

## CONCERNING THE POWER TRANSFORMERS INSULATION SYSTEMS MONITORING

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### Abstract

*Considering the importance of power transformers condition monitoring concerning the improvement of power quality, the paper presents information regarding the degradation processes of the transformer insulation system (paper-oil) and the methods for their lifetime estimation (standard and activation energy method). Further, the experiments carried out in order to determine the lifetime curves (through both methods) are presented. The insulation lifetime calculation corresponding to constant operating temperature and the loss and remaining lifetimes in case of variable temperatures of the oil and paper are presented in this paper, as well. In the end, a new equation to calculate the remaining lifetime of an in-service transformer based on monitoring of its oil resistivity is proposed. In this equation, the temperature changes due to daily load variation is no longer involved.*

**Key words:** power transformers monitoring, mineral oil, transformer paper, insulation systems, ageing, lifetime

### 1. INTRODUCTION

Transmission and distribution operators target continuously the quality increase of the delivered power. Among the most important factors that worsen the power quality are the short and long term outages, as a result of in-service transformer failures. Such unplanned outages create losses both on the generation side, as well as on the consumers side by interrupting their activity. World-wide transmission and distribution systems consist of a large number of transformers. For instance, only in the USA at the end of 20th century over 30 million units were reported (Rouse 1998). Therefore, the evaluation of transformers condition overall and remaining lifetime is an important activity that could help to prevent forced outages and to support the increase of the consumer's energy availability.

The transformers in-service time is continuously increasing and their failure rate increases with the transformer age (Fig. 1) (van Schijndel 2010). The repair activities often require long duration outages especially in cases when transportation to the factory or repair workshop is required. On the other hand, these are costly activities especially when the overall solid insulation shows an advanced degradation condition. Depending on the transformer design and application, the refurbishment costs may come close to the cost of a new transformer – which represents about 60 % of the cost of other equipment from the substation (Jahromi 2009).

Failure factors in transformers include electrical breakdown, lightning, dielectric fault, loose connection, incorrect maintenance, moisture, excessive overloading, and other causes (Fig. 2) (Zhang 2008). A recently published survey (CIGRE 2015) indicates that the on-load tap changers and the windings are the components with the highest failure rate (Fig. 3). However, the winding-related repair activities are more costly and require longer remedial times in comparison with the tap-changer-related repairs (Gorgan 2012). Thus, the safe operation of a transformer is directly connected to the condition of the windings insulation system. According to (Jahromi 2009, Wang 2002), the transformers are reliable pieces of equipment with average lifetimes in the range of 20-35 years and by adopting the appropriate maintenance strategies their lifetimes could be extended up to 60 years (Wang 2002).

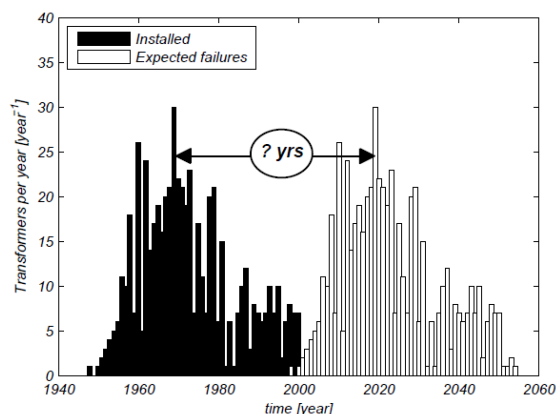


**Fig. 1.** Yearly commissioned power transformers and their estimated end of life assuming an average lifetime of 50 years (van Schijndel 2010).

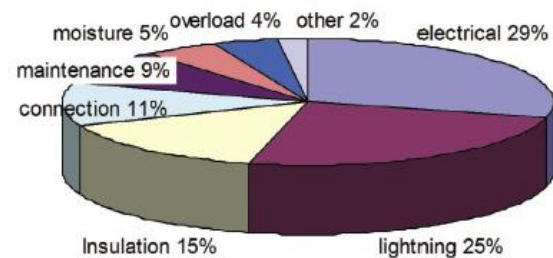


**Fig. 2.** Transformer failure causes (Zhang 2008).

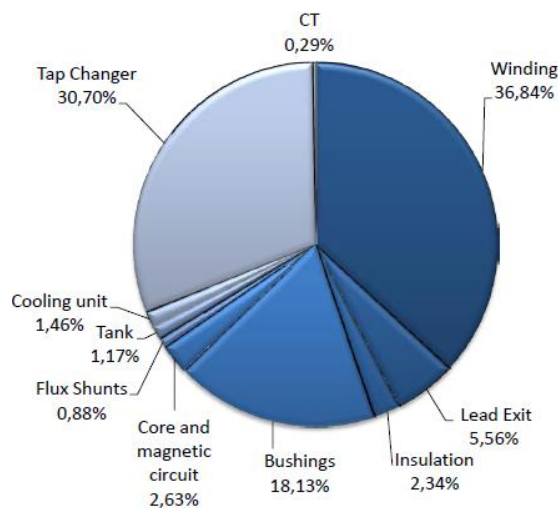


**Fig. 3.** Failure location in transformers produced after 1980 (342 failures,  $U \geq 100$  kV) (CIGRE 2015).

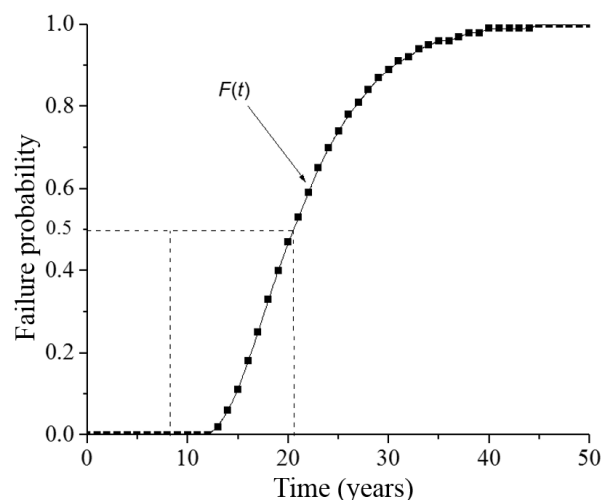


**Fig. 4.** Failure probability  $F(t)$  variation with the transformer service time (Gorgan 2012).

The insulation systems of transmission and distribution transformers (excluding the dry-type transformers) consist of mineral oil, cellulosic paper, pressboard, pertinax and a series of other wooden elements. Within the last decades, considerable efforts were taken in order to improve the insulation system performance by replacing the traditional cellulosic paper with other types (Nomex) and the mineral oil with synthetic oils or natural esters (Frimpong 2011, Martins 2010, Prevost 2006). However, given the very good cost-performance ratio, the oil-paper insulation system remains the most commonly used in the transformer manufacturing industry (Schaut 2011, Wang 2002).

In case of oil-paper insulated transformers, enhanced attention needs to be paid for the diagnosis of the cellulose-based elements. The turn insulation degrades due to the high operating temperatures, the ohmic and eddy currents losses, and as a result of water presence. Consequently, the effects of the temperature and water on the insulation lifetime needs to be taken into account, especially because they occur in combination with other types of stresses. In case of long duration electrical stress, the local decomposition of the insulation elements may occur, producing the contamination of the insulated surfaces with conductive by-products, leading in the end to a reduction of the insulation breakdown voltage.

Generally, the main cause of the winding insulation systems failures is the reduction of paper mechanical strength determined by the reduction of its degree of polymerization (DP). Fig. 4 presents the failure probability  $F(t)$  over the service time, providing the probability of the estimated DP (at a given time  $t$ ) to be below a minimum admissible value (Gorgan 2012). The mineral oil is subjected to the degradation processes as well, resulting in the reduction of its dielectrical properties, especially of its dielectric strength (which implies the increase of the transformer failure probability).

## 2. DEGRADATION OF THE POWER TRANSFORMER INSULATION SYSTEM

### 2.1. Structure and degradation of the solid component

The solid elements of the transformer insulation system are: the turn insulation (Kraft paper, synthetic varnish, cotton fibers and strip), the discs insulation (Kraft paper, pressboard, transformer board), main insulation (pertainax or pressboard rings, cylinders and boards), auxiliary insulation (pressboard and pertainax boards, wooden elements for clamping etc.) (Jezierski 1966).

The transformer paper consists of cellulose, hemicellulose and tiolignin residues not completely removed after the raw material processing. The cellulose consists of polymeric chains of  $\beta$ -D-glucopiranozil rings interconnected by the glycosidic bonds ( $1 \rightarrow 4$ , Fig. 5) (Notingher 2016). The number of rings of each chain ( $n$ ) gives the DP of the paper. The DP of new manufactured paper (not aged) takes values of approximately 1000-1200. If the DP goes below the value of 200, it is considered that the paper reached its end of life criterion (Lundgaard 2004, Institute of Electrical and Electronics Engineers 1995).

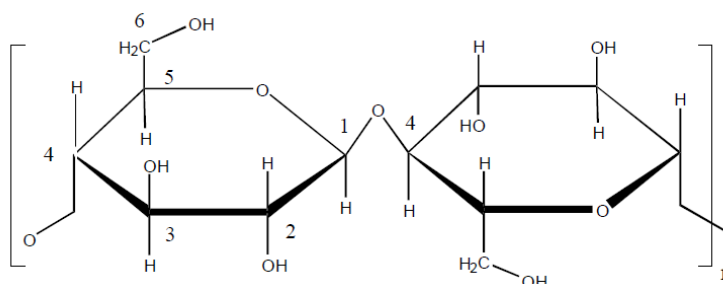


Fig. 5. Cellulose monomer (Notingher 2016).

Several parallel oriented chains create micelles, which, if similarly arranged, create fibrils and then the cellulosic fibers (Notingher 2005). This structure gives to the cellulose – and the transformer paper – a high degree of porosity. The cellulose mechanical strength comes from the linear orientation of the chains and from the bonds between the chains through the hydrogen atoms (Notingher 2016). The DP and the tensile strength provide information about the molecular chains number and about the unbroken hydrogen bonds between the chains. At the molecular level, the cellulose shows a semicrystalline structure, where the amorphous and crystalline zones alternate. The amorphous zones allow the water ingress, while the crystalline zones are tight, inert, ordered and relatively impermeable. Thus, the major disadvantage of the cellulose based products is their hygroscopicity requiring the need to maintain them dry. At room temperature ( $20 - 25\text{ }^{\circ}\text{C}$ ) the cellulose may absorb 4 to 8 % moisture (Notingher 2016). The cellulose does not melt. When overheated under vacuum carbonizes directly. Overheated under reduced pressure, it gets depolymerized and turns into glucose.

Cellulose degradation is triggered by several factors such as water, heat, oxygen, light, air pollution, microorganisms etc. (Area 2015). The main cellulose reactive centers are the secondary groups of hydroxyl (OH) located at positions C-2 and C-3 and the primary groups located at C-6 (Fig. 5). These groups are parts of the hydrogen bonds located between the chains, which enables the cellulose

reactivity at high temperatures. The water reaches these zones and breaks the hydrogen bonds between the chains, leading to a local destruction of the molecular matrix.

The accelerated thermally induced degradation is a combination of hydrolytic breaks and thermal fractions (1→ 4) of the glycosidic bonds. The oxidation and the other side-reactions involving the hydroxyl groups C-2, C-3 and C-6 are the second most important degradation factor.

From the combined effect of the oxygen and the heat a wide range of degradation by-products result. The most important are H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, H<sub>2</sub>, CH<sub>4</sub>, carboxylic acids (low molecular mass), furanic compounds and a series of other by-products whose nature depends on the paper chemical type and on the temperature (Madorsky 1958, Morais 1999). Additionally, as a result of the cellulose thermal oxidation, a series of very unstable free radicals may result, which trigger avalanche reactions of the macromolecular cellulosic chain depolymerization. Cellulose depolymerization due to oxidation reactions is accelerated by the hydroxyl radicals (HO•) which result from the hidroperoxids (H<sub>2</sub>O<sub>2</sub>) decomposition. The hidroperoxids may occur as a result of the reactions between the oxygen and water accelerated by the transition metal cations (Cu<sup>+</sup>/Cu<sup>2+</sup> or Fe<sup>2+</sup>/Fe<sup>3+</sup>) (Badicu 2011, Lundgaard 2004).

The water affects the cellulose degradation by triggering the hydrolysis reactions. Due to the cellulose hygroscopic nature and due to the capillary structure of the fibers, the water accumulates between the cellulose molecules and induces the breakage of the bonds between them, accelerating the ageing process of the cellulose. The production of the water and acids as a result of cellulose oxidation, facilitate the acid-hydrolysis reactions. The main cause of this reaction type is the dissociation of the carboxylic acids in water. The fast increase of the H<sup>+</sup> ions concentration is the result of this process. The undissociated carboxylic acids do not enhance the acid-hydrolysis reaction and, implicitly the cellulose depolymerisation reactions. Thus the water is not directly involved in the cellulose decomposition (worsening its mechanical characteristics) but it influences the H<sup>+</sup> ions concentration enabling the acids dissociation (Ciuriuc 2015). It has to be noted that the hydrolysis-triggered cellulose degradation is not homogenous. The depolymerization rate takes high values in the amorphous regions and very low values in the crystalline areas of the material (Ding 2008).

The moisture concentration of the insulation system components depends on the thermo-dynamic equilibrium between the oil and the paper, strongly influenced by the temperature variation. The water migration happens until the pressure of the water vapors in both components of the insulation system (oil and paper) is the same. The water solubility in the oil increases once the temperature rises. In the same time, the water absorption capacity of the paper decreases, leading to the water migration from the paper to the oil (Li 2014). The cellulose degradation mechanism is schematically presented in Fig. 6. It can be noticed that a dehydration reaction is produced, eliminating the formaldehyde (CH<sub>2</sub>O) and generating of 2-furfural (Miyagi 2011). Therefore, the 2-furfural concentration is one of the chemical parameters used to assess the degradation condition of the transformer paper (Morais 1999).

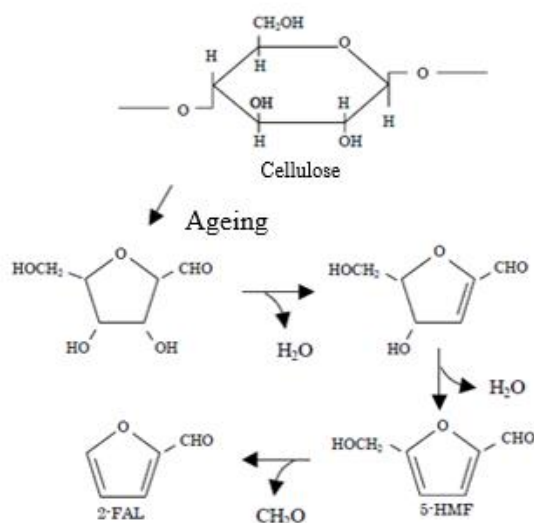


**Fig. 6.** Cellulose degradation generating 5-Hidroxitilfurfural (5-HMF) ( $C_6H_6O_3$ ) and 2-Furfural (2-FAL) ( $OC_4H_3CHO$ ) (Miyagi 2011).

Cellulose degradation means the breakage of the macromolecular chains and is the effect of three dedicated processes: oxidation, hydrolysis and pyrolysis. Many papers deal with the analysis of the transformer paper thermal ageing phenomena in the presence of the mineral oils and natural esters. The aged paper was analyzed by considering the variation of its dielectric properties (breakdown voltage and loss factor (Li 2014, Hemmer 2003)), physical and chemical properties (water content (Martins 2010, Rapp 2005, Yao 2014), furan concentration in the oil (Li 2014, Yao 2014)) and its DP (Coulibaly 2012, Lundgaard 2005, Tenbohlen 2010, Yang 2008). It was noticed that, under the same conditions, the ageing rate of the paper is higher in mineral oil than in natural ester. Furthermore, it was noticed that the breakdown voltage is higher in case of the paper aged in natural ester. The moisture concentration decreases with the ageing duration, no matter what oil is used as impregnation medium. Additionally, a higher concentration of furans was found in the aged mineral oil in comparison with the aged natural esters. On the other hand, the DP for paper aged in natural ester was twice as higher than the DP of the paper aged in mineral oil.

The most important parameters that characterize the degradation (ageing) condition of the paper are tensile strength and the DP (Gasser, 2011). The variation of these quantities over the thermal stress duration were analyzed in (Notingher 2016). The effects of the ageing temperature on the tensile strength and on the DP value are presented in Figs. 7 and 8 (McNutt 1992, McShane 2001).

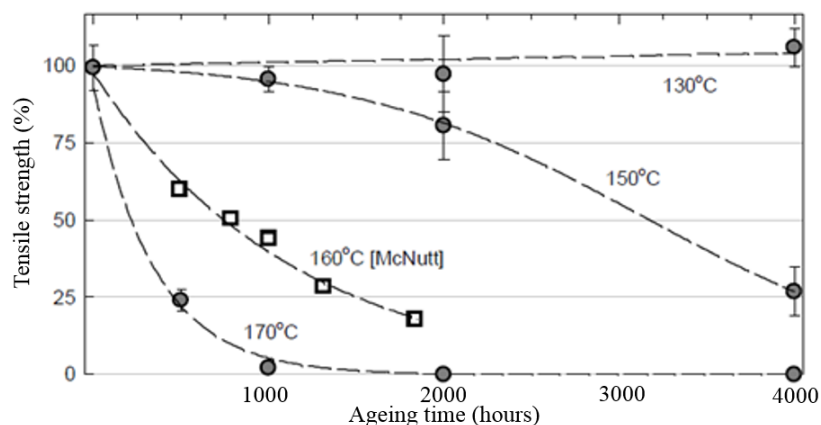


**Fig. 7.** Tensile strength variation as a function of the accelerated ageing time of the thermally upgraded paper (McNutt 1992, McShane 2001).

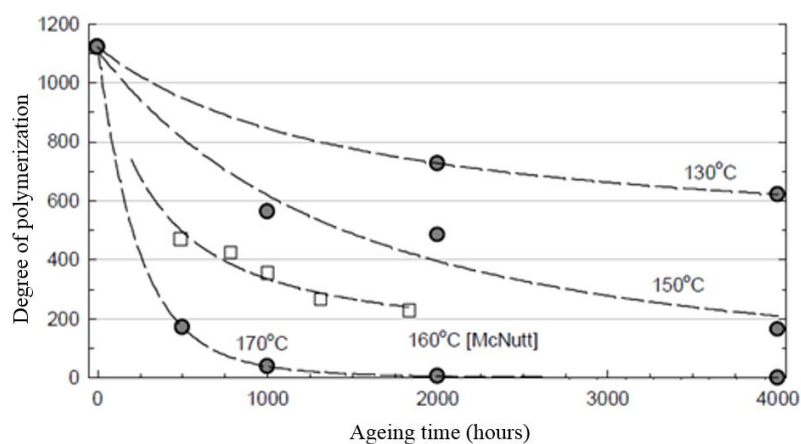


**Fig. 8.** Degree of polymerization variation as a function of the accelerated ageing time of the thermally upgraded paper (McNutt 1992, McShane 2001).

## 2.2. Structure and degradation of the liquid component

The most commonly used impregnation medium for oil-immersed transformers is still the row petrol-based mineral oil highly purified (Notinger 2017). On one hand is the mineral oil widely used, given its relatively low cost and its compatibility with the cellulosic paper and, on the other hand, due to its excellent insulation and cooling properties. However, two major reasons were highlighted at the end of the last century implying the replacement of the mineral oils with natural esters, namely, the mineral oils are low biodegradable (oil leaks due to transformer failures lead to the soil contamination) and the row petrol resources are relatively limited and the daily use is continuously increasing (Bashi 2007). The synthetic oils (chlorinated, fluorinated, silicon and ester) have been used starting the second half of the last century (Gafvert 2000). Chlorinated oils (askareli, PCB) show good thermal properties but starting with 1976, they have been forbidden given their toxicity and their long environmental persistence (practically unbiodegradable). In order to replace the mineral oil alternative solutions such as synthetic esters, mixtures of mineral oils and natural/synthetic esters and – in the end – natural esters were created. The natural esters are based on castor and cotton seeds, cocoanuts, soya, rape, sunflower, palm-tree or indian beech-tree seeds and have some superior physical, chemical and electrical properties in comparison with the mineral oils, being highly biodegradable (Bashi 2007).

The mineral oils are obtained through the row petrol (paraffinic and naphthenic) and natural gas refinement and are mixtures of different proportions of paraffinic  $C_nH_{2n+2}$  (less than 30 %), naphthenic

$C_nH_{2n}$  (over 60 %), aromatics  $C_nH_n$  (less than 10 %) and olefin hydrocarbons (Notingher 2005). The paraffinic hydrocarbons may have linear (*n*-hexane) or branched (2, 3-dimethylbutane) molecules and high pour points, implying the increase of the oil viscosity at lower temperatures. The naphthenic hydrocarbons (saturated paraffins whose structures include rings of 5, 6, or 7 carbon atoms) can have linear or branched allcane side chains (Rouse 1998), are stable and have a low pour point (Notingher 2005). Aromatic hydrocarbons contain unsaturated ring moieties: the mono-aromatic – discrete benzene ring structures (methyl benzene-toluene, biphenyl)-, and the poly-aromatic – two or more benzene rings fused together (naphthalene, anthracene), eventually with alkyl side chains and naphthenic ring substituents (Rouse 1998). The carbon atoms can be released under the electrical arcing, worsening the dielectric properties of the oils.

The transformer oil characteristics depend on their chemical composition (paraffinic, naphthenic and aromatic concentrations), on the concentration of the contaminants used at the refinement process, that could not be completely removed (heterocyclic compounds, organic acids, alcohols, aldehydes, ketones etc.) on the type of the inhibitors and on the type of the in-service stresses the oils are subjected to.

During transformer operation, the mineral oil degrades and hydrogen- and carbon-based products result, such as, 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. (Badicu 2012, Georgiev 2008). The impurities and oxidized degradation products alter the properties of the oils which cause problems to the electrical equipment (Arakelian 2009, Georgiev 2008). The transformer oil degradation occurs as a result of the irreversible reactions triggered and enhanced by a series of stress factors such as temperature, moisture, oxygen, acids etc. There are three energy sources that can break the mineral oil covalent bonds enabling the gas and decay products generation: the electric field, core and ohmic losses and the chemical energy. The strong electrical fields enable the electron injection in the mineral oil contributing to the increase of the gas and decomposition by-products concentrations. The liquid degradation under PD activity results in heat, ionizing collisions between charged particles, radiation, and shock waves. The PD activity on the solid surfaces leads to the formation of discharge channels heating the liquid, breaking the molecular bonds and ionizing the molecules. These electrical discharges provide the energy required to break the covalent hydrocarbon molecule bonds, leading to oil decomposition and to gas generation (Arakelian 2009).

The mechanisms of hydrocarbon decomposition due to the thermal stresses depend on the temperature value and are difference in comparison with the decomposition mechanisms under electrical stress. At operating temperatures below 100 °C, only the energy values corresponding to the vibration and rotation of the molecular chain are increasing and they are rather small. Consequently, just the weakest bonds C–C located in the middle of a hydrocarbon molecule (with bond energy of 346 kJ/mol) are prone to decomposition (the terminal C-H bonds have a bond energy of 413 kJ/mol), resulting hydrogen and unsaturated compounds (Arakelian 2009). The oil bubbles formation is the result of these reactions. These bubbles may host PD activity, may increase (size and number) and may even lead to flashovers (Emsley 1994).

The oil condition can be assessed based on electrical (absorption/resorption currents, DC and AC conductivities, loss factor, permittivity, partial discharges etc.) and/or chemical (gases concentration, number of solid particles, total acidity number etc.) diagnosis factors. The main monitoring methods of the transformer insulation components are presented in details in (Duval 2002, Kovacevic 2006, Wang 2002, Wouters 2011, Zhang 2008).

### 3. ABSORPTION AND RESORPTION CURRENTS

If a DC voltage step  $U_0$  is applied to a plane capacitor (dielectric thickness  $g$ , conductivity  $\sigma$  and permittivity  $\varepsilon$ ) for a duration  $t_a$ , a time variable current  $i_1(t)$  will flow through the capacitor (Fig. 9):

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

where  $i_i(t)$  is the capacitor charging current component in vacuum,  $i_p(t)$  – polarization current,  $i_{ss}(t)$  – space charge current component and  $i_c(t)$  – the conduction current component (Notingher 2008).

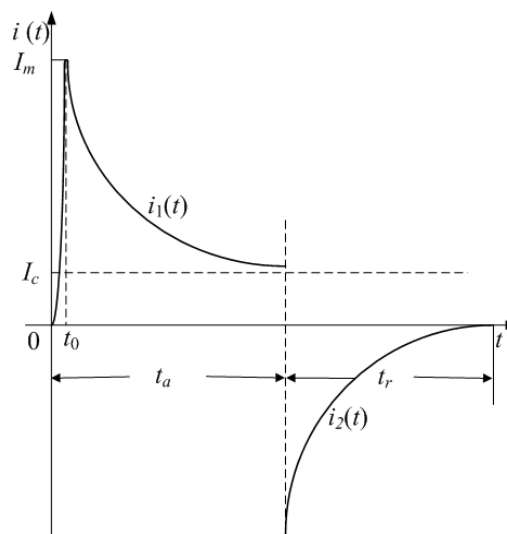


**Fig. 9.** Time variation of the current through a real capacitor with ( $i_1(t)$ ) and without applied step voltage ( $i_2(t)$ ) (Notingher 2008).

The component  $i_i(t) = \varepsilon_0 A \partial E / \partial t$  is the charging current of the capacitor filled with vacuum ( $\varepsilon = \varepsilon_0$ ) and it drops to zero very fast (immediately after  $t_0$ , Fig. 9). Therefore, the increasing part of the curve  $i_1(t)$  (Fig. 9) is often not measured.

The component  $i_p(t)$  is the polarization current through the capacitor's dielectric, which corresponds to very small movements of a large number of charges (particles or groups of particles which form the dielectric molecules) that return to their initial position when the voltage drops to zero.

The component  $i_{ss}(t)$  is the space charge within the dielectric, generated during manufacturing process (fracturing the molecules) or degradation phenomena from operation conditions (thermal, electrical, mechanical, radiative, etc.). This is done through charge injection caused by sharp edges and protrusions of the electrodes etc. Charge carriers are fixed in traps with different depths and if an electric field is applied, they move within the dielectric, totally bridging its volume. The current  $i_{ss}(t)$  drops down to zero after a certain time because either these charge carriers will reattach themselves into other traps (which are often between the homogenous areas of the dielectric) or reach the electrodes surface (thus their concentration is decreasing with time).

The component  $i_c(t) = I_c = A \sigma U_0 / g$  (Fig. 9) is the conduction current which appears based on electrons, voids, molions and ions movement. The concentration of each of the charge carriers depends, among others, on the chemical nature and physical structure of the dielectric, often the conduction phenomena being caused by electrons or ions (Notingher 2005). This does not change in time (voltage is or not applied) and allows the experimental determination of the dielectric's electrical conductivity (resistivity).

Among the different charge carriers sources are electrode injections, band-band tunneling, impurities ionization, thermal jumping phenomena etc. The concentration of these charge carriers is influenced by the electric field, temperature, radiations, humidity etc. and it is therefore, dependent on dielectrics (insulation systems) degradation (ageing).

If the DC voltage is switched off ( $U_0 = 0$ ) and the capacitor arms are short-circuited, the capacitor discharges, causing a transient current  $i_2(t)$ :

$$i_2(t) = i_d(t) + i_{dp}(t) + i'_{ss}(t) \quad (2)$$

where  $i_d(t)$  is the discharging current component in vacuum,  $i_{dp}(t)$  – depolarization current component and  $i'_{ss}(t)$  – the space charge current component.

The measured current when the voltage is switched on is also called absorption current  $i_a(t)$ , and the current which is measured when the voltage is switched off is called resorption current  $i_r(t)$ .

Knowing the values for the absorption and resorption currents at a moment  $t$  (caused by switching on and off the DC voltage  $U_0$ ), the dielectric resistivity  $\rho_v(t)$  can be calculated:

$$\rho_v(t) = \frac{S}{g} \frac{U_0}{i_a(t) - i_r(t)} \quad (3)$$

where  $S$  is the electrode area and  $g$  is the dielectric thickness (Notingher 2016).

In this paper, mineral oil and transformer Kraft paper have been used as dielectric materials.

#### 4. THERMAL LIFETIME

The lifetime of a power transformer is the time in operation, in other words, the time interval since the commissioning till its failure. For the transformer insulation system, the lifetime is the time when an essential parameter (e.g. dielectric strength etc.) which describe the condition of one of its components (paper, oil) has reached the correspondent admissible limit. To estimate the lifetime is necessary to define a relevant diagnostic factor, which describes with high accuracy the material condition and its critical value (end of life criterion) in terms of correct operation of the insulation system (Setnescu 2014). In general, the diagnostic factors used for paper insulation are its DP and tensile strength, but also dielectric strength, resistivity, dissipation factor, etc. For mineral oil, one can use the water content, acids concentration, dissipation factor, electrical resistivity, etc. It was considered, for both insulation components (paper and oil), that the degradation rate under thermal stress ( $v_T$ ) variates with the temperature according to an Arrhenius law:

$$v_T = v_0 \exp\left(-\frac{E_a}{RT}\right) \quad (4)$$

where  $v_0$  is a material constant,  $E_a$  – apparent activation energy (associated to the electrical conduction process within the paper or oil) and  $R = 8314 \text{ J/kmolK}$  – ideal gas constant.

Assuming that, as a consequence of the degradation process with temperature  $T$ , the electrical resistivity decreases until it reaches the limit value, for which the paper or the oil cannot fulfill any longer the insulating role (the end of life criterion is reached), during the time interval  $D$  (lifetime) and by using (4), the following equations are obtained:

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

$$\ln D = a + b/T \quad (6)$$

where  $a = \ln D_0$  and  $b = E_a/RT$  are material constants which are determined based on experiments (Nottingham 2005).

Equation (5) is, in semilogarithmic coordinates ( $\ln D(T) = f(1/T)$ ), the lifetime curve for thermal ageing mechanism at constant temperature  $T$  (Setnescu 2014). To determine  $a$  and  $b$  constants, two methods were used: the standard method of the three temperatures  $M_T$  (International Electrotechnical Commission 2013) and the activation energy method  $M_{EA}$  (Setnescu 2014).

The method of the three temperatures ( $M_T$ ) implies thermal ageing at three temperatures, chosen according to (International Electrotechnical Commission 2013b) ( $T_{1,2,3}$ ), finding the variation of resistivity  $\rho$  with the ageing time ( $\rho(\tau)$ ), the end of life criterion and determining the points which intersects curves  $\rho(\tau)$  with end of life criterion horizontal line ( $Q_{1,2,3}$ ) and their abscissa ( $\tau_{1,2,3}$ ) (Fig.10) (Dumitran 2014). Based on  $P_1(1/T_1, \ln \tau_1)$ ,  $P_2(1/T_2, \ln \tau_2)$  and  $P_3(1/T_3, \ln \tau_3)$  the lifetime curve is plotted (Fig. 11) and the values for  $a$  and  $b$  parameters from (6) are determined.

The method  $M_{EA}$  implies the laboratory thermal ageing at the highest temperature value, according to the (International Electrotechnical Commission 2013b), respectively  $T_3$  (Fig. 10) and the determination of the activation energy based on DSC curves (Differential Scanning Calorimetry) by which the oxidation temperatures of paper can be highlighted (Setnescu 2014). Knowing the activation energy value  $E_a$ , the parameter  $b' = E_a/R$  is calculated. The value of parameter  $a'$  is determined by finding out the coordinates of point  $P_3$  ( $1/T_3, \ln \tau_3$ ) and using (6) (Setnescu 2014).

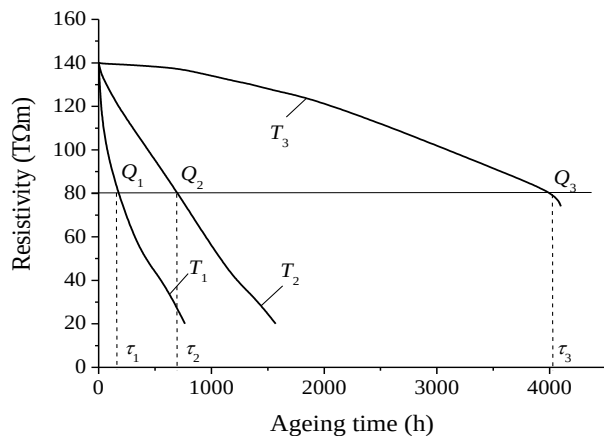


**Fig. 10.** Resistivity variation of Kraft paper with ageing time (for  $T_1 = 155^\circ\text{C}$ ,  $T_2 = 135^\circ\text{C}$  and  $T_3 = 115^\circ\text{C}$ ).

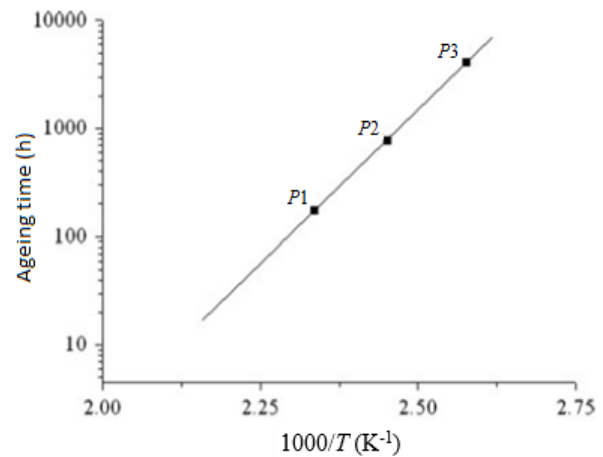


**Fig. 11.** Lifetime curve for Kraft paper.

## 5. LOSS OF LIFE AND REMAINING LIFETIME

If the power transformer is operating at a constant temperature  $T$ , the loss of life  $D_c$  is equal to the total time in operation  $D_f$ , thus the remaining lifetime is:

$$D_r = D - D_f \quad (7)$$

where  $D$  is the estimated lifetime for the operating temperature  $T$ .

In operation, the load and temperature of the insulation system are time variable ( $T = T(t)$ ), therefore the calculation of  $D_c$  and  $D_r$  is much more complex. For this, the insulating material thermal usage in time (the degradation rate of the material)  $U^*$  is defined, based on the equation of the lifetime ( $D^* = A \cdot \exp(b/T(t))$ ), which was proposed by Dakin (Notingham 2016):

$$U^* = \frac{1}{D^*} = \frac{1}{A} e^{-b/T(t)} \quad (8)$$

the material usage  $U^*(\Delta t)$  within the time interval  $\Delta t$  and the relative loss of life for interval  $\Delta t$  ( $D_{rel,c}^*$ ):

$$U^*(\Delta t) = D_{rel,c}^* = \frac{1}{A} \cdot \int_0^{\Delta t} e^{-b/T(t)} dt \quad (9)$$

The loss of life with respect to the interval  $\Delta t$  ( $D_c^*$ ) is:

$$D_c^* = D_{rel,c}^* \cdot D \quad (10)$$

and the remaining lifetime  $D_r^*$  for the variable temperature  $T(t)$  is:

$$D_r^* = D - D_c^* \quad (11)$$

## 6. MONITORING OF INSULATION SYSTEMS

Transformer oil can be monitored relatively easy due to the fact that oil samples from the tank can be taken, at different time intervals, for different types of analysis, e.g. physical, chemical and electrical. Based on these results, the oil condition can be assessed and the elapsed and remaining lifetime can be estimated. Among the analyzed parameters, the water content, impurities, resistivity and electrical permittivity, loss factor, dielectric strength, partial discharge activity can be distinguished etc. Most of these parameters (with few exceptions, e.g. water content) can be analyzed in specialized laboratories and not on-site. This paper describes a new method for monitoring the insulating oil condition, based on an oil cell installed within the oil flow circuit and using the equipment developed by SC SIMTECH INTERNATIONAL SRL (Bucharest, Romania). This equipment measures on-site the absorption and resorption currents of the oil, calculates the electrical resistivity and, further, the elapsed and remaining lifetime.

Thus, the oil usage (degradation)  $U$  for the interval  $\Delta t$  is calculated, taken into account the variable temperature and the resistivity values, measured at  $t_0$  ( $\rho(\Delta t, t_0)$ ). This parameter is equal to the relative loss of life  $D_{rel,c}(\Delta t)$ :

$$U(\Delta t, t_0) = D_{rel,c}(\Delta t, t_0) = \frac{\rho_0(t_0) - \rho(\Delta t, t_0)}{\rho_0(t_0) - \rho_{eol}} \quad (12)$$

where  $\rho_0(t_0)$  is the oil resistivity before transformer commissioning and  $\rho_{eol}$  is the resistivity for which the oil is at the end of its dielectric life. It can be observed that, for  $\Delta t = 0$ ,  $\rho(0, t_0) = \rho_0(t_0)$  and  $U(0) = D_{rc} = 0$ . For  $\Delta t = D$  (oil lifetime at constant temperature) results  $\rho(D, t_0) = \rho_{eol}$  and  $U(D) = D_{rc}(D) = 1$ .

Knowing the relative elapsed lifetime for  $\Delta t$  interval, the elapsed lifetime can be determined:

$$D_c(\Delta t) = D_{rc}(\Delta t) \cdot D \quad (13)$$

and the remaining lifetime of the transformer taking into account the variable temperature for  $\Delta t$  ( $D_r(\Delta t)$ ) is:

$$D_r(\Delta t) = D - D_c(\Delta t) \quad (14)$$

which is a very important parameter to determine the proper moment when the preventive maintenance of the transformer can be done.

For the paper insulation, applying equation (12) is much more difficult, if there aren't paper samples already introduced in the transformer tank, for such tests. In this case, it can be used the insulation resistance measured on-site, as diagnostic parameter. This case will be treated in a future paper.

## 7. EXPERIMENTS

The experiments were done on MOL mineral oil samples and Kraft paper samples (impregnated with MOL oil). The used oil was free of inhibitors (MOL To 30.01R, provided by Mol Romania Petroleum Products) and with a content of 53.1 % paraffinic carbons, 39 % naphthenic carbons and 7.1 % aromatic carbons and with 2-furfural content lower than 0.1 mg/kg (Dumitran 2014). The oil was introduced in sealed glass cells, which together with the Kraft paper, were subjected to thermally accelerated ageing within a lab drying oven (Trade Raypa), having an air forced circulation. The ageing was done at three temperatures ( $T_1 = 155$  °C,  $T_2 = 135$  °C and  $T_3 = 115$  °C), for intervals between 1000 and 4000 hours. At different time intervals ( $\tau$ ), groups of 5 samples were extracted and the absorption and resorption currents were measured using a Keithley 6517 electrometer. For the oil, a special IRLAB liquids cell was used, and for the paper a measurement cell Keithley 8009 and a cell developed within the University Politehnica of Bucharest were used. Inside these cells, square plates of 100 mm width, of 0.24 and 0.5 mm thick were introduced (Badicu 2011).

The DSC tests to determine the activation energy were done at ICPE-CA Institute, using the equipment Setaram 131 EVO (Setaram Instrumentation, France), for both oil and paper samples. Before oil impregnation, the paper samples were thermally conditioned for 24-48 hours at 90 °C.

## 8. RESULTS

Figs. 12 and 13 present the time variation of the absorption and resorption currents, measured at  $U_0 = 300$  V, 3600 s on oil samples, aged at  $T_1 = 155$  °C,  $T_2 = 135$  °C and  $T_3 = 115$  °C. On y axis were represented the arithmetic averages of the currents, measured on 5 probes of each sample. For every ageing temperature, 5 measurements were made (on 5 samples). It can be concluded that, for each value of the ageing temperature, the values for both type of currents increase with the ageing time. This is due to the oil degradation in time and thus to the increase of the charge carriers concentration. In addition, the increase in the ageing temperature leads to an increase of the current values, due to the fact that the intensity of the thermal degradation of the oil (thermos-oxidation etc.) is directly influenced by the temperature (Notingher 2017).

The absorption and resorption currents, measured on Kraft paper samples - aged at the  $T_{1,2,3}$  temperatures -, have similar variations than the oils samples (Figs. 10 and 11) (Notingher 2016).

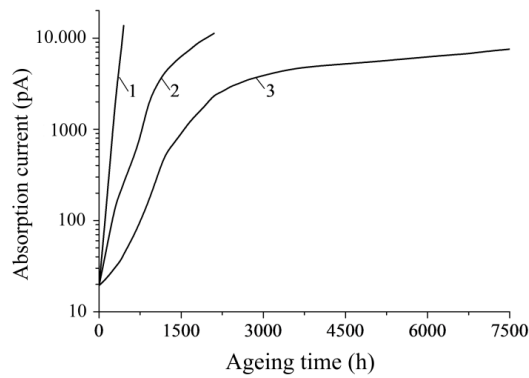


**Fig. 12.** Absorption currents variation with thermal ageing time (oil samples) at 155 °C (1), 135 °C (2) and 115 °C (3).

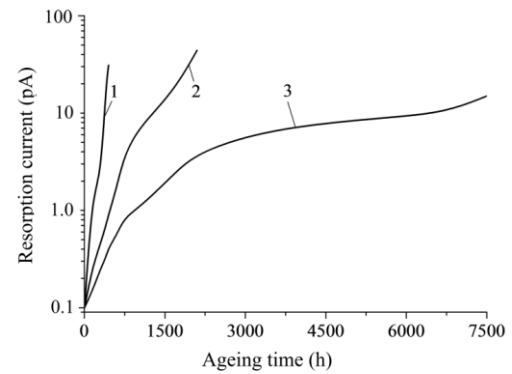


**Fig. 13.** Resorption currents variation with thermal ageing time (oil samples) at 155 °C (1), 135 °C (2) and 115 °C (3).

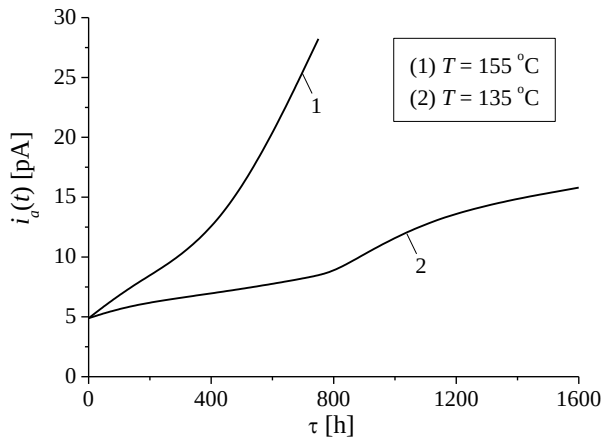


**Fig. 14.** Absorption currents  $i_a$  variation with ageing time  $\tau$  for impregnated paper, accelerated thermally aged at  $T_1 = 155$  °C (1) and  $T_2 = 135$  °C (2).

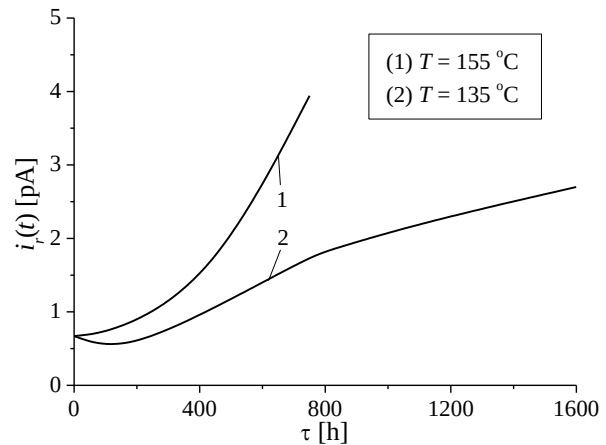


**Fig. 15.** Resorption currents  $i_r$  variation with ageing time  $\tau$  for impregnated paper, accelerated thermally aged at  $T_1 = 155$  °C (1) and  $T_2 = 135$  °C (2).

Based on (3), the volume resistivity values were calculated (using the currents values measured for 1 h since the voltage  $U_0$  was applied) and their variation curves with the ageing time at three temperatures ( $T_{1,2,3}$ ) were drawn (Figs. 10 and 16).

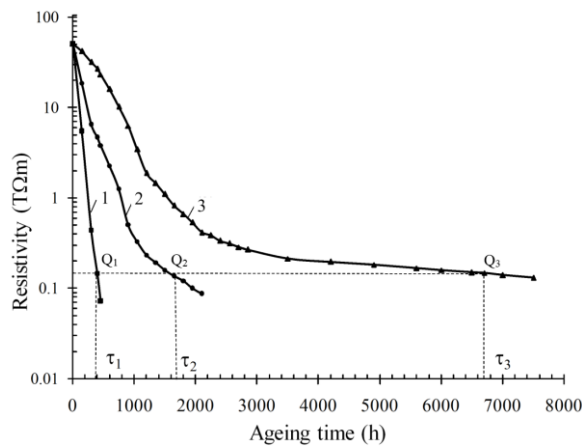


**Fig. 16.** Resistivity variation with oil ageing time at 155 °C (1), 135 °C (2) and 115 °C (3).

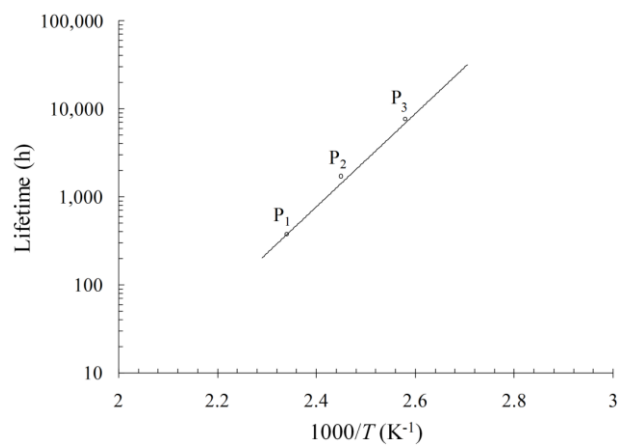


**Fig. 17.** Mineral oil lifetime curve with  $M_T$  method.

It can be concluded that the resistivity is decreasing with the ageing time and temperature, due to cellulose (Fig. 10) and oil degradation (Fig. 16), degradation which causes an increase of charge carriers' concentration (ions, molions).

The electrical resistivity was used as diagnostic factor for determining the lifetime curves equations. For paper the value  $\rho_{eol} = 20 \text{ T}\Omega\text{m}$  (Fig. 10) was used as end of life criterion while for oil the value  $\rho_{eol} = 0.15 \text{ T}\Omega\text{m}$  (Fig. 16). The equation for paper is:

$$\ln D(T) = -25.49 + 13114.16/T \quad (15)$$

with parameters (according to equation (6))  $a_T = -25.49$  and  $b_T = 13114.16 \text{ K}$ .

The lifetime curve ( $\ln D(T)$ ) was drawn and presented in Figure 11.

Using  $b_T$  value, the activation energy  $E_{aT} = 109 \text{ kJ/mol}$  was determined. This value is in accordance with other values presented in existing literature by different researchers, respectively between 91 and 120 kJ/mol (Ding 2008, Emsley 1994, Notingham 2016).

The value obtained for the activation energy with method  $M_{EA}$  is  $E_{aEA} = 112 \text{ kJ/mol}$ . Based on the value for  $E_{aEA}$  the parameter  $b_{EA}$  of lifetime curve was determined ( $b_{EA} = 13471.42 \text{ K}$ ). The value for the parameter  $a_{EA}$  ( $a_{EA} = -26.21$ ) and the lifetime curve equation were calculated (equation (16)) using the variation curve of the resistivity with the ageing time at 155 °C (Fig. 10) and the end of life criterion of 20 TΩm:

$$\ln D(T) = -26.21 + 13471.42/T \quad (16)$$

Using the activation energy method only 600 h of thermal ageing in laboratory were enough, 30 h for DSC measurements, processing and interpretation of results as well as approximately 600 kWh of energy.

Based on same procedures (as for paper insulation), the values for the coefficients of oil insulation lifetime curves (Table 1) and their equations were determined, using the two methods ( $M_T$  and  $M_{EA}$ ):

$$\ln D(T) = -22.737 + 12251.35/T \quad (17)$$

with method  $M_T$  and

$$\ln D(T) = -22.86 + 12295.84/T \quad (18)$$

with method  $M_{EA}$ .

For the oil activation energy the following values were obtained  $E_{aT} = 101.83$  (kJ/mol) with  $M_T$  and  $E_{aEA} = 102.40$  (kJ/mol) with  $M_{EA}$ , in accordance with those presented in (Inyang 2007) (Table 1).

**Table 1.** Values of coefficients  $a_{T,E}$ ,  $b_{T,E}$  and of activation energy  $E_{aT,EA}$  corresponding to  $M_T$  and  $M_{EA}$  methods

| Material | Method   | $a_{T,EA}$ ( - ) | $b_{T,EA}$ (K) | $E_{aT,EA}$ (kJ/mol) |
|----------|----------|------------------|----------------|----------------------|
| Paper    | $M_T$    | - 25.49          | 13114.16       | 109.00               |
| Paper    | $M_{EA}$ | -26,21           | 13471.42       | 112.00               |
| Oil      | $M_T$    | - 22.737         | 12251.35       | 101.83               |
| Oil      | $M_{EA}$ | - 22.86          | 12295.84       | 102.40               |

The lifetime values for oil and paper, corresponding to the three temperatures method as well as to the activation energy method were determined using equations (15-18). The results are for constant operating temperatures of the insulation system and are presented in Table 2.

**Table 2.** Paper and mineral oil lifetime values (in years), at constant temperature

| Material | Met./Temp. (°C) | 70    | 80    | 90   | 100  | 110  | 155   |
|----------|-----------------|-------|-------|------|------|------|-------|
| Paper    | $M_T$           | 43.73 | 15.17 | 5.58 | 2.16 | 0.88 | 0.013 |
| Paper    | $M_{EA}$        | 48.24 | 15.86 | 5.54 | 2.05 | 0.80 | 0.02  |
| Oil      | $M_T$           | 48.74 | 17.74 | 6.82 | 2.76 | 1.17 | 0.040 |
| Oil      | $M_{EA}$        | 49.07 | 17.80 | 6.82 | 2.75 | 1.16 | 0.040 |

The values for the calculated lifetime values (using both methods) decrease if the operating temperature increases, and for values higher than 100 °C, the lifetime values are lower than two years. On the other hand, there is a good agreement between the lifetimes values calculated with both methods.

The IEC 60216 ( $M_T$ ) method requires significant efforts, e.g. materials used, energy and human resources. A simple analysis shows that for materials there are necessary, using method  $M_T$ , 200 samples (100x100x0.24 mm<sup>3</sup>), over 6000 ageing hours, 90 hours of testing and an energy consumption of about 6000 kWh. With the activation energy method, only 600 hours of thermal ageing were necessary, 30 hours for DSC measurements, processing and interpreting the results and about 600 kWh of energy. Therefore it is more convenient to use the activation energy method.

The elapsed and remaining lifetimes taking into account variable temperatures of the insulation system (as in operation) were estimated based on  $a_{T,EA}$  and  $b_{T,EA}$  constants. The one-day temperature variation curves  $T(t)$ , given by the variable transformer load, are presented in Fig. 18 (Case 1) and 19 (Case 2) and the lifetime values are presented in Table 3.

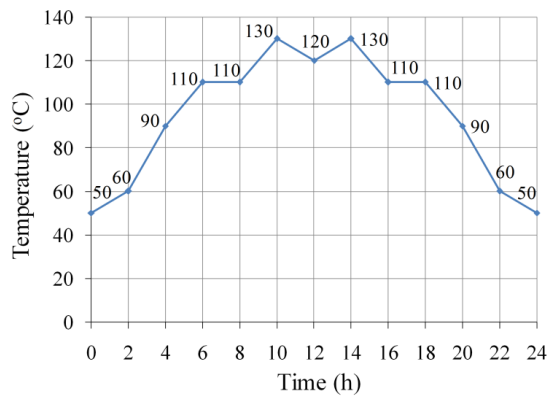


**Fig. 18.** Time variation of insulation temperature ( $T$ ) for a transformer (Case 1)

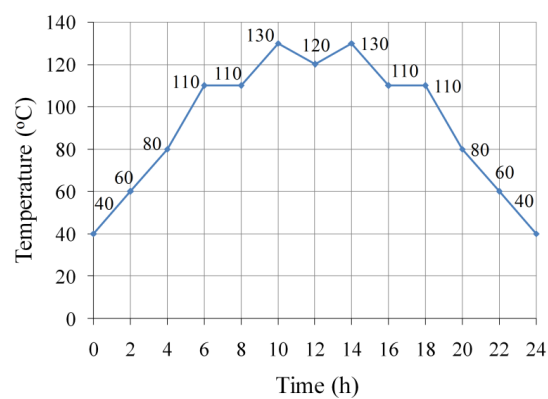


**Fig. 19.** Time variation of insulation temperature ( $T$ ) for a transformer (Case 2)

**Table 3.** One-day elapsed and remaining lifetime values, calculated with standard method ( $M_T$ ) and activation energy method ( $M_{EA}$ ) for variable temperatures (presented in Fig. 18 (1) and 19 (2))

| Material | Duration/Method | $M_{T1}$               | $M_{T2}$               | $M_{EA1}$              | $M_{EA2}$              |
|----------|-----------------|------------------------|------------------------|------------------------|------------------------|
| Paper    | $U^*(\Delta t)$ | $6.2 \times 10^{-3}$   | $6.101 \times 10^{-3}$ | $5.178 \times 10^{-3}$ | $5.1 \times 10^{-3}$   |
| Paper    | $U^* (s^{-1})$  | $7.175 \times 10^{-8}$ | $7.061 \times 10^{-8}$ | $5.993 \times 10^{-8}$ | $5.903 \times 10^{-8}$ |
| Paper    | $D_c^*$ (days)  | 29.47                  | 29.00                  | 32.99                  | 32.49                  |
| Paper    | $D_c^*$ (years) | 0.081                  | 0.0795                 | 0.0904                 | 0.089                  |
| Paper    | $D_r^*$ (years) | 15.089                 | 15.091                 | 15.77                  | 15.771                 |
| Oil      | $U^*(\Delta t)$ | $2.891 \times 10^{-3}$ | $2.832 \times 10^{-3}$ | $2.92 \times 10^{-3}$  | $2.861 \times 10^{-3}$ |
| Oil      | $U^* (s^{-1})$  | $3.346 \times 10^{-8}$ | $3.278 \times 10^{-8}$ | $3.38 \times 10^{-8}$  | $3.311 \times 10^{-8}$ |
| Oil      | $D_c^*$ (days)  | 18.738                 | 18.333                 | 18.98                  | 18.60                  |
| Oil      | $D_c^*$ (years) | 0.051                  | 0.050                  | 0.052                  | 0.051                  |
| Oil      | $D_r^*$ (years) | 17.689                 | 17.690                 | 17.748                 | 17.749                 |

**Notes:**  $U^*(\Delta t)$  – insulation usage (degradation) during interval  $\Delta t = 86400$  s (equivalent with the relative elapsed lifetime in  $\Delta t$  ( $D_{rel,c}^*$ ));  $U^*$  - insulation usage (degradation) in time;  $D_c^*$  - elapsed lifetime during  $\Delta t$ ;  $D_r^*$  - insulation remaining lifetime after one cycle in operation.

If the temperature of the insulation system presents the variations from Figs. 18 and 19, the elapsed lifetime would have a high value, approximately 30 times higher than the case where the temperature would be constant at 80 °C (Table 2). Therefore, to estimate the elapsed and remaining lifetimes the hot-spot temperatures have to be used as input data (measured on-line).

The estimated lifetimes based on the temperature variation curves and on the material constants can be used to assess the paper and oil conditions, and thus to be able to apply the preventive maintenance to the asset.

On the other hand, if the temperature variation curves are unknown, but the lifetime's curves at constant temperatures were determined, one can make an assessment of the insulation condition based on (12-14). For example, for the mineral oil a lifetime of  $D = 17.74$  years (using  $M_T$  or  $M_{EA}$  methods) was estimated if the transformer operates at a temperature of 80 °C, (Table 2). Further, it is assumed

that after being in operation for a  $\Delta t = 1$  year, the resistivity is reduced from an initial value of  $\rho_0(t_0) = 10 \text{ T}\Omega\text{m}$  to the value  $\rho(\Delta t, t_0) = 5 \text{ T}\Omega\text{m}$ . If the end of life criterion of  $\rho_{eol} = 0.15 \text{ T}\Omega\text{m}$  is chosen, a relative elapsed lifetime  $D_{rel,c}(\Delta t) = 0.51$ , an elapsed lifetime of  $D_c(\Delta t) = 9$  years and a remaining lifetime of  $D_r(\Delta t) = 8.73$  years are obtained.

It has to be noticed that using equations (12-14) the elapsed and remaining lifetimes can be determined even though the transformer load variation is unknown.

Regarding the paper insulation, one can apply the equations (12-14) only if the measurements were done on paper samples which were already introduced within the transformer tank by the manufacturer. Assuming that this would be the case, tensile strength, DP, electrical resistivity etc. can be measured whenever the transformer (transformer windings) is opened for maintenance or repair.

For the paper oil insulation, one diagnostic factor that could be used is the insulation resistance, measured on-site (off-line), both between windings and between windings and ground. In this case, laboratory tests have to be performed to estimate the lifetime curves for constant (steady state) temperatures ( $D$ ) and the coefficient values  $a$  and  $b$  of the life curve for paper insulation system, using models as similar as possible to the real insulations systems.

## 9. CONCLUSIONS

The lifetime values obtained through the  $M_T$  and  $M_{EA}$  methods are relatively close. Drawing the lifetime curve through the  $M_{EA}$  method requires less effort and resources in comparison with the  $M_T$  method and is recommended to be used in the case of in service power transformers oil replacement.

The lifetime of the insulation operating at higher temperature (on top of the windings) is considerably lower than the insulation lifetime on the bottom part of the winding.

Using the equations presented in this paper, the loss and remaining lifetimes of the insulation can be estimated if the variation of the service temperature is known.

With the proposed equation and measuring the resistivity of the insulation system components, the estimation of the loss and remaining lifetimes is possible without involving the transformer temperature variation profile.

Using the off-line measured insulation resistance as a diagnostic factor, the effectiveness of the maintenance strategies could be improved.

## ACKNOWLEDGMENTS

A part of the results presented in this paper are the outcome of the research performed within the project PN-III-P2-2.1-PTE-2016-0053, financed by The Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI).

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