Investigation of IEC Thermal Models of Power Transformers

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Abstract

Power transformers are crucial components of electric power systems for continuity of electricity. The reliability of power system depends greatly on the operational performance of the power transformers under different operating conditions. The most important indicator of the operating performance of oil-immersed transformers is the top-oil and the hottest-spot temperature values. Therefore, different thermal models have been developed in the literature to estimate temperature changes of power transformers. In this study, thermal models developed by IEC Loading guide for oil and winding temperatures of power transformers are studied. To the best of our knowledge, description of IEC models in the literature have some ambiguous points. Thus, ambiguous points have been clarified and some modification to IEC models has been introduced to have better estimates of top-oil and hottest-spot temperatures of power transformers. With these modifications, top-oil and hottest-spot temperatures, which are given for 250MVA ONAF transformer unit in IEC Annex-b, are presented during different load variations as an example.

1. Introduction

The heating and cooling processes in transformers are quite complicated phenomenon and therefore, the change of temperature depends on many factors such as temperature difference between heated solid parts and coolant, the thermal conductivity of the fluid and structural features of the transformer. The thermal behavior of a transformer has a great role for determining the transformer life expectancy and transformer loading capability. The variations of top-oil and hottest-spot temperature need to be observed or estimated for normal operation and for emergency loadings.

Transformer temperatures can be obtained by using direct measurement method. In the direct measurement method, the fiber optic sensors are placed at various locations inside the transformer, and then the oil and winding temperatures are measured via fiber optic sensors during the heat run tests. Fiber optic sensors provide sensitive measurements but this, direct measurement technique, is costly and challenging procedure. In addition, placing sensors and then removing them from the transformer is a process that requires considerable efforts. For this reason, computer-based simulation and modeling techniques developed by researchers have been used to determine transformer temperature rises [1],[2],[3],[4],[5]. These models determine temperature change inside transformer by applying fundamentals of heat transfer theory and fluid mechanics.

Electric charge and discharge process have similarity with temperature increase and decrease of a mass. Therefore, a simple electric RC circuit may represent the thermal behavior of power transformer. Reference [1] has suggested a simple equivalent circuit model (EC Model) to comprehend thermal behavior of power transformer, and it has proposed a thermal model that is determined by differential equations based on heat transfer principles to calculate top-oil and hottest-spot temperature. However, the equivalent circuit in reference [1] does not include the nonlinear thermal resistance of the transformer oil to represent the thermal behavior of the power transformer. The physical parameters of the transformer oil vary depending on temperature, and the oil viscosity is one of the most affected parameters of the temperature change [2]. For this reason, the change of viscosity has considerable influence on the thermal resistance of oil. The thermal model in [1] has been extended by [3]. The thermal model in [3] offers a new calculation method based on heat transfer theory, lumped capacitance method and thermal-electrical analogy. The model includes two individual RC circuit for top-oil and hottest-spot temperature. The circuit equations take account of the oil viscosity changes and loss variations with temperature. The equivalent circuit model have been studied in detailed before [3],[6] ,[7].

IEEE and IEC loading guides have suggested computational procedures to determine the temperature change of a transformer throughout different loading periods [5],[4]. IEEE provides two different procedures to calculate hottest-spot and top-oil temperatures in loading guide C57.91 [5]. The first method proposed by IEEE is called as the Clause 7 and has relatively simpler equations than the other method recommended in loading guide. The method accepts that the top-oil temperature is the same as the oil temperature in the cooling ducts during overloading. Comprehensive researches with thermocouples and fiber optic detectors have shown that oil temperature in the cooling ducts may exceed top-oil temperature in the tank during overloading [2]. Based on these findings, IEEE suggests alternative calculation procedure which is called as the Annex G in loading guide. Annex G is a more detailed calculation method and assumes that the oil temperature rise in the cooling ducts is higher than the top-oil temperature rise in the tank during overloading.

Other methods which can be used to estimate thermal behavior of transformer are presented by International Electrotechnical Commission (IEC) [4]. IEC proposes two separate calculation procedures for temperature calculations of power transformers which are different from the methods suggested by IEEE: the exponential method and the differential method. The first method which is called exponential method uses separate equations based on load increase or load decrease, and accepts the loading curves as the step function. The exponential method assumes that the cooling and heating processes in the windings due to the load variation of the transformer have different rates of change. The differential method, which is the second method suggested, calculates the hottest-spot temperature in the windings by taking the difference of the two differential equations. The exponential method can be considered as a special case of the differential method. The differential method is more general since it has no restrictions on the load shape.

In this study, thermal models developed by IEC Loading guide for oil and windings temperatures of power transformers are investigated. These models are IEC Exponential, and IEC Differential models. To the best of our knowledge, description of IEC models in the literature have some ambiguous points. The key problem in IEC [4] methods is that the hottest-spot temperature gets equal to top-oil temperature instantly or may reach values less than the top-oil temperature at decreasing load steps. A new function which represents the hottest-spot temperature rise over oil during the load reduction in the exponential method is proposed for solving this problem. It is also shown that the two diverse equations proposed by the exponential method for the top-oil temperature rise over ambient are actually the same equation. Using a similar approach applied to the exponential method, a new differential equation is proposed which represents the temperature change in the windings for the hottest-spot temperature rise during load decrease. The calculation results for top-oil and hottest-spot temperatures, which are given for 250MVA ONAF transformer unit in IEC Annex-b, are presented during different load variation. All the data of the transformer used in this study are adapted from reference [4]. The computer programs for thermal models are written and run for 250MVA ONAF transformer unit given by reference [4].

2. Modification on IEC Exponential Model

The exponential method accepts step changes for transformer loading, and the key restriction of the method is that each of increasing load step must be followed by a decreasing load step or vice versa. In addition, the exponents used in exponential method are obtained from tests or manufacturers. During calculations, separate temperature functions are used for an increasing loading steps and for a decreasing loading step. The IEC utilizes three functions to calculate hottest-spot temperature and top-oil temperature values for increasing and decreasing load cycles. The relative increase of the top-oil temperature rise is described in equation *1*.

$$f_1(t) = \left(1 - e^{\frac{-t}{k_{11}\times\tau_o}}\right) \tag{1}$$

The relative increase of the hottest-spot to top-oil gradient is defined by equation *2*.

$$f_2(t) = k_{21}\times\left(1 - e^{\frac{-t}{k_{22}\times\tau_w}}\right) - (k_{21}-1)\times\left(1 - e^{\frac{-t}{\tau_o/k_{22}}}\right) \tag{2}$$

The relative decrease of the top-oil to ambient gradient is given by equation *3*.

$$f_3(t) = e^{-t/(k_{11}\times\tau_o)} \tag{3}$$

In these functions, the constants k_{11}, k_{21}, k_{22} and time constants τ_o, τ_w are determined in prolonged heat-run test for different loading and cooling conditions. The equations *1*, *2* and *3* are used for the top-oil temperature and hottest-spot temperature calculations. For an increasing load step, the top-oil temperature rise over ambient ($\Delta\theta_o$) is given by equation *4*.

$$\Delta\theta_o = \Delta\theta_{oi} + \left[\overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x - \Delta\theta_{oi}\right]f_1(t) \tag{4}$$

Where $\Delta\theta_{oi}$ is the initial top-oil temperature rise over ambient temperature for any time interval, $\overline{\Delta\theta}_o$ is the top-oil temperature rise over ambient temperature at rated load, *K* is load factor, $\bar{R}$ is the ratio of load loss at rated load to no-load loss and *x* is exponential constant obtained from heat run test. For a decreasing load step, the top-oil temperature rise over ambient ($\Delta\theta_o$) is given by equation *5*.

$$\Delta\theta_o = \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x + \left[\Delta\theta_{oi} - \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x\right]f_3(t) \tag{5}$$

Although the model suggests two equations to be used separately for increasing and decreasing load changes during top-oil temperature rise ($\Delta\theta_o$) calculations, it can be seen that only one equation is enough to describe the top-oil temperature change in transformers. If we substitute equation *1* into *4*, we obtain equation *6*.

$$\Delta\theta_o = \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x - \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x e^{\frac{-t}{k_{11}\times\tau_o}} + \Delta\theta_{oi}e^{\frac{-t}{k_{11}\times\tau_o}} \tag{6}$$

Similarly, the top-oil temperature rise over ambient during load decrease is obtained by substituting equation *5* into equation *3*. So, the expression obtained is as follows

$$\Delta\theta_o = \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x - \overline{\Delta\theta}_o\left[\frac{1+\bar{R}K^2}{1+\bar{R}}\right]^x e^{\frac{-t}{k_{11}\times\tau_o}} + \Delta\theta_{oi}e^{\frac{-t}{k_{11}\times\tau_o}} \tag{7}$$

The equation *6* for the load increase and equation *7* for the load decrease are the same equations. Therefore, there is no need to use distinct equations for the top-oil temperature. Moreover, this equality shows that the load decrease and increase have same effect in the change of the top-oil temperature.

A similar situation is not observed over the hottest-spot temperature rise over oil ($\Delta\theta_h$) because the method proposes the following expression for load increase.

$$\Delta\theta_h = \Delta\theta_{hi} + (Hg_r K^y - \Delta\theta_{hi}) f_2(t) \qquad (8)$$

However, the method uses an expression that does not change in time for hottest-spot temperature rise over oil during load decrease, which is physically impossible since windings are submerged in oil. Nevertheless, the used expression of temperature rise produces a constant value for each corresponding decreased load steps in IEC standard. The hottest-spot temperature rises over oil ($\Delta\theta_h$) during load decrease is given by equation *9*.

$$\Delta\theta_h = Hg_r K^y \qquad (9)$$

Equations *8* and *9* suggested by IEC can be interpreted as following. Firstly, the method assumes that the hottest-spot temperature rise over oil temperature has a different dynamic during load increase and decrease. Secondly, the method accepts that the difference between the top-oil and the hottest-spot temperature is constant during the load decrease. The equations based on an assumption of a constant temperature difference between hottest-spot and top-oil for dynamically evolving heating and cooling processes may not produce accurate results. Particularly, the consequence of constant temperature difference acceptance is that the hottest-spot temperature directly reaches the top-oil temperature under decreasing load steps. This behavior may be explained by an example of 250 MVA ONAF cooled transformer given in IEC Annex-b. The transformer data have been taken from IEC standard as it is, without any change, and the transformer data used can be examined in [4]. The loading of the transformer is chosen in the form of step function in which each load increase is followed by a load decrease. The loading factor used for simulation is given in *Table 1*. During simulation, the ambient temperature is taken as constant and it is equal to 25.6℃. The initial values of top-oil and hottest-spot temperatures are taken as equal to ambient temperature. The hottest-spot and the top-oil temperatures are calculated based on IEC standard and their dynamics are shown in *Figure 1*.

Table 1. Load step of the 250 MVA ONAF transformer

Time period (min)	Load factor (pu)
0-190	1
190-365	0
365-500	1
500-710	0
710-735	1
735-750	0

The temperature difference ($\Delta\theta_h$) between the hottest-spot and the top-oil takes the constant value (zero) in each of duration of load decreasing periods. This means that the transformer windings are cooling down much faster than oil. In other words, the hottest-spot temperature gets equal to the top oil instantly, but this is an impossible situation for the winding which is the source of heat and it is submerged in oil. The quick decline in the hottest-spot temperature rise can be corrected only by redefining the equation used for the time intervals in which the load decrease occurs. For this reason, the equation *10* (simplified expression of equation *2*), which determines the rate of temperature change at the hottest-spot over top-oil, needs to be examined.

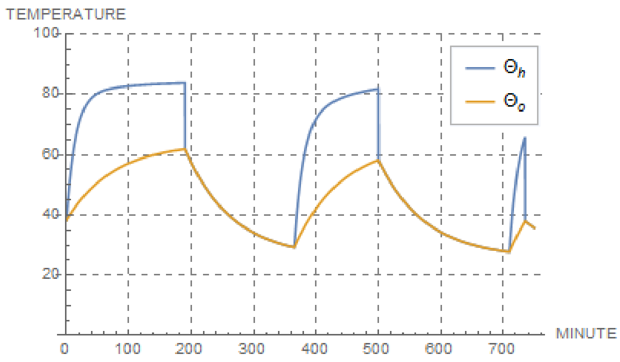

Fig. 1. Hottest-spot and top-oil temperature for 250MVA transformer using IEC exponential model

The equation *10* is obtained by taking the difference between the two components with the winding time constant and the oil time constant. These components are given by equations *11* and *12*.

$$f_2(t) = f_{21}(t) - f_{22}(t) \qquad (10)$$

$$f_{21}(t) = k_{21} \times \left(1 - e^{\frac{-t}{k_{22} \times \tau_w}}\right) \qquad (11)$$

$$f_{22}(t) = (k_{21} - 1) \times \left(1 - e^{\frac{-t}{\tau_o / k_{22}}}\right) \qquad (12)$$

The constants k_{21} and k_{22} used in both components are the empirical values determined according to the type of transformer cooling in the IEC heat-run tests. In *Figure 2*, the graphs of equation *10,* and its components are given for 250 MVA ONAF cooling transformer in IEC loading guide.

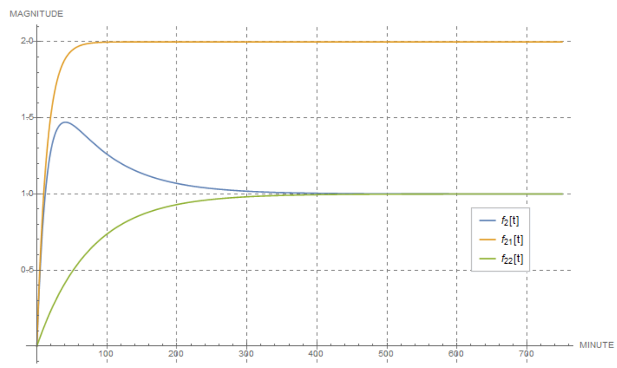

Fig. 2. The functions $f_2(t)$, $f_{21}(t)$ and $f_{22}(t)$

The reason of this overshoot above the rated value is the constant k_{21} in the equation and it can be interpreted physically as it corresponds to an inability of the oil to circulate in the tank immediately after initial loading. In other words, the oil will take some time to change its circulation velocity once the load is increased and this will result with an overshoot in the winding temperature until the oil removes larger heat to the environment by the increased velocity in the tank. The rate of exponential change of function is determined by the winding time constant. Similarly, the cooling in the windings can be represented by an exponential function that varies depending on the winding time constant during load decrease. However, cooling of winding cannot be determined by the equation *2* used during load increase because the temperature of the windings should not reach lower values than the oil temperature during load decrease. For this reason, an expression that varies depending on the winding time constant for the hottest-spot temperature rise over oil during load decrease, but does not reach negative values is needed. Therefore, a function is proposed to account the temperature change in the winding during load decrease as following.

$$f_4(t) = \left(1 - e^{\frac{-t}{k_{22}\times\tau_w}}\right) \tag{13}$$

The function $f_4(t)$ determines the cooling rate of the winding based on the winding time constant during load decrease. The hottest-spot temperature rise over oil can be expressed as below for decreasing load.

$$\Delta\theta_h = \Delta\theta_{hi} + (Hg_r K^y - \Delta\theta_{hi})f_4(t) \tag{14}$$

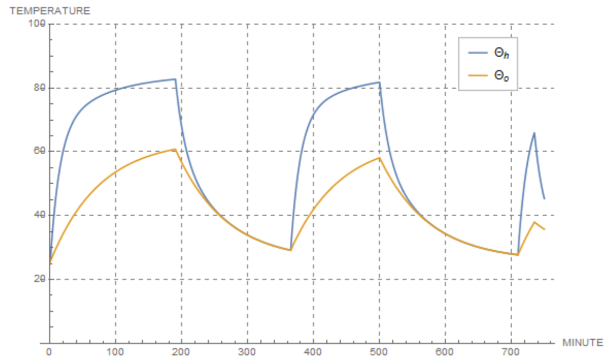

Fig. 3. Hottest-spot and top-oil temperature for 250MVA transformer using modified IEC exponential model

With the proposed correction, the top-oil and the hottest-spot temperature obtained for the 250MVA ONAF transformer are given in *Figure 3*. The time constant of the windings is smaller than the oil time constant. For this reason, the windings are heated and cooled much faster than the oil. The arrangement made provides that the difference between the hottest spot and the top oil is at a temperature which varies with the winding time constant during the load decrease. In *Figure 3*, the transformer windings start to cool down depending on the winding time constant when the load is removed, and the hottest-spot temperature reduces to the top-oil temperature rapidly and becomes equal until loading the transformer again.

3. Modification on IEC Differential Model

Another problem for the hottest-spot temperature is observed in the differential model. The differential model produces lower values than the oil temperature for the hottest-spot temperature during load decrease. Hence, the equations proposed by the differential method need to be re-arranged. *Figure 4* shows the top-oil and the hottest-spot temperatures for 250MVA ONAF transformer. The load factor of the transformer is as in *Table 1*.

The differential model computes the hottest-spot temperature rise for both cases of the load increase and decrease via the difference between two different differential equations. Related equations have been given in reference [4]. In *Figure 4* the differential method produces negative values for the hottest-spot temperature rise during load decrease. Because of the different heating and cooling rates of the windings, the equations used for the winding temperature rise during the load increase generate incorrect (negative) values when used for load decrease.

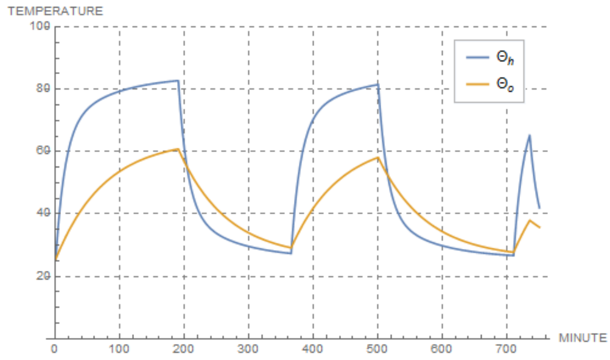

Fig. 4. Hottest-spot and top-oil temperature for 250MVA transformer using IEC differential model

For this reason, a new differential equation is needed for the hottest-spot temperature rise which is different from suggested differential model during the load decrease. The differential equation which represents rapid cooling at the winding temperature during the load reduction can be expressed by equation *15* below.

$$K^y \overline{\Delta\theta}_h = k_{22}\tau_w \frac{d\Delta\theta_{h3}}{dt} + \Delta\theta_{h3} \tag{15}$$

The equation *15* represents the cooling of the windings during each load decrease based on the winding time constant (τ_w) and the coefficient (k_{22}). The coefficient k_{22} is determined according to the cooling type of the transformer [4]. The equation *15* is used for the hottest-spot temperature rise in time intervals during each load decrease. $\Delta\theta_{h3}$ performs a rapid decrease in time intervals where the load factor is zero but does not reach negative values. The hottest-spot and top-oil temperatures for the 250 MVA ONAF transformer using modified differential equation model are given in *Figure 5*.

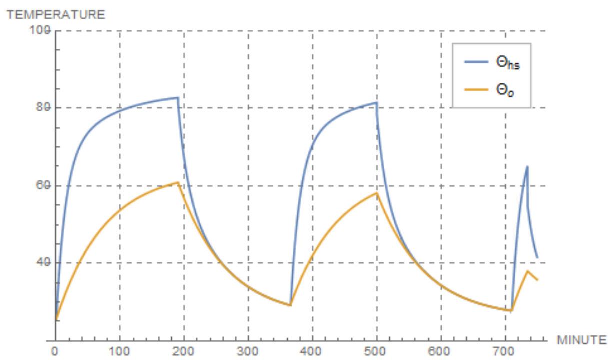

Fig. 5. Hottest-spot and top-oil temperature for 250MVA transformer using Modified IEC differential model

The hottest-spot temperature with the use of the equation *15* does not become lower than the top-oil temperature during load decrease. In Figure *5*, the temperature of the winding decreases rapidly when the load is removed, and it reaches the top-oil temperature based on the winding time constant.

4. Conclusions

Two thermal models presented by IEC have been examined in this study. It has been shown that the distinct equations, which are suggested by IEC exponential method for top-oil temperature during load decrease and increase, are the same equations and there is no need to use two different equations. It has also been shown that the equation proposed during the load decrease for the hot-spot temperature increase produces a constant value at the decreasing load step. To correct this erroneous situation, a new equation has been proposed to represent the cooling of the winding depending on the winding time constant during load decrease. It was observed that the hot-spot temperature value for the differential model reaches lower values than the top- oil temperature in the load decreasing steps. This is not physically possible situation and a new differential equation has been proposed to be used during load reduction in the differential model. The suggested modifications are applied to the 250MVA ONAF transformer given in the IEC standard. The study needs to be extended for different transformer units, and different loading conditions.

5. References

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