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ASSESSMENT OF THE STATE OF INSULATION SYSTEMS FOR LARGE ELECTRICAL MACHINES

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***Abstract* - Degradation of insulation systems of electrical equipments increases the space charge density and the concentration of electrical dipoles. By consequence, the permittivity, the resistivity and the maximal values and slopes of the absorption/resorption currents change with the ageing of insulation systems.**

In this paper an analysis of the nature and shapes of the absorption/resorption currents and the importance of their components is presented. The experimental study concerns the current measurements of the accelerated aged samples. The obtained results show that the thermal stresses influence the dielectric properties and the values and the shapes of the absorption/resorption currents. The possibility of assessment of the state of insulation systems from currents measurements is discussed.

Keywords: *Insulation Systems, Ageing, Resistivity, Permittivity, Loss Factor, Absorption/Resorption Currents*

1. INTRODUCTION

When a step voltage U_0 is applied to a condenser (with electrodes of surface A and the dielectric of thickness g, electrical conductivity σ and permittivity ε), the current that appears i_1(t) has 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 charging current of the condenser with vacuum dielectric, $i_p(t)$ is the polarization current, $i_{ss}(t)$ - the space charge current and $i_c(t)$ - the conduction current [1].

The component $i_p(t)$ is given by the dielectric polarization phenomena that consist in very small motions of a large number of attached charges [2].

The current $i_{ss}(t)$ corresponds to the movement of the existing space charge in the dielectric volume that can be generated by the technological process (molecules' fractures etc.), degradation process during the work service (thermal, electric, mechanic and radiation etc.) and charge injection at the surface of the electrodes. In a certain time depending of dielectric properties the currents $i_p(t)$ and $i_{ss}(t)$ become zero.

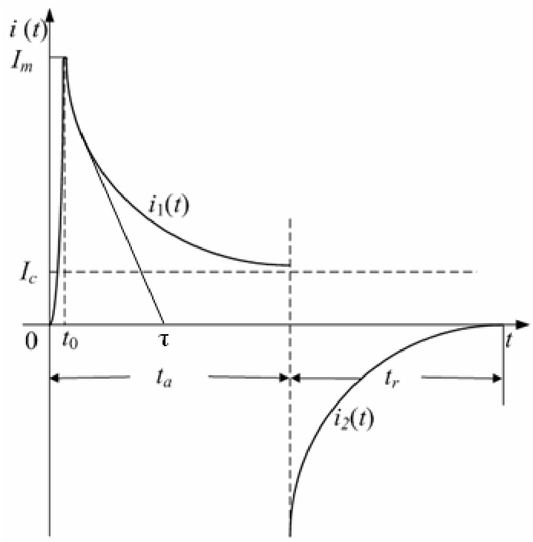

Figure 1: Time variation of the current i in a condenser dielectric for a step applied voltage ($i_1(t)$) and after the supply disconnection and electrode short-circuit ($i_2(t)$).

The conduction current $i_c(t) = I_c = A\cdot\sigma\cdot U_0/g$ (Fig. 1) is given by the convection of electrons, ions and molecular ions. The concentration of each charge type depends on the chemical nature and physical structure of dielectric and gives an electronic or ionic preponderant conduction [1]. This component of the total current is unchanged in time and permits the determination of the electrical resistivity of dielectric.

The sum of the polarization current and space charge current gives the decreased absorption component of the dielectric $i_{aps}(t)$:

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

When $U_0 = 0$ and the condenser electrodes are connected in short circuit, the dielectric is passed by a transitory current $i_2(t)$:

$$i_2(t) = i_d(t) + i_{dp}(t) + i_{ss}^{'}(t), \qquad (3)$$

where $i_d(t)$ is the discharge current of the vacuum dielectric condenser, $i_{dp}(t)$ – depolarization current and $i_{ss}'(t)$ - the current that corresponds to the dielectric spatial charge.

The sum between the depolarization current $i_{dp}(t)$ and spatial charge current $i_{ss}'(t)$ gives the decreased resorption component of the dielectric $i_{rps}(t)$:

$$i_{rps}(t) = i_{dp}(t) + i_{ss}^{'}(t)\,. \tag{4}$$

Taking into account that the U_0 voltage is inferior to 1 kV and its applied time is not very large (minutes or hours), in the case of usual insulation systems do not appear the important transformations (notable chemical degradations) that can modify the values of the electrical dipoles' concentration or/and of the space charge density. It results: $i_p(t) = i_{dp}(t)$, $i_{ss}(t) = i_{ss}'(t)$, respectively, $i_{aps}(t) = i_{rps}(t)$.

For insulation systems (particularly those based on cellulose) that work in humid environments, $i_{ss}(t) << i_p(t)$ and $i_p(t) \cong i_{aps}(t)$. Consequently, $i_c(t) << i_p(t)$, and it can be considered for $t > t_0$, $i_1(t) = i_p(t)$ and the polarization index k_p can be defined [2 - 4]:

$$k_{\mathrm{p}} = \frac{I_{600}}{I_{60}}\,, \tag{5}$$

where I_{600} is the current $i_1(t)$ measured after 600 seconds and I_{60} – the value of $i_1(t)$ measured after 60 seconds from the applied voltage U_0 start.

For the composite dry insulating systems, the space charge current cannot be neglected compared to the polarization current. Moreover, the values of $i_{ss}(t)$ can substantially increase as a result of the degradation process and the direct measurement or determination of $i_{aps}(t)$ can permit the estimation of the ageing state of insulation systems [3-11].

In previous papers [5, 9 - 12] the absorption/resorption currents obtained in homogenous polymer samples or paper-oil insulations were presented. In this paper are presented their variations in samples made of composite materials and the analysis of the modifications dependent of the thermal ageing state of the samples.

2. EXPERIMENTS

2.1 Samples and experimental set-up

For the experimental study four types of samples - noted by A, B, and C - were used. The samples A are polymeric plates having the dimensions of 100x100x0.5 mm^3. The samples B have the same surface (as A) and thickness of 1 … 2 mm and are made up of tape CALMICAGLAS (ISOVOLTA) that contains glass texture, mica paper and epoxy resins. Using the steel plates of 650x110x2.5 mm^3, seven layers of tape with 0.18 mm in thickness were rolled up (with ½ superposition). These plates was pressed at p = 3 bar and T = 160 ^{o}C for t = 2.5 hours. The values of T, p and t correspond to those used in technological process of large power electrical machines manufactured by Gena Electric Society. From these plates were made samples of 100x100 mm^2, which have been processed to obtain a requested thickness and a fine surface.

The samples C (400x41.2x18.1 mm^3) were made up from parallelepiped copper bars (that contain 20 conductors with 2.65x10 mm^2 in section), insulated with seven layers of mica tape CALMICAGLAS (rolled up with ½ superposition), pressed to p = 3 bar and T = 160 ^{o}C for t = 2.5 hours.

All samples were thermally conditioned at T = 190 ^{o}C for 48 h.

The accelerated thermal ageing of the samples has been made in a forced air flow oven with adjustable temperature varying between 30 and 250 ^{o}C.

The experimental set-up used to measure the absorption/resorption currents is presented in Figure 2. The used electrometer can measure the current with a delay of 0.145 s after the applied voltage U_0 start. In order to measure the capacitance and dielectric loss factor, we used a LCR Hewlett Packard 4263B bridge and an Agilent 16451B measuring device (Fig. 3). The mass loss during the ageing process was measured with a SHIMADZU AW220 electronic balance.

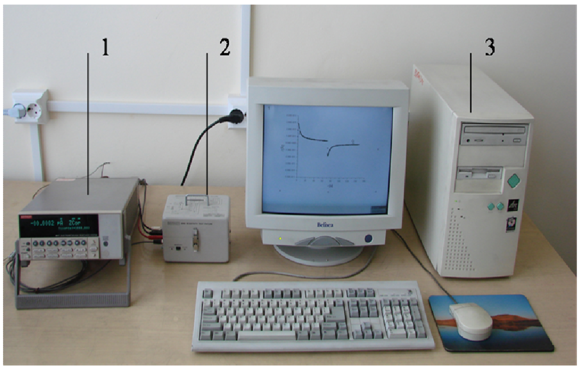

Figure 2: Experimental set-up for absorption/resorption currents measurement: 1 – Electrometer Keithley 6517, 2 – Resistivity Test Fixture Keithley 8009, 3 – PC.

2.2 Measurements

The tests were made on groups of five samples of each type.

To establish a quantitative relation between maximal values and/or slope of the absorption currents' curves and the ageing state of the samples (plates and bars), the current has been measured for four ageing temperatures. The ageing durations β and temperature values T (T_1 = 190 °C, T_2 = 210 °C, T_3 = 230 °C and T_4 = 250 °C) were chosen according to the IEC 60216 procedure [8]. The used applied voltage was 500 and 1000 V. The capacitance and loss factor were measured for two frequencies: 1 and 100 kHz. Some experimental results were presented in Section 3.

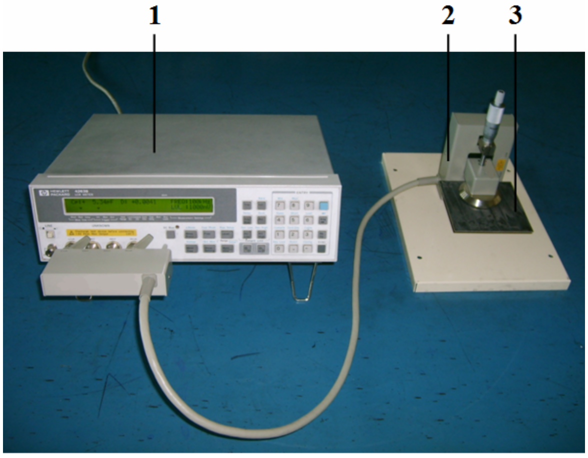

Figure 3: Experimental set-up for capacitance and loss factor measurements: 1 – Hewlett Packard 263B bridge; 2 – Agilent 16451B measuring device; 3 – Sample.

3. RESULTS. DISCUSSION.

Mass loss variation Δm with ageing time at T = 230 °C is presented in Figure 4. We noticed that when stress duration β increases, Δm values increses, which shows that the samples underwent irreversible chemical degradation.

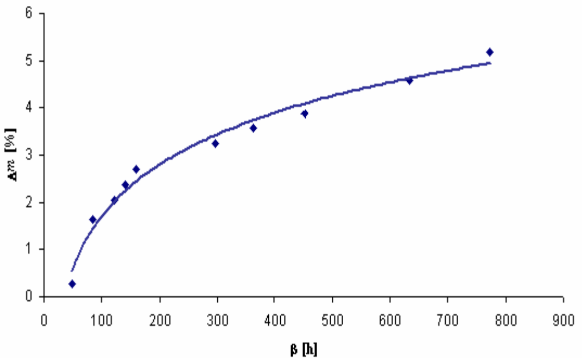

Figure 4: Mass loss variation with ageing duration β for B-type samples aged at T = 230 °C.

Figure 5 shows the variation in time of the absorption/resorption current for an un-aged sample. The current measurement (for U_0 = 1000 V) was made for a relatively long time in order to observe the tendency of the current $i_1(t)$ to be stabile around the I_c value and the resorption current $i_2(t)$ to decrease to zero. For this reason, the first values of the absorption current were recorded after about 7 seconds (the start curve parts of $i_1(t)$ and $i_2(t)$ are missing).

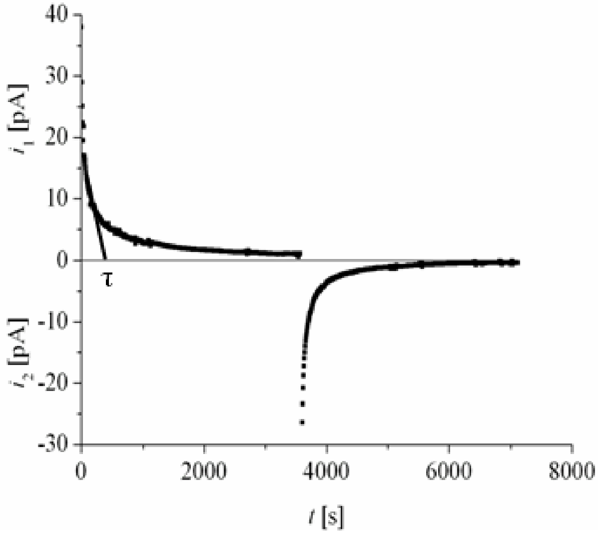

Figure 5: Absorption/resorption current variation for an un-aged sample B (U_0 = 1000 V).

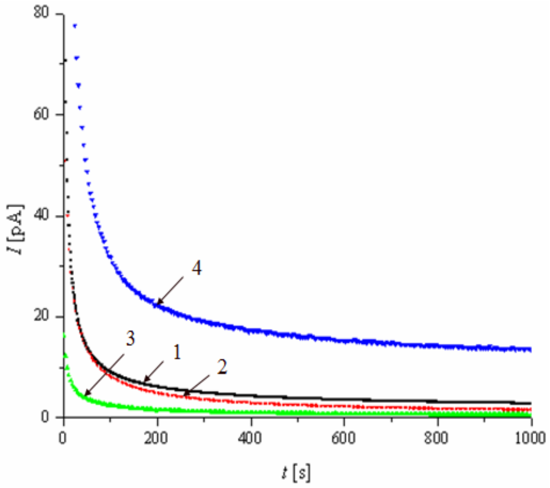

Figure 6: Time variation of absorption/resorption currents for B-type samples, unaged (1), thermally conditioned (48 h) at T = 190 °C (2) and aged at T = 230 °C for β = 112 h (3) and β = 312 h (4).

Absorption currents in samples B un-aged and aged are presented in Figures 6, 7 and 8. Because these samples were made from preimpregnated tape and were incompletely polymerized, they contain the reaction products and an important space charge located at the layers' interfaces. Consequently, during the thermal conditioning (Fig. 6, curve 2) and at the beginning of the ageing process, these products are eliminated and current values decrease (Fig. 6, curves 2 and 3) compared to the ones in unaged samples (Fig. 6, curve 1). If ageing duration increases, current values exceed the ones matching the unaged samples (Fig. 6, curve 4 and Fig. 7-8, curve 3).

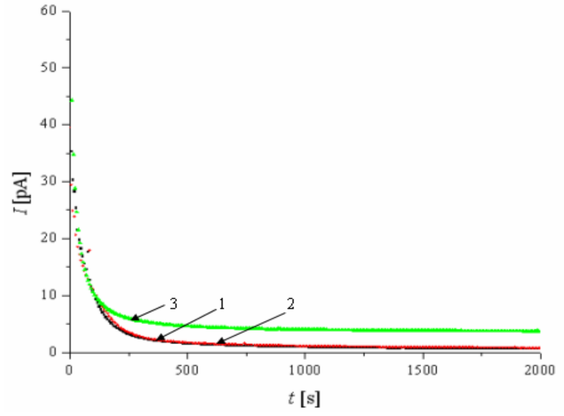

Figure 7: Time variation of absorption/resorption currents I for *B*-type samples, unaged (1) and thermally accelerated aged at 250 °C for β = 66 h (2) and β = 182h (3).

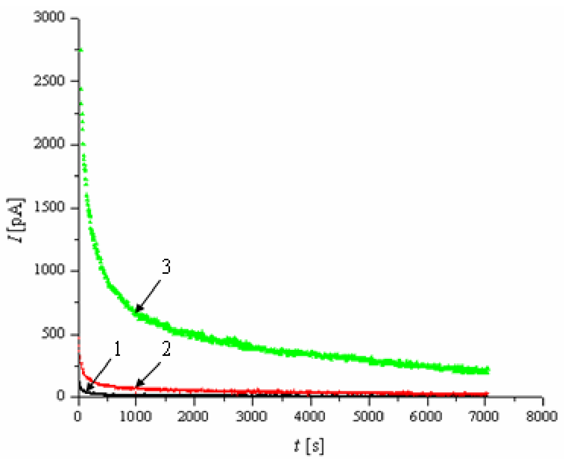

Figure 8. Time variation of absorption/resorption currents I for *C*-type samples, unaged (1) and thermally accelerated aged at 250 °C for β = 66 h (2) and β = 114 h (3).

On the other hand, the increase of time duration of thermal ageing β above 200 h produces a decrease in the values of the slopes of the curves $i_1(t)$ and an increase of the conduction currents I_c . This behavior is done by the increase of the space charge density, respectively, the increase of the currents $i_{ss}(t)$ and $i_p(t)$ due to the chemical degradation reactions (highlighted, too, by the increase of the conduction current I_c).

The experimental results illustrated in Figures 6 - 8 also show that the time constant τ (Fig.1 and 5) increases with the ageing time duration β. This observation can be explained by the increase of the equivalent relative permittivity of the samples as a consequence of the higher concentration of electrical dipoles due to the thermal degradation.

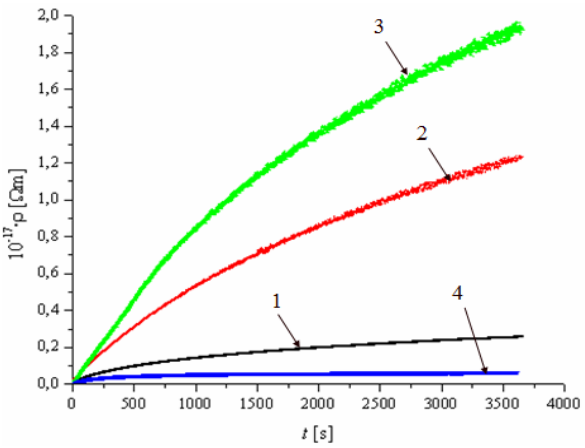

Figure 9: Time variation of resistivity ρ for *B*-type samples, unaged (1), thermally conditioned at 190 °C (2) and thermally accelerated aged at 230 °C for β = 112 h (3) and β = 312 h (4).

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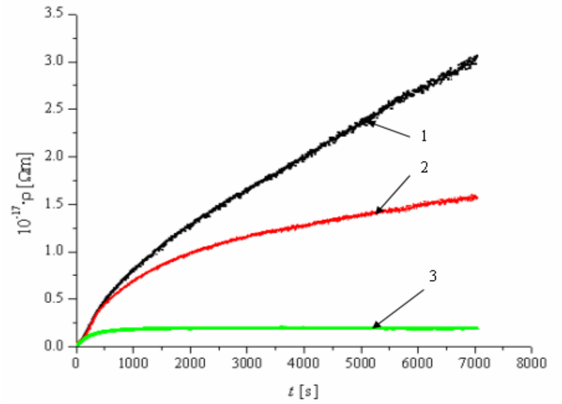

Figure 10: Time variation of resistivity ρ for *B*-type samples, unaged (1) and thermally accelerated aged at 250 °C for β = 66 h (2) and β = 182h (3).

In Figures 9 and 10 are shown the variations of volume resistivity of samples B, unaged and aged at 230 °C and 250 °C. It is seen that the increase of ageing duration β leads, at first, to the increase of the resistivity (respectively, to the decrease of electrical conductivity), and then to its decrease (respectively, the increase of electrical conductivity) due to the increase in space charge concentration after the thermal degradation.

Relative permittivity (ε_r) and loss factor (tg δ) variations with ageing time β nare presented in Figures 11 and 12. It can be seen that both ε_r, and tg δ decrease at the beginning of the ageing process and then increase.

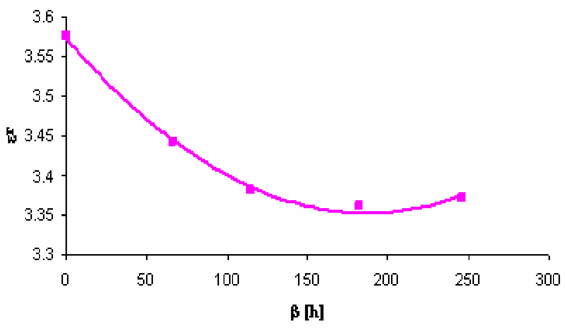

Figure 11: Relative permittivity ε_r variation with ageing time β (250 °C) for samples *B* (*f* = 100 kHz).

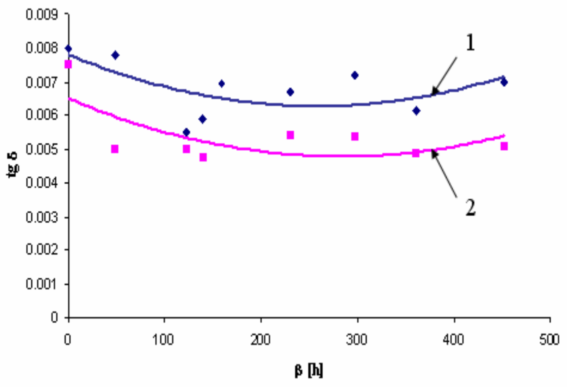

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Figure 12: Loss factor tg δ variation with ageing time β (230 °C) for samples *B* at *f* = 1 kHz (1) and *f* = 100 kHz (2).

4. CONCLUSION

The characterization of the water content of the strong hydrophilic insulation systems can be estimated using the values of the polarization index k_p. In the case of dry insulation systems (like those of the electrical machines), where the humidity is very small, the polarization current $i_p(t)$ can be less important. On the other hand, the presence of the space charge at the surface of the homogenous regions give the high values of the $i_{ss}(t)$ current and the use of k_p to characterize the humidity content of insulation can lead to important errors.

If the insulation system is degraded, the degradation products have an important contribution to the formation of the new charges and dipoles. In these cases, the analysis of the absorption currents and particularly of the currents given by the space charge can offer the important information concerning the assessment of the ageing state of insulation systems.

The estimation of the insulation systems' degradation based on the comparison of the absorption/resorption currents obtained on the accelerated ageing samples directly made up from used insulation with those obtained for un-aged samples will be presented in a next paper.

Acknowledgements

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