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Estimating the Loss of Life of the Electrical Power Transformer based on TOT and HST

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Extended Abstract

Temperature, especially the hot spot temperature and top oil temperature, have played the most effective factor on the insulation life of the transformer. The prediction of top oil temperature and hot spot temperature is very important for estimating the loss of life of the transformer in the system. Therefore, an accurate technique is needed for solving the thermal models. This study determines an accurate hot spot temperature and then evaluates the loss of life of transformer according to the numerical analysis method. An alternative solution for solving the thermal model is proposed in this work. Results are compared with the actual temperature, which were measured by fiber optic sensors. The proposed technique is implemented on 250 electrical power transformer.

I. Introduction

Transformers are one the most important facilities in electrical power systems that the correct operation of it has played main rule in provide reliability of these systems. By notice the costs of transformers and permanent connection of transformers to transmission and distribution systems, any action to increase the life cause improvement in the operation of power systems. Insulation life of the transformer and loading capabilities depend on several parameters.

Oil and paper in transformers are two insulation materials, that the integrity of them warranties the life of transformers. Hot spot temperature (HST) and top oil temperature (TOT) are two criteria to evaluate the integrity of these two insulation materials and transformers as important facility in power network. These criteria determine the temperature limitation of transformer for loading capability, for example the IEEE standard suggests that the TOT rise over ambient temperature 65°C and depend on it has considered 110°C for HST. It means that increasing the temperature of transformer over this standard value causes the degradation of insulation life of transformer and based on some research from 90°C to 110°C the tensile strength aging rate is doubled for approximately each 5°C to 10°C increase in temperature[1-3].

There are some dynamic factors in oil immersed transformer such as ambient temperatures, winding losses and oil viscosity of transformer [1, 4].

In this article, two thermal models, classic thermal model as famous and reliable thermal model and dynamic thermal model as improved thermal model, has been used. Moreover, TOT and HST is calculated for both thermal model by IEEE standard method that has been available in [1] and also these temperatures are calculated by proposed method. To validate and show the tolerance of numerical technique, the results of models compare with measured value.

Doi:

II. Thermal Model

2.1 Classic Thermal Model

Thermal model is used to estimate the different temperature of transformer. The classic thermal model was given based on the heat generated and distributed in the windings and oil of transformer[1, 5, 6].

The classic thermal model is governed by a differential equation as[1]:

$$T_0 \frac{d\theta_{top}}{dt} = -\theta_{top} + \theta_u + \theta_{amb} \tag{1}$$

The solution as follow:

$$\theta_{top} = (\theta_u + \theta_{amb} - \theta_{topi})(1 - e^{-(\frac{t}{T_0})}) + \theta_{topi} \tag{2}$$

And

$$\theta_u = \theta_{fl} \left[\frac{I_{pu}^2 R + 1}{R + 1} \right]^n \tag{3}$$

$$T_0 = \frac{C\theta_{fl}}{P_{fl}} \tag{4}$$

Where

θ_{TOP} top-oil rise over ambient temperature (C) ;

θ_u Ultimate top-oil rise for load L (C);

θ_i Initial top-oil rise for t=0 (C);

θ_{fl} Top-oil rise over ambient temperature at rated load;

T_0 Time constant;

n Oil exponent—(an empirically derived coefficient selected for each cooling mode to approximately account for change in resistance with load);

I : is the specified load

I_{rated} : is the rated load

I_{pu} : is the ratio of specified load to rated load.

The model for hot spot temperature rise over top oil is depending on the fact that an increase in the loading (current) causes an increase in the losses within transformer windings. Therefore, there is an increase in the temperature. Transient winding hottest- spot temperature rise over top oil temperature can be calculated as follow[1]:

$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,i}) \left[1 - \exp^{\frac{-t}{T_0}} \right] + \Delta\theta_{H,i} \tag{5}$$

That the initial value for hot-spot temperature rise over top-oil temperature is given by:

$$\Delta\theta_{H,i} = \Delta\theta_{H,R} I_{i,pu}^{2m} \tag{6}$$

And the ultimate hot spot as follow:

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} I_{U,pu}^{2m} \tag{7}$$

That the rated value of hot-spot is given by:

$$\Delta\theta_{H,R} = \Delta\theta_{H/A,R} - \Delta\theta_{TO,R} \tag{8}$$

Where

$\Delta\theta_H$	hot spot rise over top oil temperature (C).
$\Delta\theta_{H,U}$	ultimate hot spot temperature rise over top oil temperature for load(C).
$\Delta\theta_{H,i}$	initial hot spot temperature rise over top oil temperature for t = 0 (C).
T_0	winding hot spot time constant of the transformer(h)
t	duration of the load (h)
$\Delta\theta_{H,R}$	rated hot spot rise over top oil temperature (C).
I	load current per unit.
m	Exponent which defines non-linearity (accounts for the effects in resistance and oil viscosity change has been shown in table (1)).

The value of n has been specified by the manufacturer for each mode of cooling to approximately account for effects of change in resistance with change in load. Table 1 show the amount of n and m for each type of cooling .[2, 7]

Table 1. : Exponents used in temperature determination equations[7]

Type of cooling	M	N
OA	0.8	0.8
FA	0.8	0.9
Non-directed FOA or FOW	0.8	0.9
Directed FOA or FOW	1	1

After solving the differential equation (1), TOT has been achieved. Then, HST will be calculated by equation (9).

$$\theta_{HST} = \Delta\theta_{TOT} + \Delta\theta_{HST} + \theta_{amb} \tag{9}$$

2.2. Dynamic Thermal Model

Dynamic thermal model of a transformer based on the principals of heat transfer theory has been offered by Swift for the first time[8] and then Susa introduced improved model by assuming the non-linear thermal oil resistance based on swift's approach. The variations of viscosity with temperature were included in this model[9, 10].

TOT of dynamic thermal model is governed by equation (10)[9, 10],

$$\frac{1+R\times K^2}{1+R}\times\mu_{pu}^{n}\times\theta_{fl}=\mu_{pu}^{n}\times\tau_0\times\frac{d\theta_{oil}}{dt}+\frac{(\theta_{oil}-\theta_{amb})^{1+n}}{\theta_{fl}^{n}} \quad (10)$$

Oil viscosity is added as a parameter. This can be determined by [11].

$$\mu_{pu}=\mathrm{e}^{\left[\left(2797.3/\theta_{top}+273\right)-\left(2797.3/\theta_{fl}+273\right)\right]} \quad (11)$$

Where

K load current per unit,

R ratio of load to no-load losses,

τ_0 top oil time constant, (min),

θ_{fl} rated top oil rise over ambient, (K),

θ_{oil} top oil temperature gradient,(K),

θ_{amb} ambient temperature,(K),

μ_{pu} oil viscosity per unit,

empirical constant, the value of n has been specified for each mode of cooling in Table (2)[9].

Tabel 2. :Empirical constant n for the top oil thermal model

Oil circulation	n		
	With external cooling		Without external cooling
Initial oil circulation	ONAF/OFAF	ONAN	ONAN
Speed=0(cold start)	0.5	0	0.25
Initial oil circulation Speed>0(transformer on load)	0.2	0.25	0.25

HST of dynamic thermal model is given as [4, 9, 12]:

$$\left[K^2\times P_{wd,pu}\right]\times\mu_{pu}^{n}\times\Delta\theta_{hs,rated}=\mu_{pu}^{n}\times\tau_{wd,rated}\times\frac{d\theta_{hs}}{dt}+\left(\frac{(\theta_{hs}-\theta_{oil})^{n+1}}{\Delta\theta_{hs,rated}^{n}}\right) \quad (12)$$

Pwd,pu, is the load loss's dependence on temperature that can be determined by (13).

$$P_{wd,pu}=P_{dc,pu}\times\left(\frac{\theta_{hs}+\theta_k}{\theta_{hs,rated}+\theta_k}\right)+P_{eddy,pu}\times\left(\frac{\theta_{hs,rated}+\theta_k}{\theta_{hs}+\theta_k}\right) \quad (13)$$

Where Pdc,pu and Peddy,pu are the behavior of the DC and eddy losses depend on temperature. The DC losses vary directly with temperature, whereas the eddy losses vary inversely with temperature. Θk is the temperature factor for the loss correction, equal to 225 for aluminum and 235 for copper.Oil time constant (τ0) is one of the most important parameters that should be determined accurately. Note that, there are specific methods for each thermal model to calculate τ0. The oil time constant for dynamic thermal model is given by[13]:

$$\tau_0=\frac{C_{th-oil}\times\Delta\theta_{oil,rated}}{P_{total}} \quad (15)$$

III. Solving Techniques

3.1. Ieee Standard Method

IEEE standards C57.91-1995 has offered an exponential method based on the equation (14) to calculate the TOT to determine the HST of transformers for classic thermal model[1]. The equation (14) is derived of equation (1).

$$\Delta\theta_{TO}=(\Delta\theta_{TO,U}-\Delta\theta_{TO,i})\left[1-\exp^{\frac{-1}{T_0}}\right]+\Delta\theta_{TO,i} \quad (16)$$

The ultimate value of top oil rise for each step is given by,

$$\Delta\theta_{TO,u}=\theta_{fl}\left[\frac{(I_{pu,u}^{2}R+1)}{(R+1)}\right]^{n} \quad (17)$$

For calculating the initial value for the first time, t=0, knowing the record of loading profile can be so useful. The current at t=0, determined by RMS value of the loading currents for the former loadings [1]. Equation (3.5) can be used to estimate the initial value for other steps to calculate the top-oil temperature rise.

$$\Delta\theta_{TO,i}=\theta_{fl}\left[\frac{(I_{pu,i}^{2}R+1)}{(R+1)}\right]^{n} \quad (18)$$

3.2. Numerical method

Numerical methods are the solutions of ordinary differential equation (ODE) of initial value. In this paper, two numerical solvers are used to calculate the thermal models. First one is Euler's method that is the simplest solver where it cannot be considered as an adequate solver in most application. However, it is easy to explain, and it indicates important features that are common to all solvers. Another one is a more advanced technique used in solving the ODE, i.e. Runge-Kutta (R-K) solvers.

The R-K solvers are adequate solvers and can be used in many applications [14-16].

The algorithm shows in Figure 2 demonstrates in an Euler's method. The Fourth-Order R-K Method probably the most commonly used solution algorithm. It is suitable for any system as it is claimed to fast and accurate. For this method, there are four slopes, and begin with an initial value (t0,y0).

$$\begin{aligned} K_1 &= f(t_0, y_0), \\ K_2 &= f(t_0 + \frac{h}{2}, y_0 + \frac{h}{2}K_1), \\ K_3 &= f(t_0 + \frac{h}{2}, y_0 + \frac{h}{2}K_2), \\ K_4 &= f(t_0 + h, y_0 + hK_3), \end{aligned} \tag{19}$$

With these slopes the next values of the dependent variable can be calculated as,

$$y_k = y_{k-1} + h\frac{K_1 + 2K_2 + 2K_3 + K_4}{6} \tag{20}$$

Figure 3 summarizes the procedures in the Fourth-order R-k's method

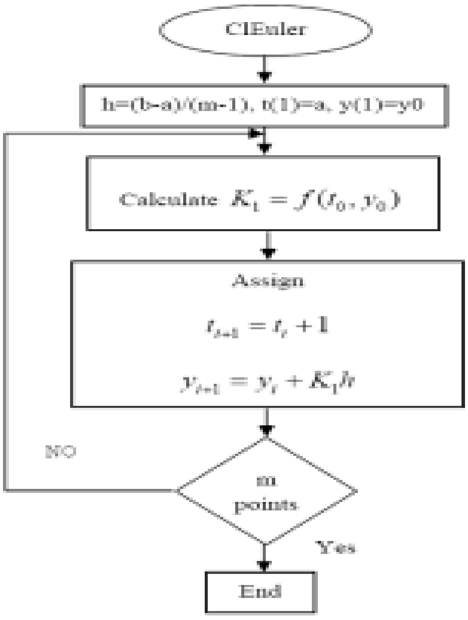

Figure 2 :Algorithm for Euler's method

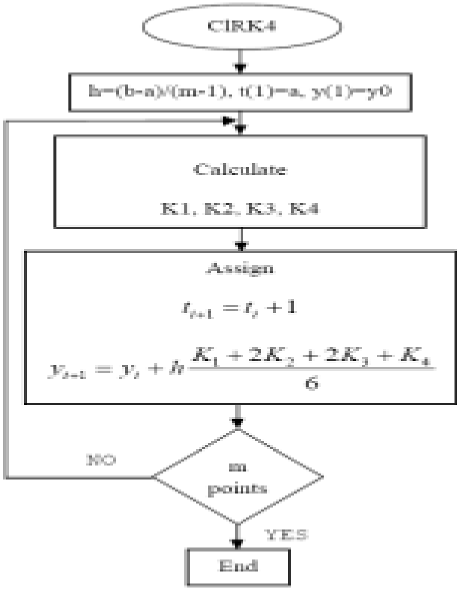

Figure 3: Algorithm for R-K's method

The input data can be classified in two groups i.e constant and variable input data. Constant data are n, m, weight of oil per kg, load losses and no-load losses, oil time constant and winding time constant, DC and eddy losses, and hot spot temperature at rated load. While variable input data are something that can be changed by time including current or loading of transformers and ambient temperature.

IV. Loss Of Life Of Transformer

The life of transformers is directly proportional to the quality of insulation of transformers such as oil and paper, that the conditions of paper play the main rule in the life of the transformers. Moisture, heat and oxygen are the most important parameters that from these parameters the hottest temperature in transformer is determined and these parameters cause deterioration of paper and decrease the life of the electrical transformer.

Insulation deterioration can be modelled as a per unit quantity and calculated as [17-19];

$$per-unit-life = Ae^{\left[\frac{B}{\theta_{HST}+273}\right]} \tag{21}$$

Where

A is a modified constant based on the temperature established for one per unit life,

B is the aging rate slope.

IEEE standard C57.91-1995 considered B=15000 is appropriate and is used in per-unit-life equation for loading of transformers. For θ_{HST} =110 C, and per-unit-life=1, the value of A constant becomes 9.8×10-18.

The aging factor that indicates the comparison between the acceleration of transformer insulation aging with the aging rate at a reference hottest spot temperature, the reference hottest spot temperature based on IEEE standard is 110C for 65C average winding rise and 95C for 55C average winding rise transformers, can be calculated [17, 18, 20, 21]:

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} \tag{22}$$

The following equation could be used to determine the equivalent aging of the transformer with regard to the reference temperature for hottest spot is $110°C$ [1, 17]:

$$F_{EQA} = \frac{\sum_{n=1}^{N} FAA_n \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{23}$$

Where

F_{EQA} is equivalent aging factor for the total time period,

n is index of time interval,

N is total number of time intervals,

Δt_n is time interval.

And, the percent loss of life can be calculated as [1, 17, 22]:

$$\%loss - of - life = \frac{F_{EQA} \times t \times 100}{NIL} \tag{24}$$

V. Thermal tests for case of study

5.1. Three Phase 250 MVA Transformer

The ratio of voltage of transformer is 230/118 KV and cooling system is with external cooling system, ONAF. The data has been collected from references [12] and [17] . The top oil and hot spot temperature were collected by thermocouples and have been embedded on this transmission transformer.

The measured hot-spot temperature results, recorded during a varying load current test, have been given in Table 3.

Table 3.: Load steps of the 250 MVA transformer

Time intervals (minutes)	Load (PU)
0-187.4	1
187.4-364.9	0.6
364.9-503.4	1.5
503.4-710	0.3
710-735	2.1
735-750	0

VI. Results

In this section the results of Matlab program for the case study are presented. Whilst, transformer has been investigated for two types of the thermal models i.e. dynamic and classic thermal model, their results were compared with each other. And also, transformer was investigated for classic thermal model. The model was employed to estimate the TOT, HST and LOL of the transformer. Furthermore, the absolute differences of each solution method, i.e. numerical methods, and exponential method, were determined with measured values. In the second step, the results were calculated for dynamic thermal model and were compared with three types of numerical methods i.e RK4, RK2, and Euler.

Finally, the errors for each thermal model were compared and the results were tabulated in Tables (4) and (5). Based on the aim of this research the errors for different techniques from the exponential method to numerical methods indicate and compare with each other.

6.1. 250 MVA Transformer Based on Classic Thermal Model

The 250 MVA transformer was tested for 750 minutes by Susa [12]. Figures 4 shows the comparison between the measured hot spot temperatures and the hot spot temperatures obtained by the numerical methods and exponential method. Graphs have been plotted based on the classic thermal model. Figure 5 shows FAA

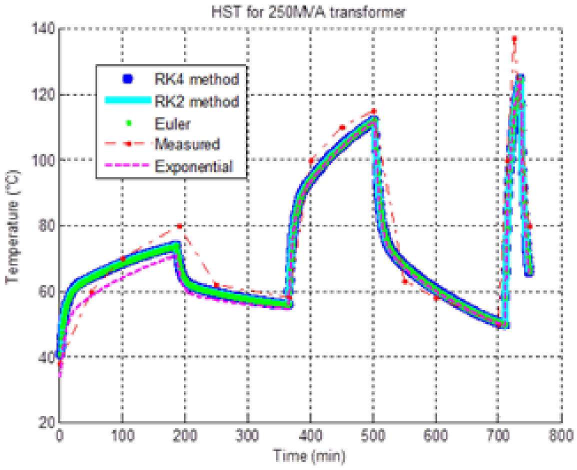

Figure 4: Hot spot temperature of 250 MVA transformer based on classic thermal model

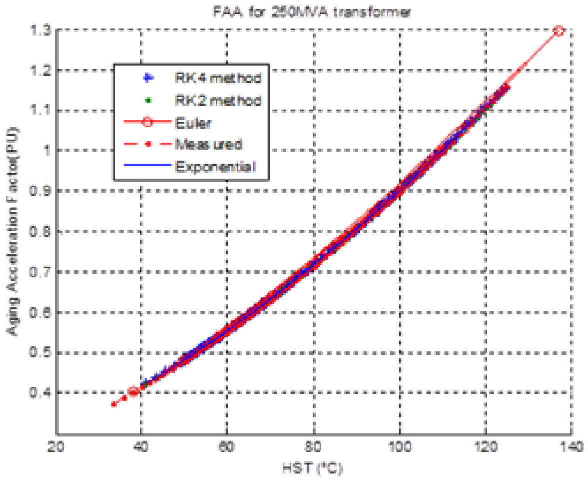

Figure 5: Aging acceleration factor of 250 MVA transformer based on classic thermal model

Table 4. : Results of classic thermal model of 250 MVA transformer
(ERROR OF LOL)

Error for RK4 $\left\|(LOLNUM - LOLMeasured)\right\|$	Error of exponential $\left\|(LOLIEEE - LOLMeasured)\right\|$
14.86 (min)	25.9162 (min)

Table 5. : Results of dynamic thermal model of 250 MVA transformer

(ERROR OF LOL)

Error for RK4 method-min $\left\|(lolRK4 - lolMeasured)\right\|$	Error for Euler method-min $\left\|(lolEuler - lolMeasured)\right\|$	Error for RK2 method-min $\left\|(lolRK2 - lolMeasured)\right\|$
2.2583	2.4397	2.2594

VII. Conclusion

Several models and solutions have been suggested for solving various thermal models to determine the TOT and HST of transformer due to loss of life evaluation. These methods involved a linear and nonlinear regression and exponential methods that proposed by IEEE standard. An improved numerical method called R-K technique was proposed in this paper for solving two type of thermal models i.e. classic thermal model (that was suggested by IEEE standard C57.91-1995) and thermal-electrical model or dynamic thermal model (that assumed number of variable parameters such as viscosity of oil, ambient temperature, eddy losses). Results concluded that the dynamic model has performed well as compared to the classic thermal model whilst and the R-K technique provided better accuracy as compared to other traditional techniques.

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