Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **68**, *3*, pp. 277–282, Bucarest, 2023

A NEW HYBRID MODEL TO EVALUATE THE LOSS OF LIFE OF POWER TRANSFORMERS

BOGDAN LEU[1], GEORGE SERIȚAN[2], BOGDAN ENACHE[2]

Keywords: Loss of life; Aging; Transformers; Thermal model; Insulation resistance model.

Following the thermal model for assessing the degradation of transformer units, as advocated by IEEE and IEC standards, existing literature posits that the transformers do not exhibit significant aging at hot-spot temperatures below 90°C. Contrary to this prevailing understanding, the current study demonstrates that when using a model based on insulation resistance measurements, discernible aging of transformers occurs even at these lower hot-spot temperature thresholds. Consequently, this paper introduces a novel evaluative hybrid model for transformer degradation, designed to be applicable across the entire range of hot-spot operational temperatures.

1. INTRODUCTION

Transformers rank among the most crucial elements in a power system since they are essential to maintaining its performance at the needed level. Since transformers are the most expensive equipment in an electrical substation, extending their lifespan is a significant concern for every grid operator. Most transformer units have an average of 30 to 40-year life cycles, per the nameplate specifications and manufacturer's recommendations regarding their operation. The remaining life of the transformer is immediately impacted by any operational overload that exceeds the manufacturer's stated ratings. The aging of transformers and how to appropriately estimate their loss of life are two critical concerns that technical specialists face [1].

IEC and IEEE standards are currently the foundation for the solutions used globally to evaluate the technical status of transformers using various monitoring systems. The hot-spot temperature of transformers is used in these standards, which define the thermal models, to assess the loss of life. However, these models only apply to temperatures reached at nominal loads and overloads, not the entire temperature range [2].

Mathematical models standardized by both IEC and IEEE standards for evaluating the loss of life of transformers have been used in the energy industry for more than 15 years by power grid operators [3,4]. They are used in power substations by installing transformer condition monitoring systems that measure real-time parameters related to the condition of the equipment, which are then used for the automatic calculation of the system's lifetime [5–7]. Since the main internal parameters of the transformer that are used to determine its aging are TOT (top oil temperature) and HST (hot-spot temperature) temperatures, this model is called the thermal model [8,9].

The hot-spot temperature significantly impacts the rate at which transformer insulation degrades compared to all other operating characteristics that may be assessed [10]. There are different mathematical methods for calculating the hot-spot temperature. Still, the one supported by the IEC 60076-7 standard is the one that is most used in industry for mineral oil transformers at the European level.

According to a recent study, a new method has been proposed to determine the loss of life of an oil-insulated transformer unit using a mathematical model based on the transformer insulation resistance values obtained between specific time intervals. This method builds on conventional thermal models used for years in industry to determine transformer aging. It works as a complementary method that is very useful in operating these types of equipment, as demonstrated in this chapter.

This method introduces a new diagnostic factor, namely the insulation resistance of the paper-oil insulation system in the transformer, to assess its degradation.

The current research aims to investigate the efficacy of the two existing models for evaluating the loss of life of power transformers. The study demonstrates the vulnerabilities of the conventional standardized thermal model and the contributions of the insulation resistance model, depending on the operation conditions of the transformer.

Based on that, a new hybrid model that aims to improve the existing loss of life evaluation models has been developed through this research. This new hybrid model assesses transformer degradation across a comprehensive hot-spot temperature spectrum [11].

2. EXISTING MODELS FOR EVALUATING THE LOSS OF LIFE OF POWER TRANSFORMERS

Currently, in the power systems industry, there are two models for evaluating the loss of life of power transformers:

- The thermal model: a mature, standardized model that uses the hot-spot temperature as the main parameter for evaluating the loss of life;
- The insulation resistance model: a recent model that wasn't applied on a large scale and uses the insulation resistance as the main parameter for evaluating the loss of life.

2.1 THERMAL MODEL FOR DETERMINING THE LOSS OF LIFE ACCORDING TO IEEE AND IEC STANDARDS

A. THE THERMAL MODEL FOR EVALUATING THE LOSS OF LIFE OF POWER TRANSFORMERS, USING THE IEEE C57-91 STANDARD:

The experimental basis accumulated over time has proven that transformer insulation deterioration due to temperature and aging follows the Arrhenius reaction rate theory, which has the following form, according to the IEEE standard

$$\text{Per Life Unit}=Ae^{\left[\frac{B}{\theta H+273}\right]}. \quad (1)$$

where θ_H – hot-spot temperature, A & B – constants, e – the basis of the natural logarithm.

The aging acceleration factor (F_{AA}) is greater than 1 for hot-spot temperatures above the reference temperature of 110 ºC and less than 1 for temperatures below 110 ºC. The equation for determining the F_{AA} is:

[1] Transelectrica, Technical, Energy Efficiency and New Technologies Division, Romania. E-mail: bogdan.leu@transelectrica.ro
[2] Faculty of Electrical Engineering, Politehnica University of Bucharest, Romania. E-mail: george.seritan@upb.ro, bogdan.enache2207@upb.ro

DOI: 10.59277/RRST-EE.2023.68.3.5

$$F_{AA}=e^{\left[\frac{15000}{383}-\frac{15000}{\theta H+273}\right]}. \quad (2)$$

The relative aging of the transformer is determined using eq. (2). It shows the equivalent aging factor at the reference temperature for the specified time and temperature [11]:

$$F_{EQA}=\frac{\sum_{n=1}^{N} F_{AA,n}\Delta t_n}{\sum_{n=1}^{N} \Delta t_n}, \quad (3)$$

where, F_{EQA} – the equivalent ageing factor for the total period considered, $F_{AA,n}$ – the equivalent aging factor for the temperature of the period considered, n – Δt time interval index, N - total number of intervals, Δt_n – the time interval "h".

The number of hours consumed divided by the insulation's average lifespan (in hours) and multiplied by 100 equals the percentage of life lost for the considered period. Typically, 24 hours are selected as the time frame [12]:

$$\%\ LOL=\frac{F_{EQA}\times t\times 100}{\text{Normal lifetime of insulation}}. \quad (4)$$

B. THE THERMAL MODEL FOR EVALUATING THE LOSS OF LIFE OF POWER TRANSFORMERS, USING THE IEC 60076-7 STANDARD:

In the model described in the standard, only the insulation temperature (hot-spot temperature) is considered to determine aging even though the IEC standard states that the aging and deterioration of transformer insulation is a function of time and depends on factors like temperature, the amount of moisture inside the tank, or other dissolved gases.

The insulation area inside the transformer operating at the highest temperature value (hot-spot temperature) will suffer the most significant damage since the temperature distribution is not uniform. Equation (5) defines the relative aging rate "V" as a result [11,13]:

$$V=2^{(\theta_h-98)/6}, \quad (5)$$

where, θ_h is the hot-spot temperature.

Equation (6) summarizes the mathematical estimation of the transformer's loss of life over a specific period:

$$L=\int_{t1}^{t2} V dt \qquad \text{or} \qquad L=\sum_{n=1}^{N} V_n\times t_n, \quad (6)$$

where, V_n – the relative aging rate in the interval "n", t_n – time interval with number "n", n – number of each time interval, N – the total number of intervals during the considered period.

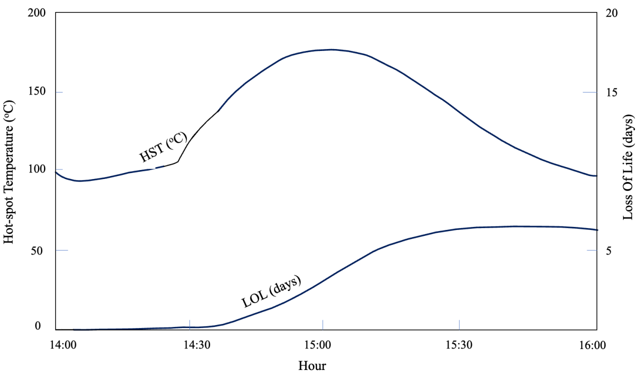

Fig. 1 – Evolution of the loss of life as a function of temperature according to the example from IEC 60076-7 standard [12].

In the example results shown using the graph in Fig. 1 extracted from the IEC standard, it can be seen how for the internal hot-spot operating temperatures that are below 90 ˚C corresponding to the loadings below 81 % (according to IEC 60076-7), the transformers are producing LOL results of 0 minutes aging. The results give the impression that under this range of hot-spot temperature and loading, the transformer does not age. However, the typology of the mathematical model in IEC 60076-7 provides accurate results of the loss of life predominantly for values above these thresholds, i.e., for transformer operating regimes at or above nominal level, corresponding to overloads or fault regimes producing loads above 100 % and therefore accelerated aging of the equipment. Under this temperature and load range, the thermal model produces results with low aging values depending on the technical specifications of each transformer's age and operating conditions.

The main advantages of the thermal models for loss of life evaluation:

- Mature methods to evaluate the loss of life of transformers that were used for more than 15 years in the power systems industry;
- Easy to integrate into a condition monitoring system that can be installed on the power transformers to assess the health of the equipment;
- They can provide accurate time evaluation of loss of life due to constant hot-spot measurements when the transformer is in operation.

The disadvantages of the thermal models for loss of life evaluation:

- They don't provide notable results of aging for low-level loads, only for rated loads and overloads;
- The need to install condition monitoring systems on the transformers to collect the parameters must be included in the loss of life calculation.

2.2. INSULATION RESISTANCE-BASED MODEL FOR EVALUATING THE LOSS OF LIFE OF POWER TRANSFORMERS

According to the model described in [14, 15], the insulation resistance is the diagnostic parameter used to determine the "a" and "b" coefficients of the transformer lifelines based on the Dakin and Montsinger aging models, respectively on the activation energy associated with aging under thermal stress. The formulas below will be used to calculate the lifetime values for the paper-oil insulation under constant thermal stress:

$$D_D=A_D\exp\left(\frac{b_D}{T}\right), \quad (7)$$

$$D_M=A_M\exp(-b_M\theta), \quad (8)$$

where, D_D – predicted life in line with the Dakin model, D_M – predicted life in line with the Montsinger model, A_D, A_M, b_D, b_M – material constants, θ – measured temperature (ºC), E_a – activation energy, T – measured temperature (K), k – Boltzmann's constant.

If the temperature variation curve is unknown, eq. (9) can be used to determine the relative loss of life (D_{cr}) in the range Δt [2,11,14,15]:

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

where, $R_i(0)$ – The winding's insulation resistance that was measured at the time $t=0$, $R_i(\Delta t)$ – the winding's insulation resistance that was measured at the time $t=\Delta t$, $R_{i,eol}$ – insulation resistance at the end of transformer life.

Equation (9) becomes valid when the insulation resistance measured at time t = Δt and the end-of-life criterion to its initial value $R_i(0)$ are related to each other:

$$D_{cr}(\Delta t)=\frac{1\text{-}R_{ir}(\Delta t)}{1\text{-}R_{ir,eol}}. \quad (10)$$

The main advantages of the insulation resistance model for loss of life evaluation:

- It provides notable results of aging for low-level loads;
- It doesn't need any additional equipment and systems to be installed on the transformer to calculate the loss of life;
- It can use historical insulation resistance data to analyze the depreciation of the loss of life in time.

The disadvantages of the insulation resistance model for loss of life evaluation:

- Lack of maturity of the model within the power systems industry;
- It can't provide real-time data for the loss of life evaluation because the equipment is not in operation for the insulation resistance measurement.

This research used ten transformer units installed in the Romanian power grid, from which hourly operating parameters were obtained for a 1-year sample (2022). It used a condition monitoring system, which complies with IEC 60076-7 standard, installed on these transformers in different power substations to determine their loss of life according to the thermal model [16–18]. Data from these ten transformers were also used to evaluate their aging using the model based on insulation resistance.

The ten transformer units that were used in the research have the following main specifications [19]:

Table 1

Technical specifications of transformers used in the research.

	Values		
No. of transformers	4	2	4
U_n (kV)	420/123/24	231±12x1.25%/ 121/10.5	231±12x1.25%/ 121/10.5
I_n (A)	360.8/1193/ 2309	1000/1909/3299	500/954.5/3299
S_n (MVA)	250/250/80	400/400/60	200/200/60

where, U_n – rated voltage, I_n – rated current, S_n – rated power.

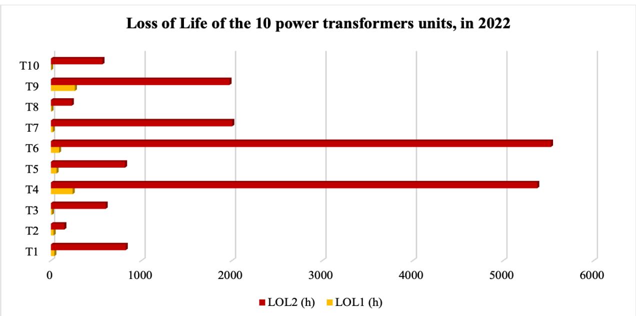

Fig. 2 – The loss of life calculated with the thermal and insulation resistance models for ten power transformers.

The differences that resulted from evaluating the loss of life for the ten transformer units with thermal and insulation resistance models can be seen in Fig. 2, where LOL1 – Loss of Life according to the thermal model, and LOL2 – Loss of Life according to the insulation resistance model.

Thus, with these data plotted in Fig. 2 above, the values of the loss of life calculated using the insulation resistance model for all ten transformers exceed each time the values obtained using the thermal model. While for the LOL1 case (thermal model), in each of the 10 cases, the transformers depreciate their lifetime very little in one year, with values in the order of hours, in the LOL2 case (insulation resistance model), there were recorded aging values ranging from a few hours to more than half a year, depending on the transformer.

This is mainly because all ten transformers were loaded during 2022 at sub-nominal levels, and the thermal model for such cases provides very low transformer aging results. Unlike the thermal model, the insulation resistance model provides higher results for this type of sub-nominal operation, which shows that the transformer units also depreciate their lifetime for this type of operation.

Integrating the results in the context of normal operating transformers, whereby the average lifetime is 30-40 years, the values of the loss of life are closer to the results provided by the model based on the insulation resistance. Over a year, even if there were no overloads or fault regimes, the transformer still underwent a process of wear and aging. This means the results obtained in days or months are closer to the operating experience than values in hours based on a full year of continuous operation [20].

Thus, we can see how the insulation resistance model produces notable results on transformer aging for the lower range of internal operating temperatures corresponding to the sub-nominal load level. On the other hand, the thermal model delivers very good results validated for many years in the industry when transformers are loaded at least at the nominal level, especially for overloads.

3. NEW HYBRID MODEL FOR EVALUATING THE LOSS OF LIFE OF POWER TRANSFORMERS

This section proposes a new hybrid model developed through this research for evaluating the loss of life of power transformers, applicable over the entire hot-spot temperature range.

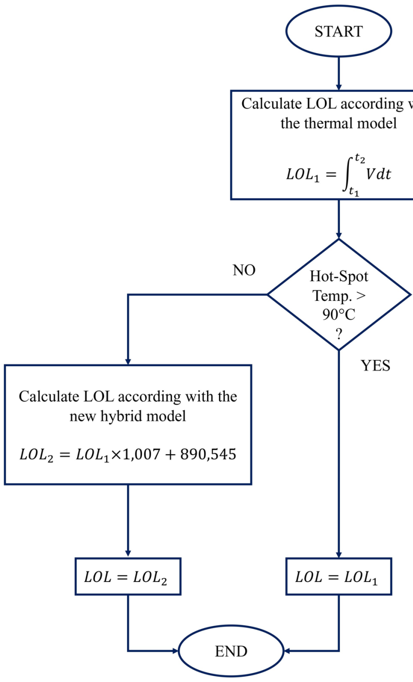

Fig. 3 – Logic diagram of the new hybrid model for aging assessment.

The new hybrid model was created using a complex statistical study and combines the thermal model with the insulation resistance model for determining the loss of life. Applying this model in the industry can be used, as displayed in Fig. 3. Further, the statistical study is presented to obtain the new hybrid model for evaluating the loss of life of power transformers, valid over the whole hot-spot temperature range.

The input data is represented by the calculated loss of life using thermal and insulation resistance models for the ten power transformers described above.

Thus, in the first statistical analysis stage, several algorithms were checked for approximating the data evolution, as shown in Fig. 4.

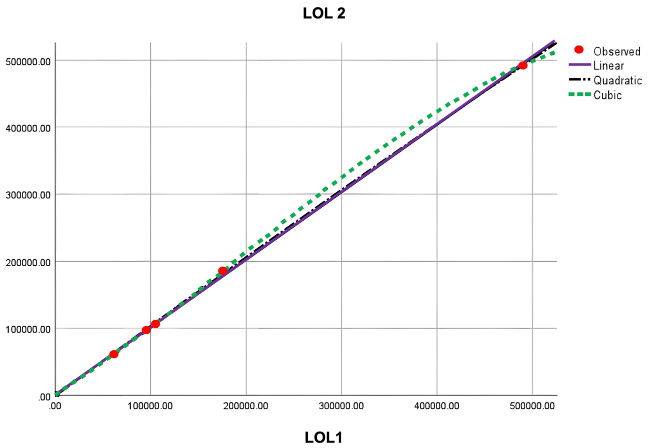

Fig. 4 – Approximation of the evolution of the data obtained with the two methods LOL1 and LOL2.

It can be seen how the three linear, quadratic, and cubic interpolation algorithms, which approximate the evolution of the points belonging to the two methods of evaluating the loss of life, produce very close results, and the linear regression model will be studied further due to its ease of implementation.

Before running the linear regression model, it is necessary to check the following working assumptions:

- If the variables chosen are independent, the Durbin-Watson statistical test is used;
- If the variables chosen are correlated, the Pearson statistical test is used;
- If there is a statistically significant relationship between the input and output variables, the Anova test is used.

A linear regression model can be performed if all these conditions are met simultaneously.

3.1 DURBIN-WATSON STATISTICAL TEST PERFORMED ON THE POWER TRANSFORMERS

Durbin-Watson statistical test is used in regression analysis to detect whether the chosen variables are independent.

Table 2.

Durbin-Watson statistical test

Model	1
R	1.000[a]
R^2	1.000
Adjusted R^2	1.000
Std. Error of the Estimate	3447.8458
R^2 Change	1.000
F Change	16958.47
df	7
Sig. F Change	.000
Durbin-Watson	2.467

It produces a result of -3 ÷ 3, corresponding to the assurance of independence between variables [21,22]. Any value obtained outside this range will lead to the conclusion that at least two variables in the input set are independent. After performing the Durbin-Watson statistical test, the value of 2.467 was determined, which falls in the range -3 ÷ 3, allowing us to conclude that the chosen variables are independent.

3.2 PEARSON CORRELATION TEST PERFORMED ON THE POWER TRANSFORMERS

The Pearson correlation test determines the degree of linear correlation between two continuous variables. This statistical analytic technique establishes the strength of the linear relationship between two variables [21,22]. The Pearson coefficient computed for the two variables of the mode has a value of 1, showing a strong correlation between them.

3.3 ANOVA STATISTICAL TEST PERFORMED ON THE POWER TRANSFORMERS

To determine the existence of statistically significant disparities among the means of three or more independent groups, the analysis of variance (ANOVA) statistical methodology is commonly employed. The central premise of the ANOVA test is to compare intra-group and inter-group variability. Should the variance between groups substantially exceed the variance within groups, it may be deduced that at least one group possesses a significantly divergent mean from the others [21,22].

Table 3

ANOVA statistical test

Model	Regression	Residual	Total
Sum of Squares	201596208068.491	83213484.575	201679421553.066
df	1	7	8
Mean Square	201596208068.491	11887640.654	
F	16958.471		
Sig.	.000[b]		

Here LOL2 is the dependent variable, LOL1 is the independent variable. Since the level is within this range and F is high enough, the null hypothesis is rejected, and the alternative hypothesis is admitted for a loading level of 95 % ($p \leq 0.05$). As a result, it was determined that the independent and dependent variables have a statistically significant association.

3.4 DETERMINATION OF LINEAR REGRESSION COEFFICIENTS

Determining the coefficients of a linear regression involves identifying the numerical values that best describe the linear relationship between the independent variables and the dependent variable in a data set. These coefficients are essential linear regression model parameters used to predict the dependent variable's values based on the independent variables' values [21,22]. To determine them, the least squares method was obtained as follows:

Table 4. Determination of linear regression coefficients

Model	Constant	LOL1
B	890.545	1.007
Std. Error	1400.096	.008
Beta		1.000
t	.636	130.225
Sig.	.0545	.000

Thus, the equation of the multiple linear regression model is:

$$LOL2=LOL1\times 1{,}007+890{,}545. \tag{11}$$

In essence, the model suggests allocating a value of 890,545 hours of loss of life over a year for a transformer that has been evaluated, plus a variable value of the loss of life calculated using the thermal model that rises with the hot-spot temperature.

3.5 VALIDATION OF THE FINAL STATISTICAL MODEL

The final statistical model was validated based on the residual calculation and the application of the model to the data obtained from power transformer T10. The age of this transformer was 412,002 operating hours, at the start of the study.

Table 5

Residual calculation for statistical model validation

	Minim.	Maxim.	Mean	Std. Deviation	N
Predict. Value	890.5453	494414.2813	105023.0175	158743.58572	9
Std. Predict. Value	-.656	2.453	.000	1.000	9
Std. Error of Predict. Value	1149.365	3203.411	1507.159	645.322	9
Adjust. Predict. Value	1066.3932	509984.5938	106712.2012	163406.40357	9
Resid.	-2466.82	8453.6894	.00000	3225.16443	9
Std. Resid.	-.715	2.452	.000	.935	9
Stud. Resid.	-1.935	2.639	-.130	1.178	9
Deleted Resid.	-18037.1	9796.7216	-1689.1837	7099.45169	9
Stud. Deleted Resid.	-2.626	35.466	3.455	12.030	9
Mahal. Distanc	.000	6.017	.889	1.932	9
Cook's Distanc	.003	11.812	1.379	3.917	9
Center. Leverage Value	.000	.752	.111	.242	9

After one year of operation, the age of T10 was re-evaluated using the LOL1, LOL2, and the proposed hybrid model. The results are presented in Table 6.

Table 6

Age evolution of the LOL1, LOL2 and hybrid-model

	LOL1	LOL2	New model
Age (hours)	412003.81	412571.08	412894.36

The value produced by the LOL2 model was considered the reference value. Compared to it, the LOL1 model reported a 567.27-hour difference, which can accumulate over time, leading to an unexpected failure. On the other hand, the proposed model led to only a 323.28-hour difference, which can be compensated over time, considering the nature of the model [21,22].

4. **RESULTS AND DISCUSSION**

Within this research, a new hybrid model was developed to evaluate the loss of life of power transformers applicable over the entire hot-spot temperature range. The new hybrid model proposed at section 3 was developed using both the thermal and insulation resistance models, and it is applicable for the isolated cases where the power transformers are loaded below the rated level. For all the other cases where the power transformers are loaded at nominal values or above, the standardized thermal model presented in subsection 2.1 will be applied.

The main difference found in this research is that the insulation resistance model produces notable aging results for the lower temperature range corresponding to the sub-nominal transformer loads. Although the operating experience has shown that they age through wear in continuous operation regardless of the load level, the standardized thermal model used in the industry does not provide results for the lower temperature range, and aging starts practically at an internal hot-spot temperature of the transformers of about 90ºC according to the standards.

The new hybrid model applies to transformers' internal hot-spot temperature range below 90 ºC, and its final output is represented by eq. (11), where the correction coefficients applied to the thermal model are observed so that the new model produces loss of life results, including the lower temperature range and loads.

Thus, the algorithm of the method underlying the developed model is represented in the logic diagram in Fig. 3, where the calculation steps for evaluating the loss of life as a function of the temperature range are presented. The steps that should be followed are:

- start by evaluating the loss of life of the transformer using the conventional standardized thermal model.
- if the hot-spot temperature of the transformer is over 90 ºC, the loss of life value is accurate, and the evaluation is valid;
- if the hot-spot temperature of the transformer is below 90 ºC, the loss of life value is not accurate, and the proposed hybrid model should be applied to obtain a valid evaluation.

The main benefits brought by the proposed new hybrid model for the evaluation of the loss of life of transformers, compared with the thermal and insulation resistance models, are:

- It provides notable results of aging for both low-level loads and overloads;
- It is applicable for the entire hot-spot temperature range of a transformer;
- It is complementary to the conventional thermal model, which could bring more accurate results when calculating the loss of life.

Given the small number of transformer units that were the subject of the research study for the present regression model, the results obtained will have limited applicability. To extend them to the whole population of 218 transformer units [19] in operation in the Romanian Transmission Grid, at least a sample of 59 transformers is needed. This value was calculated based on Morgan's relationship for a 95 % confidence level and 5 % error.

5. **CONCLUSIONS**

In this work, a new hybrid model for evaluating the loss of life of power transformers was developed using statistical analysis research performed on ten transformer units. For this research, the thermal and insulation resistance models were used to evaluate the loss of life of the transformers to find a comprehensive model applicable to any operation of the power transformers.

The key finding of this research is that the insulation resistance model produces results for transformer aging at the lower temperature range associated with sub-nominal transformer loads. The industry's standard thermal model does not produce results for the lower temperature range. According to the specifications within standards, aging only begins when the transformers' internal hot spot temperature reaches roughly 90 ºC. Operating experiences have proven that transformers age through wear in continuous operation independent of the load level, not only for hot-spot temperatures above 90 ºC.

Given these issues, a new hybrid model for assessing transformer aging has been developed through this research as a complement to the traditional standardized model now in use in the industry. This model is suitable for the entire temperature range. The result of the model is represented by equation (11), where the correction coefficients applied to the thermal model are observed so that the new model produces loss of life results for the lower temperature range and loads. The methodology of using the model by grid operators to assess the aging of transformers more accurately is displayed in Fig. 3.

It is important to note that this newly developed model only applies if the transformers are continuously operating. If the transformer has had interruptions in operation over extended periods, then the model will no longer produce valid results. Another important aspect is that this method is limited, given the number of transformers used and the years studied. The resulting correction coefficients could differ in the case of a more extensive set of data and transformers, and the proposed model would also differ. However, the method described in this research for obtaining the loss of life evaluation model that applies to the whole temperature range will remain the one proposed, regardless of the data gained from other transformers.

ACKNOWLEDGEMENT

The results presented in this article have been funded by the Ministry of Investments and European Projects through the Human Capital Sectoral Operational Program 2014-2020, Contract no. 62461/03.06.2022, SMIS code 153735.

Received on 6 September 2023

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