecules etc.) and during service (thermal, electrical, mechanical, irradiative degradation etc.), by carrier injection at sharp conducting edges etc. The charge carriers are trapped in deep or shallow traps and can move more or less within the dielectric (some of them being able to reach the electrodes). As these carriers either got re-trapped (mostly at interfaces between homogenous regions of the dielectric) or reach the electrodes (thus their concentration decreasing), the current $i_{ss}(t)$ tends to zero after a certain time.

The conduction current $i_c(t) = I_c = A\sigma U_0 / g$ (Fig. 1) is due to electron, hole and ion convection. The concentration of each carrier species depends, among others, on the chemical nature and on the physical structure of the dielectric, which lead either to major electronic or ionic conduction [1]. This component of the measured current is time-independent (from voltage switch on to voltage switch off) and allows determining experimentally the electric conductivity (or resistivity) of the dielectric.

The *decreasing absorption current component* of the dielectric $i_{aps}(t)$ is obtained by adding the polarization and space charge components:

$$i_{aps}(t) = i_p(t) + i_{ss}(t).$$
(2)

The value of i_{aps} is directly related to the ageing state of the insulation system, the degradation process resulting both in the appearance of polar radicals and trapped charge carriers. Thus, it can be written:

$$i_1(t) = i_i(t) + i_{aps}(t) + i_c(t).$$
(3)

If the voltage is switched off and the electrodes are short-circuited, the capacitor is discharged, and a transient current $i_2(t)$ is measured:

$$i_2(t) = i_d(t) + i_{dp}(t) + i'_{ss}(t),$$
(4)

where $i_d(t)$ is the discharge current of the capacitor having the vacuum as dielectric, $i_{dp}(t)$ is the depolarization current and $i'_{ss}(t)$ the current corresponding to space charge.

The sum of the depolarization and space charge currents is called the *decreasing resorption current component* of the dielectric $i_{rps}(t)$

$$i_{rps}(t) = i_{dp}(t) + i'_{ss}(t).$$
(5)

If the voltage U_0 is low (less than 1 kV), and its time of application is of the order of minutes or hours, usual insulation systems ($g > 1$ mm) do not suffer important transformations (significant chemical degradation), able to modify dipole or space charge concentration. Consequently,

$$i_p(t) = i_{de}(t),$$
$$i_{ss}(t) = i'_{ss}(t),$$
(6)

respectively,

$$i_{aps}(t) = i_{rps}(t).$$
(7)

This case is usually referred as the case where a *reversible absorption current* is present.

In polar insulation systems, and particularly in the cellulose-based systems placed in wet environments, the polarization current takes higher values. In these cases $i_{ss}(t) \ll i_p(t)$, so $i_p(t) \cong i_{aps}(t)$. As the absorption current is also reduced ($i_c(t) \ll i_p(t)$), it is considered that $i_1(t) = i_p(t)$ for $t > t_0$ (Fig. 1). Thus, the *polarization index k_p* for a given voltage U_0 is defined as [2]:

$$k_p = \frac{I_{60}}{I_{600}}, \qquad (8)$$

where I_{60} is the value of the current $i_1(t)$ measured after 60 s of applying U_0 and I_{600} is the value of $i_1(t)$, measured after 600 s of applying U_0.

As water is a very polar dielectric ($\varepsilon_r = 81$), the value of the polarization component $i_p(t)$ increases with the water content of the insulation, and the index k_p can be used for characterizing the "wetting state" of insulation systems. This method is used particularly for oil-cooled power transformers, insulation of disconnected electrical machines placed in wet environments etc. [3, 4]. It must be pointed also that the use of k_p is correct only if the conduction and space charge components $i_c(t)$ and $i_{ss}(t)$ are much lower than the polarization component $i_p(t)$.

In the case of dry composite insulation systems containing defects, the space charge component of the current i_{ss} can not be neglected any more with respect to the polarization current. Moreover, the value of i_{ss} may increase significantly as a result of degradation processes. Consequently, the direct measurement of i_{ss} or its determination from $i_{aps}(t)$ could allow to estimate the degradation state of insulation systems [3–7]. Thus, the increase of the maximum value of $i_1(t)$ reflects an increase of the charge carrier concentration, respectively a degradation of the insulation system, whilst the increase of the time constant τ characterizes a permittivity increase, respectively an increase of dipole concentration as a consequence of dielectric molecules breaking and/or of water penetration.

In the following, we present results of tests carried out for determining absorption/resorption and space charge currents for unaged polymeric samples and for polymeric samples aged thermally and electrically in an accelerated manner.

2. EXPERIMENTAL

2.1. SAMPLES

The measurements presented herein after have been carried out on low density polyethylene (LDPE) samples. The $100 \times 100 \times 0.5$ mm^3 flat samples used in this work were obtained by pressmoulding from pellets provided by Nexans Benelux (Belgium) and Borealis (Sweden). After measuring the space charge and the absorption/resorption currents just after manufacturing, the samples have been subjected to accelerated thermal ageing and/or to electrical ageing in the presence of a NaCl/H$_2$O solution. Superficial defects have been produced on one side of each sample by pressing with abrasive paper. The other side has been covered by a colloidal graphite semi conducting layer or by a metallic layer (aluminium). Before wet ageing, the samples have been stuck onto polyethylene tubes to form test cells like the one presented in Fig. 2, which were then filled with the aqueous solution.
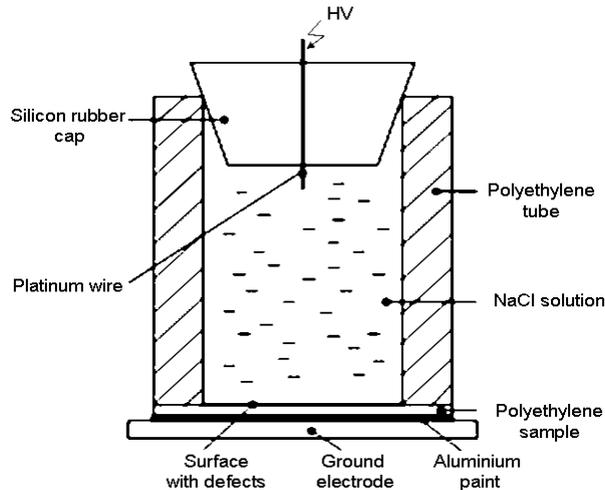
Fig. 2 – Test cell for ageing under combined stress of water and ac electric field.

Rubber caps were placed on the top of each cell. Each cap was crossed by a platinum wire in contact with the solution and connected to a ac high voltage power source.

2.2. EXPERIMENTAL SET UP FOR TESTS AND MEASUREMENTS

The thermal ageing of the samples has been carried out in an air-pulsed laboratory oven. The accelerated ac ageing in the presence of water has been made using the set up from Fig. 3, where sets of 5 test cells were placed in a sample holder and connected to the ac high voltage source.

The principle of the Thermal Step Method (TSM), which has been employed for space charge measurement in the studied samples, is summarized in Fig. 4a. A photograph of the measurement bench is shown in Fig. 4b.Thus, if we consider an insulating sample provided with conducting electrodes and short-circuited via a low current measurement device, the electric charge Q_i trapped within the material induces influence charges at electrodes (namely Q_1 and Q_2). When a low thermal step ΔT is applied to one side of the specimen (e.g., a negative step to the left electrode in Fig. 4a), the propagation of the thermal front across the sample gives rise both to local variations of the permittivity and to very slight and reversible movement of the space charge Q_i, caused by the dilation (or contraction) of the material. The thermal step can be applied, for instance, by means of a warm or cold liquid circulating in a thermal diffuser.
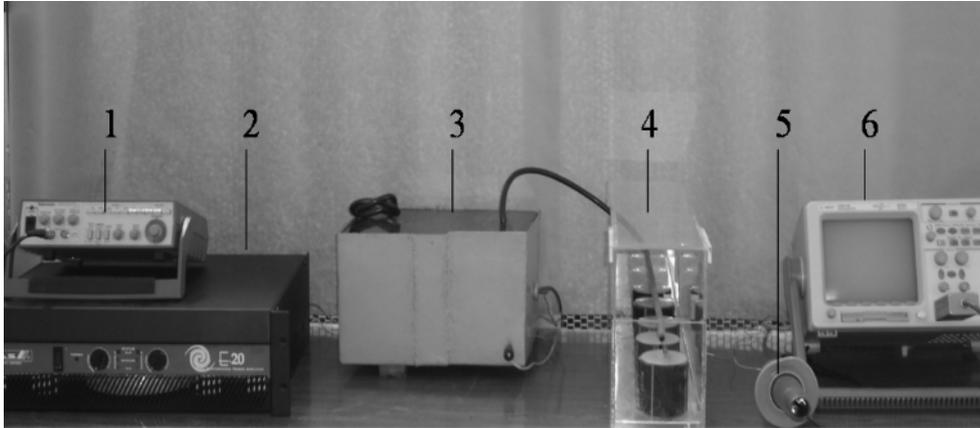
Fig. 3 – Experimental set-up for laboratory development of water trees in flat samples:
1 – variable frequency ac voltage source, 2 – wide band amplifier,
3 – 100/5.000 V/V transformer, 4 – sample holder with test cells,
5 – 1/1000 voltage probe, 6 – Agilent 54621A oscilloscope.

The electrostatic equilibrium of the material being thus modified, a transport of influence charges (Q_1, Q_2) occurs in the external circuit from an electrode to the other, as a consequence of the natural tendency of the system to rebalance. The result is an electric current of intensity $I(t)$ which can be measured by a current amplifier and recorded on a computer (Fig. 4b)

$$I(t) = -\frac{dQ_1}{dt}.$$ (9)
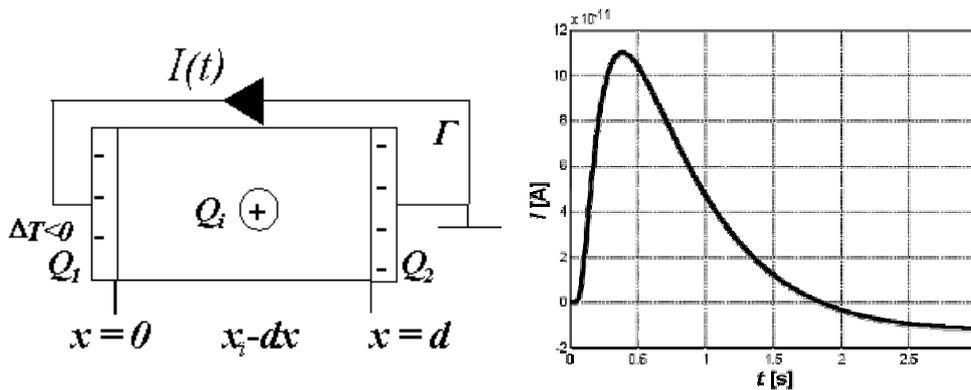
a)
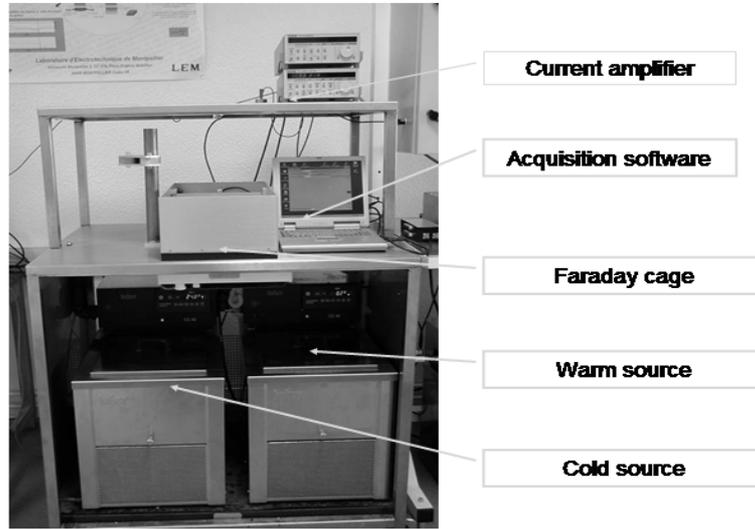
b)

Fig. 4 – Principle (a) and measurement bench (b) for space charge
measurements on flat samples by the thermal step method.

The expression of this "thermal step current" in a sample of homogenous permittivity and of thickness g is given by [9]:

$$I(t) = -\alpha C \int_0^g E(x) \frac{\partial \Delta T(x,t)}{\partial t} \, \mathrm{d}x \,, \tag{10}$$

where α is the relative variation of the sample's capacitance with the temperature, $E(x)$ is the electric field at the point of coordinate $x \in [0, g]$, C is the capacitance of the sample before the application of the thermal step, and $\partial \Delta T(x,t)/\partial t$ is the temperature derivative at the instant t and at the coordinate x, obtained by solving the heat equation.

In the case of a sample of homogenous permittivity ($\frac{\partial \varepsilon}{\partial x} = 0$), by knowing the propagation law of the temperature across the material and by applying an adequate numerical treatment to the recorded current (10), the electric field repartition $E(x)$ across the thickness of the sample, as well as the volume density of space charge $\rho(x) = \varepsilon \mathrm{d}E(x)/\mathrm{d}x$, can be determined. If the permittivity is not constant with respect to the depth coordinate x (i.e., $\varepsilon = \varepsilon(x)$), the analytical expression of the current, which may be obtained from (9) using the laws of the electrostatics,

depends on the function $\varepsilon(x)$. In most cases, it can be broadly considered that the thermal step current amplitude is directly related to the amount of charge Q_i trapped in the sample. For the sake of simplicity, this approach has been used for interpreting the thermal step currents measured on the samples tested in this work.

The absorption/resorption current measurements have been made with the installation presented in Fig. 5a and b, which allows starting to record the absorption current 0.142 s after the application of the voltage U_0.

2.3. TESTS

For establishing quantitative relations between the maximum values and/or the slopes of the absorption currents, the value of the space charge and the ageing degree of the samples, LDPE samples have been tested before and after ageing. Each sample was subjected to space charge measurements before and after the ageing process.

The thermal ageing has been made during 500 h at two temperatures lower than the LDPE melting temperature: $T_1 = 95\ °C$ and $T_2 = 105\ °C$.

The electrical accelerated ageing in the presence of water has been made under an ac voltage of value $U_{RMS} = 2$ kV and of frequency $f = 5$ kHz. For facilitating water tree initiation, superficial defects have been produced on the side of the samples in contact with the aquous solution (0.1 mol/l $NaCl/H_2O$) (Fig. 2). The defects (Fig. 6) were created using a Carver press by pressing P 240 abrasive paper onto the samples during 2 minutes, at a pressure $p = 10$-20 MPa. A higher value of the voltage frequency (5 kHz) than the power network one (50 Hz) has been used for accelerating water trees growth [10, 11].
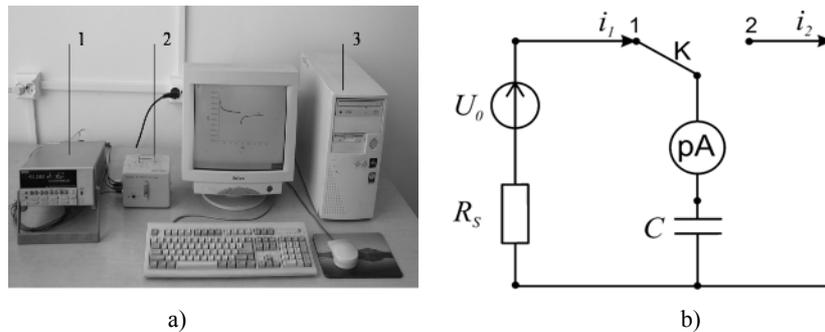

a)   b)

Fig. 5 – a) Experimental set up for measuring absorption/resorption currents: 1 – Keitlhey 6517 electrometer, 2 – Keithley 8009 measurement cell, 3 – computer;
b) Equivalent diagram of the measurement circuit for absorption (i_1) and resorption (i_2) currents: U_0 – applied dc voltage, R_s – source resistance, C – sample capacitance, pA – electrometer, K – switch allowing measuring either absorption or resorption current.

The absorption/resorption currents were measured after the application of a dc voltage $U_0 = 1000$ V.

3. **RESULTS AND DISCUSSION**

Superficial defects produced on the surface of the samples pressed onto the abrasive paper are presented in Fig. 6.
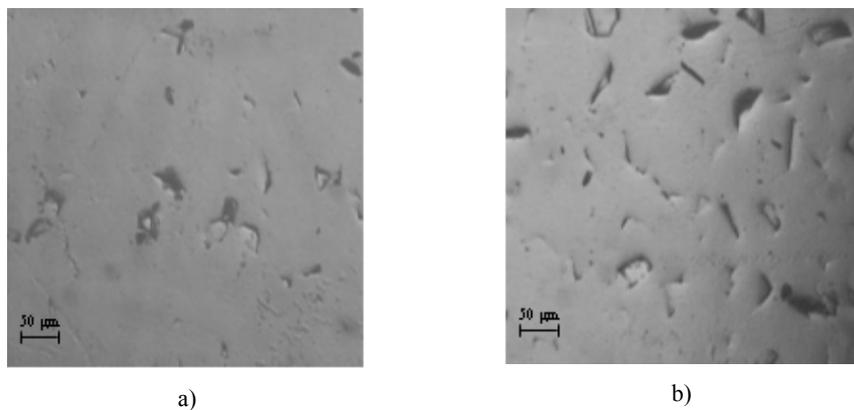

a)   b)

Fig. 6 – Superficial defects produced after application of pressures
of 11.05 MPa (a) and 22.1 MPa (b) during 2 minutes.

The increase of the pressure from 11 MPa to 22.1 MPa determines an increase of the superficial defects concentration from 0.01 mm^{-2} to 0.015 mm^{-2} (Fig. 6b), *i.e.* by 1.5 times. As the surface with superficial defects is in contact with the "water electrode" (connected to a potential of 2 kV RMS), it comes out that in the defect areas the electric field takes very high values. This leads to faster initiation of water trees and to the increase of their number with respect to [5, 12, 13] the case of a flat surface (Fig. 7) [5, 12, 13].

Fig. 8 shows thermal step currents measured on unaged polyethylene samples and on samples aged thermally during 500 hours at and 105 $^{\circ}$C. The value of the thermal step current is related to the amount of space charge trapped in the samples. Thus, the thermal step currents measured on the samples before ageing witness the presence of space charge in the materials from the very manufacturing (otherwise, they would have been equal to zero). In other words, even virgin, the material already contains a certain amount space charge.
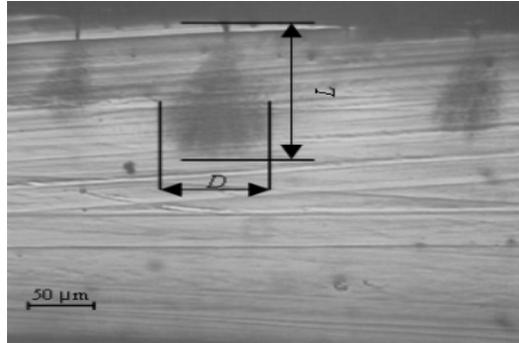
Fig. 7 – Water trees developed in polyethylene samples ac aged during 24 hours in aqueous
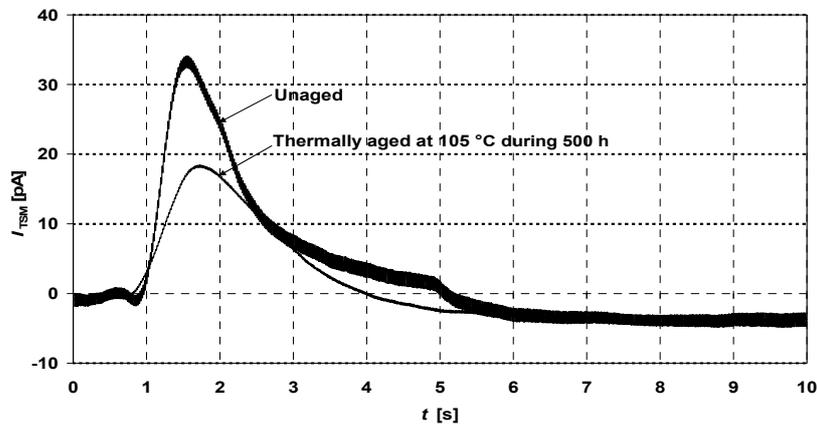NaCl/H$_2$O solution (U = 2 kV RMS, f = 5 kHz, c = 0.1 mol/l).

Fig. 8 – Thermal step currents measured in unaged samples and in samples
aged thermally during 500 hours at 105°C.

The importance of the bulk non homogeneity depends on the cooling rate. If
the cooling is slow, the bulk temperature is close to the surface temperature, and
the bulk non homogeneity of the material will be low. In contrast, fast cooling
leads to a higher bulk temperature gradient, and consequently to a higher gradient
of matter. It is therefore clear that a thick sample must be cooled down much
slower than a thin one, which is very well known by process engineers and cable
manufacturers.

It must be pointed out that space charge measurement methods like the TSM,
which are more sensitive than most of the classical methods, allow to non
destructively put into focus low non homogeneity ratios. Thus, the difference
observed between the thermal step currents measured on the two samples in virgin

state is related to the fact that their cooling rate, even if close, was not exactly identical.

The amplitudes of the thermal step currents presented in Fig. 8 decrease significantly after the submission of the samples to high temperatures. This decrease, corresponding to a decrease of the amount of trapped space charge, is due to the fact that, under the effect of the temperature, a part of the charges (*i.e.*, those trapped in shallow traps) can be released from their traps and recombine. In addition, a fraction of the water trapped in the samples at manufacturing (source of non homogenous polarization) has certainly been eliminated after the submission of the samples to temperatures of the order of 100 °C.

It must be therefore speculated that a "thermal purge" of a polymeric insulation system may have positive effects. However, it must not be forgotten that polymer submission to high temperatures, even if it allows material recristallisation and release of trapped charges (which are good things), also accelerates chemical reactions leading to material degradation (chain breaks, oxidation), increasing the number of charge traps which are likely to be filled if the material is simultaneously submitted to electric field (which are bad things). Thus, "material renovation" by thermal treatment in electrical engineering applications is a complex problem which must be treated thoroughfully on a case-by-case basis, as the beneficial effects can be completely counter-balanced if the system is exposed to too high temperatures for too long periods of time.

As one can see in Fig. 9, the thermal step currents measured on the samples containing water trees are higher than those measured before their submission to ac field and water stress.
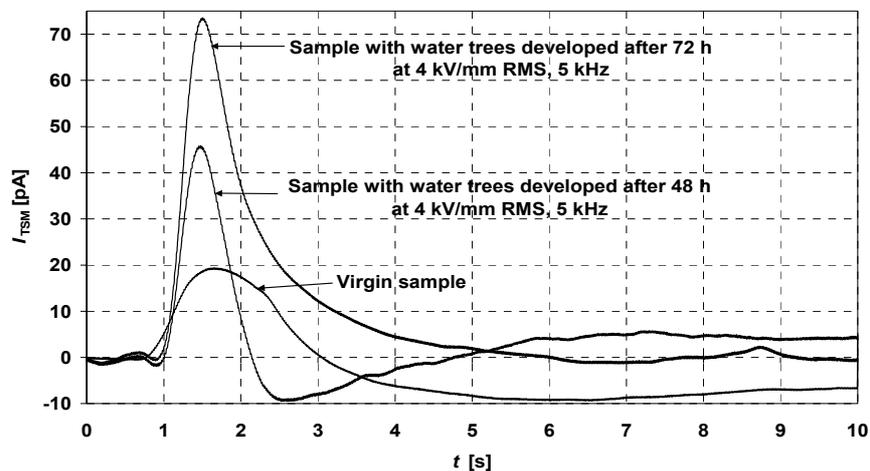

Fig. 9 – Thermal step currents measured in non treed samples and in samples containing water trees developed after 48 h and 72 h of submission to ac and water stress.

Moreover, the thermal step currents (and thus the space charge amount in the samples) tend to increase with the stress duration. Indeed, increasing the stress time from 24 h to 72 h leads to an increase of the thermal step current of 52 %. This is due to water tree development in the samples, which is correlated to the increase of the total surfaces of the interfaces where the space charge accumulates. Thermal step current analysis and simulations are currently under way for estimating the amount and the repartition of the space charge associated to water trees. Absorption/resorption currents recorded in unaged LDPE samples are presented in Fig. 10. The records have been made after applying a dc voltage $U_0 = 1000$ V over a relative long duration.

The aim of the measurements was to put into focus the stabilization of the current $i_1(t)$ at the value I_c and the cancellation of the current $i_2(t)$ (and the resorption current, respectively). For these reason, the records have been started 7 s after the application of the dc voltage, so the raising portions of the curves $i_1(t)$ and $i_2(t)$ were not recorded.

The thermal ageing leads both to a decrease of the absorption/resorption current maximum values and to an increase of their slopes (Fig. 10), which can be attributed to material recristallisation and to water elimination, as in the case of space charge measurements. An increase of the maximum value of the absorption current and a decrease of its slope can observed if the material undergoes significant ageing (resulting particularly in chemical degradation), which was apparently not the case for the studied samples.

In contrast, an opposite variation of the absorption currents is observed for the samples aged in the presence of electric field and water (Fig. 11).
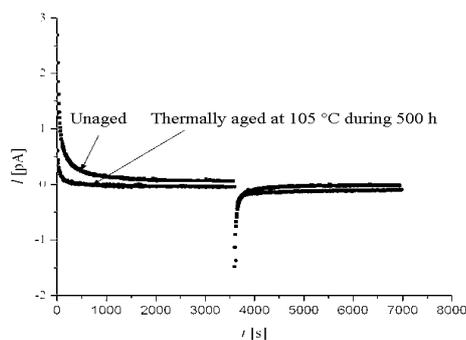

Fig. 10 – Absorption/resorption currents recorded in an unaged sample (1) and in samples aged thermally during 500 h at 95°C (2) and at 105°C (3) ($U_0 = 1000$ V).
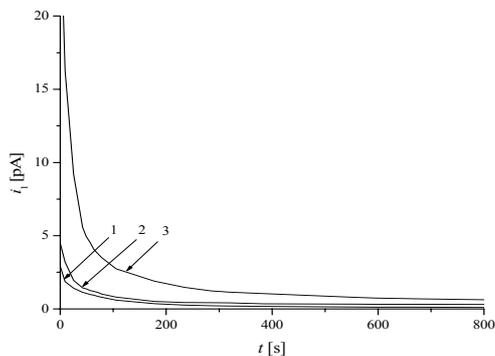
Fig. 11 – Absorption currents recorded in an unaged sample (1) and in samples aged in the presence of electric field and water during 24 h (2) and 48 h (3) ($U_0 = 1000$ V).

Thus, the increase of the conditioning time from 24 to 72 hours leads to an increase of the maximum value from 4.48 pA to 136 pA for i_1 and from 9.6 to 132 pA for i_2. This is due to the penetration in the material of highly polar water molecules and of ions resulted from the decomposition of NaCl of the aqueous solution. This phenomenon is brought in focus by the increase of the water tree dimensions (length L and diameter D, Fig. 12), concentrations and volumes (Table 1).

For instance, the increase of the ageing time from 24 h to 72 h led to an increase of water tree concentration by a factor of 2.38, as well as to an increase by a factor of 16.5 of the volume occupied by the trees.

Table 1

Values of parameters related to water trees

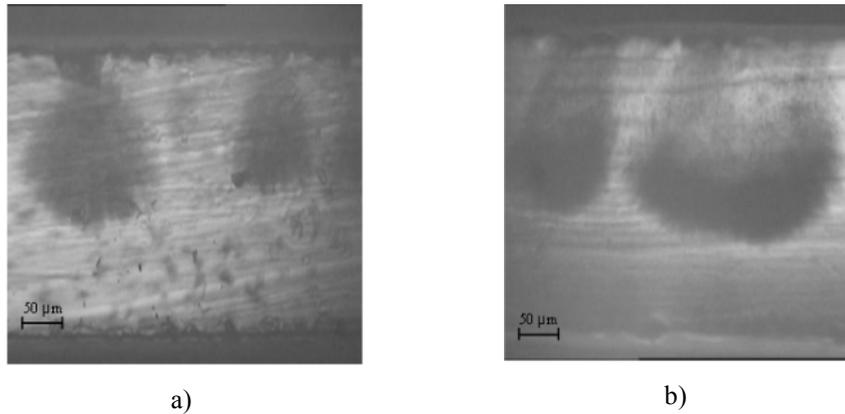| Ageing time [h]	Water tree average length L [µm]	Water tree average diameter D [µm]	Water tree concentration [mm^{-2}]	Water tree volume [mm^3]
24	138.54	151.06	1.90	9.26
48	226.50	226.19	4.20	74.97
72	265.22	287.94	4.53	153.46

a) b)

Fig. 12 – Water trees developed in low density polyethylene samples after ageing during a) 48 h, b) 72 h ($c = 0.1$ mol/l, $U = 2$ kV RMS, $f = 5$ kHz).

From the curves presented in Fig. 12, it comes out that their slopes decrease when the ageing duration increases. At the same time, the time constant τ (corresponding to the time after which the current value is divided by $e = 2.71\ldots$) increases. In other words, the increase of the dimensions of the grown water trees leads to an increase of the time constant $\tau = RC$ of the circuit to which the step voltage U_0 is applied (R being the resistance of the measurement circuit and C the

capacitance of the sample, Fig. 5b). This increase of the time constant is due to the increase of the sample permittivity as a consequence of water tree development and, consequently, to an increase of the average concentration of electric dipoles and space charge in the samples.

4. CONCLUSIONS

Polymer degradation leads to an increase of space charge amount and of the absorption/resorption current amplitudes. In the case of electrical ageing in the presence of water, the tests performed on low density polyethylene have shown a significant increase of the maximum values of the absorption currents, as well as a decrease of their slopes. In these cases, the components corresponding to polarization currents are significant. Consequently, in highly hydrophilic insulation systems, the content of absorbed water can be characterized by measuring the values of the absorption currents at 60 s and 600 s, i.e. by measuring the polarization index k_p. The same index can be used in insulation systems of which degradation results in the appearance of an important amount of water.

For dry insulation systems (as those used in electrical machines), where the humidity is relatively low and where, due to the composite structure of the insulation, the accumulation of space charge at the interfaces between homogeneous zones leads to relatively high $i_{ss}(t)$ currents, a characterization made by dividing the values of $i_1(t)$ measured at 60 s and 600 s can lead to significant errors. In contrast, the analysis of the absorption currents and the identification of the components related to space charge can provide valuable information about the degradation state of insulation systems. An estimation of insulation systems degradation state based on the comparison of absorption/resorption currents measured after a certain service time with the ones measured on unaged insulations will be presented in a future paper.

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