

Ageing Assessment of Insulation Systems by Absorption/Resorption Currents

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Abstract—Degradation of polymeric insulation systems of electrical equipments increases the space charge density and the concentration of electrical dipoles. By consequence, the maximum values and the slopes of absorption/resorption (A/R) currents can change with insulation systems ageing. In this paper, an analysis of the nature of the A/R currents and the importance of their components, especially the polarization current and the current given by the space charge, is presented. The experimental study concerns the A/R currents measurements of plane samples (made from CALMICAGLAS tapes), virgin and thermally accelerated aged. The obtained results show that the ageing process produces an increase of the values and a decrease of shapes of the A/R currents. Finally, the possibility of estimating insulations ageing state and lifetime from A/R currents measurements is discussed.

Keywords—Insulation Systems, Absorption/Resorption Currents, Ageing, Lifetime.

I. INTRODUCTION

DURING electrical equipments functioning, the insulation systems are exposed to normal permanent (thermal, electrical, mechanical, environmental, etc.) and accidental (overvoltage, overcurrent, etc.) stresses. These stresses initiate and maintain degradation processes (oxidation, molecule fracture, micro-cracks, etc.), which lead to the deterioration of mechanical and electrical insulation characteristics (increase of charge carriers and polar radicals concentration, etc.) and consequently to the insulation systems breakdown and electrical equipments premature take out [1]. Therefore, the knowledge regarding the condition of the insulation systems and their lifetime estimation has become a present-day problem.

The frequently used methods are destructive (based on the mass loss determination, on the chemiluminescence's

intensity, etc.) or global (based on the measurement of the insulation resistance, loss factor, partial discharge level, gas analysis, etc.) [2]-[15]. Recently, there are attempts to analyze the ageing of electrical equipment insulation systems based on absorption/resorption (A/R) currents [16]-[21].

The absorption current $i_1(t)$ appears 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) (Fig. 1):

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

where $i_i(t)$ is the charging current of the condenser with vacuum dielectric, $i_p(t)$ is the polarization current, $i_{ss}(t)$ is the space charge current and $i_c(t)$ is the conduction current [1].

The current $i_i(t) = \epsilon_0 A \partial E / \partial t$ is due to the charging of vacuum dielectric condenser ($\epsilon = \epsilon_0$) and decreases to zero very quickly. By consequence, for usual measurements, the start of the curve $i_1(t)$ (Fig. 1) is not recorded [16].

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. When the applied voltage is reduced to zero, these charges return to their initial positions.

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

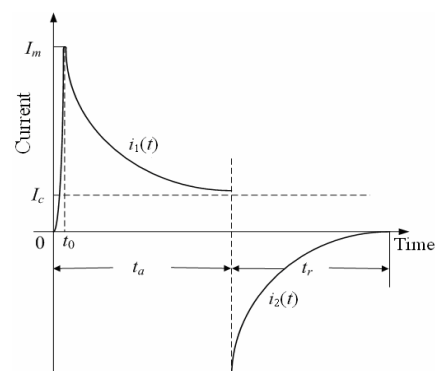


Fig. 1 Time variation of the current in a condenser dielectric for a step applied voltage U_0 ($i_1(t)$) and after the supply disconnection and electrode short-circuit ($i_2(t)$)

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P. V. Notingher thanks the Romanian Ministry of Education, Research and Youth for its financial support.

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], [16]. This component is unchanged in time (from the start moment of applied voltage until its turn off) and allows the determination of the electrical resistivity of dielectric. Concerning the electric charge sources, the electrodes' injection, band-band tunnels, impurities' ionization and thermal step play an important role. On the other hand, the concentration of these charges depends on the applied electric field strength, temperature, radiation, humidity etc. and is in relation to the ageing state of the dielectric.

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

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

The value of $i_{aps}(t)$ directly depends on the ageing state of the insulation system (polar radicals and trapped charges being generated in the ageing process). It results:

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

When the voltage supply is turned off ($U_0 = 0$) and the condenser electrodes are connected in short-circuit, the discharge of the condenser begins and the dielectric is passed by a transitory current $i_2(t)$:

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

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 space charge.

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

$$i_{rps}(t) = i_{dp}(t) + i_{ss}'(t). \quad (5)$$

Taking into account that the U_0 voltage is inferior to 1 kV and the 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 electrical dipoles' concentration or the values 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 polar insulation systems and particularly those based on cellulose fibers that work in humid environments, $i_{ss}(t) \ll i_p(t)$ and $i_p(t) \equiv i_{aps}(t)$. Consequently, $i_c(t) \ll i_p(t)$, and it can be considered for $t > t_0$ (Fig. 1), $i_1(t) = i_p(t)$ and the polarization index k_p can be defined [3], [7]:

$$k_p = \frac{I_{60}}{I_{600}}, \quad (6)$$

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

Insulation systems degradation can be highlighted by the modification of the conductivity factor k_c [17]:

$$k_c = \frac{i_1(30) - i_2(30)}{i_1(60) - i_2(60)}, \quad (7)$$

where $i_{1,2}(30, 60)$ are the currents $i_{1,2}(t)$ measured after 30 and 60 seconds from the U_0 start, respectively from the voltage stop and electrodes' short-circuiting.

The current $i_1(t)$ is called polarization current or absorption current and his time variation can be given by the equation:

$$i_1(t) = I_c + I_m \cdot \exp(-t/\tau), \quad (8)$$

where I_c is the conduction current, I_m – the maximum value of $i_1(t)$ and τ – the time constant of the charging circuit ($\tau = R \cdot C$, R – electrical resistance of the circuit and C – condenser capacity) [19].

For the composite dry insulation 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 $i_{aps}(t)$ allow the estimation of the ageing state of insulation systems [3], [17]-[25]. In this way, the increase of the maximum value of $i_1(t)$ shows the increase of the charge concentration, respectively the degradation of the insulation system. A large value of the time constant τ shows the increase of the permittivity, respectively the increase of the electrical dipoles concentration as a consequence of the molecules' fractures and/or water contamination.

In previous papers [3], [16]-[17], the A/R currents from different types of samples were presented. In this paper, the variations of the relative mass loss Δm_r , the relative maximum values of the absorption currents $I_{\max,r}$ and the polarization index k_p on the thermal ageing state of the different samples (made from materials used for stator winding insulations of medium power rotating machines) are analyzed. The estimated lifetime values are also presented, using the above-mentioned values (Δm_r , $I_{\max,r}$ and k_p).

II. EXPERIMENTS

A. Samples and Experimental Set-up

For the experimental study, two types of samples – named A and B – were used.

The A samples are polymeric (polyethylene) plates having the dimensions of 100 mm x 100 mm x 0.5 mm. The B samples 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 steel plates of 650 mm x 110 mm x 2.5 mm, seven layers of tape with 0.18 mm in thickness were rolled up (with $\frac{1}{2}$ superposition). These plates were pressed at $p = 3$ bar and $T = 160$ °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 Ltd. From these plates were made samples of 100 mm x 100 mm, which have been processed to obtain a requested thickness and a fine surface. Adherent semiconductor electrodes were stuck to the surfaces of the samples in order to measure the A/R currents [3].

All samples were thermally conditioned for 48 h, at 60 °C – A samples and at 190 °C – B samples. The samples' accelerated thermal ageing was done in a Trade Raypa forced air flow oven with adjustable temperature varying between 30 and 250 °C.

The experimental setup used to measure the A/R currents is presented in Fig. 2. The used electrometer can measure the current with a delay of 0.145 s after the applied voltage U_0 start [16].

The mass loss during the ageing process was measured with a SHIMADZU AW220 electronic balance.

B. Measurements

To establish a quantitative relation between the values of the A/R currents and the ageing state of the samples, the currents have been measured for different ageing times β (between 0 and 1600 h) for the following ageing temperatures: $T_1 = 210$ °C, $T_2 = 230$ °C, and $T_3 = 250$ °C (according to the Procedure IEC 60216) [22]. The used applied voltage was 500 and 1000 V. Some experimental results are presented in Section III.

III. RESULTS. DISCUSSION

Fig. 3 shows the variation as a function of time of the A/R current for an un-aged A sample. The currents measurement (for $U_0 = 1000$ V) was done for a relatively long time (1-2 h) in order to observe the tendency of the current $i_1(t)$ to be stable 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 1.4 seconds (the start curves parts of $i_1(t)$ and $i_2(t)$ are missing).

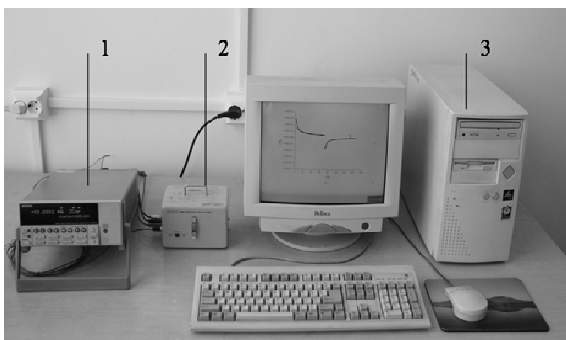


Fig. 2 Experimental setup for absorption/resorption currents measurement: 1 – Electrometer Keithley 6517, 2 – Resistivity Test Fixture Keithley 8009, 3 – PC

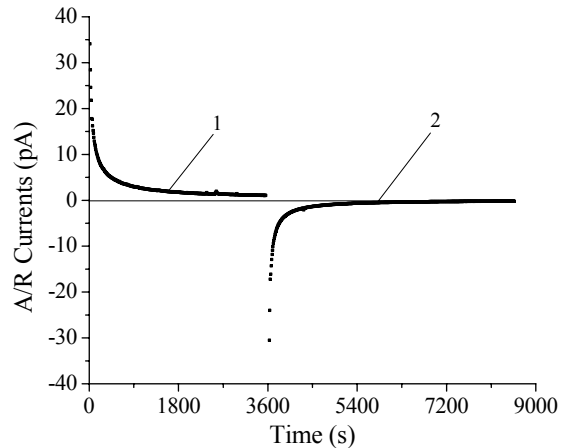


Fig. 3 Time variations of the A/R currents for an un-aged A sample ($U_0 = 1000$ V)

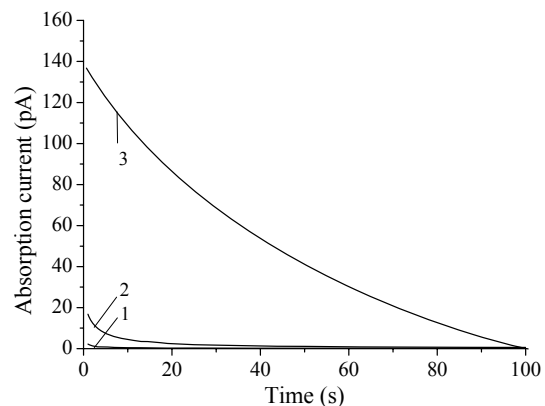


Fig. 4 Time variation of the absorption current for A type samples: un-aged (1) and thermally aged at $T_4 = 95$ °C (2) and $T_5 = 105$ °C (3) ($\beta = 480$ h, $U_0 = 1000$ V)

Absorption currents in A samples (for the same thermal aged duration $\beta = 480$ h) at two temperatures, $T_4 = 95$ °C and $T_5 = 105$ °C are presented in Fig. 4. It can be seen that if the ageing temperature increases, the maximum values of the currents increase too and the slope of the curves becomes smaller. This is due to the increase of the degradation products' content of the samples (ions and electric dipoles), respectively to the increase of the i_p and i_{ss} components values.

In Fig. 5, the variations of medium absorption currents determined on groups of 5 B samples, unaged and aged for small β times at 210 °C (176 h), 230 °C (118 h) and 250 °C (107 h) are presented. It can be seen that, in the first part of the experiment, absorption current values decreased and slopes values increased compared to the ones for the unaged samples. This is due to the elimination of polar products (solvents) and of space charge left inside the samples after the fabrication process and, therefore, of the reduction of the polarization and space charge components (i_p and i_{ss}) from the absorption current. Certainly, with the increase of the ageing temperature, particles elimination (diffusion) is faster and i_{aps} values become smaller, respectively $i_1(T_4) < i_1(T_3) < i_1(T_2)$ (Fig. 5, curves 2, 3 and 4).

Time variations of the absorption currents in B samples thermally stressed for longer periods of time are presented in Fig. 6. It is noticed that, for all ageing temperatures, current values increased with ageing time β , which was due to the degradation of epoxy resins molecules and generation of polar

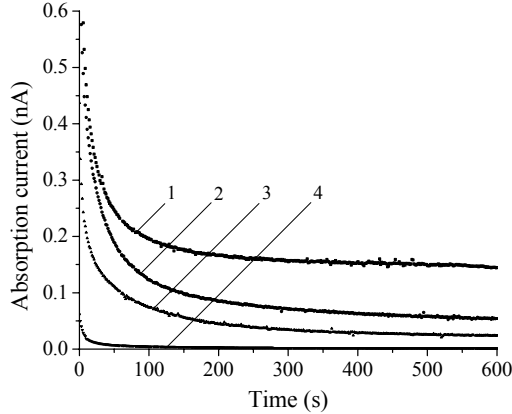


Fig. 5 Time variation of the absorption current for short time aged B samples: 1 – unaged, 2 – $T_1 = 210$ °C and $\beta = 176$ h, 3 – $T_2 = 230$ °C and $\beta = 118$ h, 4 – $T_3 = 250$ °C and $\beta = 107$ h

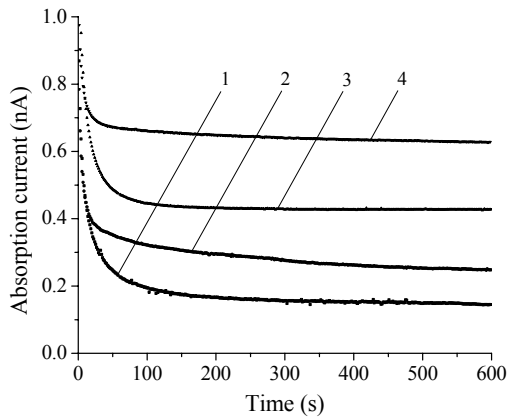


Fig. 6 Time variation of the absorption current for long time aged B samples: 1 – unaged, 2 – $T_1 = 210$ °C and $\beta = 679$ h, 3 – $T_2 = 230$ °C and $\beta = 626$ h, 4 – $T_3 = 250$ °C and $\beta = 432$ h

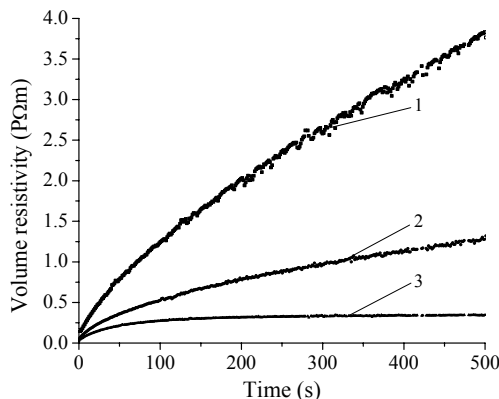


Fig. 7 Time variation of the volume resistivity for long time aged B samples: 1 – unaged, 2 – $T_1 = 210$ °C and $\beta = 411$ h, 3 – $T_2 = 230$ °C and $\beta = 500$ h

products (which led to the increase of the polarization current i_p) and charge carriers (electrons and ions), part of them fixed on the interfaces between the mica paper and glass texture layers, leading to the increase of the space charge current i_{ss} .

Obviously, as a result of the samples' epoxy resin degradation, an increase of the conduction component I_c of the absorption current i_1 is also produced, respectively a decrease of the samples' electrical resistivity (Fig. 7, curves 2 and 3).

TABLE I
VOLUME RESISTIVITY VARIATION $\Delta\rho_v$ WITH DIFFERENT AGEING TEMPERATURES T FOR B SAMPLES AGED AT $\beta = 432$ h ($\rho_v(0) = 4.2$ PΩm)

T [°C]	210	230	250
ρ_v [PΩm]	1.2	0.35	0.024
$\Delta\rho_v$ [%]	28.6	8.3	0.6

Table I presents the volume resistivity ρ_v values and its variation $\Delta\rho_v$ ($\Delta\rho_v = \rho(\beta)/\rho(0)$) for B samples aged at $\beta = 432$ h ($\rho(\beta)$ representing the value at $\beta = 432$ h, while $\rho(0)$ – the value for the un-aged samples). It can be seen that volume resistivity decreases at 28.6 % for $T_1 = 210$ °C, at 8.3 % for $T_2 = 230$ °C and at 0.6 % for $T_3 = 250$ °C, compared to their initial value.

In Fig. 8 are presented the epoxy resin relative mass loss variation curves $\Delta m_r(\beta)$, defined by:

$$\Delta m_r(\beta) = \frac{m(0) - m(\beta)}{m(0)}, \quad (9)$$

where $m(0)$ is the initial mass of the samples' epoxy resin and $m(\beta)$ – the mass of the epoxy resin at ageing time β .

Taking as end-of-life criterion the value $\Delta m_{r, eof} = 8$ % [23], the lifetime equation $\ln\beta = 14448/T - 22.483$ is obtained (Fig. 9).

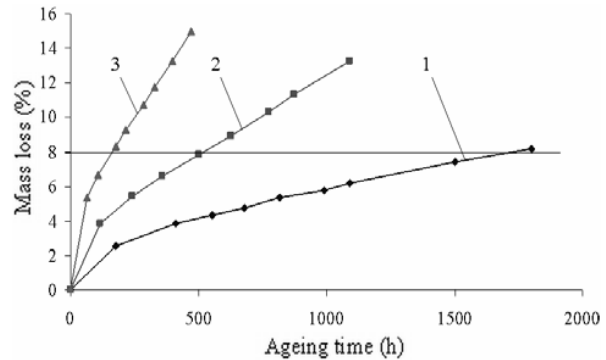


Fig. 8 Mass loss variations with ageing time for B samples at ageing temperatures $T_1 = 210$ °C (1), $T_2 = 230$ °C (2), and $T_3 = 250$ °C (3)

Using the lifetime curve (Fig. 9), insulation lifetime was determined for two functioning temperatures: for $T_6 = 155$ °C, it is obtained $L_{m6} = 9.46$ years, while for $T_7 = 120$ °C, $L_{m7} = 182$ years.

From all measured absorption currents, the first measured values were gathered after each interspace (1.4 seconds after applied voltage start), marked $I_{\max}(1.4)$ and, for each ageing temperature, the currents' relative maximum values f were

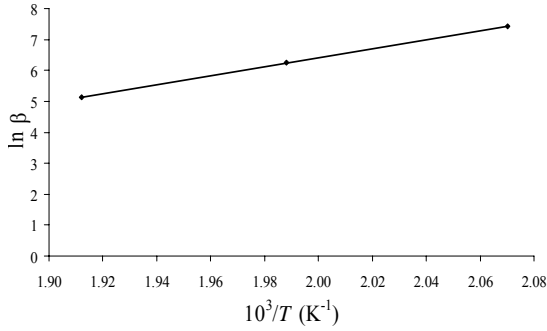


Fig. 9 Lifetime curve for B samples corresponding to mass loss diagnostic factor and end-of-life criterion $\Delta m_{r,eof} = 8 \%$

determined, corresponding to the ageing time β ($I_{\max,r}(\beta)$), defined as:

$$I_{\max,r}(\beta) = \frac{I_{\max}(1.4) - I_{\max}(\beta)}{I_{\max}(1.4)} \quad (10)$$

Relative maximum absorption currents variations with ageing time β ($I_{\max,r}(\beta)$) are presented in Fig. 10.

As is can be seen in Fig. 5 and 6, the samples thermal stress facilitates polar products and space charge diffusion towards the electrodes, leading to the decrease of $I_{\max,r}$ values; the increase of β values leads to the epoxy resin degradation and also to the increase of maximum values of the absorption currents.

Choosing the end-of-life criterion the value $I_{\max,r,eol} = 1.8$ (meaning an 80 % increase in the maximum current), lifetime equation $\ln \beta = 15531/T - 24.949$ is obtained (Fig. 11). Based on the curve presented in Fig. 10, lifetime values L_I can be obtained for different temperatures. Thus, for $T_6 = 155^\circ\text{C}$, it is obtained $L_{I6} = 9.64$ years, while for $T_7 = 120^\circ\text{C}$, $L_{I7} = 248$ years.

It is noticed that the difference ΔL between the values of the lifetime obtained for the mass loss and the relative maximum values of the absorption currents methods at $T_6 = 155^\circ\text{C}$ is small: $\Delta L_{155} = 1.87 \%$.

The variations of the polarization index k_p with ageing time β , for B samples aged at 210, 230 and 250 $^\circ\text{C}$ are presented in Fig. 12.

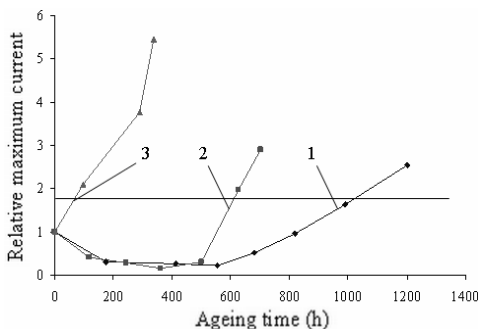


Fig. 10 Variations of the maximum relative values of the absorption current $I_{\max,r}$ with ageing time β , for B samples at $T_1 = 210^\circ\text{C}$ (1), $T_2 = 230^\circ\text{C}$ (2), and $T_3 = 250^\circ\text{C}$ (3)

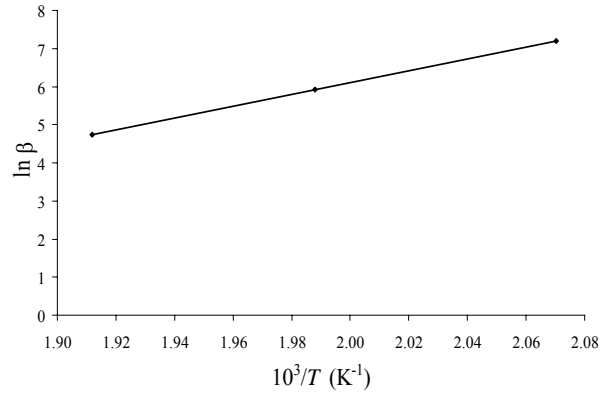


Fig. 11 Lifetime curve for B samples corresponding to the $I_{\max,r}$ diagnostic factor and end-of-life criterion $I_{\max,r,eol} = 1.8$

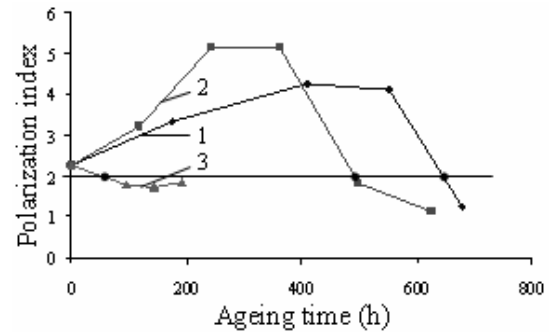


Fig. 12 Variation of the polarization index k_p with ageing time β for B samples at $T_1 = 210^\circ\text{C}$ (1), $T_2 = 230^\circ\text{C}$ (2) and $T_3 = 250^\circ\text{C}$ (3)

It can be seen that, for $\beta = 0$, in all cases, the values of the k_p factor are small and that these values increase at the beginning of the ageing processes. If T increases, under heat effect, some electrons, ions and electric dipoles trapped in more significant potential gaps are detrapped. Consequently, the i_{ss} and i_p currents increase and an important increase of the polarization index k_p appears (Fig. 12).

The $k_p(\beta)$ curves have maximum values for the β values (named β_{\max}) dependent on the ageing temperature. For the B samples, in the case of the 210°C ageing temperature, $\beta_{\max} \approx 450$ h. When the ageing temperature increases, the particles gather the escape energy faster, so the values of β_{\max} decrease (for 230°C , $\beta_{\max} \approx 350$ h).

For β values bigger than the ones of β_{\max} , the values of k_p decrease, due to the increase of the dipoles' and charge carriers' concentration (produced by the thermal degradation of the epoxy resins).

If the polarization index k_p is used as a diagnostic factor, for the end-of-life criterion set at $k_{p,eol} = 2$, from the curves presented in Fig. 12, the lifetime equation $\ln \beta = 16769/T - 27.887$ is obtained. The lifetime values at 155 and 120°C , obtained from the lifetime curve presented in Fig. 13, are $L_{k6} = 9.7$ years and $L_{k7} = 300$ years respectively.

The difference ΔL between the values of the lifetime for the mass loss and the polarization index methods at $T_6 = 155^\circ\text{C}$ is small: $\Delta L_{155} = 0.24 \%$.

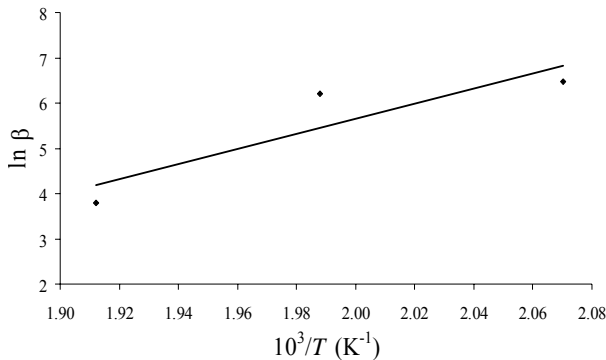


Fig. 13 Lifetime curve for B samples corresponding to the k_p diagnostic factor and end-of-life criterion $k_{p,eol} = 2$

For the functioning temperature $T_7 = 120^\circ\text{C}$, the lifetime values obtained by the three methods well surpassed 180 years, and for $T_6 = 155^\circ\text{C}$, these values exceeded 9.5 years.

It should be noticed, however, that the calculated lifetime values do not take into account other stresses which insulation systems suffer during service. For multiple synergetic stresses, lifetime duration values are smaller [1].

IV. CONCLUSION

The characterization of the water content of the strong hydrophilic insulation systems (like those of the transformers) can be estimated using the values of the polarization index k_p . In the case of the 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.

These errors can increase when the insulation system is degraded and the degradation products have an important contribution to the formation of the new charges and electric 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 ageing of insulation systems.

The values of lifetime L obtained based on the absorption currents are relatively close to the ones obtained using mass loss determination (for $T_6 = 155^\circ\text{C}$, the variations do not exceed 2 %), which confirms, in case of our samples, the accuracy of the results obtained through A/R method.

The method of absorption currents presented in this paper is a nondestructive one and can be applied for ageing estimation and for the diagnosing and monitoring of insulation systems of high power electrical equipment in situ (through off-line and/or on-line measurements) [24-26]. For this, the unifactor ageing tests presented in this paper must be completed with multi-factor ageing tests, for thermal, electrical and mechanical stresses.

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 (stator bars) with those obtained for unaged samples will be presented in a next paper.

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