INSULATION RESISTANCE – MONITORING PARAMETER OF POWER TRANSFORMERS INSULATIONS

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Abstract

Power transformers are one of the most important elements of electricity transport and distribution systems. Their failure and accidental shutdown results in significant economic losses and pollution of the air, soil or water. Therefore, monitoring the state of transformers and especially their insulation systems is a permanent concern for users of these equipments.

This paper presents a study on the evaluation of oil-paper insulation of power transformers, using a new diagnostic factor, i.e. insulation resistance. The laboratory model used for the experiments, the methods and procedures for the accelerated ageing of samples ("motorette"), the absorption and resorption current measuring system, the equations to calculate the insulation resistance and the estimated, consumed and remaining lifetime corresponding to the constant and variable temperature operation of the insulation are presented. Finally, the results of a numerical calculation of the lifetime for a power transformer that has been operating for 4 years and for which the temperature variation curve is known, are also presented.

Keywords: *Power transformers, oil-paper insulation, thermal ageing, insulation resistance, monitoring, estimated lifetime, consumed lifetime, remaining lifetime*

1. INTRODUCTION

Transmission and distribution electricity grids contain a very large number of transformers: only in the US there were over 30 million transformers at the end of the 20th century (Rouse 1998). The failure of a power transformer leads to major damage to producers (through the impossibility of energy supply) and energy consumers (by interrupting their activities), as well as environmental pollution (air, water, soil). A more accurate assessment of the state and lifetime reserve of transformers in operation can be an important tool for avoiding damage and increasing the safety of consumers' electricity supply (Notingher 2017 a).

The age of power transformers is continuously increasing (Van Schijndel 2010) and their failure rate increases with their service life (Fig. 1) (Gorgan 2012). Repairs to old-age transformers often require them to be removed from service for a long period of time and shipped to the manufacturer or to a specialised repair workshop. On the other hand, these repairs are very expensive, especially if insulation shows advanced aging and needs to be replaced. In such cases, the repair / upgrading cost is relatively close to the cost of a completely new transformer. Power transformers represent the most important investment in equipment installed in high-voltage stations (60% of the total investment (Jahromi 2009)).

Among the main components of power transformers (control switch, windings, bushings, tank, core and relay, Fig. 2, (Dolata 2011)), tap changers, bushingsand windings are the elements that fail most often (Fig. 3, (CIGRE 2015, Gorgan 2012, Metwally 2011, Zhang 2008)). If the switches can be easily repaired or replaced, it is difficult and expensive to re-build the winding insulation and the bushings. So the proper operation of a power transformer is directly related to the state of its insulation system. Generally, transformers are relatively reliable equipment with an average life of 20-35 years (Jahromi 2009, Wang 2002), and with good preventive maintenance, this lifetime can reach up to 60 years (Wang 2002).

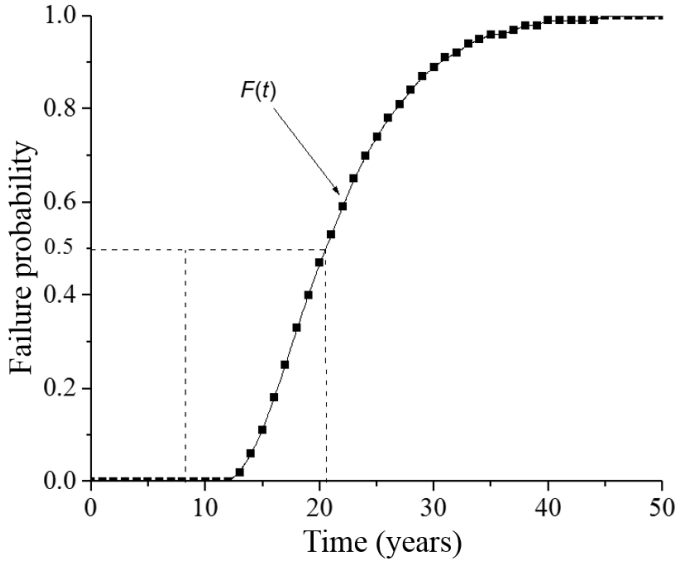


Fig. 1. Failure probability variation with the transformer service time (Gorgan 2012).

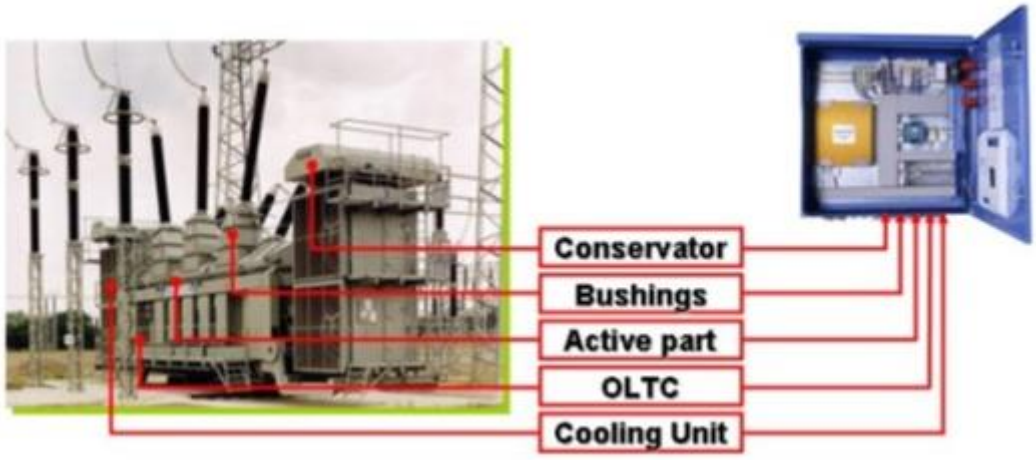


Fig. 2. Main components of power transformers (Dolata 2011).

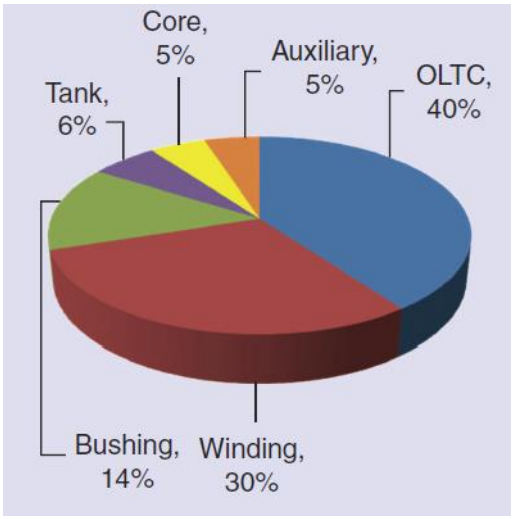


Fig. 3. Failure of transformer components (Metwally 2011).

For power transformers in transmission and distribution systems, the main insulation is made of paper and mineral oil, pertinax, textile strips, etc. Recently, significant efforts have been made to improve the performance of insulation systems by replacing cellulose paper with other types of paper (Nomex paper) and mineral oil with synthetic and vegetable oils (Frimpong 2011, Martins 2010, Prevost 2006). However, due to low costs and good operating behavior, the classic insulation system used for power transformers is still the paper-mineral oil system (Schaut 2011, Wang 2002).Therefore, avoiding the accidental shutdown of power transformers and their proper maintenance involves, first of all, a good monitoring and diagnosis of the oil-paper insulation states (Notingher 2017).

2. TRANSFORMER MONITORING

Transformer monitoring requires that, based on some methods, to select certain relevant parameters to determine their technical states, to install sensors and suitable transducers to provide relevant signals regarding these parameters, to ensure the acquisition and then transmission of the data to database systems in order to create databases with the values of these parameters. Diagnosis includes models and / or methods of correlating and interpreting measured data (and stored in databases) for the purpose of assessing the technical state of electrical equipment and lifetime reserves.

Transformer monitoring can be done online (without disconnecting the transformers from the grid) or off-line (with the disconnection of the transformers from the grid). On-line monitoring is done by means of sensors, as real-time values of some transformer diagnostic factors are recorded (Table 1) (Dolata 2011, Gorgan 2012, Wang 2002).

Classical monitoring methods are based on monitoring the temperature of the oil at various points of the transformer (hot-spots), the vibrations of the windings and tank, the level of gas dissolved in oil and partial discharges from the insulation. Modern monitoring methods are based on dielectric spectroscopy over time and frequency (monitoring the dielectric properties of insulation) and high frequency transfer function analysis (monitoring the movement and deformation of coils and magnetic core).To each monitoring method corresponds a diagnostic method, that allows the interpretation of results from different monitoring parameters, and finally the evaluation of the transformer's status. Diagnostic methods can be grouped into chemical (Fig. 4, (Schwarz 2008)), thermal, optical (Fig. 5, Schwarz 2008), mechanical (Fig. 6) and electrical (Fig. 7, Gorgan 2012, Schwarz 2008) and allow assessment of the transformer's health condition, providing information on the causes of aging components and recommendations for quality improvement and lifetime assessment (Schwarz 2008, Zhang 2008).

The most efficient method in the recognition and classification of thermal and electrical defects is the dissolved gases analysis (DGA).With DGA, certain types of defects, such as internal electric arcs, weak electrical contacts, hot spots, partial discharges, overheating of oil, cellulose paper, tank or conductors, can be identified (Zhang 2008).

Table 1. On-line monitoring parameters (Gorgan 2012)

Loading factor
Ambient temperature, electro-insulating oil, hot spot, winding and core
Oil level in conservator tank
Moisture in the oil
Partial discharges
Analysis of dissolved gases in oil (H_2, CO and volume of gases in the Buchholz relay)
Analysis of the cooling system (pumps, fans, thermal resistance)
CRS Function Analysis (Switch Position, Switching Number, Total Switched Current)
Bushings analysis (leakage currents, electrical capacity, tgδ)

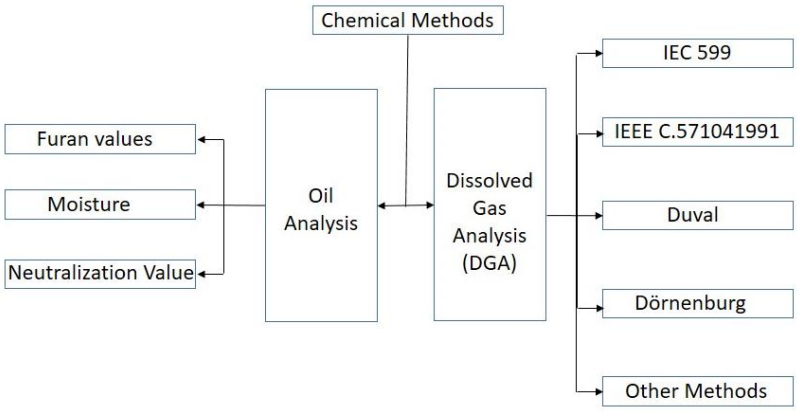


Fig. 4. Chemical diagnostic methods (Schwarz 2008).

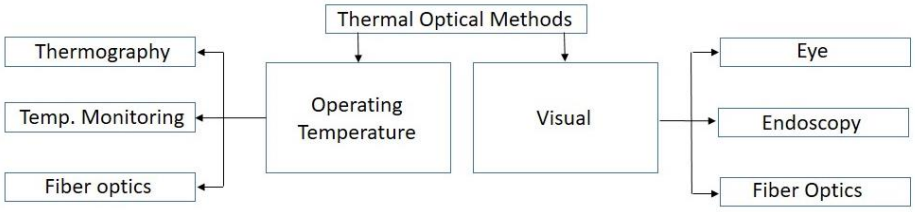


Fig. 5. Thermal and Optical diagnostic methods (Schwarz 2008).

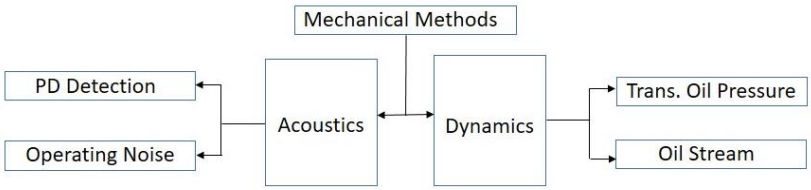


Fig. 6. Mechanical diagnostic methods (Schwarz 2008).

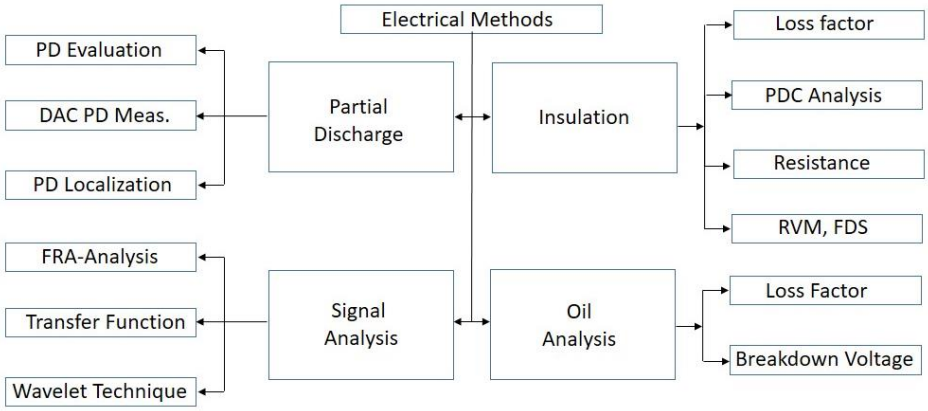


Fig. 7. Electrical diagnostic methods (Schwarz 2008).

The majority of defects cause temperature variations that can be detected by thermal analysis. The most common abnormal operating state detected by thermal analysis is transformer overload. Thermography allows for remote identification of thermal anomalies of electrical and mechanical components

(involving excessive heat release), such as blockages in the cooling system, hot spots, loose or weak connections, etc.

Frequency Response Analysis (FRA) is used to identify possible deformations and displacements of the transformer core and coil assembly as well as other internal defects. With the analysis of resonant frequencies, different ageing mechanisms such as short circuits, open circuits, core-earth connections, etc. can be identified (Schwarz 2008).

Among the transformers insulation evaluation methods based on the measurement of electrical quantities, the most important are those based on the dielectric response analysis over time (measuring the return voltage and measuring the absorption and resorption currents) and frequency (measuring the relative complex permittivity and the loss factor) (Badicu 2011, Bouaicha 2009, Gubanski 2010, Gubanski 2010 a, Notingher 2010, Saha 2004).

Time domain spectroscopy is one of the most efficient methods of assessing the behavior of dielectrics in electric field (Schwarz 2008, Badicu 2011a). This is based on the time-varying curves of the absorption / resorption currents. Thus, if an electrically insulating material (thickness g, conductivity σ_0 and permittivity ε) is placed between the armatures (with surface A) of a capacitor to which a voltage U_0 is applied, the capacitor absorbs a variable current over time $i_a(t)$, called the absorption current:

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

where $i_i(t)$ is the charging current of the capacitor with vacuum as dielectric, i_p(t) is the polarization current, $i_{ss}(t)$ is the space charge current and $i_c(t)$ is the conduction current (Notingher 2010).

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

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

where $i_d(t)$ is the discharge current of the capacitor with vacuum as dielectric, $i_{dp}(t)$ – depolarization current and i_{ss}'(t) – the current that corresponds to the dielectric space charge (Notingher 2010).

The current $i_i(t) = \varepsilon_0 A\partial E/\partial t$ is due to charging the capacitor in the absence of a dielectric ($\varepsilon = \varepsilon_0$) and decreases to zero very quickly (is not recorded in usual measurements). The component $i_p(t)$ is given by the dielectric polarization phenomena consisting of reduced spatial displacements of a large number of attached charges (particles or group particles of dielectric molecules) and decreases slowly to zero.

The current $i_{ss}(t)$ corresponds to the space charge in the dielectric volume. This charge is generated by the technological process, degradation process during service, charge injection at the surfaces of the metallic small radius curvature electrodes and protuberances etc. In a certain time depending on dielectric properties, $i_{ss}(t)$ becomes zero.

The conduction current $i_c(t) = A\sigma_0 U_0/g$ is given by the convection of electrons, ions and molecular ions. This component is unchanged in time and allows the determination of the electrical conductivity (resistivity) of dielectric.

If the voltage U_0 voltage is lower than 1 kV and the applied time is not very large (minutes or hours), in the case of usual insulation systems no important transformations appear (notable chemical degradations) that can modify the electrical dipoles' concentration or space charge density values. As a result, $i_p(t) \approx i_{dp}(t)$ and$i_{ss}(t) \approx i_{ss}'(t)$, the conduction current is:

$$i_c(t) = i_a(t) - i_r(t), \quad (3)$$

and the electric resistance of dielectric $R(t)$ can be computed with the equation:

$$R(t) = \frac{U_0}{i_a(t) - i_r(t)}. \quad (4)$$

Spectroscopy in frequency domain allows the determination of complex permitivity components and the loss factor at very low frequency values (i.e. for $f = 10^{-5}$ - 10^{-3} Hz), based on which the state of the tested sample can be estimated. On the other hand, using the absorption current values, the compoents of the complex relative permittivity (ε_r' and ε_r''), complex conductivity (σ' and σ'') and loss factor (tgδ) can be calculated (Joncher 1990, Joncher 1996).

Therefore, by choosing certain diagnostic factors (characteristics of each component of the transformer) and using sensors suitable for measuring their values, it is possible to develop monitoring and diagnostic systems for the states of a power transformer. Furthermore, based on the recommendations of the IEC 61850 standard, integration of this information can also be achieved into the on-line condition monitoring and expert system by means of analogue or digital signals and different protocols (IEC 60870-5-101/104, Modbus, DNP3 etc.) (IEC 61850-7-4). The analogue signals from the sensors are digitalized and transferred to the server via field bus (Dolata 2011).

Figure 8 presents the structure of a condition monitoring system MS 3000, manufactured by ALSTOM (Alstom 2017, Dolata 2011). Information regarding the transformer condition can be transmitted externally (via telephone line, Ethernet, etc.), viewed and stored by a Web Server. By processing these data, it is possible to diagnose the state of a transformer and to calculate the value of its health index. Using the health index value, a predictive maintenance procedure can be established for the grid operation of the equipment (Gorgan 2010, Gorgan 2011, Gorgan 2012, Janromi 2009).

Several diagnostic factors are used to determine the Health Index (HI) for the status of oil in the transformer, tap changer, bushings, tank, cooling equipment, conservator tank, connections, etc. as well as transformer loading and its maintenance. For HI computation Janromi proposed an equation using 24 diagnostic factors (Table 2, Janromi 2009):

$$HI = A_1 \cdot \frac{\sum_{i=1}^{n-3} c_i \cdot DI_i}{\sum_{i=1}^{n-3} 4 \cdot c_i} + A_2 \cdot \frac{\sum_{i=n-3}^{n} c_i \cdot DI_i}{\sum_{i=n-3}^{n} 4 \cdot c_i}, \quad (5)$$

where c_i is a mark given to each element (on a scale from 1 to 10, the value 10 corresponding to a very good state, Table 2), DI_i - the diagnostic index (on a scale from 0 to 4), n - the total number Diagnostic Factors, A_1 and A_2 - the weights with which the elements describing the transformer condition or the tap changer contribute to the calculation of the health index.

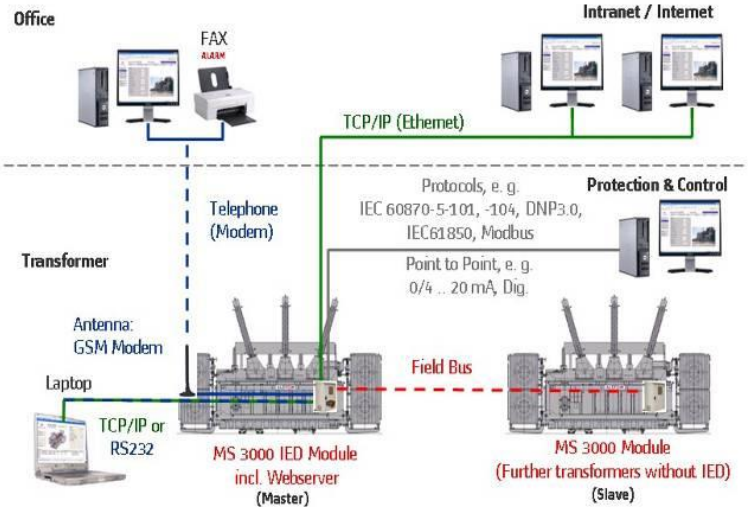


Fig. 8. Principal architecture of the MS 3000 comprehensive and interactive condition monitoring system for power transformers (Dolata 2011).

In (Gorgan 2010), Gorgan et al. propose adding three more diagnostic factors, namely the conductivity factor, the polarization index and the loss factor of the oil, and in (Gorgan 2012) - adding another diagnostic factor, i.e. the electrical conductivity of the oil.

Table 2. Diagnostic factors used to calculate the health index (Gorgan 2012)

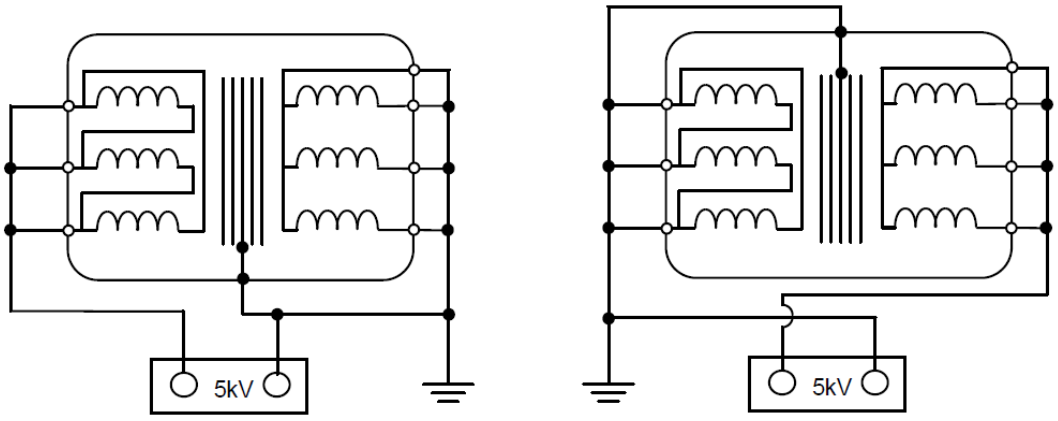
No.	Diagnostic factors	c_i	DI_i
1	Dissolved gas analysis (DGA)	10	4,3,2,1,0
2	Load history	10	4,3,2,1,0
3	Global loss factor	10	4,3,2,1,0
4	Infrared thermography	10	4,3,2,1,0
5	Oil quality	6	4,3,2,1,0
6	Overall transformer condition	8	4,3,2,1,0
7	Furans content	5	4,3,2,1,0
8	Turns ratio	5	4,3,2,1,0
9	Leakage reactance	8	4,3,2,1,0
10	Winding resistance	8	4,3,2,1,0
11	Core-to-ground connection	2	4,3,2,1,0
12	Bushing condition	5	4,3,2,1,0
13	Main tank corrosion	2	4,3,2,1,0
14	Cooling equipment	2	4,3,2,1,0
15	Oil tank corrosion	1	4,3,2,1,0
16	Foundation	1	4,3,2,1,0
17	Grounding	1	4,3,2,1,0
18	Gaskets, seals	1	4,3,2,1,0

19	Connectors	1	4,3,2,1,0
20	Oil leaks	1	4,3,2,1,0
21	Oil level	1	4,3,2,1,0
22	Dissolved gas analysis of LTC	6	4,3,2,1,0
23	LTC oil quality	3	4,3,2,1,0
24	Overall LTC condition	5	4,3,2,1,0
25	Conductivity factor k_c	10	4,3,2,1,0
26	Polarization index k_p	10	4,3,2,1,0
27	Loss factor tgδ at f = 1mHz	10	4,3,2,1,0
28	Electrical conductivity of oil	10	4, 3, 2, 1, 0

Since, during the operation of power transformers, the values of the insulation resistance between the high and low voltage windings and between each of them and the earth are measured periodically, it is useful that this parameter be used as a diagnostic factor in the monitoring of insulation states and calculation of transformer health index values. For this reason, the present paper presents the results of an experimental study performed on laboratory models of power transformers ("motorette") regarding variations of the resistance of oil-paper insulation subjected to accelerated aging at 115 °C, 135 °C and 155 °C. Considering the known value of the lifetime criterion, the parameters of the lifetime line, the lifetimes estimated for operation at constant temperatures and the consumed and remaining lifetime corresponding to the operation at constant and variable temperatures were determined.

3. INSULATION RESISTANCE

The electrical resistance of the oil-paper insulation, simply called insulation resistance, is defined as the ratio between the applied continuous voltage and the current passing through the tested insulation. The experimental determination of the insulation resistance is done by applying a continuous voltage between each winding and the ground (the other windings being connected to the ground) and measuring the absorption current at different moments from the application of the voltage (30 ... 600 s) (MEGGER 2017). If the measurements were made at a temperature T_1 different from the reference temperature T_0 (corresponding to insulation at the commissioning of the transformer or where the insulation resistance measurements were made by the equipment manufacturer), the resistance values are corrected by temperature coefficients whose values are normalized (for each measuring temperature) (IEEE C57.12.90). For two-winding transformers, measurements will be made at least for the combinations: IT - (JT + ground) and JT - (IT + ground) (Fig. 9) (ANSI 2013).



a) b)

Fig. 9. Test connections for insulation resistance testing of primary transformers for HV winding test (a) and LV winding test (b).

Table 3. Minimum allowed values at 20º C and 50º C (MΩ) for insulation resistance of transformers with rated voltage U_n

U_n **(kV)**	**20 ºC**	**50 ºC**
< 110	300	90
110 - 220	600	180
400	1000	300

Insulation resistance measurements shall not be less than the minimum limits specified by the transformer manufacturer (Table 3).

Since the reduction in insulation resistance of a transformer is due to the degradation of its two components (paper and oil), the values of this can be used to calculate the transformer health index, respectively to diagnose and monitor its state and to establish a predictive maintenance. In this way, the absorption / resorption currents are measured offline after certain intervals of operation of the transformer. Thus, applying a continuous voltage U_0 between an HV or LV winding (for example one phase) and the ground for a period t_a, the absorption current $i_a(t)$ is measured, then, after disconnecting the DC source and shortening the terminals, current $i_r(t)$ is measured (within a t_r interval). Then, the insulation resistance $R_{iz}(t)$ is calculated with equation (4), or more simply with equation (6):

$$R_{iz}(t) = \frac{U_0}{i_a(t)}. \tag{6}$$

The R_{iz} values, calculated at 45 s, 60 s and 600 s from applying the voltage, can be used to monitor and diagnose the insulation status as well as to estimate the consumed and remaining lifetime of the insulation. To highlight how this parameter was used, a series of accelerated thermal ageing tests of transformer winding models were performed, with some of the results presented below.

4. EXPERIMENTS

In order to determine the lifetime line parameters associated with the oil-paper insulations of the transformers, an experimental laboratory model was done, respectively a plane winding model (“motorette”, Fig. 10), corresponding, especially, to the windings of the very high power and voltage

transformers (1200 kV) (Metwally 2011). Rectangular aluminum conductors insulated with 0.24 mm Weidmann transformer paper were used to make the model.

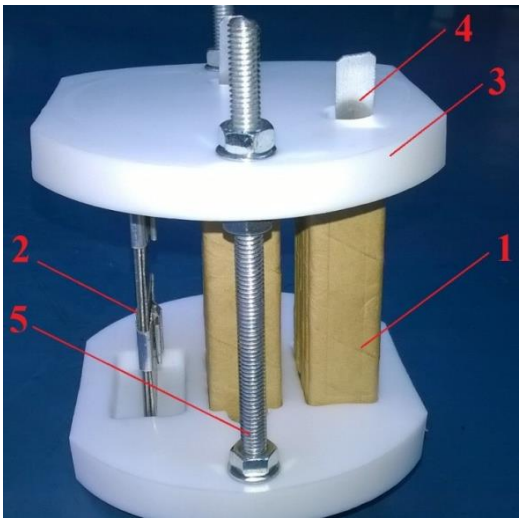


Fig. 10. Experimental plane model ("motorette"): 1) Aluminum profiled conductor; 2) Fe-Si sheets; 3) PTFE fixing plate; 4) Measurement terminal; 5) Clamping screw.



Fig. 11. Stainless steel cell for thermal ageing of "motorette".

The „Mottorette" were introduced into cylindrical stainless steel cells with a diameter of 90 mm and a height of 120 mm (Fig. 11). After the „motorette" were inserted, the cells were filled with PRISTA mineral oil. To estimate the ageing states of the components of the transformer insulation system, 7 samples of Weidmann paper were inserted in addition to oil. Groups of 3 cells (M1, M2 and M3) were placed in RAYPA forced air circulation ovens and subjected to constant heat stresses at 155, 135 and 115 ^{o}C for a periodranging from 1200 h to 5000 h. Prior to the heat stresses, all „motorette" were thermally conditioned at 60 ^{o}C for 48 h, the absorption / resorption currents being then measured.

Temperature values (115, 135 and 155 ^{o}C) and ageing times corresponding to each temperature were chosen in accordance with IEC (IEC 60216-1) prescriptions. At initially set intervals (depending on the ageing temperature), the oven temperature was reduced to 27 ° C, the "motorette" were removed from the oven and the absorption and resorption currents were measured for both the oil-paper insulation and the oil and paper.



Fig. 12. Standard IRLAB CL-1 cell for measuring absorption / resorption currents ($i_a(t)$ and $i_r(t)$) in liquids.

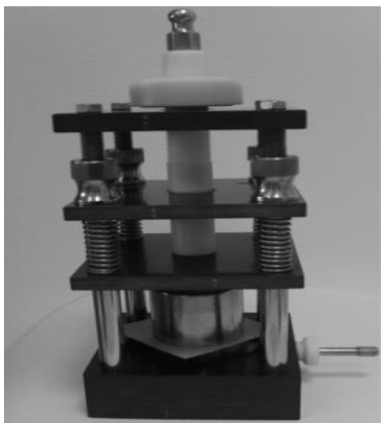


Fig. 13. Cell for measuring absorption and resorption currents ($i_a(t)$ and $i_r(t)$) for oil impregnated paper.

The measurement of the absorption / resorption currents of the oil-paper insulation of "motorette" was made directly with a Keithley 6517B Electrometer for a voltage U_0 = 200 V. In the case of oil, a standard cell for electrically insulating liquids (Fig. 12) was used at a voltage of U_0 = 100 V, and a special cell (Fig. 13) for paper was used for U_0 = 100 V.

5. RESULTS

5.1. Insulation resistance

Accelerated aging tests of "motorette" insulations (at 155 ºC, 135 ºC and 115 ºC) were performed, the absorption / resorption currents for oil-paper, oil and paper insulation were measured, the lifetime line was drawn for oil-paper insulation and the consumed and remaining lifetime for operation of the insulation at constant temperature were calculated. Also, the parameters of the lifetime were calculated in the case of insulation service at an unknown variable temperature.

Figures 14-16 show the variations in absorption / resorption currents with the measurement and the ageing time. It is noted that both absorption and resorption currents decrease over time (Fig. 14) as a result of the reduction of the polarization and space charge currents (Notingher 2017). On the other hand, increasing the aging time leads to increased absorption currents as a result of the degradation of the insulation components and the increase in the concentration of charge carriers in the insulation (Figs. 15-16).

Figures 17 and 18 show the variations in the oil-paper insulation resistance of M1, M2 and M3 "motorette", with the ageing time at 155 ºC, measured at 60 s (R_{60}) and 600 s (R_{600}) after voltage application (U_0 = 200 V). Generally, these insulation resistance values (R_{60} and R_{600}, respectively) are used to characterize the states of insulation of electrical equipment (MEGGER 2017). It is noted that in the first part of the ageing process the values of the R_{60} and R_{600} increase as a result of the elimination of a part of the water contained in paper and oil. After some time typical of each ageing temperature (for example, 110 h for T_1 = 155 ºC) resistance values begin to decrease as a result of the fracture of paper and oil macromolecules and the increase in the concentration of electrical dipoles and charge carriers. The same types of variations of the R_{60} and R_{600} parameters were also obtained for "motorette" aged at T_2 = 135 ºC (Figs. 19 and 20) and T_3 = 115 ºC (Figs. 21 and 22).

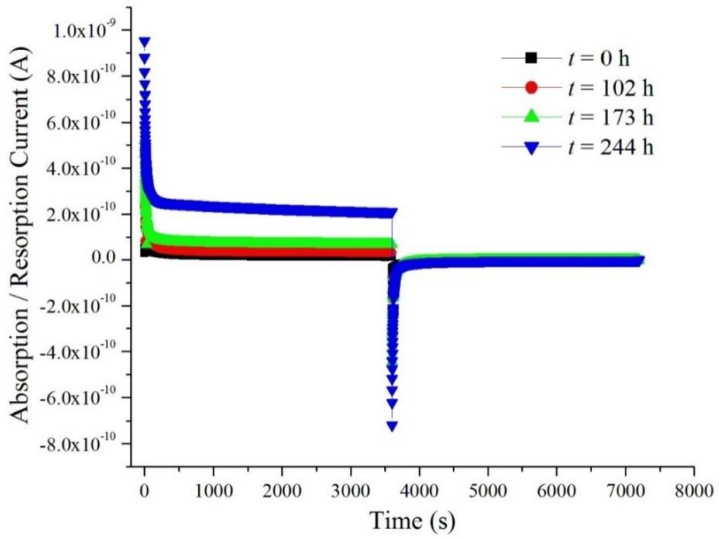


Fig. 14. Time variations of the absorption/resorption currents for oil-paper insulation of « motorette » M1, aged at 155 ºC, during 0, 102, 173 and 244 h (U_0 = 200 V).

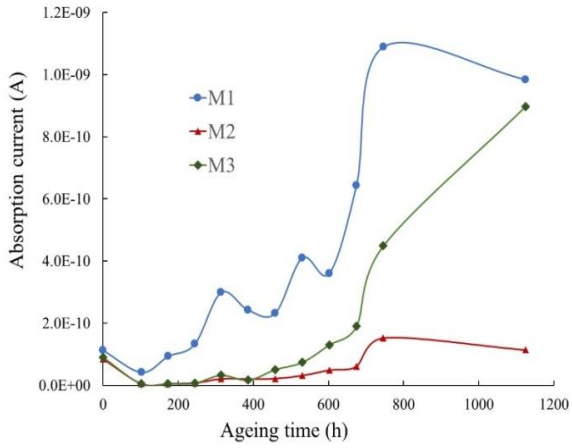


Fig. 15. Variations of absorption currents of « motorette « M1, M2 and M3, measured 60 s after the voltage application (I_{60}) with the ageing time at T_1 = 155 ºC (U_0 = 200 V).

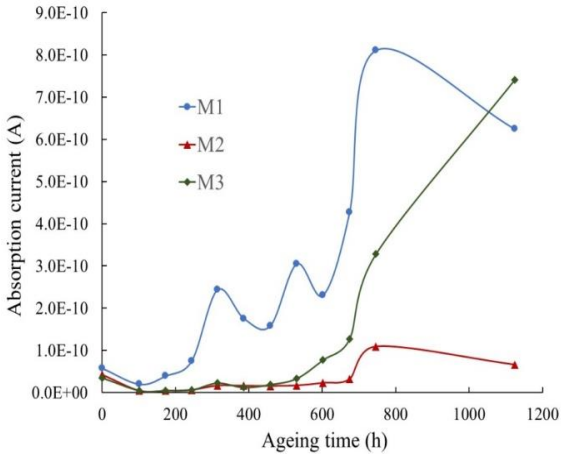


Fig. 16. Variations of absorption currents of « motorette » M1, M2 and M3, measured 600 s after the voltage application (I_{600}) with the ageing time at T_1 = 155 ºC (U_0 = 200 V).

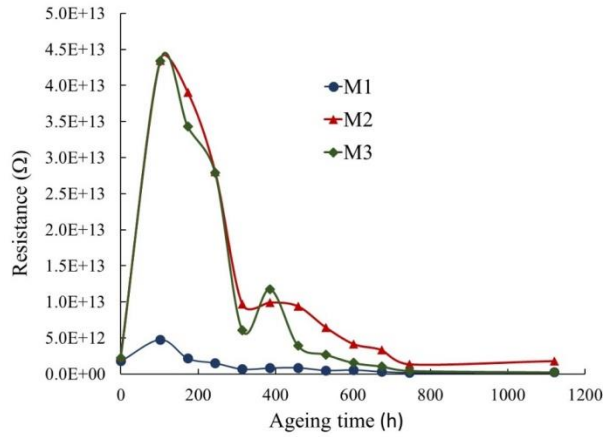


Fig. 17. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 60 s after the voltage application (R_{60}) with the ageing time at T_1 = 155 ºC (U_0 = 200 V).

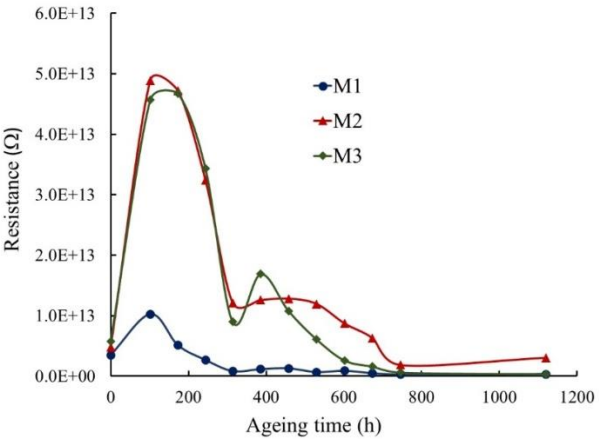


Fig. 18. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 600 s after the voltage application (R_{600}) with the ageing time at T_1 = 155 ºC (U_0 = 200 V).

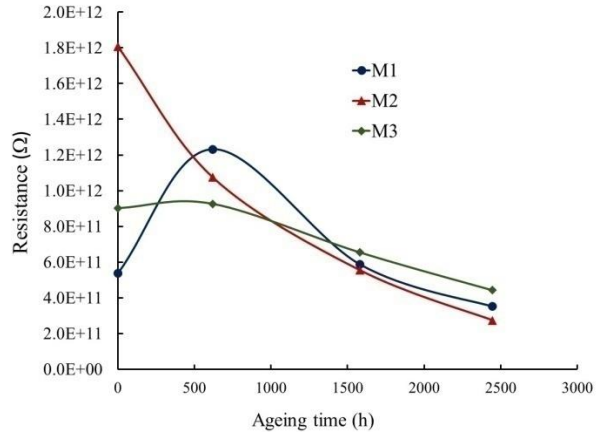


Fig. 19. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 60 s after the voltage application (R_{60}) with the ageing time at T_1 = 135 ºC (U_0 = 200 V).

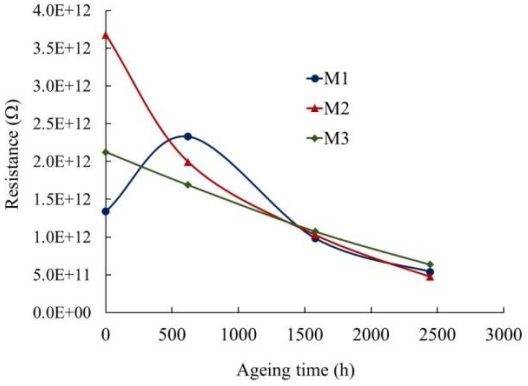


Fig. 20. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 600 s after the voltage application (R_{600}) with the ageing time at T_1 = 135 ºC (U_0 = 200 V).

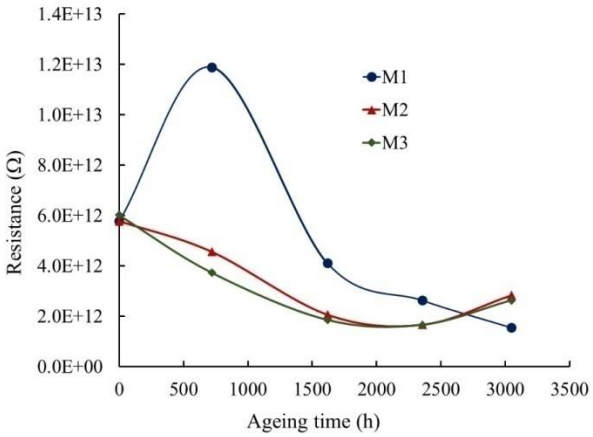


Fig. 21. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 60 s after the voltage application (R_{60}) with the ageing time at T_1 = 115 ºC (U_0 = 200 V).

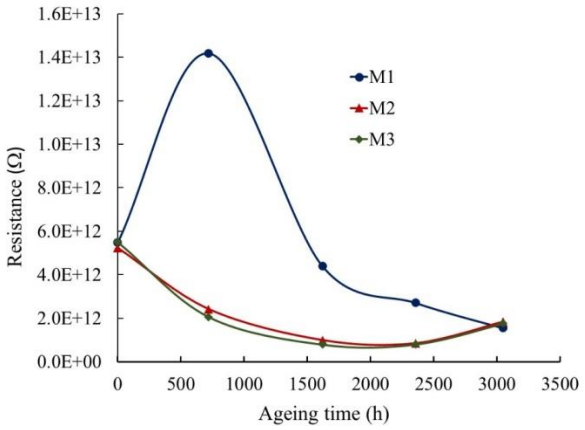


Fig. 22. Variations of insulation resistance of « motorette » M1, M2 and M3, calculated 600 s after the voltage application (R_{600}) with the ageing time at T_1 = 115 ºC (U_0 = 200 V).

In order to verify the correctness of the insulation resistance variation for aged ”motorette”, measurements of the oil and the transformer paper resistivity, aged under the same conditions were performed separately at T_1 = 155ºC. Resistivity variations with aging time are shown in figures 23 (for oil) and 24 (for paper). It is found that both the resistivity of the oil and that of the paper decrease with the increase in the ageing time (as with oil-paper insulation), but not in the same ratio. Thus, after 1120 h of ageing, the resistivity of the oil measured at 60 s from the application of the voltage is reduced by more than 300 times, while the paper resistivity decreases only 3 times. Smaller variations in paper resistivity may also explain less variations in oil-paper insulation, only 23 times.

On the other hand, the degradation state of the paper is best characterized by the degree of polymerization and tensile strength. It is admitted as a minimum value of the degree of polymerization of paper PD_{lim} = 200 (Emsley 1994). In our tests at 155 ºC, this value was reached after τ_{eol} = 418 h (Fig. 25) and represents the end-of-life criterion (PD_{leol} = 200) used to determine the lifetime of the oil-paper insulation on the basis of the new diagnostic factor, respectively insulation resistance.

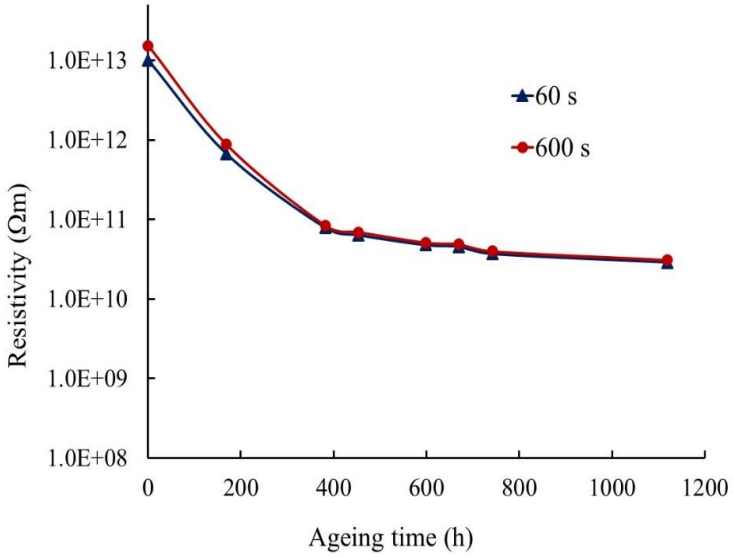


Fig. 23. Variations of PRISTA oil resistivity with the ageing time at T_1 = 155 ºC, measured at 60 s (▲) and 600 s (●) after voltage application (U_0 = 100 V).

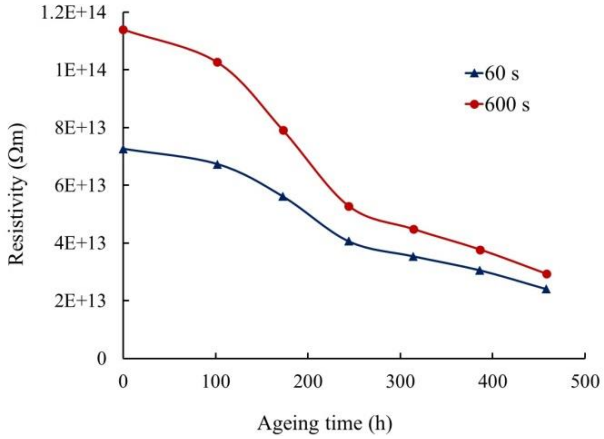


Fig. 24. Variations of resistivity measured 60 s (▲) and 600 s (•) after the voltage application with the ageing time at T_1 = 155 ºC (U_0 = 100 V).

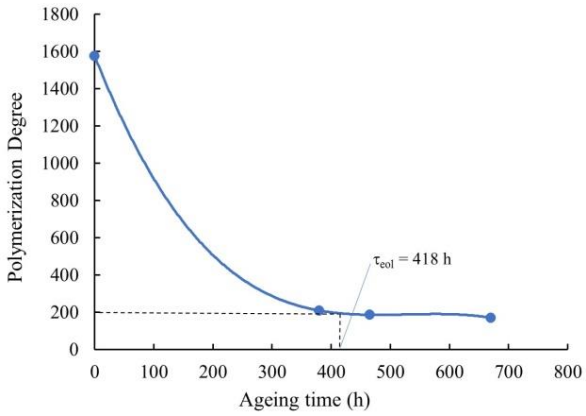


Fig. 25. Variation of the degree of polymerization paper with the ageing time.

5.2. Lifetime

The Dakin model was used to determine the lifetime line of the oil-paper insulation:

$$D = A \cdot \exp(E_a/kT), \tag{7}$$

resulting,

$$\ln D = a + b/T \tag{8}$$

where D represents the lifetime corresponding to the service of the insulation at temperature T, E_a - activation energy, k - Boltzmann constant, $a = \ln A$ and $b = E_a/k$ (Dumitran 2014, Rusu-Zagar 2017, Setnescu 2014).

Since the insulation resistance was used as a diagnostic factor, the average insulation resistance variation curves (for the three M1, M2 and M3 "motorette") with the ageing time τ, measured at 60 s from the voltage application, were drawn at a convenient scale (Fig. 26). Considering that the time of reaching the end-of-life criterion for ageing at 155 ºC is $\tau_1 = \tau_{eol}$ = 418 h, figure 25 gives the value of the end-of-life criterion for insulation resistance, i.e. R_{60eol} = 0.8 TΩ. This criterion was also used to deduce the lifetime of the oil-paper insulation corresponding to its ageing at 135 and 115 ºC.

Figure 26 shows that the end-of-life criterion of the oil-paper insulation (0.8 TΩ) aged at 135 ºC is reached after τ_2 = 1105 h, and from Figure 27 it results that this criterion is reached after τ_3 = 3340 h for insulation aged at 115 ºC. Thus, the three points of the lifetime of the oil-paper insulation, respectively $P_1(1/T_1', \ln\tau_1)$, $P_2(1/T_2', \ln\tau_2)$ and $P_3(1/T_3', \ln\tau_3)$, where $T_{1,2,3}' = T_{1,2,3} + 273.15$ K (Table 4) were obtained. Using the points $P_{1,2,3}$, the lifetime line of the oil-paper insulation was drawn, the line which has as diagnostic factor the insulation resistance and the end-of-life criterion R_{60eol} = 0.8 TΩ (Fig. 28, curve 1).

Knowing the coordinates of the points $P_{1,2,3}$, the parameters of the lifetime line $\ln\tau = a + b/T$ 'can be determined by means of the recommended IEC (IEC 60216-8) equations:

$$b = \frac{\sum xy - \sum x \sum y / n}{\sum x^2 - \left(\sum x\right)^2 / n} \tag{9}$$

$$a = \frac{\left(\sum y - b\sum x\right)}{n} \quad . \tag{10}$$

where $x = 1/T$, $y = \ln\tau$ and $n = 3$ represents number of pairs (x,y).

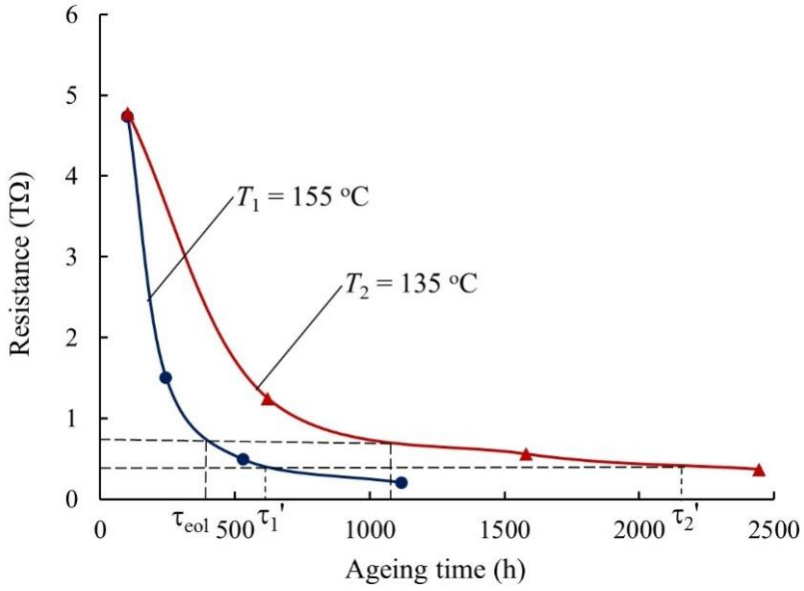


Fig. 26. Variations of insulation resistance measured 60 s after the voltage application with the ageing time for oil-paper insulation aged at T_1 = 155 °C and T_2 = 135 °C.

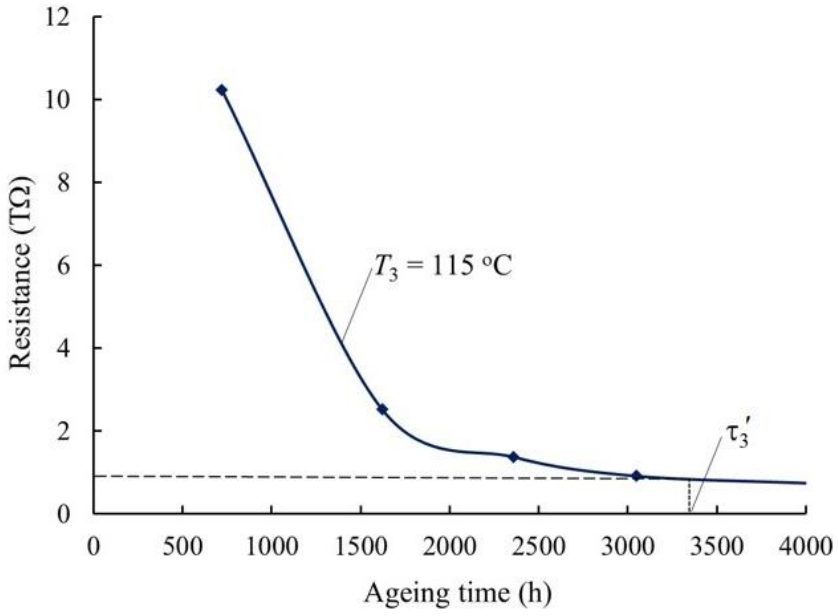


Fig. 27. Variation of insulation resistance measured 60 s after the voltage application with the ageing time for oil-paper insulation aged at T_3 = 115 °C.

Table 4. Coordinates of the lifetime line points ($R_{iz,\,eol}$ = 0.8 TΩ)

Point	**P$_1$**	**P$_2$**	**P$_3$**
1/T'	2.336.10^{-3}	2.450.10^{-3}	2.576.10^{-3}
lnτ	6.035	7.008	8.113

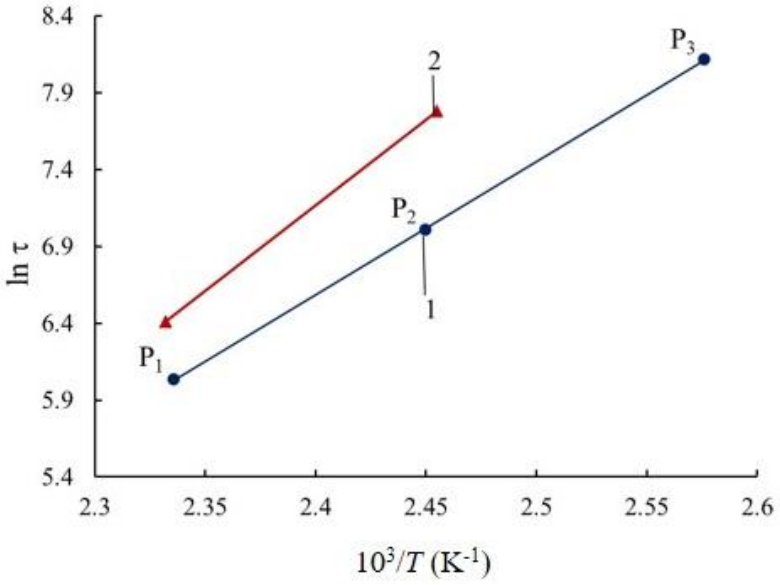


Fig. 28. Lifetime lines of oil-paper insulation for R_{izeol} = 0.8 TΩ (1) and R_{izeol} = 0.4 TΩ (2).

Using the values of the point coordinates $P_{1,\,2,\,3}$ of Table 5 and equations (9) - (10) the numerical values of the lifetime line parameters, respectively b = 8333 K, a = - 13.4, and the value of activation energy E_a = 69.22 kJ / mol were obtained. Therefore, the lifetime line of the oil-paper insulation has the following equation:

$$\ln D = -13.4 + 8333/T' \quad . \tag{11}$$

Using equation (11), the expected lifetime values of the oil-paper insulation D were determined for its operation at different temperatures T supposed as constant (Table 5). It follows that if the insulation works a time interval Δt = 2 years at temperature T_4 = 80 °C ($D(T_4)$ = 3.02 years, Table 5)), the lifetime consumed is $D_c(T_4) = \Delta t$ = 2 years and the remaining lifetime - for operation at the same temperature T_4 - is $D_r(T_4) = D(T_4) - D_c(T_4)$ = 3.02 - 2 = 1.02 years.

It should be noted that the estimated lifetime values were calculated for a relatively severe end of life criterion (i.e. 10 times lower than the maximum insulation resistance value) and therefore the value of the activation energy is much lower than the usual paper values (112 kJ/mol, (Setnescu 2014)) and oil (102.4 kJ/mol, (Dumitran 2014)). For example, considering for the end-of-life criterion a lower value R_{iz60} = 0.4 TΩ in Figure 26, it follows that this criterion corresponds to an aging period τ_1'= 600 h for the insulation aging at 155 °C and a period τ_2' = 2200 h for aging at 135 °C. With these values of the end-of-life values, the new values of the lifetime line parameters a'= - 20.24 and b' = 11400 K, respectively its new equation are obtained:

$$\ln D' = -20.24 + 11400/T'. \tag{12}$$

For activation energy the value $E_a' = k \cdot b'$ = 94.71 kJ / mol, corresponding to those for paper (112 kJ / mol) and oil (102.4 kJ / mol), is obtained.

Table 5. Values of expected lifetimes of oil-paper insulation *D* and *D*' for operation at different temperatures *T*

***T* (ºC)**	**60**	**65**	**70**	**80**	**90**	**100**	**110**	**115**
T' (K)	333.15	338.15	343.15	353.15	363.15	373.15	383.15	388.15
10^3/T' (K^{-1})	3.00	2.96	2.91	2.83	2.75	2.68	2.61	2.58
D (hours)	110498	76336	53307	26801	13994	7566	4224	3192
D (years)	12.61	8.71	6.08	3.05	1.59	0.86	0.48	0.36
D' (hours)	1176413	709282	433992	169407	69644	30028	13528	9221
D' (years)	134.3	80.97	49.54	19.34	7.95	3.43	1.54	1.05

Knowing the value of parameter *a* results $A' = e^{a'} = e^{-20.24} = 1.62 \cdot 10^{-9}$ h and then the expression of the lifetime of the oil-paper insulation:

$$D' = 1.62 \cdot 10^{-9} \cdot \exp(11400/T) \quad (13)$$

Using the equation (13) the new values of the estimated lifetime *D* '(Table 5) are obtained, values much closer to those encountered in the operation of the power transformers.

Knowing the expression of the consumed lifetime (Notingher 2002)

$$D_{rel,c}(\Delta t) = \frac{1}{A'} \cdot \int_0^{\Delta t} e^{-b/T(t)} dt \quad (14)$$

where ($D_{rel,c}(\Delta t)$ represents the relative lifetime consumed over time Δt and $T(t)$ - the temperature variation function in Δt, the lifetime consumed in the range $\Delta t(D_c(\Delta t))$can be calculated:

$$D_c(\Delta t) = D_{rel,c}(\Delta t).D \quad (15)$$

and the remaining lifetime after operation in the range Δt at variable temperature $T(t)$ ($D_r(\Delta t)$) can be calculated:

$$D_r(\Delta t) = D - D_c(\Delta t). \quad (16)$$

For example, we consider that in the [0, t_2] range the temperature of the insulation in operation varied as in Figure 29 and T_1 = 70 ºC, T_2 = 80 ºC, t_1 = 2 years and t_2 = 4 years. From (14) it follows:

$$D^1_{rel,c} = \frac{1}{A'} \int_0^{t_t} e^{\frac{-b'}{T_1}} dt \quad (17)$$

$$D^2_{rel,c} = \frac{1}{A'} \int_0^{t_t} e^{\frac{-b'}{T_1}} dt + \frac{1}{A'} \int_{t_1}^{t_2} e^{\frac{-b'}{T_2}} dt \quad , \quad (18)$$

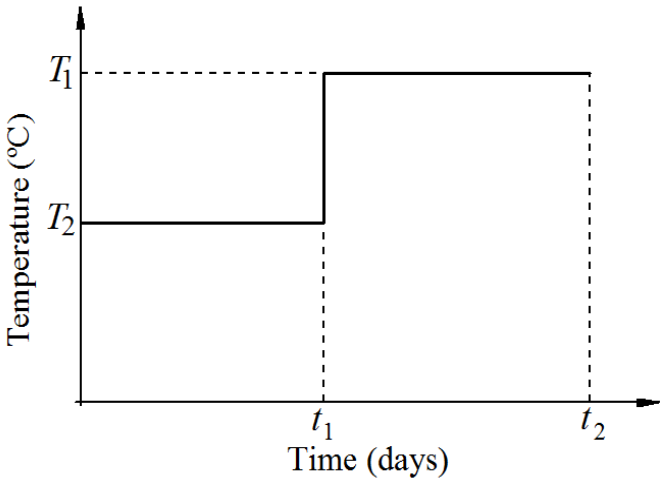


Fig. 29. Variation of insulation temperature in operation.

respectively:

$$D_{rel,c}^{1} = \frac{t_1}{A'} e^{\frac{-b'}{T_1}} \tag{19}$$

$$D_{rel,c}^{2} = \frac{t_1}{A'} e^{\frac{-b'}{T_1}} + \frac{t_2 - t_1}{A'} e^{\frac{-b'}{T_2}} \tag{20}$$

By replacing the values of the parameters A', T_1, T_2, t_1 and t_2 in (19) and (20), the values of the relative consumed lifetimes, respectively $D_{rel,c}^{1}$ = 0.0474 and $D_{rel,c}^{2}$ = 0.1688, are obtained.

Taking into account the lifetime value estimated at 70 °C, respectively D'= 49.54 years, from (15) the consumed lifetimes, respectively $D_c^1 = D_{rel,c}^1 \cdot D'$ =0.047x49.54= 2.33 years and $D_c^2 = D_{rel,c}^2 \cdot D'$ = 0.1688x49.54= 8.36 years are obtained.

Using equation (16) the values of the remaining lifetimes, respectively D_r^1 = 47.21 years and D_r^2 = 41.18 years, are obtained.

If the temperature variation curve is not known, a similar relation to that proposed by Notingher for the liquid component of the insulation (Notingher 2017) could be used to calculate the relative consumed lifetime until instant t:

$$D_{rel,c}(t) = \frac{R_{iz}(0) - R_{iz}(t)}{R_{iz}(0) - R_{iz,eol}}, \tag{21}$$

Where $R_{iz}(0)$ represents the insulation resistance value at the initial moment, $R_{iz}(t)$ - the insulation resistance value measured at time t and $R_{iz,eol}$ - the end-of-life criterion.

For example, a transformer for which the lifetime estimated at the nominal operating temperature D'= 30 years and the end-of-life criterion $R_{iz,eol}$ = 0.4 TΩ, which worked for 4 years at an unknown temperature (constant or variable) is considered. For the oil-paper insulation the initial value (before commissioning) of the insulation resistance ($R_{iz}(0)$ = 2.2 TΩ) and its value after 4 years of operation ($R_{iz}(4)$ = 1.8 TΩ) was measured. Using equation (21) the relative consumed lifetime $D_{rel,c}$= (2.2-1.8)/(2.2-0.4) = 0.222 was deduced. With equation (15) the consumed D_c = 0.222x30 = 6.66 years, and with (16) - the remaining lifetime D_r = 30 -6.66 = 23.34 years were determined.

It is found that the consumed lifetime value in 4 years (4.8 years) is superior to the service life (4 years), which shows that insulation has been subjected to higher stresses than expected. Consequently, the measurement of the absorption and resorption currents and the determination of the insulation resistance allow the monitoring of the insulation status, i.e. the indication of a reduction of the remaining lifetime, the more accurate determination of the transformer health index, the monitoring of the state and the achievement of its efficient maintenance.

6. CONCLUSIONS

Measuring the absorption and resorption currents in power transformer insulation allows determination of insulation its resistance values.

The results of the accelerated aging tests carried out in the laboratory on the oil-paper insulating systems of the power transformers allowed to highlight the reduction of the insulation resistance values with the increase of the aging time, according to the results obtained on its components, paper and oil.

The values of parameters *a* and *b* of the lifetime line of the oil - paper insulation are strongly influenced by the chosen end - of - life criterion. Establishing a certain criterion depends, among other things, on the manufacturer's experience and on the safety required by the user.

Using the insulation resistance parameter it is possible to calculate the values of the consumed and remaining lifetime and the health index, the health condition of the insulation can be determined and the predictive maintenance policy of the transformer can be elaborated.

The use of the calculated relative consumed lifetime based on the insulation resistance measurement proposed in the paper allows a very rapid calculation of the consumed and remaining lifetime of the transformer insulation.

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