Determination of Estimated, Consumed and Remaining Lifetimes of Paper - Oil Transformers Insulation Based on Winding Insulation Resistance

P. V. Notingher[1*], G. Tanasescu[2]
[1]Electrotechnic Materials Laboratory, University Politehnica of Bucharest, Romania
[2]SIMTECH INTERNATIONAL, Bucharest, Romania
*e-mail: petrunot@elmat.pub.ro

Abstract: **In this paper a study on the use of insulation resistance of power transformer windings as a diagnostic factor for determining the lifetime line parameters of their insulation is presented. Accelerated thermal aging was carried out for plane winding models at 115, 5 and 155 °C, for 1200 ... 7000 h. For some values of the aging duration τ, the reported values of the insulation resistance $R_i(\tau)$ were determined, and for two values of the end-of-life criterion $R_{i,eol}$, the lifetime lines corresponding to the Dakin and Montsinger aging models were drawn A new method for determining parameters *a* and *b* (by measuring three values of the windings insulation resistance) and calculating the consumed and remaining lifetimes is proposed.**

I. INTRODUCTION

Power transformers are reliable equipment with an average life span of 20 to 35 years [1-2].Among the power transformers components, windings and bushings insulations are relatively often damaged and their replacement is rather difficult [3]. It is believed that the main cause of failure for paper-oil insulation systems is the decrease in mechanical strength of paper due to degradation and reduction in time of degree of polymerization (*DP*) (Fig. 1 [4].

To estimate the lifetime corresponding to the constant thermal stress of a component and/or paper-oil insulation, the Dakin or Montsinger models are used:

$$D_D = A_D \exp(b_D / T), \quad (1)$$

$$D_M = A_M \cdot \exp(-b_M \cdot \theta), \quad (2)$$

where $D_{D,M}$ are the estimated lifetimes in Dakin and Montsinger models, $A_{D,M}$, $b_D = E_a/k$ andb_M – material constants, E_a – activation energy, k – Boltzmann constant, θ – temperature in °C and $T = \theta + 273.15$ – temperature in K [5].

The equations of lifetime lines for the two models are :

$$\ln D_D = a_D + b_D/T, \quad (3)$$

$$\ln D_M = a_M - b_M \theta, \quad (4)$$

where $a_{D,M} = \ln A_{D,M}$.

Knowing the values of the lifetime lines parameters ($a_{D,M}$ and $b_{D,M}$), the estimated lifetimes corresponding to the operation of components or paper oil insulation at a constant temperature *T*,

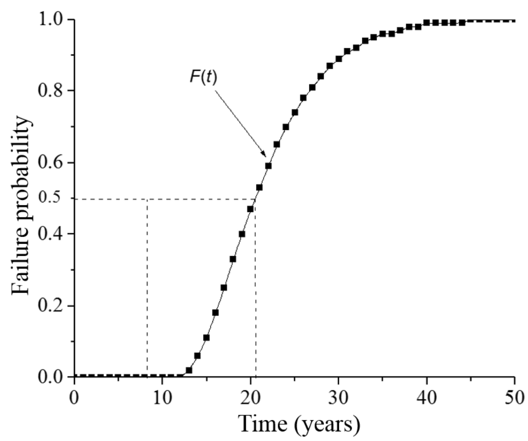

Figure 1. Failure probability variation with the transformer service time [4]

respectively θ ($D_{D,M}(T,\theta)$) can be calculated. Therefore, if the insulation is in operation for a certain time Δ*t* at the temperature *T*, the consumed lifetime is $D_{cD,M}(T,\theta) = \Delta t$ and the remaining lifetime is $D_{rD,M}(T,\theta) = D_{D,M}(T,\theta) - \Delta t$.

If the insulation was in operation at a variable temperature $T(t)$, the relative consumed lifetime can be calculated using one of the following equations[3,6]:

$$D_{crD}(\Delta t) = \frac{1}{A_D} \int_0^{\Delta t} e^{-\frac{b_D}{T(t)}} dt \quad (5)$$

$$D_{crM}(\Delta t) = \frac{1}{A_M} \cdot \int_0^{\Delta t} e^{b_M \theta} dt, \quad (6)$$

The consumed ($D_{cD,M}(T,\theta)$) and remaining ($D_{rD,M}(T,\theta)$) lifetimes are:

$$D_{cD,M}(T,\theta) = D_{D,M}(T,\theta) \cdot D_{crD,M}(\Delta t) \quad (7)$$

$$D_{rD,M}(T,\theta) = D_{D,M}(T,\theta) - D_{cD,M}(T,\theta). \quad (8)$$

If the temperature variation curve is unknown, the relative consumed lifetime during Δ*t* can be calculated with the equation (9):

978-1-5386-5086-8/18/$31.00 ©2018 IEEE

$$D_{cr}(\Delta t) = \frac{R_i(0) - R_i(\Delta t)}{R_i(0) - R_{i,eol}}, \tag{9}$$

where $R_i(0)$ and $R_i(\Delta t)$ are the values of the winding insulation resistance, measured at the $t = 0$ and $t = \Delta t$ since the beginning of transformer operation and $R_{i,eol}$ – end-of-life criterion.

The consumed lifetimes during Δt and the remaining lifetimes can be calculated using equations (7) - (8).

This paper presents a part of the results of a study concerning the determination of the parameters $a_{D,M}$ and $b_{D,M}$ of the thermal lifetime lines (Dakin and Montsinger) of a paper - oil insulation and it was done on plane winding models, using the diagnostic factor winding insulation resistance R_i in order to assess insulation aging. The consumed and remaining lifetime corresponding to paper-oil insulation submitted to constant and variable temperatures is also calculated.

II. Experiments

In order to determine the lifetime lines parameters, an experimental model was done, consisting of plane coils (Fig. 2), corresponding to winding of power transformers of very high voltages (1200 kV). The coils were made from aluminum conductors, insulated with Weidmann paper with thickness of 0.24 mm [8]. The samples were placed in cylindrical stainless steel cells with diameter of 90 mm and height of 120 mm (Fig. 3). After the samples were placed, the cells were filled with PRISTA mineral oil. In each cell were also placed 7 Weidmann paper samples. Groups of 3 cells were placed in RAYPA ovens with forced air flow and were subjected to constant thermal stresses at 155, 135 and 115 °C, for durations ranging from 1200 to 7200 h. Before the start of the aging tests, all samples were thermally conditioned at 60 °C for 48 h, after which the absorption/resorption currents were measured.

Temperature values (115, 135 and 155 °C) and aging times for each temperature were chosen according to IEC 60216-1specifications. For certain values of the aging time τ (specific to each aging temperature), the oven temperature was reduced to 27 °C, the samples were taken from the oven and the absorption i_a and resorption i_r currents were measured for the paper-oil insulation using a Keithley 6517B electrometer (at voltage U_0 = 200 V and for the duration of 600 s). The procedures for samples production and the necessary measurements are presented in [8].

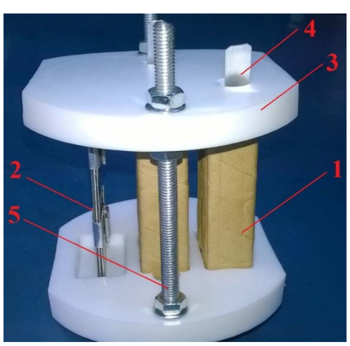

Figure 2. Experimental plane model: 1) Coil; 2) Fe-Si sheets; 3) PTFE plate; 4) Measurement terminal; 5) Screw

Figure 3. Stainless steel cell for samples thermal aging

The insulation resistance value at time t since the voltage U_0 start ($R_i(t)$) was calculated with the equation:

$$R_i(t) = \frac{U_0}{i_a(t) - i_r(t)}. \tag{10}$$

In order to determine the lifetime line parameters, resistance values measured at 60 s since voltage start (respectively, $R_i(60)$) were used. For each aging temperature, the variation curve of the reported resistance was drawn: $R_{i,r}(\tau) = R_i(60,\tau)/R_i(60,0)$, $R_i(60,\tau)$ being the resistance value of the insulation aged for time τ and measured after 60 s and $R_i(60,0)$ – the initial value of the insulation resistance (measured at τ = 0).

III. Results

In Figure 4 the variation curves of the reported resistance $R_{i,r}(\tau)$ with aging time, for the three values of the temperature θ (155, 135 and 115 °C) are presented. Considering the end-of-life criterion $R_{ir,eol} = 0.4$ and intersecting the curves $R_{i,r}(\tau)$ with the horizontal line $R_{i,r}(\tau) = R_{i,eol}/R_i(60,0) = 0.4$, aging time values are obtained for the three temperatures at which this criterion is achieved, respectively τ_1= 418 h (θ_1 = 155°C), τ_2= 1315 h (θ_2 = 135°C) si τ_3= 3115 h (θ_3 = 115°C) (Fig. 4). Considering a smaller value for $R_{ir,eol}$, respectively $R_{ir,eol} = 0.1$, the τ values are τ_1' = 770 h, τ_2' = 2820 h and τ_3' = 6900 h (Fig. 4). Using the values $\tau_{1,2,3}$ and $\tau_{1,2,3}'$, lifetime lines are determined for the aging models Dakin and Montsinger.

A. Dakin line

In order to draw the Dakin lifetime line $\ln\tau = f(1/T)$ (equation (3)), the coordinates for the three points corresponding to the chosen end-of-life criterion $R_{ir,eol}$ were determined. For $R_{ir,eol}$ = 0.4, were obtained the coordinates for points $P_{1,2,3}(x_{1,2,3}, y_{1,2,3})$, respectively $x_{1,2,3} = 1/T_{1,2,3}$ and$y_{1,2,3} = \ln\tau_{1,2,3}$, while for $R_{ir,eol}$ = 0.1 were obtained the coordinates for points $P_{1,2,3}'(x_{1,2,3}, y_{1,2,3}')$, respectively $x_{1,2,3} = 1/T_{1,2,3}$ and $y_{1,2,3}' = \ln\tau_{1,2,3}'$ ($T_{1,2,3} = \theta_{1,2,3}$ + 273.15 K) (Table I). Using the points $P_{1,2,3}$ and $P_{1,2,3}'$, the Dakin lifetime lines were drawn ($\ln\tau = f(10^3/T)$ corresponding to $R_{ir,eol}$ = 0.4 (Fig. 5, curve 1) and $R_{ir,eol}$ = 0.1 (Fig. 5, curve 2).

Knowing the coordinates of the points $P_{1,2,3}$ and $P_{1,2,3}'$ and using the equations recommended by IEC 60216-8, the values of parameters a_D and b_D of the lifetime lines ($\ln\tau = a_D + b_D/T$) were determined: a_{D1} = - 12,955, b_{D1} = 8167 K, $\ln D_{D1}$ = - 12.955 +8167/T and:

$$D_{D1}(T) = 2.36.10^{-6}\exp(8167/T), \tag{11}$$

TABLE I
COORDINATES VALUES OF THE LIFETIME LINES POINTS $P_{1,2,3}$ AND $P_{1,2,3}'$

$\theta_{1,2,3}$ (°C)	155	135	115
$T_{1,2,3}$ (K)	428.15	408.15	388.15
$10^3 . x_{1,2,3}$ (K^{-1})	2.336	2.451	2.576
$\tau_{1,2,3}$ (h)	418	1315	3115
$y_{1,2,3}$	6.035	7.182	8.044
$\tau_{1,2,3}'$ (h)	770	2820	6900
$y_{1,2,3}'$	6.646	7.946	8.840

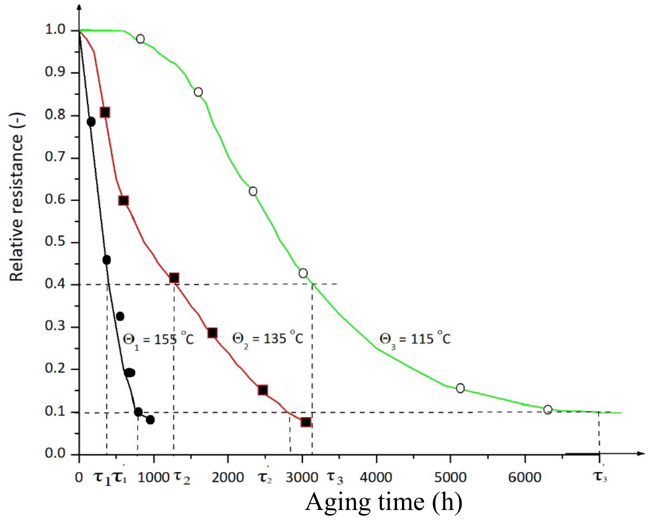

Figure 4. The variation of the relative insulation resistance with aging time at temperatures θ_1 = 155 °C, θ_2 = 5 °C and θ_3 = 115°C

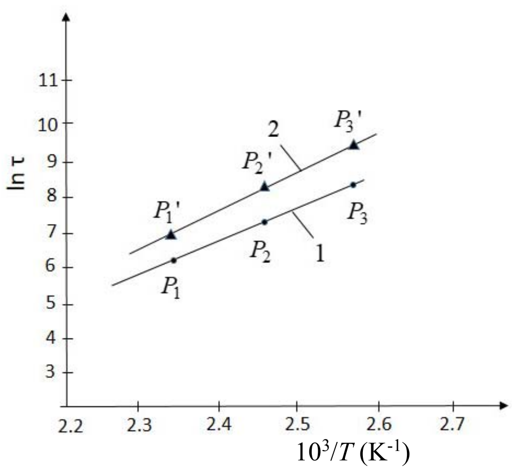

Figure 5. Dakin lifetime lines for $R_{ir,eol}$ = 0.4 (curve 1) and $R_{ir,eol}$ = 0.1 (curve 2)

for $R_{ir,eol}$ = 0.4, respectively a_{D2} = -16,17, b_{D2} = 9770,3 K, $\ln D_{D2} = -16.17 + 9770.3/T$ and:

$$D_{D2}(T) = 9.49\cdot 10^{-8}\cdot \exp(9770.3/T) \tag{12}$$

for $R_{ir,eol}$ = 0.1.

Using the equations (11) - (12), estimated lifetimes for different constant temperatures were calculated (Table II). It is noticed that the lifetime values obtained for the end-of-life criterion $R_{ir,eol}$ = 0.4 (D_{D1}) are very small compared to the results obtained on transformers still in operation. The values obtained for $R_{ir,eol}$ = 0.1 (D_{D2}) are bigger, but they also seem to be smaller compared to the ones in operation.

If the curve $T(t)$ is known and the winding insulation resistance is measured at three distinct moments (t = 0 ($R_i(0)$, $t = t_1$ ($R_i(t_1)$) and $t = t_2$ ($R_i(t_2)$)), the values of parameters a_D and b_D can be calculated using equation (9).Therefore, by dividing equation (9) by R_i (0), the following equation is obtained

TABLE II
VALUES FOR THE DAKIN ESTIMATED LIFETIMES OF THE PAPER-OIL INSULATION D_D FOR OPERATION AT DIFFERENT TEMPERATURES T, FOR $R_{ir,eol}$ = 0.4 (D_{D1}) AND $R_{ir,eol}$ = 0.1 (D_{D2})

θ (°C)	60	70	80	90	100	110
T (K)	333.15	343.15	353.15	363.15	373.15	383.15
D_{D1} (h)	103172	49470	25740	14754	8204	4269
D_{D1} (y)	11.78	5.65	2.94	1.68	0.94	0.49
D_{D2} (h)	509355	211414	96756	44282	24640	11277
D_{D2}(y)	58.15	24.	11.05	5.06	2.81	1.29
D_{D3} (h)	903453	340724	143205	60188	27710	11646
D_{D3} (y)	103.13	38.90	6.35	6.87	3.16	1.33
D_{M1} (h)	370426	193380	100953	52702	27513	14363
D_{M1} (y)	42.28	22.08	11.2	6.01	3.14	1.63
D_{M2} (h)	492599	220015	98268	43890	19603	8756
D_{M2} (y)	56.23	25.12	11.22	5.01	2.24	1.00
ε_{M2-D2}(%)	3.30	- 4.10	- 1.56	0.89	20.44	22.48

$$D_{cr}(\Delta t) = \frac{1 - R_{ir}(\Delta t)}{1 - R_{ir,eol}}, \tag{13}$$

which is used to calculate the relative lifetimes consumed $D_{cr}(\Delta t)$ before moments $\Delta t = t_{1,2}$.

From the curves $R_{ir}(\tau)$ (Fig. 4), the reported values of the paper-oil insulation resistance are obtained for the initial moment (t = 0), respectively $R_{ir}(0)$ = 1 and for moments t_1 = 1580h – for θ_3 = 115°C (T_3 = 388.15 K) – and t_2 = 2000 h – for θ_2 = 135°C (T_2 = 408.15 K) –, respectively $R_{ir}(1580)$ = 0.845 and $R_{ir}(2356)$ = 0.23. By inputting R_{ir} values in (13), it results $D_{cr}(t_1)$ = 0.1722 and $D_{cr}(t_2)$ = 0.856.

On the other hand, the relative lifetime consumed in Δt can be calculated, in the Dakin model, with equation (5). Considering, in Δt, $T(t) = T$ = const., it results from (5):

$$D_{cr,D}(\Delta t) = \frac{\Delta t}{A_D} e^{-\frac{b_D}{T}}, \tag{14}$$

and then:

$$D_{cr,D}(t_1) = \frac{t_1}{A_D} e^{-\frac{b_D}{T_3}} = D_1, \tag{15}$$

$$D_{cr,D}(t_2) = \frac{t_2}{A_D} e^{-\frac{b_D}{T_2}} = D_2. \tag{16}$$

From (15) - (16), the values of b_D, A_D anda_D are obtained:

$$b_D = \frac{T_3 T_2}{T_3 - T_2} \ln \frac{D_1}{D_2} \cdot \frac{t_2}{t_1}, \tag{17}$$

$$A_D = \frac{t_1}{D_1} \mathrm{e}^{-\frac{b_D}{T_3}}, \tag{18}$$

$$a_D = \ln \frac{t_1}{D_1} + \frac{T_2}{T_2 - T_3} \ln \frac{D_1}{D_2} \frac{t_2}{t_1} \tag{19}$$

After replacing in (17) - (19) the values of T_2, T_3, D_1, D_2, t_1 and t_2, it results: b_{D3} = 10835 K, $A_{D3} = 6.905.10^{-9}$ h and a_{D3} = -18.79, in according to the ones obtained for paper and oil [8].Therefore, the estimated lifetime for operation at constant temperature T can be calculated using the equation:

$$D_{D3}(T) = 6.905\cdot 10^{-9} \exp(10835/T). \tag{20}$$

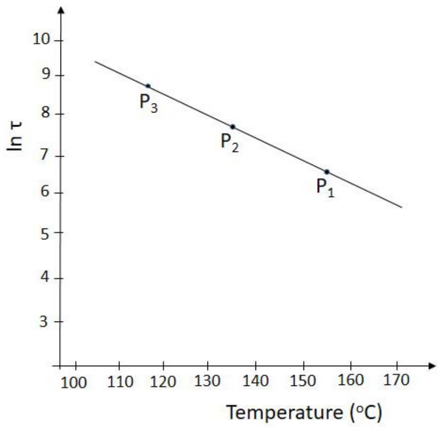

Figure 6. Lifetime line for Montsinger model

The lifetime values calculated using equation (20) (D_{D3}) are presented in Table II. It is noticed that these values are bigger than those obtained using the equations (11) and (12), the constant b_{D3} and the activating energy E_{a3} ($E_{a3} = b_{D3} \cdot k = 90.013$ kJ/mole) having bigger values.

B. Montsinger line

Considering $R_{iz,r,eol} = 0.1$ and the times necessary to reach this value at temperatures $\theta_{1,2,3}$ (Table I), the coordinates of the points for Montsinger lifetime line were obtained, $P_i(\theta_i, \ln\tau_i^{'})$, $i = 1,2,3$ and the corresponding lifetime line was drawn (Fig. 6). Using the equations recommended by IEC 60216-8, the Montsinger line parameters were calculated, respectively $a_{M1} = 16.721$, $b_{M1} = 0.065$ °C^{-1} and $A_{M1} = 1.83.10^7$ h and the lifetime equation for the Montsinger model was obtained:

$$D_{M1}(\theta) = 1.83 \cdot 10^7 \cdot \exp(-0.065\theta) \text{ (h)}. \tag{21}$$

In Table II the lifetime values estimated for different temperatures, noted with D_{M1} are presented. It is noticed that these values are smaller than those obtained with the Dakin model (D_{D2}) for temperatures of 60 – 70 °C, close to those in the Dakin model for θ = 80 °C and slightly bigger for θ > 90°C.

Parameters a_M and b_M of the Montsinger line were calculated using the parameters a_D and b_D of the Dakin line (§3.1). For this, the Dakin lifetime equations ($D_{D1,2}$), corresponding to chosen temperatures $T_{1,2}$ (from (1)) and Montsinger equations ($D_{M1,2}$) for $\theta_{1,2} = T_{1,2} - 273.15$ (°C) (from (2)) were used. From the equations $D_{M1} = D_{D1}$ and $D_{M2} = D_{D2}$, it results:

$$b_M = \frac{\ln(D_{D_1} / D_{D_2})}{\theta_2 - \theta_1}, \tag{22}$$

$$A_M = D_{D_1} \cdot e^{b_M \cdot \theta_1}. \tag{23}$$

Considering T_1 = 343,15 K, T_2 = 353,15 K and the Dakin parameters a_D = - 16,17 and b_D = 9770,3 K, the parameters $b_{M2} = 0.0806$°C^{-1}, $A_{M2} = 6.205 \cdot 10^7$ h and $a_{M2} = 17.91$ were obtained and the values of the Montsinger lifetime $D_{M2}(\theta)$ were calculated (Table II). It is noticed that the lifetime values obtained using the new a_{M2} and b_{M2} values significantly differ from those obtained using these parameters after drawing the $R_{ir}(\tau)$ curves: they are bigger for smaller θ values (60 - 80 °C) and by 22 % smaller for θ > 90 °C. On the other hand, the lifetime values calculated using parameters a_{M2} and b_{M2} are, for T < 90 °C, very close to those obtained using the Dakin model D_{D2} (Table I), the difference being less than 5 %. These differences increase up to 30 % for temperature values close to 115 °C. It results that, in order to calculate the Montsinger line parameters, it is preferable to use the Dakin line parameters.

In order to verify paper aging, its volume resistivity ρ_v and degree of polymerization DP were determined. For T = 155 °C, after 480 hours, a 20-times decrease of ρ_v and a 6-times decrease of DP were noticed. Measuring insulation resistance and oil resistivity the paper resistivity can be estimated.

For example, a transformer which the lifetime at the nominal operating temperature is D = 30 years and the end-of-life criterion $R_{iz,eol}$= 0.4 TΩ, and which worked for 4 years at an unknown temperature is considered. The initial value of the insulation resistance was $R_{iz}(0)$ = 2.2 TΩ and after 4 years of operation $R_{iz}(4)$ = 1.8 TΩ. Using equation (9) the relative consumed lifetime $D_{rel,c}$= 0.222 was deduced.With equation (7) the consumed D_c = 6.66 years, and with (8) - the remaining lifetime D_r = 23.34 years were determined.

IV. CONCLUSIONS

By measuring the insulating resistance of the windings, *a* and *b* parameters of the Dakin and Montsinger lifetime lines can be determined. These parameters allow the calculation of the consumed and remaining lifetimes of the insulation.

The lifetime values obtained with Dakin and Montsinger models are closer for temperatures in the 70-90 °C range.

The values of parameters *a* and *b* depend on the values of the lifetime criterion: the lower these values are, the higher *b* values get, and the lifetimes estimated for operation at a certain temperature are higher.

The method proposed in this paper will be verified using other methods (gas analysis, paper polymerisation degree, etc.)

ACKNOWLEDGMENT

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 UEFISCDI, Romania.

REFERENCES

[1] A.N. Jahromi, R. Piercy, S. Cress, R.R.S. Service, W. Fan, "An approach to power transformer asset management using health index", *IEEE Electrical Insulation Magazine*, vol. 25, no. 2, pp. 20-34, 2009.

[2] M. Wang, A.J. Vandermaar, K.D. Srivastava, „Review of condition assessment of power transformers in service", *IEEE Electr. Insul. Magazine*, vol. 18, no. 6, pp. 12-25.

[3] P.V. Notingher e.a.,"Concerning the power transformers insulation systems monitoring", *J.Materials, Methods &Techn.*, Vol. 11, pp.101-120.

[4] B. Gorgan, "Estimation of degradation condition and remaining life of power transformers", PhD Thesis, University Politehnica of Bucharest, Bucharest, Romania, 2012.

[5] P.V. Notingher, *Materials for electrotehnics. technical properties,* Vol. 2, POLITEHNICA PRESS, Bucharest, 2005.

[6] P.V. Notingher, L.M. Dumitran, G. Tanasescu, S. Busoi, L.V. Badicu, „Determination of the remaining lifetime of power transformers liquid insulations based on the absorption/resorption currents", *Proceedings of ATEE 2017*, Bucharest, 23-25 Mars, pp. 1-6, 2017.