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Original Article

Transformer's Loss of Life Prediction using a Dynamic Thermal Model

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Abstract - *Predicting the loss of life of an operating power transformer is of great interest in the economic, technical and social fields. The thermal modelling approach is widely used for estimating the loss of life of a transformer due to its ease of integration into a real-time tracking tool and the relatively small amount of input information. This article proposes a dynamic thermal model to predict the loss of life of a power transformer. The proposed model takes into account the variations in the operation of certain parameters of the transformer, such as the load, the thermal capacity, the oil time constant and the ambient temperature. The formulated model calculates the hot spot temperature by the differential equations method, and the aging rate is calculated by the conventional IEEE technique. The model inputs are derived from information acquired by sensors and stored in an Excel database. The model was tested on two transformers, ONAF 400 MVA transformer and OFAF 605 MVA transformer. The results obtained are compared to two other thermal models and measured values. A loss of life prediction accuracy is 1.96 minutes on average for the first transformer and 6.40 minutes on average for the second transformer during a load cycle of 780 minutes and 1200 minutes, respectively. The comparative study between the results obtained and the other thermal models validates the relevance and reliability of the proposed model.*

Keywords - *Power transformer, Ageing, Hot spots temperature, Thermal, Loss of life.*

1. Introduction

The power transformer is one of the essential elements of the electrical power distribution network. [1], [2] The transformer is located at the interface of the electrical transport network and the electrical distribution network. While a transformer is in service, it ages due to electrical, thermal, mechanical and environmental stresses. [3] These various stress are manifested in the transformer by the growth in the temperature of the oil, the emission of mould, some gases, and acids and the development of certain chemical reactions.[4] .The direct consequence is the degradation of the insulation of the transformer. Most scientific works [5, 6], [28] related to the life expectancy of transformers agree on the fact that the end of life of a transformer is the end of life of its insulation system.

Due to the high cost of the transformer, many transformers remain in service beyond their life expectancy, which is, on average, 40 years [7]: One of the consequences of using a transformer at the end of its life expectancy is the risk of sudden cessation of activity, which would paralyse the supply of electricity to consumers. However, according to [8], the lifetime expectancy of a transformer is probably higher if the transformer operates under a lower load with excellent cooling conditions and continuous analysis and follow-up of the transformer.

Considering the cost and importance of the transformer, it is interesting to predict the loss of life with significant accuracy. This will enable us to identify transformers in poor conditions, optimise the scheduling of the purchase of new transformers, and maintain the efficient performance of the electrical network.

In order to do that, one has to build a model that describes the aging of the transformer, and from that model, one can estimate the loss of life of the transformer over time.

This paper proposes a dynamic thermal model based on a differential equations method to calculate the loss of life of a transformer in operation. The proposed model formulation considers variations in certain parameters such as thermal capacity, oil time constants and winding.

The remaining part of the paper is as follows: section two is state of the art, section three presents the methodology, section four proposes a dynamic thermal model, section five presents the results, section six presents a discussion and section seven is the conclusion of the article.

2. State of the Art

According to [8], there are three main approaches to predicting a power transformer's loss of life. The first approach is that of modelling the degradation of the transformer. This approach consists in modelling the evolution over time of certain quality parameters of the transformer. The quality parameter can be the mechanical tensile strength [9], the degree of polymerization [6], the breakdown voltage and so on. Models based on transformer degradation have the advantage of considering the internal behaviour of the elements making up the transformer. They have the disadvantage of not considering the monitoring data. Therefore, the models of the first approach cannot be integrated into a real-time monitoring device of the transformer's life. The second approach is statistical. The statistical approach is based on the history of the behaviour and failures of the transformer.

The data can be treated by an algorithm that can predict the loss of life of the transformer. Chantola and al [10] in their work propose a fuzzy algorithm, Saleh Forouhari and A. Abu Siada [29] presented in their work an adaptive neural fuzzy model estimating the life of the transformer. K. Ibrahim et al. [12] propose an enhanced model that associates the health index and the transformer load conditions for transformer life expectancy. Norazhar Abu Bakar et al. [13] propose an ANN model to determine the interfacial tension of a power transformer based on UV spectroscopy. Statistical models benefit from advances in artificial intelligence and data acquisition techniques that make them very efficient. The quality of the prediction depends closely on the reliability of the data from which the model was built. They do not take into consideration the monitoring data. The third approach builds a model using transformer monitoring data. The data usually used for this type of modelling are the hot spot temperatures [14], the concentration of certain gases [30], the dielectric dissipation factor [16], and moisture content [17]. The model using transformer monitoring data has the advantage of integrating monitoring data. The model, in this case, considers the transformer's actual operation. The model based on condition monitoring data can be implemented in a transformer's life in a real-time tracking system. The disadvantage of models using monitoring data is that they do not consider all phenomena related to ageing.

Thermal models are among the most widely used because they require very few data acquisition tools. The majority of the phenomena that lead to the ageing of the transformer cause temperature increases in the oil, windings and especially the appearance of hot spots [5]. There are two main families of thermal models [5]:

- Models based on electrical-thermal analogy,
- Models representing the temperature distribution in the winding.

Models based on electrical-thermal analogy have the advantage of being easily integrated into a computer program for real-time monitoring of transformer life but have the disadvantage that 'they do not locate hot spots and are less accurate than models representing the temperature distribution. Models representing the temperature distribution in the winding have the advantage of having better precision and making it possible to locate hot spots. However, they have the disadvantage that it is very difficult to integrate into a computer program to monitor the transformer in real-time. Haritha V S, T R Rao, Amit Jain and M Ramamoorty [31] propose a model which, from the finite element method, gives the temperature profile of a single phase transformer and simultaneously indicates the location of hot spots and the temperature value of hot spots. The method gives fairly satisfactory results but is limited only to single-phase transformers which are small power transformers. D.P. Rommel, D. Di Maio and T. Tinga [19] propose a model based on measurements of voltages and current with the different phase shifts to describe the temperature profile of the transformer. The model takes into account a large number of internal dynamics of the transformer but is not suitable for real-time monitoring of the loss of life of the transformer.

Thermal models are essentially based on temperature variations within the transformer. One of the difficulties with this modelling approach is to determine with good precision the internal temperature of the transformer and especially the hot spot temperature. In the IEEE and IEC guides [20], [21] for calculating the hot spots temperature, two approaches are recommended: the method of exponential equations and the method of differential equations. The exponential equation method presents the variation of the increased temperature of top oil and hot spot temperatures as an exponential function of time. The differential method is applicable regardless of the transformer load. The different thermal quantities are calculated for each time interval. This technique has the advantage that it offers the possibility of monitoring the transformer in real-time. However, choosing an iteration step that is not very large compared to the thermal time constants is necessary for a quality result. Chandran [11, 32] made a comparative study between the differential equations method and the exponential equations method. He showed that the exponential equations method provides better results than the differential equations method in the case of step profile load. Therefore the exponential method requires, in order having suitable results that the transformer operates at loads varying in steps and alternating steps of overload or rated load with steps of underload [20]. Consequently, the differential method could be practically more efficient in a real-time application if substantial improvements are made.

Shraddha Acharya and Pawan C.Tapre [14] present a model that uses the differential method proposed by the IEEE guide and considers the value of the ambient temperature and static parameters of the oil with an integration step of one hour. The results obtained show that the loss of life increases with the age of the transformer. However, it does not consider the transformer's internal dynamics and the impact of maintenance on the transformer's life. Sarah Afifah, Jannus Maurits Nainggolan et al. [23] propose a model that uses the differential equations method to calculate the temperature of hot spots. It assesses each parameter's impact on the transformer's loss of life and establishes a bottom-up classification of the transformer ageing factors. The integration step is one hour, and the prediction is on 24 hours. They do not consider all internal dynamics of the transformer. Yunus Biçen, Faruk Aras and Hulya Kirkici [5] propose a model that exploits the differential method and considers the average value of the annual load factor to predict the loss of transformer life. The cumulated effect of ageing is achieved by conventional methods that consider cumulated effects, namely SMA (Simple Moving Average) and WMA (Weight Moving Average).

O.E. Gouda et al. [2] propose a thermal model for predicting temperature rise in the presence of harmonic current. These harmonics generally observed in electrical power distribution networks are derived from non-linear loads [24]. Thus, taking these harmonics into account in the models allows us to get as close as possible to the real operation conditions of the transformer.

3. Methodology

3.1. General Presentation of Thermal Modelling based on Electrical-Thermal Analogy

Several studies have been carried out on the basis of the transformer's thermal-electric analogy to determine its loss of life. The approach calculates the hot spot temperature and determines the transformer's ageing. The most common formulation is the one described in the IEEE and IEC guides [21] and [20]. The different temperatures are calculated based on the simplified heat diagram of the transformer shown in Figure 1.

3.2. Top Oil Temperature Rise Equation

The top oil temperature rise equation given by IEEE [21] is a first-order differential equation.

$$\tau_o \frac{d}{dt}\left(\Delta\theta_o(t)\right) = \Delta\theta_o(f) - \Delta\theta_o(t) \qquad (1)$$

Where:

τ_o : Is the oil time constant (min)

$\Delta\theta_o(f)$: Is the final top oil temperature rise (°C)

$\Delta\theta_o(t)$: Is the top oil temperature rise at the time t (°C)

The above equation solution is given by equation 2,

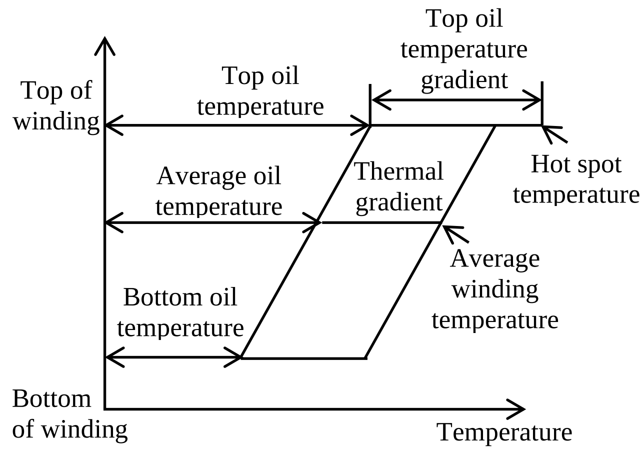

Fig. 1 Transformer thermal diagram [20]

$$\Delta\theta_o(t) = [\Delta\theta_o(f) - \Delta\theta_o(i)]\left[1 - e^{-\frac{t}{\tau_o}}\right] + \Delta\theta_o(i) \qquad (2)$$

Where:

$\Delta\theta_o(i)$: Is the initial top oil temperature rise (°C)

Final top oil temperature rise is given by equation 3,

$$\Delta\theta_o(f) = \Delta\theta_{or}\left(\frac{1+k^2R}{1+R}\right)^x \qquad (3)$$

K : Represents the load factor

$\Delta\theta_{or}$: Is the top oil temperature rise in steady state (°C)

R : Is the ratio of load losses at rated current to no-load losses

x : Is the oil exponent

3.3. Hot Spot Temperature Rise Equation

While the transformer is in operation, it outputs a current which depends on the load; when the load increases, the output current will also increase and tacitly, the winding temperature and hot spot temperature of the transformer will increase. The hot spot temperature rise equation given by IEEE is a first-order differential equation. [21]

$$\tau_w \frac{d}{dt}\left(\Delta\theta_h(t)\right) = \Delta\theta_h(f) - \Delta\theta_h(t) \qquad (4)$$

Where:

τ_w : Is the winding time constant (min)

$\Delta\theta_h(f)$: Is the final hot spot temperature rise (°C)

$\Delta\theta_h(t)$: Is the hot spot temperature rise at the time t (°C)

The above equation solution is given by equation (5),

$$\Delta\theta_o(t) = [\Delta\theta_h(f) - \Delta\theta_h(i)]\left[1 - e^{-\frac{t}{\tau_w}}\right] + \Delta\theta_h(i) \qquad (5)$$

Where:
$\Delta\theta_0(i)$: Represents the initial hot spot temperature rise (°C)

Final hot spot temperature rise is given by equation (6),

$$\Delta\theta_h(f) = \Delta\theta_{hr} k^y \tag{6}$$

$\Delta\theta_{hr}$: Is the Hot spot temperature rise in steady state (K)
Y : Is the winding exponent

3.4. Calculation of Hot Spot Temperature

The IEC and IEEE [20] and [21] guides provide two techniques for calculating transformer hot spots temperature during operation:

- Exponential equations method;
- Differential equations method.

3.4.1. Exponential Equations Method

The exponential equation method is as follows [22]:

For an increase in load, we have:

$$\theta_h(t) = \theta_{amb} + \Delta\theta_{oi} + \left[\Delta\theta_{or}\left(\frac{1+k^2R}{1+R}\right)^x\right] f_1(t) + \Delta\theta_{hi} + [\Delta\theta_{hr}k^y - \Delta\theta_{hi}] f_2(t) \tag{1}$$

For a decrease in load, we have:

$$\theta_h(t) = \theta_a + \Delta\theta_{or}\left(\frac{1+k^2R}{1+R}\right)^x + \left[\Delta\theta_{oi} - \Delta\theta_{or}\left(\frac{1+k^2R}{1+R}\right)^x\right] f_3(t) + \Delta\theta_{hr}k^y \tag{2}$$

The functions, $f_1(t), f_2(t), f_3(t)$ are defined as follows:

$$f_1(t) = \left(1 - e^{-\frac{t}{k_{22}\tau_o}}\right)$$

$$f_2(t) = e^{-\frac{t}{k_{11}\tau_o}}$$

$$f_3(t) = k_{21}\left(1 - e^{-\frac{t}{k_{22}\tau_w}}\right) - (k_{21}-1)\left(1 - e^{-\frac{t}{k_{22}\tau_o}}\right)$$

3.4.2. Differential Equations Method

The top oil temperature rise is given by equation (9)

$$\Delta\theta_o = \frac{\Delta t}{k_{11}\times\tau_o}\left(\frac{1+k^2R}{1+R}\right)^x \times \Delta\theta_{or} - (\theta_o - \theta_a) \tag{3}$$

The top oil temperature at each step is the sum of the top oil temperature at the previous step and the top oil temperature rise at the step.

$$\theta_o(n) = \theta_o(n-1) + \Delta\theta_o(n) \tag{4}$$

Similar equations are applied for hot spot temperature calculation.

$$\Delta(\Delta\theta_{h1}) = \frac{\Delta t}{k_{22}\times\tau_w}\left(k_{21}\times k^y \times \Delta\theta_{hr} - \Delta(\Delta\theta_{h1})\right) \tag{5}$$

$$\Delta(\Delta\theta_{h2}) = \left(\frac{\Delta t \times k_{22}}{\tau_w}\right)\left[(k_{21}-1)\, k^y \Delta\theta_{hr} - \Delta(\Delta\theta_{h2})\right] \tag{6}$$

The hot spot temperature rise at each step is the sum of the hot spot temperature rise at the previous step and the hot spot temperature rise variation at the step.

$$\Delta\theta_{h1}(n) = \Delta\theta_{h1}(n-1) + \Delta\left(\Delta\theta_{h1}(n)\right) \tag{7}$$

$$\Delta\theta_{h2}(n) = \Delta\theta_{h2}(n-1) + \Delta\left(\Delta\theta_{h2}(n)\right) \tag{8}$$

The hot spot temperature rise at each step is given by equation (15):

$$\theta_h(n) = \theta_o(n) + \Delta\theta_h(n) \tag{9}$$

Where:
Δt : The iteration step (min)
k_{11}, k_{21} and k_{22} : The thermal model constant
θ_a : The ambient temperature (°C)

3.5. Aging Calculation

The IEEE Loading guide [21] provides a methodology to calculate the loss of life of a transformer depending on the hot spot's temperature.

$$L_{life} = e^{\left(\frac{15000}{383} - \frac{15000}{\theta_h + 273}\right)} \tag{10}$$

For each value of the hot spot's temperature, we can calculate the loss of life associated with it. If we consider a period N, we can calculate the average loss of life $\overline{L_{life}}$.

$$\overline{L_{life}} = \frac{\sum_{n=1}^{N}(L_{life}(n)\times\Delta t)}{\sum_{n=1}^{N}\Delta t} \tag{11}$$

The loss of life during the period T is given by equation (18).

$$L_{total} = \overline{L_{life}} \times T \tag{12}$$

The other alternative is calculating the loss of life by cumulating the punctual loss of life at each time interval and the loss of life at the preceding time interval. Annex I of the Loading guide [21] proves that the result is the same, but with this method, we can have a real-time evolution of the loss of life of the transformer.

Table 1. Transformer parameters to simulate parameter variation

Parameters	Values
P	400 MVA
Cooling mode	ONAF
$\Delta\theta_{om}$	38°C
P_{eddy}	59778 W
P_{stray}	637100 W
P_{Jnom}	65772W
$V_2\|V_1$	400V|410V
C_w	0.11 (Wh/kg °C)
C_{fe}	0.13 (Wh/kg °C)
C_{tank}	0.13 (Wh/kg °C)
C_{oil}	0.51 (Wh/kg °C)
α_{oil}	1
m_w	45563 kg
m_{fe}	132023 kg
m_{tank}	67252 kg
m_{oil}	96018 kg

The transformer load [26] is given as:

Table 2. Transformer load profile to simulate parameter variation

Period in min	Load factor in pu
00-300	1.0
300-600	0.65
600-780	1.6

Srinivasan [25] proposes a linearized thermal model that considers the environment's effects on the transformer's ageing. Acharya [14] proposed an algorithm to calculate the loss of life of a transformer during a 24h cycle by integrating it with an hourly unit step. Afifah [23] shows that variations in input data, including ambient temperature and load, all have an impact on the prediction of transformer loss of life.

3.6. Model Parameter Variation

Thermal models have two types of parameters: fixed parameters which do not depend on the operating regime of the transformer, and variable parameters, which depend on the operating regime of the transformer.

3.6.1. The Ratio R

The ratio R is given by equation (20)

$$R = \frac{P_J}{P_{fer}} \tag{13}$$

Joule losses are proportional to the square of the current intensity. We can therefore deduce the following relationship:

$$P_J = \frac{P_{Jnom}}{I^2{}_{nom}}\ I^2 = \frac{P_{Jnom}}{k^2} \tag{14}$$

$$P_{fer} = P_{eddy} + P_{stray} \tag{15}$$

Where:

P_J : The joule losses at the assigned current (W)
P_{Jnom} : The joule losses at rated current (W)
P_{fer} : The no-load losses (W)
P_{eddy} : The eddy losses (W)
$P_{(stray)}$: The stray losses (W)
I : The assigned current (A)
I_{nom} : The rated current (A)

3.6.2. Thermal Capacity

Many works have considered the total thermal capacity of the system as constant, where in fact, this capacity depends on the operating regime of the transformer. Susa et al. [26] modelled the thermal capacity as given by equation (22).

$$C = \alpha_w m_w C_w + \alpha_{fe} m_{fe} C_{fe} + \alpha_{tank} m_{tank} C_{tank} + \alpha_{oil} m_{oil} C_{oil} \tag{16}$$

The constants α_w, α_{fe} and α_{tank} is given as follows:

$$\alpha_w = \frac{P_J}{P_{total}}$$

$$\alpha_{fe} = \frac{P_{fe}}{P_{total}}$$

$$\alpha_{tank} = \frac{P_{stray}}{P_{total}}$$

α_{oil} is a constant which depends on the cooling mode. C_w, C_{fe}, C_{tank} and C_{oil} are respectively the heat capacities of winding, core, tank and fittings and oil. m_w, m_{fe}, m_{tank} and m_{oil} are respectively the masses of the winding, the core, the tank, fittings and the oil.

3.6.3. Oil Time Constant

The oil time constant according to [20] is given by equation (23).

$$\tau_o = \frac{C \times \Delta\theta_{om} \times 60}{P_{total}} \tag{23}$$

$\Delta\theta_{om}$: The average oil temperature rise at the load considered (°C)
P_{total} : The total losses (W)

For example, consider a power transformer given by [26] (Table 1).

Figures 2 and 3 give an example of a variation of the ratio R, the thermal capacity and the oil time constant when the transformer operates for 780 minutes according to the load profile given in Table 2.

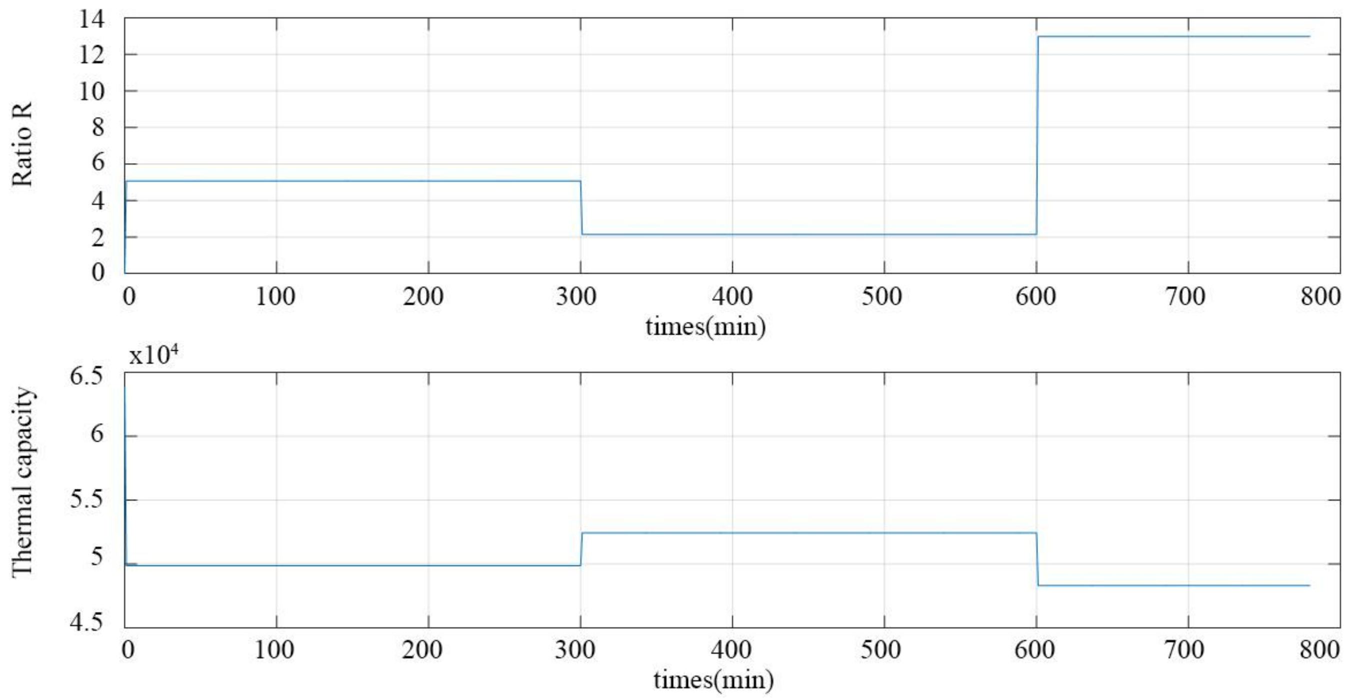

Fig. 2 Ratio R and thermal capacity variation

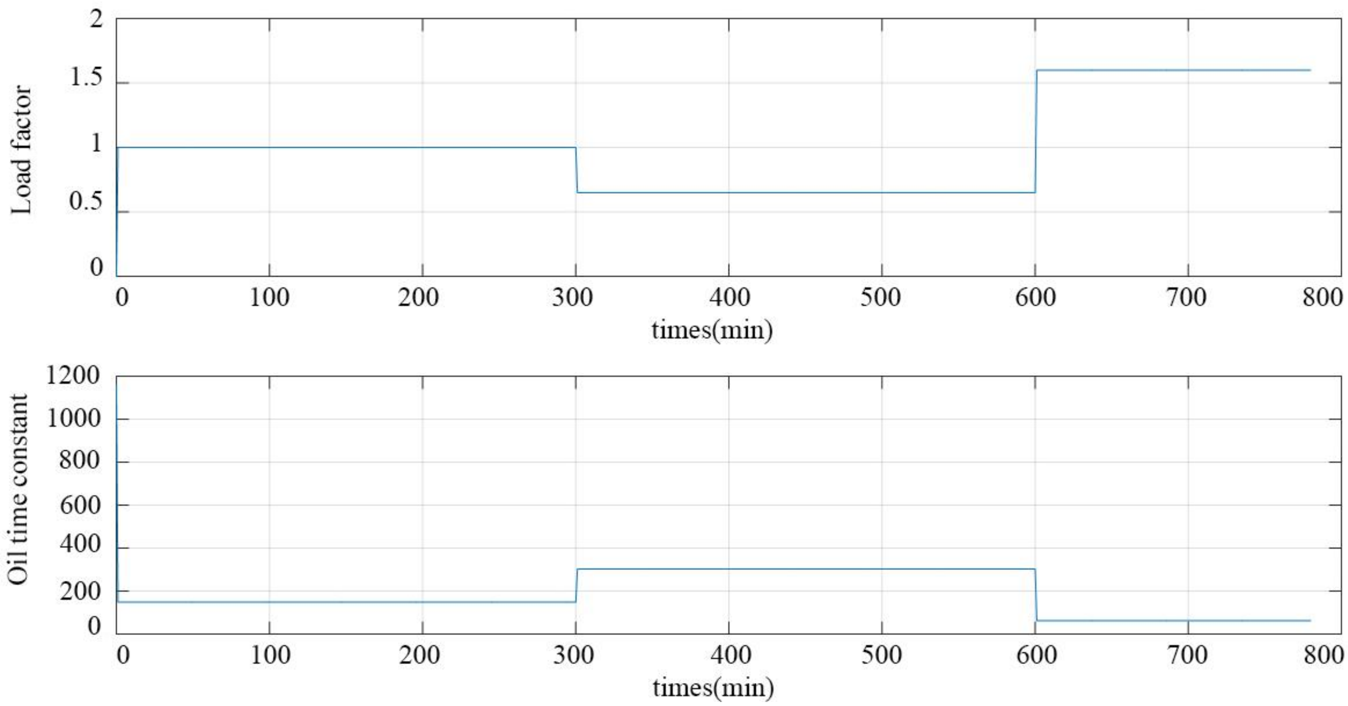

Fig. 3 Load and oil time constant variation

4. The Proposed Dynamic Thermal Model

The proposed thermal model inspired by the IEC and IEEE guide [20] and [21] related to the calculation of transformer aging using a thermal approach. The differential equation method was chosen in order to be able to monitor the thermal behaviour of the transformer in real-time. The loss of life is obtained by cumulating the ageing effect during the load cycle of the transformer.

4.1. Model Formulation

The time step chosen for this model is Δt=1min

Initial conditions: The initial conditions describe the state of the transformer insulation before the beginning of the load cycle that induced ageing. The knowledge of the different values $\theta_o(0)$, θ_{h1} (0), $\Delta\theta_{h2}(0)$, $\theta_h(0)$ allows it. In the beginning, the loss of life is equal to zero: L(0)=0.

First integration step: The behaviour of the system after a time t=Δt is described by the following equations:

Top oil temperature:

$$\Delta\theta_o(1) = \frac{\Delta t}{k_{11}\times\tau_o(1)}\left(\frac{1+k^2R}{1+R}\right)^x \Delta\theta_{or} - \left(\theta_o(0) - \theta_a(1)\right) \quad (17)$$

$$\tau_o(1) = \frac{C(1)\times\Delta\theta_{om}\times 60}{P_{total}(1)} \quad (18)$$

C(1) : The thermal capacity at t=Δt
$\theta_a(1)$: The ambient temperature at t=Δt
$P_{total}(1)$: The total losses at t=Δt

$$\theta_o(1) = \theta_o(0) + \Delta\theta_o(1) \quad (19)$$

Hot spots temperature:

$$\theta_h(1) = \theta_o(1) + \Delta\theta_h(1) \quad (20)$$

$$\Delta\theta_h(1) = \Delta\theta_{h1}(1) - \Delta\theta_{h2}(1) \quad (21)$$

$$\Delta\theta_{h1}(1) = \frac{\Delta t}{k_{22}\times\tau_w(1)}\left(k_{21}k^y\Delta\theta_{hr} - \Delta\theta_{h1}(0)\right) \quad (22)$$

$$\Delta\theta_{h2}(1) = \left(\frac{\Delta t\times k_{22}}{\tau_w(1)}\right)\left[(k_{21}-1)k^y\Delta\theta_{hr} - \Delta\theta_{h2}(0)\right] \quad (23)$$

$\tau_w(1)$ is the winding time constant at $t = \Delta t$

Loss of life:

$$L(1) = L(0) + e^{\left(\frac{15000}{383} - \frac{15000}{\theta_h(1)+273}\right)} \quad (24)$$

Second integration step: The behaviour of the system after a time t=2Δt is described by the following equations:

Top oil temperature:

$$\Delta\theta_o(2) = \frac{\Delta t}{k_{11}\times\tau_o(2)}\left(\frac{1+k^2R}{1+R}\right)^x \Delta\theta_{or} - \left(\theta_o(1) - \theta_a(2)\right) \quad (25)$$

$$\tau_o(2) = \frac{C(2)\times\Delta\theta_{om}\times 60}{P_{total}(2)} \quad (26)$$

C(2) : The thermal capacity at t=2Δt
$\theta_a(2)$: The ambient temperature at t=2Δt
$P_{total}(2)$: The total losses at t=2Δt

$$\theta_o(2) = \theta_o(1) + \Delta\theta_o(2) \quad (27)$$

Hot spots temperature:

$$\theta_h(2) = \theta_o(2) + \Delta\theta_h(2) \quad (28)$$

$$\Delta\theta_h(2) = \Delta\theta_{h1}(2) - \Delta\theta_{h2}(2) \quad (29)$$

$$\Delta\theta_{h1}(2) = \frac{\Delta t}{k_{22}\times\tau_w(2)}\left(k_{21}\times k^y\times\Delta\theta_{hr} - \Delta\theta_{h1}(1)\right) \quad (30)$$

$$\Delta\theta_{h2}(2) = \left(\frac{\Delta t\times k_{22}}{\tau_w(2)}\right)\left[(k_{21}-1)\,k^y\Delta\theta_{hr} - \Delta\theta_{h2}(1)\right] \quad (31)$$

$\tau_w(2)$ is the winding time constant at $t = 2\Delta t$

Loss of life:

$$L(2) = L(1) + e^{\left(\frac{15000}{383} - \frac{15000}{\theta_h(1)+273}\right)} \quad (32)$$

Nth integration step: The behaviour of the system after a time t=NΔt is described by the following equations:

Top oil temperature:

$$\Delta\theta_o(N) = \frac{\Delta t}{k_{11}\times\tau_o(N)}\left(\frac{1+k^2R}{1+R}\right)^x \Delta\theta_{or} - \left(\theta_o(N-1) - \theta_a(N)\right) \quad (33)$$

$$\tau_o(N) = \frac{C(N)\times\Delta\theta_{om}\times 60}{P_{total}(N)} \quad (34)$$

C(N) : The thermal capacity at t=NΔt
$\theta_a(N)$: The ambient temperature at t=NΔt
$P_{total}(N)$: The total losses at t=NΔt

$$\theta_o(N) = \theta_o(N-1) + \Delta\theta_o(N) \quad (35)$$

Hot spots temperature

$$\theta_h(N) = \theta_o(N) + \Delta\theta_h(N) \quad (36)$$

$$\Delta\theta_h(N) = \Delta\theta_{h1}(N) - \Delta\theta_{h2}(N) \quad (37)$$

$$\Delta\theta_{h1}(N) = \frac{\Delta t}{k_{22}\times\tau_w(N)}\left(k_{21}k^y\Delta\theta_{hr} - \Delta\theta_{h1}(N-1)\right) \quad (38)$$

$$\Delta\theta_{h2}(N) = \left(\frac{\Delta t\times k_{22}}{\tau_w(N)}\right)\left[(k_{21}-1)\,k^y\Delta\theta_{hr} - \Delta\theta_{h2}(N-1)\right] \quad (39)$$

$\tau_w(N)$ is the winding time constant at $t = N\Delta t$

Loss of Life:

$$L(N) = L(N-1) + e^{\left(\frac{15000}{383} - \frac{15000}{\theta_h(N)+273}\right)} \quad (40)$$

4.2. Inputs of the Model

The proposed model is a real-time model. The model needs input data from the transformer monitoring data. The necessary input data are presented in Table 3.

Table 3. Model input

N°	Symbol	Meaning
Input 1	Δt	Time step (1h, 1min)
Input 2	θ_{amb}	the ambient temperature at each at Δt
Input 3	k	Loading factor at each Δt

Table 4. Model parameter

Symbol	Meaning
P	Power in MVA
Cooling mode	Cooling mode
$\Delta\theta_{om}$	Average oil temperature rise at the load considered (K)
$\Delta\theta_{hr}$	Hot spot temperature rise in steady state (K)
$\Delta\theta_{or}$	Top oil temperature rise in steady state (K)
P_{eddy}	Eddy losses (W)
P_{stray}	Stray losses (W)
P_{Jnom}	Joules losses at a rated charge (W)
τ_w	The winding time constant (min)
I_{nom}	Nominal current (A)
x	Oil exponent
y	winding exponent
C_w	Specific heat capacity of winding (Wh/kg °C)
C_{fe}	Specific heat capacity of core (Wh/kg °C)
C_{tank}	Specific heat capacity of the tank and fitness (Wh/kg °C)
C_{oil}	Specific heat capacity of the oil (Wh/kg °C)
α_{oil}	constant
m_w	Mass of winding (kg)
m_{fe}	Mass of core (kg)
m_{tank}	Mass of tank and fitness (kg)
m_{oil}	Mass of oil (kg)

4.3. Parameters

The following parameters required by the model for the prediction of loss of life of the power transformer are listed in Table 4.

4.4. Flowchart

The model formulation can be compiled into a computer program by implementing the flowchart given in Figure 4.

5. Results

The equations model stated in section 3 can be implemented into a MATLAB program. We will simulate the MATLAB program into a DELL computer, core i7, 8Go of RAM and 500Go SSD. Two transformers are taken as an example, a 400MVA ONAF transformer and a 605MVA OFAF transformer [26].

Table 5. Transformer's parameter

Parameters	Transformer 1	Transformer 2
P	400 MVA	605 MVA
Cooling mode	ONAF	OFAF
$\Delta\theta_{om}$	38K	33.4K
$\Delta\theta_{hr}$	56.6K	65.3K
$\Delta\theta_{or}$	38K	33.4K
P_{eddy}	59778 W	285000 W
P_{stray}	65772 W	71000 W
P_{Jnom}	637100 W	929800 W
τ_w	8.2 min	5.5 min
x	0.8	0.8
y	1	1
C_w	0.11 Wh/kg °C	0.11 Wh/kg °C
C_{fe}	0.13 Wh/kg °C	0.13 Wh/kg °C
C_{tank}	0.13 Wh/kg °C	0.13 Wh/kg °C
C_{oil}	0.51 Wh/kg °C	0.51 Wh/kg °C
α_{oil}	1	1
m_w	45563 kg	48900 kg
m_{fe}	132023 kg	48900 kg
m_{tank}	67252 kg	139448 kg
m_{oil}	96018 kg	79746 kg

5.1. Parameter

Two transformers are used to evaluate the model. Table 5 shows the parameter of the two transformers used to test the transformer loss of life prediction model presented in section 4.

5.2. Inputs Data

The model needs three data: the iteration step, the per unit load and the ambient temperature. The iteration step is Δt=1min. Figure 5 presents the per unit load of the 400 MVA ONAF transformer during the 780 minutes of the operation. The load has three steps:

- Rated charge (the transformer load is 1pu) during 300min;
- Under load (the transformer load is 0.65pu) during 300min;

Over load (the transformer load is 1.5pu) during 180min;

Figure 6 presents the per unit load of the 605 MVA OFAF transformer during the 1200 minutes of the operation. The load has four steps:

- Rated charge (the transformer load is 1pu) during 300 min;
- Under load (the transformer load is 0.65pu) during 300min;
- Over load (the transformer load is 1.3pu) during 50min, 4) the transformer is put at rest (the transformer load is 0pu) during 600 min.

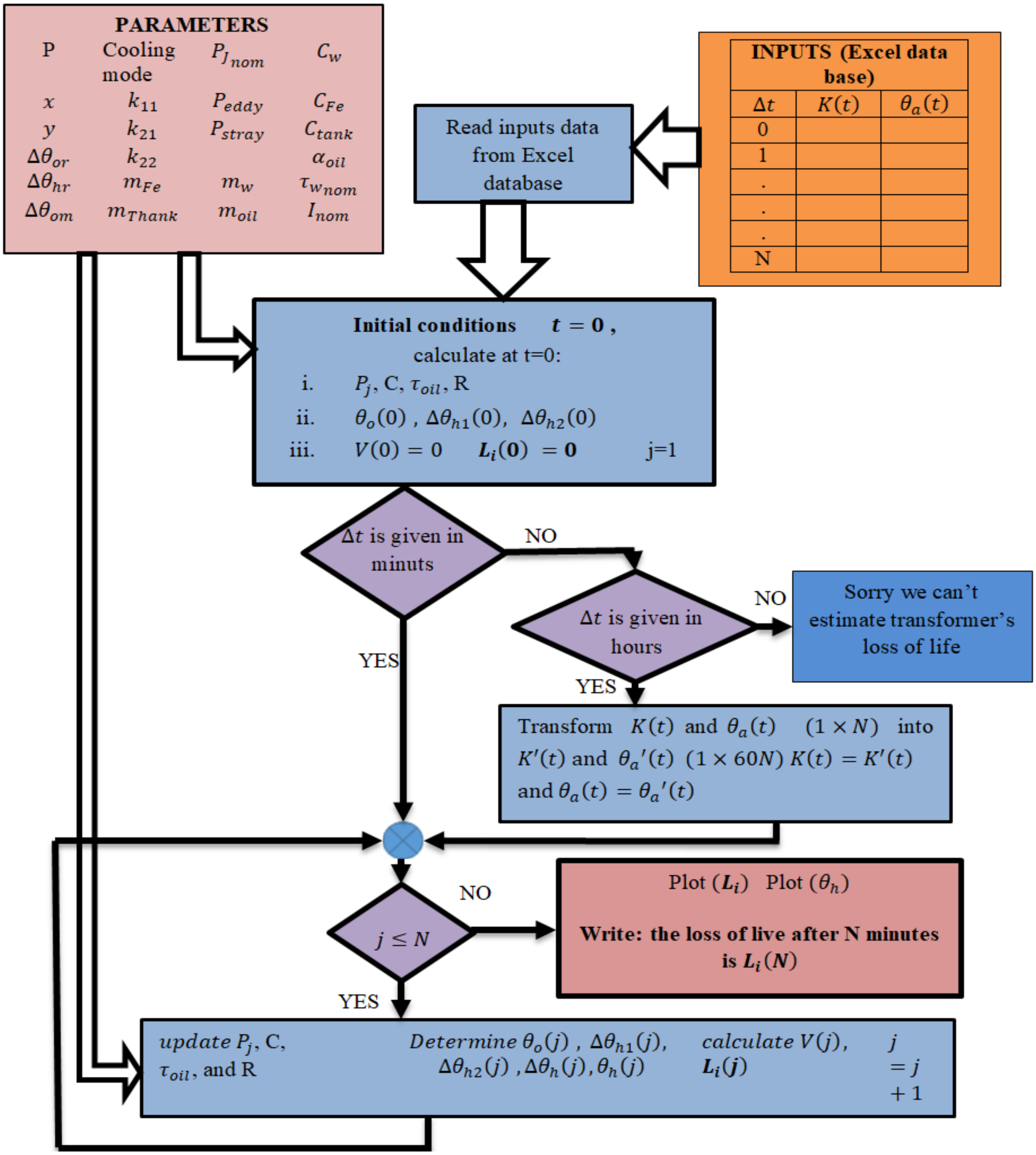

Fig. 4 Model flowchart

Figure 7 shows the evolution of the ambient temperature of the first transformer's location over time. The ambient temperature varies between 22°C and 26°C. Figure 8 shows the evolution of the ambient temperature of the second transformer's location over time. The ambient temperature varies between 22°C and 30°C.

5.3. Prediction Result

The model outputs two variables: The time course of hot spot temperature and the loss of life of the transformer. Figure 9 and Figure 10 present the transformer's hot spot temperature. The Hot spot temperature profile of the 400 MVA ONAF transformers has three phases:

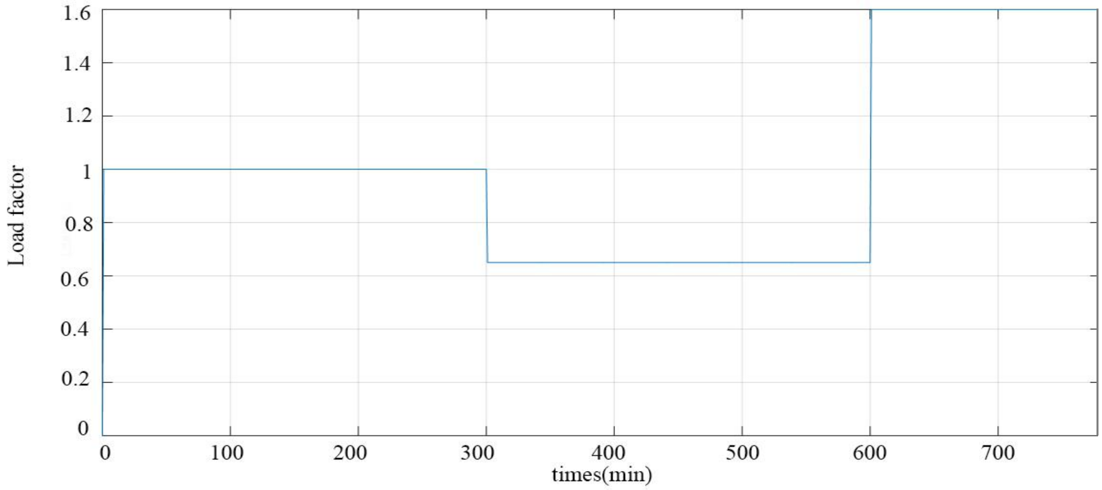

Fig. 5 400 MVA ONAF load profile

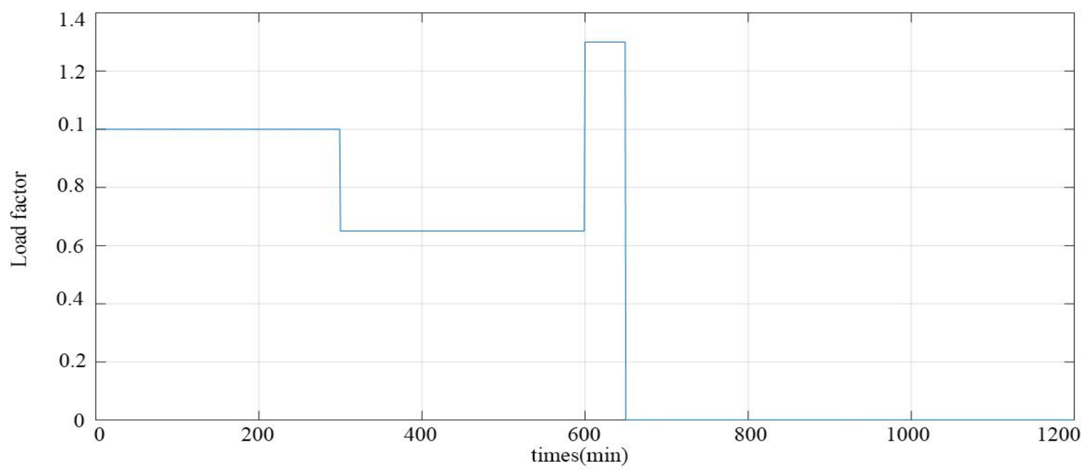

Fig. 6 605 MVA OFAF load profile

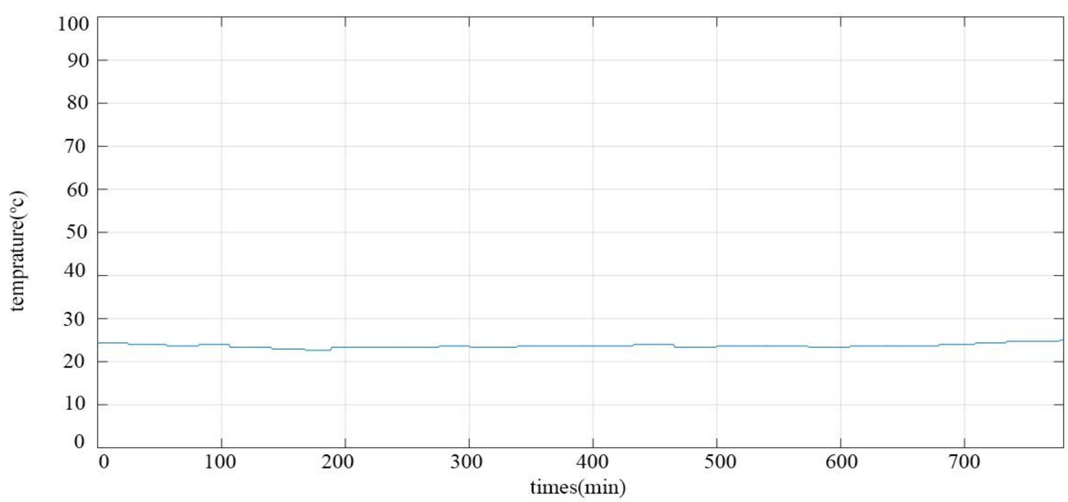

Fig. 7 400 MVA ONAF ambient temperature

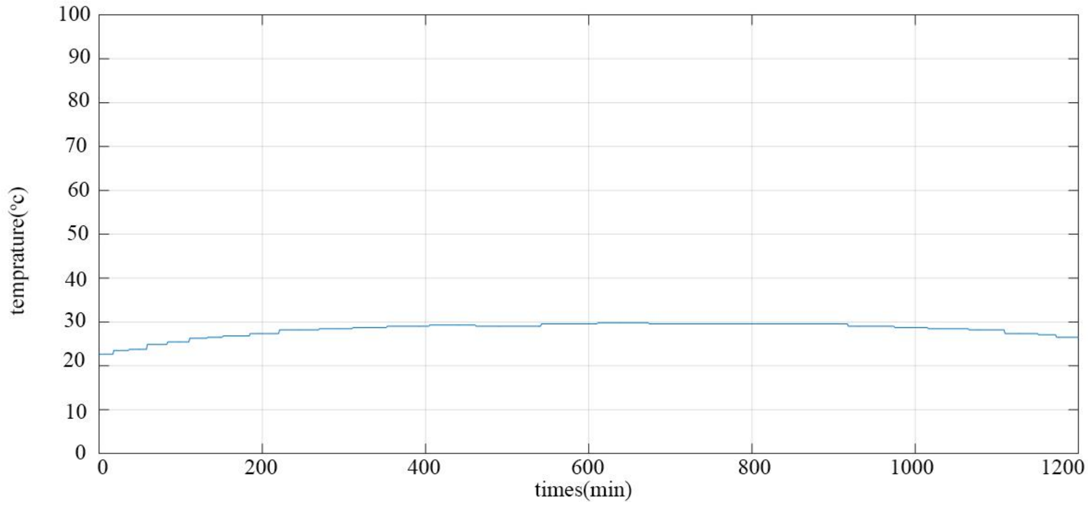

Fig. 8 605 MVA OFAF ambient temperature

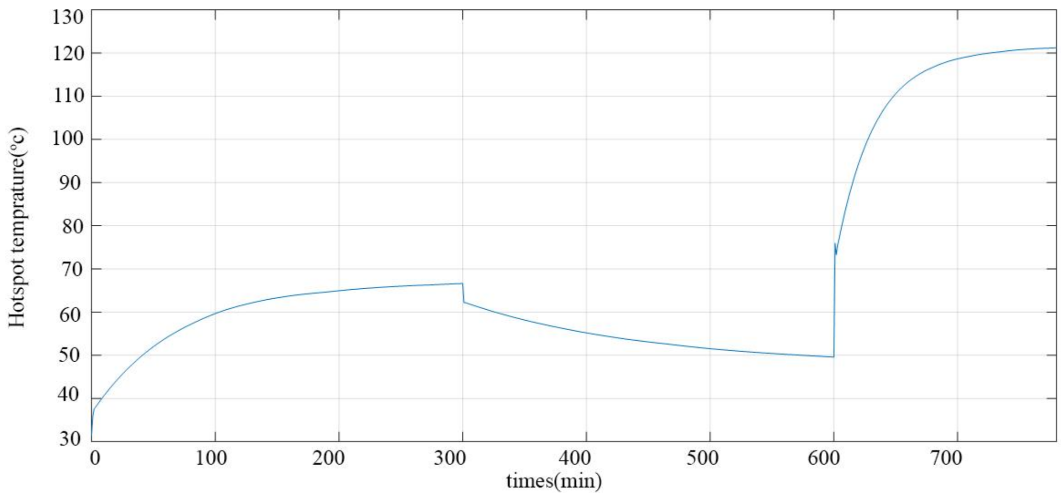

Fig. 9 400 MVA ONAF hot spot temperature prediction

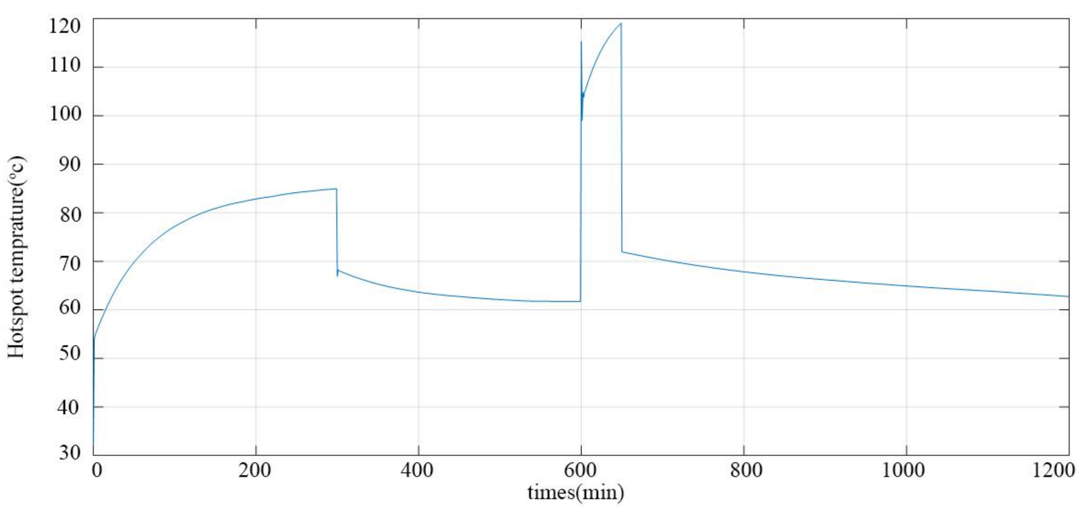

Fig. 10 605 MVA OFAF hot spot temperature

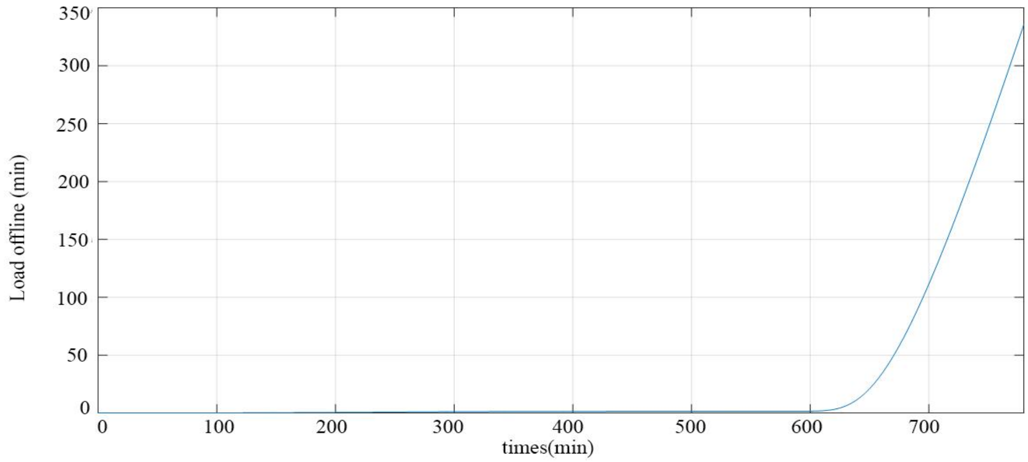

Fig. 11 400 MVA ONAF loss of life prediction

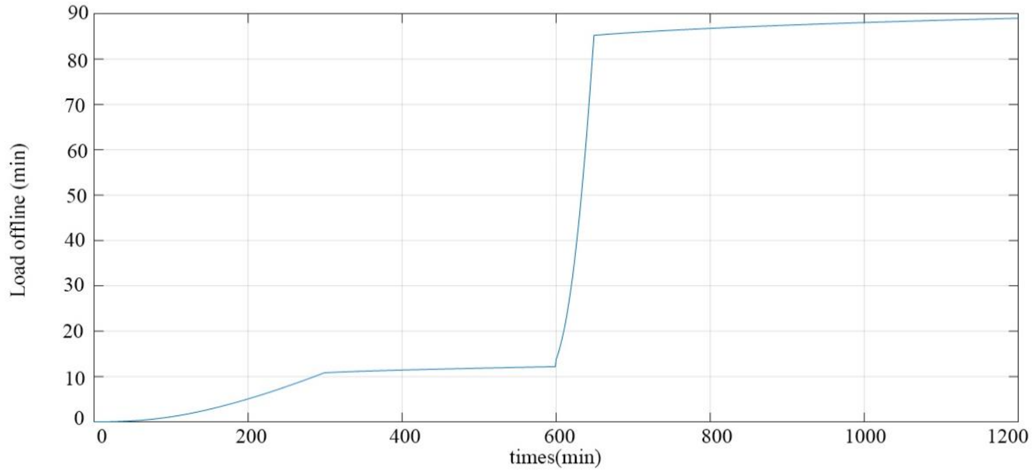

Fig. 12 605 MVA OFAF loss of life prediction

- During the time corresponding to the first load step (from O min to 300 min), the transformer operates at the rated load. The Hot Spot Temperature is increasing.
- During the time corresponding to the second load step (from 300 min to 600 min), the transformer is under-loaded, and the Hot Spot Temperature decreases slowly.
- During the time corresponding to the third load step (from 600 min to 780 min), the transformer is overloaded, and the Hot Spot Temperature grows very quickly during 100 minutes and stabilizes around 120 °C.

The Hot spot temperature profile of the 605 MVA OFAF transformers has four phases:

- During the time corresponding to the first load step (from O min to 300 min), the transformer is operating at the rated load, and the Hot Spot Temperature is increasing exponentially;
- During the time corresponding to the second load step (from 300 min to 600 min), the transformer is under loaded, and the Hot Spot Temperature decreases slowly;
- During the time corresponding to the third load step (from 600 min to 650 min), the transformer is overloaded, the Hot Spot Temperature changes abruptly from 60.73°C to 99°C, then grows exponentially until 119°C;
- During the time corresponding to the fourth load step (from 650 min to 1200 min), the transformer is off, and the Hot Spot Temperature drops abruptly from 119°C to 71.97°C, then decreases slowly during the rest of the cycle.

Figure 11 and Figure 12 present the transformer loss of life profile of the two transformers. The loss of life prediction of the 400 MVA ONAF transformers has two phases:

- From 00 min to 780 min, the transformer operates at rated load or is under-loaded, and the Loss of Life prediction is substantially equal to zero (1.56 min);
- From 600 min to 780 min, the transformer is overloaded, and the Loss of Life increases very quickly.

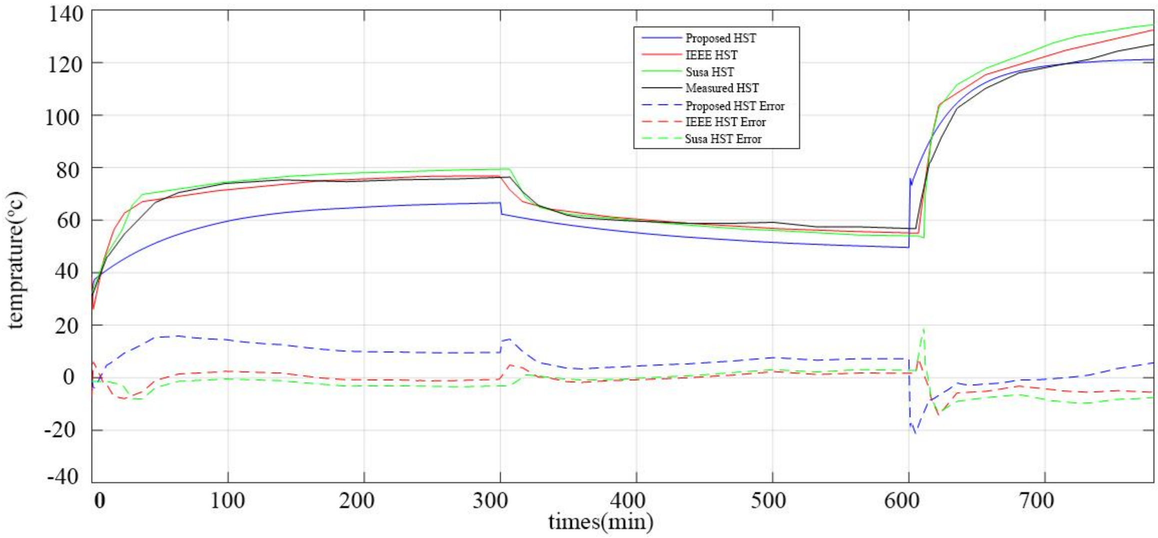

Fig. 13 400 MVA ONAF hot spot temperature comparison

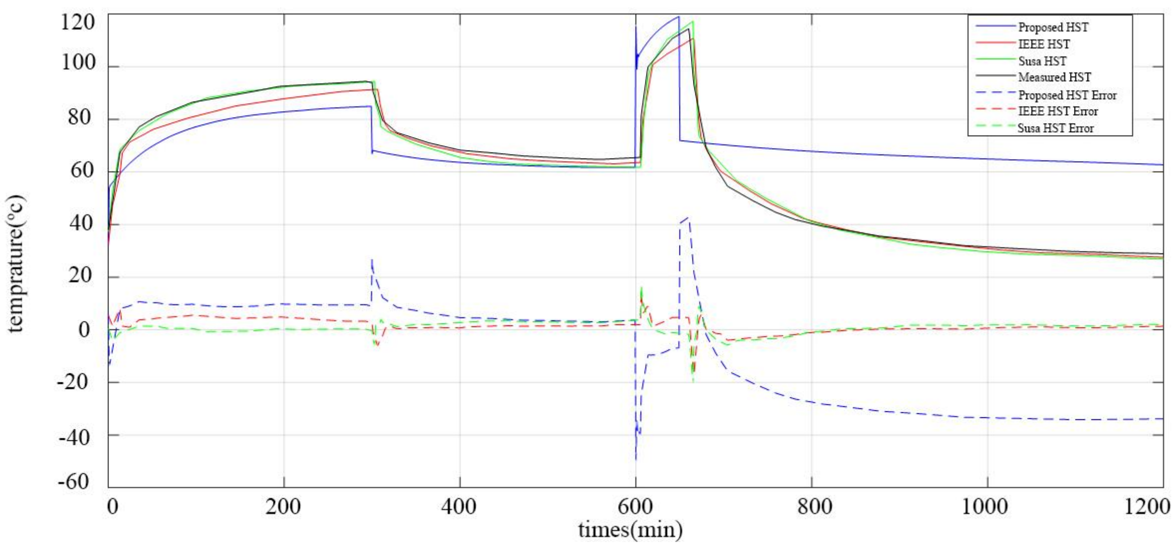

Fig. 14 605 MVA OFAF hot spot temperature comparison

The loss of life prediction of the 605 OFAF transformers has four phases:

- From 00 min to 300 min, the transformer operates at the rated load, and the Loss of Life prediction grows quickly from zero to 10.85 min.
- From 300 min to 600 min, the transformer is under loaded at 0.65 pu, and the Loss of Life grows linearly with a very low slope from 10.85 min to 12.22 min.
- From 600 min to 601 min, the transformer is overloaded, and the Loss of Life grows abruptly from 12.22 min to 85.26 min.

For the rest of the cycle, the Loss of Life increases slightly and stabilizes around 88.87 min.

6. Discussion

The model result should be compared to two other models, namely the classical IEEE exponential model [21] and the SUSA [26] model, which also uses exponential equations. Two transformers are taken, as an example, a 400MVA ONAF transformer and a 605MVA OFAF transformer.

6.1. Hot Spots Temperature Comparison

In this subsection, we will compare the Hot Spots Temperature obtained by the proposed model with those of the IEEE model and the SUSA model for a 400 MVA ONAF transformer and a 605 MVA OFAF transformer. The measured values will be the reference for hot spot temperature comparison.

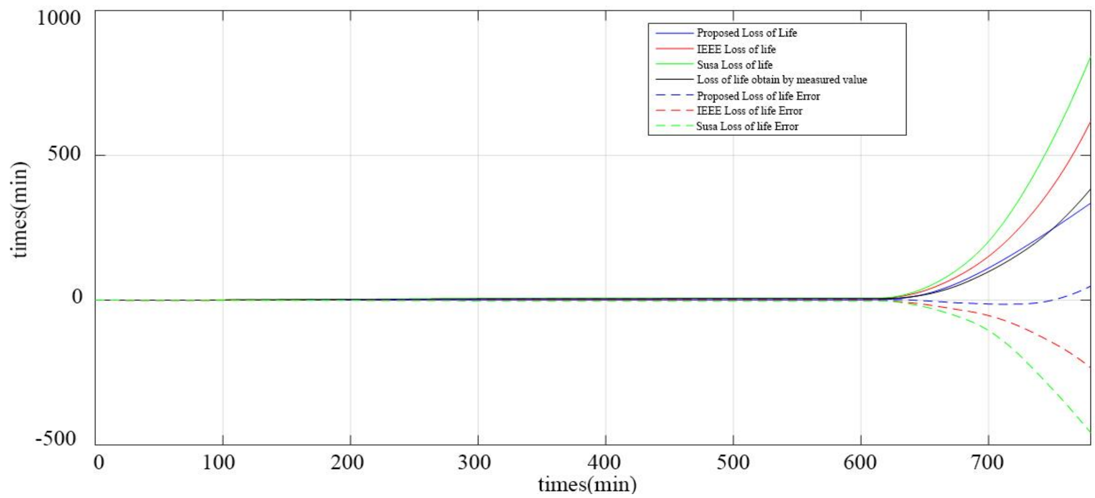

Fig. 15 400 MVA ONAF loss of life comparison

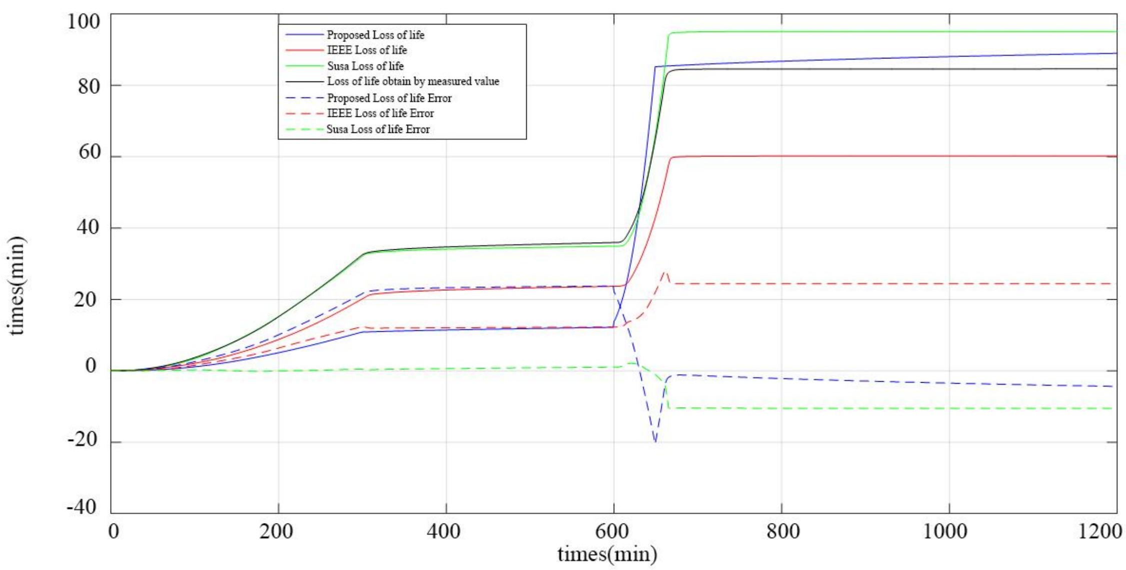

Fig. 16 605 MVA OFAF loss of life comparison

Figures 13 and 14 show, in blue, the hot spot temperature predicted by the proposed model. In red is the hot spot temperature predicted by the IEEE model. In green, the hot spot temperature is predicted by the IEEE model. In black, the measured hot spot's temperature.

Error is the difference between the values predicted by the different models and the measured values. Thus, the blue dotted curve is the error in hot spot temperature predicted by the proposed model. The red dotted curve is the error on hot spot temperature predicted by the IEEE model. The green dotted curve is the error in hot spot temperature predicted by the SUSA model.

The proposed model's hot spot temperature prediction curve looks the same as the curves of the other models and the reference curve, which is the hot spot temperature actually measured. However, when the transformer is running at its rated load or under load, the IEEE and SUSA models are closer to the actual measurements. During the overload phase, the temperature of the proposed model hot spots is closer to the measured values than the IEEE and SUSA models.

The proposed model peaked during the phases of a sudden change of load. This phenomenon is also visible in the IEEE model and the SUSA model. The measured values also show the same peaks. Peaks originate from the discontinuity in the thermal and electromagnetic phenomena that occur inside the transformer during the tap change. Tables 6 and 7 summarise the minimum, maximum and average temperature values of the hot spots for Transformer 400 MVA ONAF and Transformer 605 MVA OFAF.

Table 6. 400 MVA ONAF hot spot temperature summary (°C)

	Minimum	Maximum	Mean
Proposed Model	0	20.35	6.56
SUSA Model	0	19.17	2.218
IEEE Model	0	14.39	0.99

Table 7. 605 MVA OFAF hot spot temperature error summary (°C)

	Minimum	Maximum	Mean
Proposed Model	0	49.88	9.2
SUSA Model	0	20.66	0.86
IEEE Model	0	17.06	1.46

Table 8. 400 MVA ONAF loss of life error summary (min)

	Minimum	Maximum	Mean
Proposed Model	0	81.58	1.96
SUSA Model	0	457.2	32.6
IEEE Model	0	233.1	15.6

Table 9. 605 MVA OFAF loss of life error summary (min)

	Minimum	Maximum	Mean
Proposed Model	0	23.76	6.40
SUSA Model	0	10.58	4.46
IEEE Model	0	28.11	16.00

6.2. Loss of Life Comparison

The loss of life calculated from the measured hot spot temperatures will be the reference for comparing the loss of life. The Loss of Life prediction curve of the proposed model looks the same as the curves of the other models and the reference curve, which is the Loss of Life calculated using the measured Hot Spots Temperature. However, when the transformer is running at its rated load or under load, the IEEE and SUSA models are closer to the reference. During the overload phase, the Loss of Life proposed model and SUSA model are closer to the measured values than the IEEE model.

The proposed model converges much better than the SUSA and IEEE models at the end of the load cycle. The change of transformer taps does not create peaks on the loss of life curve, but peaks are visible on the temperature of the hot spots. This observation can be explained by the fact that the electromagnetic and thermal phenomena which create peaks are of very short duration.

Tables 8 and Table 9 summarise the minimum, maximum and average Loss of Life Error, respectively, for the 400 MVA ONAF transformers and 605 MVA OFAF Transformer.

6.3. Advantages of the Proposed Model

The comparative study between the results obtained by the proposed model with those obtained by the IEEE [21] and SUSA [20] model, as well as the measured values, allows us to note that the proposed model has the following advantages:

1) The model can be applied to any load profile and, therefore, can be integrated into a real-time monitoring tool for the life of a transformer, whereas the IEEE and SUSA models, which are constrained by the exponential approach, are only applicable for transformer load profiles varying between rated load or overload and under load;
2) Taking into account the dynamics of certain parameters of the thermal model manages to compensate for the fundamental performance drop that the method of differential equations has on the method of exponential equations;
3) The proposed model globally converges better at the end of the cycle compared to the IEEE and SUSA models;
4) The proposed model is more efficient than the others for high power consumption. Knowing, therefore, that large ones induce higher temperatures and that high temperatures are those which most influence the loss of life of a transformer, it becomes clear that this model is very suitable for transformer overload regimes.

7. Conclusion

The aging of the transformer is closely linked to its use; the transformer is very stressed in terms of overload, will have a fairly high temperature of the hot spots, and the speed of aging of the transformer will increase. It is the overload phases that have a greater impact on ageing. Thus, the performance of prediction quality is closely linked to the precision of the model during the predictive calculation of the hot spot temperature during the overload phases. Therefore, a model can have a better prediction of the hot spot temperature globally but a worse prediction of the loss of life of the transformer. The proposed model inherited the imprecision of the method of differential equations. The model proposed in this article performs thanks to the consideration of parameter dynamics. An improvement in estimating the temperature of the hot spots in the under-load phases will increase the model's accuracy.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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