Determination of the Remaining Lifetime of Power Transformers Liquid Insulations Based on the Absorption/Resorption Currents

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Abstract- **In this paper, the electrical resistivity (determined with absorption/resorption currents) is used as a diagnostic factor in order to assess the mineral oil condition and to evaluate its elapsed and remaining lifetimes. Based on experimental results of thermal accelerated ageing, the lifetime values at constant temperature are calculated by the IEC and activation energy methods. The chosen end-of-life criterion was the oil resistivity value of 0.15 TΩm. Finally, the lifetime at constant temperature and elapsed and remaining lifetimes for two variations of oil temperature are calculated.**

Keywords: **mineral oil, thermal ageing, absorption/resorption currents, lifetime, elapsed and remaining lifetime**

I. INTRODUCTION

Transmission and distribution systems contain a huge number of transformers: only in the US alone there were over 30 million transformers in the late 20th century [1]. Most of them have paper-oil insulation systems, with oil volume varying between 100 liters (for a 25 kVA transformer) and over 40,000 liters (for a 400 MVA transformer) [1-2]. Oil volume is approximately equal to that of the paper in low voltage transformers and can exceed 80% of the total insulation volume in power transformers with nominal voltages over 500 kV [3-4].

For over a century, the most used oil for all types of paper-oil insulated transformers has been crude oil based mineral oil, due to low costs, good compatibility with cellulose paper and its excellent characteristics of electrical insulator and cooling medium. However, at the end of last century, there were two important reasons for replacing it with natural oils [5]: a) mineral oil is poorly biodegradable and b) crude oil consumption has skyrocketed and its reserves are relatively limited. As some synthetic oils present high toxicity, research for obtaining new insulating liquids to replace the mineral oil led to synthetic esters, mixtures of mineral oils and synthetic or natural esters and, ultimately, to vegetable oils, (with some properties superior to those of the mineral oils and with higher biodegradability [5]).

Transformers represent the most costly elements of energy systems, and most of them have been in operation for a long time or have exceeded their estimated lifetimes [6]. Therefore, condition monitoring of power transformer insulation systems (PTIS) is absolutely necessary and has been a permanent concern of power transformers manufacturers and users [7]. Because the direct measurement of the vital macroscopic characteristics of the insulation is not always possible, several methods are often used, which provide indirect information about their vital properties [8]. Some of these methods are presented in [3, 8-11].

The present work proposes a new method of monitoring transformer oils, based on the DC resistivity determined through online measurements of the absorption and resorption currents, and which allows the assessment of their consumed and remaining lifetimes.

II. OILS STRUCTURE AND DEGRADATION

Mineral oils represent mixtures, in different proportions, of paraffinic C_nH_{2n+2} (< 30%), naphthenic C_nH_{2n} (> 60%), aromatic C_nH_n (< 30%) and olefinic (alkene) hydrocarbons [12]. Paraffinic hydrocarbons have high freezing point, which causes an increase in oil viscosity. Naphthenic hydrocarbons are stable with a low freezing point [12]. Aromatic hydrocarbons contain unsaturated ring moieties and the carbon atoms can be released under the action of the electric arc, contributing to the reduction of oil properties values.

Transformer oils characteristics depend on their chemical composition, the removal effectiveness of contaminants resulted after distillation (acids, aldehydes, ketones, etc.), the content of added additives (antioxidants etc.) and operating conditions (temperature, partial discharges etc.) [1, 12].

Mineral oils degrade during operation, resulting new hydrocarbons (CH_4, CH_2, C_2H_6, C_2H_4, RCHO, R–CO–R, ROH, RCOOH, tars), acids, CO, H_2, water, asphalt, carbene etc. [13-14]. The degradation process of transformer oil is an irreversible reaction chain, initiated and/or favored by a number of stress factors (electric field, temperature, moisture, oxygen, acids etc.). There are three energy sources which can contribute to the covalent bonds breaking of oil molecules (and the forming of gases and decay products): the energy of the electric field, thermal energy due to load and no-load

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losses and chemical energy. The intense electric fields facilitate electron injection in oils, contributing to the formation of gas and decomposition by-products. The liquid degradation under PD stress results from heat, ionizing collisions between charged particles, radiation, and shock waves. [15].

In case of thermal stresses, the mechanisms of hydrocarbon decomposition depend on the temperature value and differ from that under electric stress. At operating temperature below 100 °C, the heat only determines the increase of energy values corresponding to molecular chains vibrations and rotations, and their values are not very high. As a result, only the weakest C-C bonds located in the center of a hydrocarbon molecule (with bond energy of 346 kJ/mole) are prone to decomposition, as opposed to the terminal C-H bonds (with bond energy of 413 kJ/mole), resulting in hydrogen and unsaturated compounds [15-16].

III. ELECTRICAL CONDUCTION

Considering the insulation as a whole, it can be said that charge carriers are free electrons, holes, positive and negative ions and molions, particles charged with electric charges etc. [17-20]. For the electrons, their orderly movement under the action of the electric field is described based on three models: nearly free electron (NFE) model, the model of trap-modulated motion in delocalized states and the hopping model (Fig. 1). These physical models correspond to different values of electron mobility μ in liquids. Thus, for μ > 10 cm^2/Vs, the electrons are considered nearly free and their mobility μ_{fe} can be calculated using the equation [18]:

$$\mu_{fe} = \frac{q}{m v_{th}} l , \tag{1}$$

where q, m and v_{th} represent the charge, mass and thermal agitation velocity of the electron.

For mobility values smaller than 0.1 cm^2/Vs, the electrons can be considered located in pre-existent traps (vacancies, holes). The apparent mobility of liquid electrons μ_{el} can be estimated by the equation:

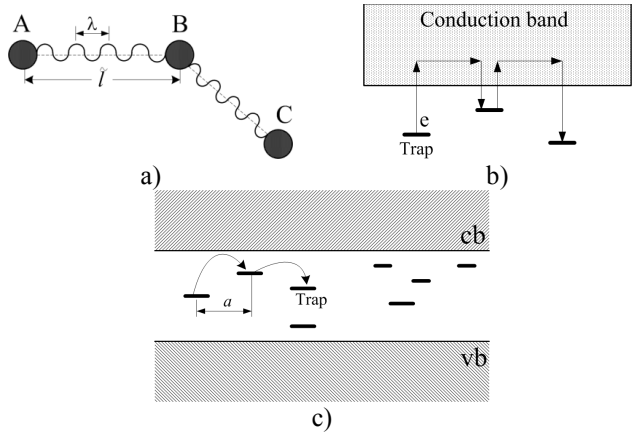

Fig. 1. Electron transport: a) Nearly free electrons in conduction band; b) Trap-controlled band transport; c) Hopping transport (A, B, C – scattering centers, λ – de Broglie wavelength, l – mean free path, e – electron, *cb* – conduction band and *vb* – valence band).

$$\mu_{el} = \frac{\mu_{fe}}{[1+\exp(-\frac{\Delta G_t}{RT})]} , \tag{2}$$

where ΔG_t represents the standard free energy change, R – gas constant and T – thermodynamic temperature.

For 0.1 cm^2/Vs < μ_{el} < 10 cm^2/Vs, the electrons can be considered as found in nearly localized states, and the transport is regarded as a classical diffusion process, from one trap to another. Their mobility $\mu_{el}(T,E)$ depends on the electric field E:

$$\frac{\mu_{el}(T,E)}{\mu_{el}(T,0)} = \frac{\sinh(\frac{q_0 E a}{2kT})}{\frac{q_0 E a}{2kT}} , \tag{3}$$

where a represents the average distance between two traps, $\mu_{el}(T,0)$ – electrons mobility in very weak fields, T – temperature and k – Boltzmann constant.

Holes occur when electrons leave the valence band of the insulator and migrate through the transfer of electrons from surrounding atoms or molecules. Holes mobility is much bigger than that of positive ions or positively charged particles (5-10 times bigger [18]) and is influenced by temperature and additives content of the liquid.

Ions and molions can occur by attaching electrons to electronegative impurities (oxygen, carbon dioxide, halogenated hydrocarbons etc.) or to the liquid's own molecules, by transferring the charge from positive charge carriers to the neutral impurities molecules, by dissociating the molecules and/or impurities from the liquid etc., their mobility being thermally activated.

To describe the ion transport in liquids, two models are used: continuous and statistical models. In the continuous model, the ion mobility μ_{ion} is given by the equation:

$$\mu_{ion} = \frac{q}{6\pi\eta R} , \tag{4}$$

where q and R represent the charge and radius of the ion and η – liquid viscosity [18].

In the statistical model, the movement of ions is described by the equations related to a self-diffusion process and the ions mobility is determined by the equation:

$$\mu_{ion} = \frac{qa^2}{kT} \nu_0 \exp(-\frac{W_b}{kT}) , \tag{5}$$

where a represents the average ion-hole distance, ν_0 – trap escalating frequency associated to ion hopping and W_b – trap depth [18].

Insulating oils also contain submicron particles (metallic, semiconducting or insulating) which can be charged with positive or negative electrical charge by attaching an electron or a hole, or under the influence of the electric field. These particles can move under the influence of the electric field, contributing to the conduction process in the liquid.

Knowing the mobility and volume concentrations of charge carriers in a liquid, the electrical conductivity of a liquid σ_l can be calculated:

$$\sigma_l = \sum_{i=1}^{n} q_i (N_+^i \mu_+^i + N_-^i \mu_-^i), \quad (6)$$

where n represents the number of species of charge carriers, q_i, N_+^i, μ_+^i, N_+^i and μ_+^i - charge, concentration and mobility of positive and negative charge carrier of the species i [20].

For liquids whose nature and concentration of charge carriers are not precisely known, equations (7)-(8) are used:

$$\sigma_l = \sigma_0 \exp(-\frac{E_a}{kT}), \quad (7)$$

$$\rho_l = \rho_0 \exp(\frac{E_a}{kT}). \quad (8)$$

where ρ_l is the liquid resistivity, σ_0 is a material constant, E_a – the global average activation energy, associated to the global electrical condition process inside these liquids and $\rho_0 = 1/\sigma_0$.

For transformer oils, it is considered that the main charge carriers are ions, whose characteristics depend on the oil nature and the nature and concentrations of additives or impurities: the contact of oil with the paper insulation introduces free hydrogen ions; the contact with air causes oxidation products of the oil (hydrogen ions).

The increase of thermal and electrical stresses during operation facilitates the fracture of molecules of oil hydrocarbon components, the dissociation of ionic complexes etc. and the reduction of its resistivity. Consequently, the oil resistivity is highly dependent on the oil condition and can be used to estimate its elapsed and remaining lifetimes.

IV. Absorption/Resorption Currents

When applying a step voltage U_0 to the armatures of a parallel plate capacitor having the surface A (with dielectric thickness g, conductivity σ and permittivity ε), it absorbs a variable current of intensity $i_a(t)$:

$$i_a(t) = i_i(t) + i_p(t) + i_{ss}(t) + i_c(t), \quad (9)$$

where $i_i(t)$ represents the charge current of a vacuum capacitor, $i_p(t)$ – polarization current, $i_{ss}(t)$ – space charge current and $i_c(t)$ – conduction current [21].

Component $i_c(t) = A\sigma U_0/g$ is due to electrons, holes, ions and molions convection. This current component is not time-variable and allows the experimental determination of electrical conductivity of the dielectric [21].

If the voltage supply is disconnected ($U_0 = 0$) and the armatures are short-circuited, the capacitor discharges and the transient current $i_r(t)$ passes through its dielectric:

$$i_r(t) = i_d(t) + i_{dp}(t) + i_{ss}^{'}(t), \quad (10)$$

where $i_d(t)$ is the discharge current of a vacuum capacitor, $i_{dp}(t)$ - depolarization current and $i_{ss}^{'}(t)$ - space charge current.

Knowing the values of the absorption and resorption currents at the moment t, the volume resistivity $\rho(t)$ of the dielectric can be calculated:

$$\rho(t) = \frac{S}{g} \frac{U_0}{i_a(t) - i_r(t)}, \quad (11)$$

where S represents the area of the active electrodes surfaces and g – dielectric thickness [22].

V. Lifetime

Oil lifetime is the time interval after which (under certain stresses) values of a critical oil parameter (called diagnostic factor) are reduced below a limit called end-of-life criterion [23]. To estimate the lifetime of an oil subjected to a thermal stress at a given temperature T, the lifetime line is used:

$$\ln L = a + b/T, \quad (12)$$

deduced from the Dakin equation:

$$L = A \exp(E_a/k\,T), \quad (13)$$

where L is the lifetime corresponding to temperature T, $a = \ln A$, A – material constant, $b = E_a/k$, E_a – activation energy associated to the electrical conductivity change due to the oil degradation and k – Boltzmann constant [23].

Parameters a and b of the lifetime line are determined based on isothermal accelerated ageing of the oil, by using the IEC60216 standard or the activation energy method [21]. Resistivity is used as a diagnostic factor, while the end-of-life criterion is ρ_{eol}, equal to the minimum allowable resistivity value according to current standards for oil.

If the operating temperature of the oil is constant, the elapsed lifetime L_c is identical to the functioning time L_f, and the remaining lifetime L_r is:

$$L_r = L - L_f, \quad (14)$$

where L is the estimated lifetime for operation temperature T.

As during transformer operation, the insulation system temperature changes in time ($T(t)$), the calculation of L_c and L_r is more complicated. Therefore, the thermal wear W of the insulating material per time unit is defined (degradation rate of the material), starting from the lifetime equation based on the Dakin model (equation (13)) [24]:

$$W = \frac{1}{L} = \frac{1}{A} e^{-b/T} \quad (15)$$

and the wear $W(\Delta t)$ of a material during a time interval Δt, respectively the relative lifetime elapsed during interval Δt ($L_{rel,c}$):

$$W(\Delta t) = L_{rel,c} = \frac{1}{A} \cdot \int_0^{\Delta t} e^{-b/T(t)} dt \cdot \quad (16)$$

The elapsed lifetime in the Δt interval (L_c) is:

$$L_c = L_{rel,c} \cdot L, \quad (17)$$

while the remaining lifetime L_r after operation during Δt interval at the variable temperature $T(t)$ is:

$$L_r = L - L_c. \tag{18}$$

VI. Resistivity – Online Monitoring Parameter

Mounting of a cell for online measurement of absorption and resorption currents in oil allows the determination of its resistivity ρ_l in real time, based on the equation:

$$\rho_l(t) = K \frac{U_0}{i_a(t) - i_r(t)}, \tag{19}$$

where $\rho(t)$ represents the resistivity value at the moment t after applying measurement voltage U_0, and K – measurement cell constant, respectively the ratio between the area S of the average lateral surface of the cylindrical electrodes (interior and exterior) and the distance between the electrodes d ($K = S/d$) or the ratio between the capacity of the cell without liquid C_0 and vacuum permittivity ε_0 ($K = C_0/\varepsilon_0$) [25].

It is recommended that the resistivity measurement should be done at such a voltage U_0, so that the electric field inside the oil has a value E between 50 and 250 V/mm ([25]), at moments t_{01} = 60 s ($\rho_l(60)$) and t_{02} = 600 s ($\rho_l(600)$) from the application of voltage U_0.

VII. Experiments

The experiments were performed on a mineral oil without inhibitors provided by Mol Romania Petroleum Products [26]. The oil was placed in sealed glass cells and thermally aged in an oven with forced air flow, at three temperatures (T_1 = 155 °C, T_2 = 135 °C and T_3 = 115 °C), for periods between 1000 and 4000 h. At defined intervals (τ), groups of 3 samples were extracted and the absorption/resorption currents were measured using a Keithley 6517 electrometer and a special IRLAB cell (3600 s at U_0 = 100 ÷ 500 V).

In order to determine the activation energy, DSC (Differential Scanning Calorimetry) measurements were done with a Setaram 131 EVO apparatus, at the temperature range 30 ÷ 310 °C and heating rates of 2, 4, 6 and 10 °C/min [26].

VIII. Results

The degradation of oil samples due to thermal stresses is evidenced in Fig. 2, which shows an increase of water content in oil with the temperature and ageing time [27].

Figs. 3 and 4 show the time variations of absorption and resorption currents, measured at the voltage U_0 = 300 V for 3600 s on oil samples aged at T_1 = 155 °C, T_2 = 135 °C and T_3 = 115 °C. For each ageing temperature the curves were plotted using five points. Each point represents the mean value of three currents that are measured on three samples.

It is noticed that, for any ageing temperature, the values of both current types increase with ageing time. This is due to oil degradation and the increase of charge carriers' concentration. Obviously, the increase of ageing temperature also leads to increased current values, because the intensity of thermal degradation phenomena (thermal oxidation, etc.) in oil is directly influenced by the temperature (Section II).

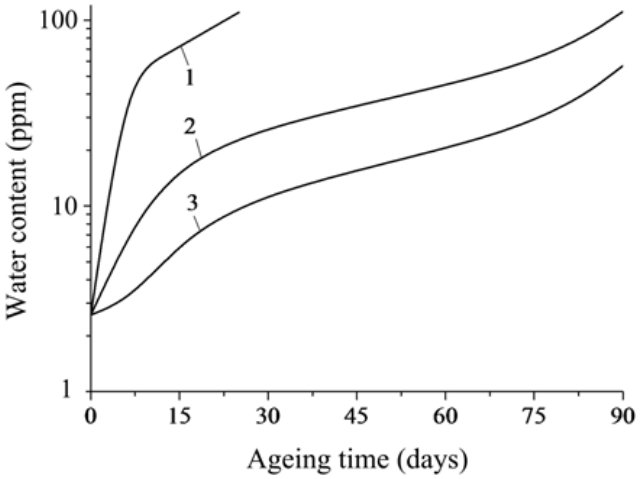

Fig. 2. The variation of water content in oil with ageing time at 155 °C (1), 135 °C (2) and 115 °C (3).

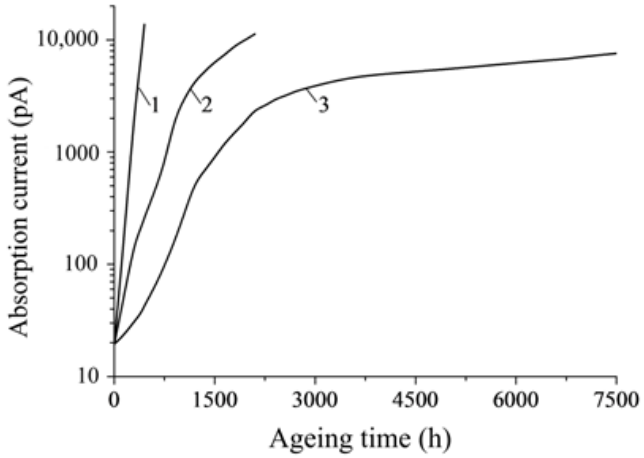

Fig. 3. Absorption currents variation with oil ageing time at 155 °C (1), 135 °C (2) and 115 °C (3).

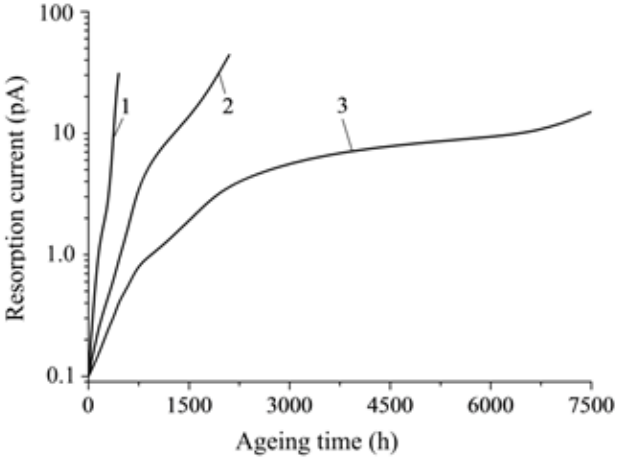

Fig. 4. Resorption currents variation with oil ageing time at 155 °C (1), 135 °C (2) and 115 °C (3).

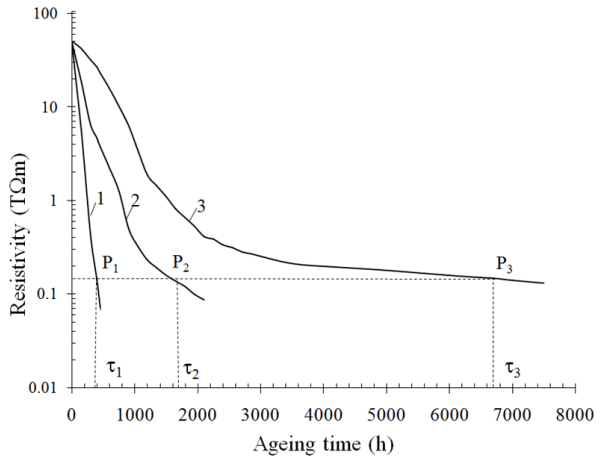

Fig. 5. Resistivity variation with oil ageing time at 155 °C (1), 135 °C (2) and 115 °C (3).

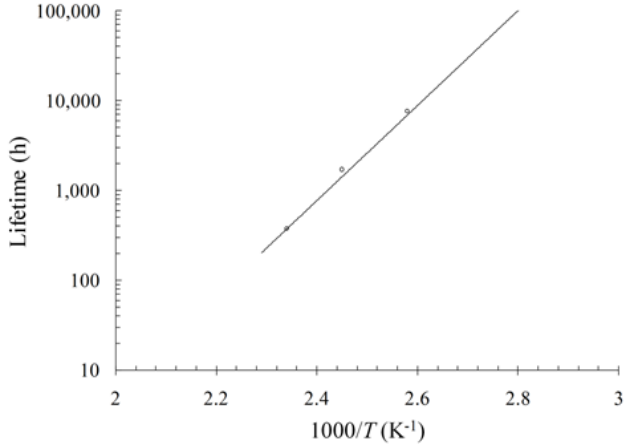

Fig. 6. Mineral oil lifetime line for M_T method.

TABLE I
VALUES OF COEFFICIENTS $a_{T,E}$, $b_{T,E}$ AND OF THE ACTIVATION ENERGY $E_{aT,E}$ CORRESPONDING TO METHODS M_T AND M_E

Method	$a_{T,E}$ (-)	$b_{T,E}$ (K)	$E_{aT,E}$ (kJ/mole)	$L_{T,E}$ (h)
M_T	- 22.737	12251.35	101.83	1.53 x 10^5
M_E	- 22.86	12295.84	102.40	1.86 x 10^5

Time variations of the DC resistivity $\rho_l(\tau)$ of the oil aged at the three temperatures presented above ($T_{1,2,3}$) are shown in Fig. 5 [27]. As expected, resistivity values decrease with temperature and ageing time τ, due to increased concentrations of charge carriers [26], in agreement with [28].

Using the IEC60216 method (of the three temperatures) M_T [23] and considering the resistivity value ρ_{eol} = 0.15 TΩm as the end-of-life criterion the abscissas of points $P_1(\tau_1$ = 380 h), $P_2(\tau_2$ = 1600 h) and $P_3(\tau_3$ = 6700 h) were determined and with the $T_{1,2,3}$ the lifetime line $L = f(1/T)$ was drawn (Fig. 6).

It must be noticed that 15 measurement points were used for drawing the lifetime line, according to standard IEC 60216-1 [23]. Using the coordinates of the 15 points, the values of parameters *a* and *b* were determined and, from *b,* the activation energy E_{aT} was calculated (Table I).

TABLE II
LIFETIME VALUES OF MINERAL OIL (YEARS)

Met./Temp.(°C)	70	80	90	100	110	155
M_T	48.74	17.74	6.82	2.76	1.17	0.040
M_E	49.07	17.80	6.82	2.75	1.16	0.040

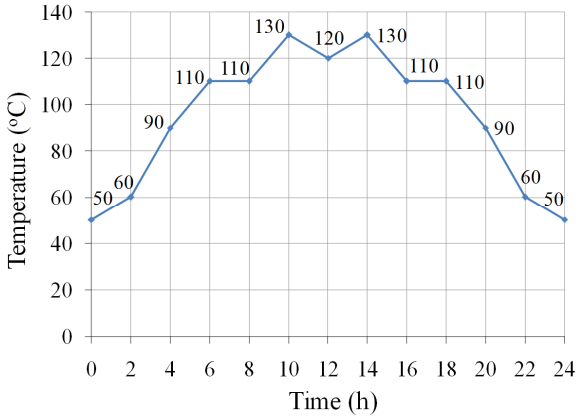

Fig. 7. Variation of the transformer insulation temperature (*T*) with time – first version.

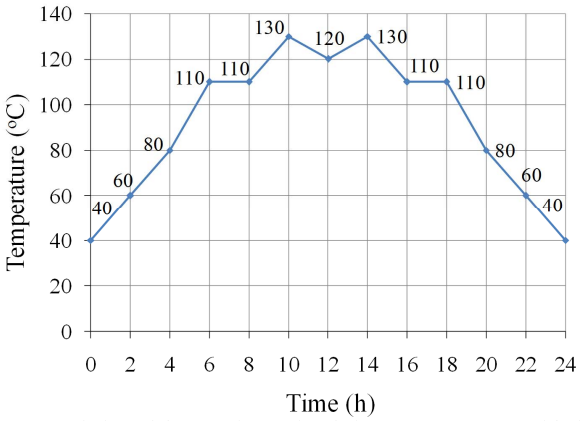

Fig. 8. Variation of the transformer insulation temperature (*T*) with time – second version.

TABLE III
VALUES OF LIFETIMES CALCULATED WITH M_T AND M_E METHODS FOR THE VARIABLE TEMPERATURES PRESENTED IN FIGURES 7 (1) AND 8 (2)

Times / Method	M_{T1}	M_{T2}	M_{E1}	M_{E2}
$W(\Delta t)$	2.891 x 10^{-3}	2.832 x 10^{-3}	2.92 x 10^{-3}	2.861 x 10^{-3}
W (s^{-1})	3.346 x 10^{-8}	3.278 x 10^{-8}	3.38 x 10^{-8}	3.311 x 10^{-8}
L_c (years)	0.051	0.050	0.052	0.051
L_r (years)	17.689	17.690	17.748	17.749
L_t (years)	0.948	0.967	0.938	0.958

Notes: $W(\Delta t)$ - oil wear during Δt = 86400 s (equal to the relative lifetime elapsed in Δt ($L_{rel,c}$); *W*- oil wear per time unit; L_c - lifetime consumed in Δt; L_r – lifetime reserve after one transformer operation cycle; L_t – oil lifetime for variable temperatures.

Using the DSC curves, the activation energy corresponding to the oil oxidation process E_{aE} was determined, using the parameter $T_{0.6}$ (60% of the oxidation peak height [26]). It was noticed that the value E_{aE} = 102.2 kJ/mole is close to E_{aT} = 101.83 kJ/mole (obtained by M_T method) (Table I). Knowing the E_{aE} and using the curve 1 from Fig. 5, oil lifetime line parameters were determined (a_E = - 22.76 and b_E = 12316.57 K) (Table I).

Using equation (12) and the values of parameters $a_{T,E}$ and $b_{T,E}$, oil lifetimes were calculated for transformer operation at different constant temperatures (Table II). It can be noticed that their values show a deviation lower than 0.7% and if the value of the end-of-life criterion is reduced (ρ_{eol} = 0.02 TΩm at 20 °C [29]), the lifetime values increase.

With the values of constants $a_{T,E}$ and $b_{T,E}$, the total lifetime L_t, consumed lifetime L_c and remaining lifetime L_r were calculated, corresponding to variable oil temperatures. Variation curves of hot-spot temperature $T(t)$ during one day, corresponding to transformer loads cycles, are presented in Figs. 7 and 8, while the values of total, elapsed and remaining lifetimes are shown in Table III.

It is noticed that, if the temperature would vary like in figure 7 or 8, lifetime consumption would be very high compared to the case of operating at the nominal temperature, and the total lifetime L_t is greatly reduced (to approx. 0.95 years) (Table III).

IX. CONCLUSIONS

For estimating the lifetimes of power transformers liquid insulations, electrical resistivity, determined by measuring the absorption/resorption currents, is a very useful diagnostic factor.

Lifetime values obtained through accelerated tests of transformer oils at constant temperature, using the standard method (M_T) and the activation energy method (M_E), are relatively close. Obtaining the lifetime line using M_E requires much less time and energy than the standard method (M_T) and can be used for replacing the oil in PTIS.

In areas of the transformer insulation systems without forced oil circulation and which have higher temperature values, oil lifetime is considerably reduced.

Knowing the variation curves of the operation temperature of insulation systems, it is possible to estimate the elapsed and remaining lifetimes of their liquid components.

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