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Top-oil Temperature Model for Transformers based on Nonlinear Thermal Resistance, Lumped Capacitance and Thermal-electrical Analogy

M. H. Roslan[1,2]*, N. Azis[2], J. Jasni[2] and Z. Ibrahim[2]

[1]*Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, 57000 Kem Sg Besi, Malaysia*
[2]*Centre for Electromagnetic and Lightning Protection Research, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*

ABSTRACT

Top-Oil Temperature (TOT) is one of the basic components to estimate the Hot-Spot temperature (HST) of the transformers. This paper presents an alternative TOT model based on the heat transfer theory that utilises Nonlinear Thermal Resistance (NTR) and Lumped Capacitance (LC) approaches. It is applied in a thermal-electrical analogy and the heat transfer equivalent equation is determined. This model is tested on a measured TOT of 250 MVA ONAF and 400 MVA ONAF transformers obtained from IEC 60076-7 and previous research. A comparison of TOT is carried out with the existing models IEC 60076-7 exponential and IEEE Loading Guide clause 7 methods. It is found that the thermal model based on the NTR and LC approach could determine the measured TOT closer than the existing methods available in the standards.

Keywords: Top-oil temperature, thermal model, transformers

INTRODUCTION

Transformers are static devices which consist of windings and a core that can transmit electrical power by electromagnetic induction between primary and secondary circuits at the same frequency but at different voltages levels (Winders, 2002). In a power system, transformers are one of the most important and expensive pieces of equipment. Due to this expense, it is important to maintain transformers in-service for as long as possible. One of the stresses that can lead to transformer failure is thermal stress which refers to the winding hottest spot temperature (HST) which can cause advance degradation of the oil and paper in transformers. It is well

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E-mail addresses:
hakirinroslan@gmail.com (M. H Roslan),
norhafiz@upm.edu.my (N. Azis),
jas@upm.edu.my (J. Jasni),
zulib78@gmail.com (Z. Ibrahim)
*Corresponding Author

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known that the HST consists of Ambient Temperature (AT), top-oil temperature rise and hotspot temperature rise over the top-oil temperature ("IEEE Guide for Loading Mineral-Oil-Immersed Transformers," 1996; Standard; Susa, Lehtonen, & Nordman, 2005). Generally, the HST can be obtained by two methods, which are direct measurement using a fibre optic sensor and a thermal model calculation. There are two standards that provide the thermal model calculation, namely the IEC 60076-7 and IEEE C57.91-1995 ("IEEE Guide for Loading Mineral-Oil-Immersed Transformers," 1996; Standard). According to IEC 60076-7, there are two methods that can be used to determine the HST which are the exponential and differential approaches. The exponential method is suitable for a load variation according to a step function (Standard). On the other hand, the differential method is suitable for online monitoring of the HST (Standard). According to IEEE C57.91-1995, there are also two methods that can be used to determine the HST known as Clause 7 and the Annex G method ("IEEE Guide for Loading Mineral-Oil-Immersed Transformers," 1996). The Clause 7 method is straightforward, but it is less accurate as compared to Annex G. However, the Annex G method is quite complex and requires a thermal parameter which is not usually available in the normal heat run test report.

Nomenclature

A	Area
C	Parameter with unit $W/m^2.K^{(1+n)}$
C^{oil}	Thermal capacitance
I	Load current
K	Load factor
n	A constant
P_w	Copper losses
P_E	Eddy losses
P_s	Stray losses
q_{cu}	Heat generated by load losses
q_{fe}	Heat generated by no load losses
R	Ratio of load losses at rated current to no load losses
R_{oil}	Oil thermal resistance
θ_α	Ambient temperature
θ_{oil}	Top-oil temperature
θ_{hs}	Hotspot temperature
$\Delta\theta_{oil,rated}$	Top-oil rise at rated
τ_{oil}	Oil time constant
rated	Subscript indicates rated value

A number of thermal models have been developed to estimate transformer thermal behaviour and to predict the HST and TOT with better accuracy (Pierce, 1992; Susa & Lehtonen, 2006a, 2006b; Susa et al., 2005; Swift, Molinski, Bray, & Menzies, 2001; Swift, Molinski, &

Lehn, 2001; Weigen, Chong, & Yuxin, 2009). One of the models, the Pierce model, indicates that there is a time lag between the top-oil temperature rise and the oil temperature rise inside the winding cooling ducts during overloading which leads to higher prediction of the HST (Pierce, 1992). The Swift model introduces the concept of a thermal-electrical analogy which is based on a simple equivalent RC circuit (Swift, Molinski, & Lehn, 2001). The thermal model applies a current source analogy to represent the heat input due to losses and a nonlinear resistance analogy to represent the effect of air or coil cooling convection currents (Swift, Molinski, & Lehn, 2001). The Dejan Susa model is based on a thermal-electrical analogy model which takes into account oil viscosity changes and loss variation with temperature. Other thermal models introduce the NTR and LC in the computation of TOT and HST (Susa & Lehtonen, 2006a, 2006b; Susa et al., 2005). In this paper, the researchers aim to develop an alternative TOT model which is based on the heat transfer and thermal-electrical analogy theory. The alternative TOT model also used the approximation of convection coefficient *h* which eliminates the input parameter such as viscosity. The input parameter of the alternative TOT model is tied with the parameter obtained from normal heat run test report which is not required input parameter such as oil temperature in cooling duct obtained from special heat run test report. This TOT model is also suitable for dynamic loading and ambient temperature, however the existing model in IEC 60076-7 exponential and IEEE C57.91-1995 Clause 7 are not suitable for this. The concept of the TOT model is presented and tested based on the measured TOT available in the standards and previous research.

HEAT TRANSFER THEORY APPLICATION TO TRANSFORMERS

Application of Nonlinear Thermal Resistance

Heat transfers occur when there is a spatial temperature difference in a medium or between media, that always flows from hot to cold (Bergman, Incropera, & Lavine, 2011). In transformers, the heat source originates from transformer losses (load and no load losses) which flow through the oil to the tank of the transformer as shown in Figure 1 (Perez, 2010). The basic components of a transformer are the windings, core, transformer oil and tank. The heat flow inside a transformer is also shown in Figure 1.

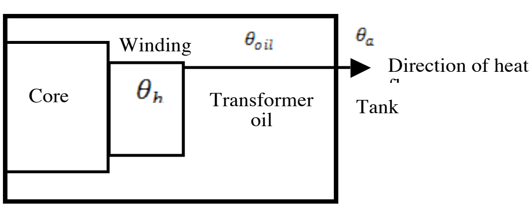

Figure 1. Heat flow inside a transformer (Swift, Molinski, & Lehn, 2001)

θ_{hs} is the HST which is the hottest temperature in a transformer and θa is the AT which is the coolest temperature. Heat will transfer through all the medium to the tank from θ_{hs} to θa. All mediums have their own thermal resistance which acts like a dissipation element. This thermal resistance is known as a nonlinear thermal resistance (Bergman et al., 2011; Susa et al., 2005; Swift, Molinski, & Lehn, 2001). Heat sources in a transformer are generated from no load and load losses.

Load losses are copper losses q_{cu} generated from the windings and no load losses are core losses q_{fe} generated from the metal parts such as the tank, core etc. (Perez, 2010). For θ_{hs} the heat source comes from copper losses, q_{cu} and for θ_{oil}, the heat source comes from q_{cu} and q_{fe}. Based on the heat flow in Figure 1, the heat transfer thermal resistance equivalent circuit with heat sources was determined and shown in Figure 2.

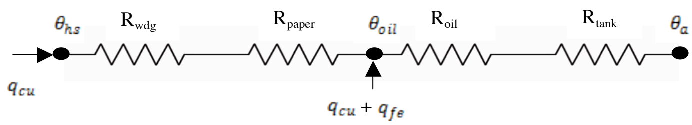

Figure 2. Thermal resistance equivalent circuit with heat source

The thermal resistance of tank R_{tank} can be neglected because it is a perfect heat conductor (Swift, Molinski, & Lehn, 2001). The heat transfer thermal resistance equivalent circuit can be re-drawn as shown in Figure 3.

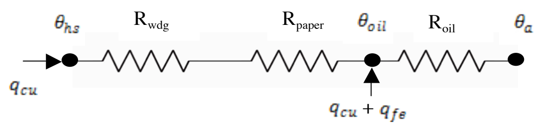

Figure 3. Thermal resistance equivalent circuit with heat sources

Application of lumped capacitance method

The thermal resistance equivalent circuit can only be used to determine the steady state condition. The LC approach is required for application in the thermal model under transient conditions (Bergman et al., 2011). In order to use this approach, the Biot number *Bi* must be below one (Bergman et al., 2011; Swift, Molinski, & Lehn, 2001). The Biot number is the ratio of the thermal resistance of conduction divided by the thermal resistance of convection. For transformers, it is the winding thermal resistance divided by the oil thermal resistance. This method uses capacitance as a component added to the heat transfer thermal resistance equivalent circuit which can be represented as an RC circuit as shown in Figure 4.

Thermal-electrical analogy

The thermal equivalent circuit which utilises the NTR and LC was used to derive the heat transfer equation. The thermal-electrical analogy was applied since its concept was the same as the thermal equivalent circuit. The thermal-electrical analogy variables are shown in Table 1.

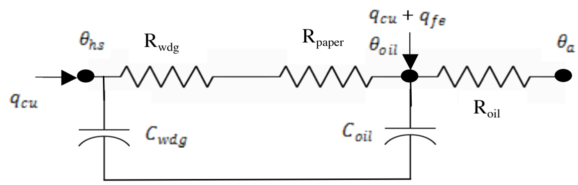

Figure 4. Thermal resistance equivalent circuit with application of lumped capacitance method

Table 1
Thermal-Electrical Analogy Variables (Susa et al., 2005; Swift, Molinski, & Lehn, 2001)

	Thermal	Electrical
Through Variable	Heat source, q units in watts	Current, *i* units in amperes
Across Variable	Temperature, θ unit in °C	Voltage, *v* units in volts
Dissipation element	Thermal resistance, R_{th} unit in °C/watt	Electrical resistance, R_{el} units in ohms
Storage element	Thermal capacitance, C_{th} unit in Joules/°C	Electrical capacitance units in Farads

Based on the thermal-electrical analogy variable and thermal equivalent circuit, a simple equivalent RC circuit Figure 5(a) was developed to represent the thermal heat transfer equivalent circuit. This can be divided into two models, namely the HST model and TOT model as shown in Figure 5(b). In this paper, only the TOT model is discussed.

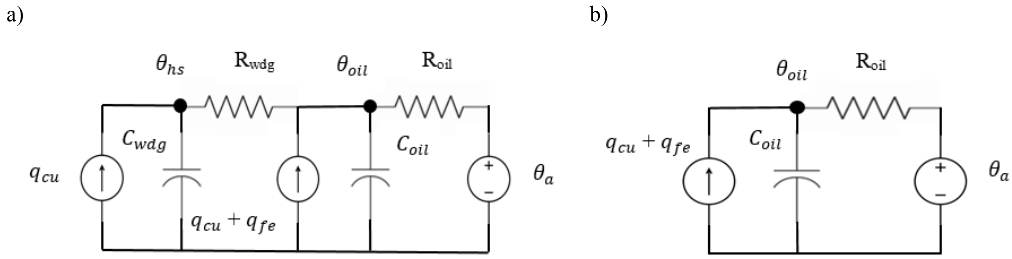

Figure 5. (a) Thermal heat transfer equivalent circuit; (b) Top-oil temperature thermal-electrical equivalent circuit

TOP-OIL TEMPERATURE MODEL

Based on the TOT thermal-electrical equivalent circuit in Figure 5(b), the differential equation can be derived by Equation (1).

$$q_{fe} + q_{cu} = C_{oil}\frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_a)}{R_{oil}} \tag{1}$$

According to the heat transfer theory and based on previous studies (Bergman et al., 2011; Susa et al., 2005), the oil thermal resistance, R_{oil} is given by Equation (2).

$$R_{oil} = \frac{1}{h.A} \tag{2}$$

Where A is the area and h is the convection coefficient. *h* is a complex coefficient because it can be affected by multiple factors. According to the heat transfer theory, *h* varies with the temperature difference between the object and the fluid. In this case, *h* is approximated by the expression in Equation (3) (Bergman et al., 2011).

$$h = C(\theta_s - \theta_\infty)^n \tag{3}$$

Where *n* is constant and the unit of C is $W/m^2.K^{(1+n)}$. θ_s refers to TOT θ_{oil} and θ_∞ refers to AT θ_a. The equation can be simplified as shown in Equation (4).

$$h = C(\Delta\theta_{oil})^n \tag{4}$$

Substitution of Equation (4) into the oil thermal resistance R_{oil} leads to Equation (5).

$$R_{oil} = \frac{1}{CA(\Delta\theta_{oil})^n} \tag{5}$$

Equation (5) is substituted in Equation (1) which leads to Equation (6).

$$q_{fe} + q_{cu} = C_{oil}\frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_a)}{\frac{1}{C.A(\Delta\theta_{oil})^n}} \tag{6}$$

The rated value for NTR, $R_{oil,rated}$ is determined based on Equation (7).

$$R_{oil,rated} = \frac{1}{C.A(\Delta\theta_{oil,rated})^n} \tag{7}$$

The rated top-oil temperature rise over the ambient temperature $\Delta\theta_{oil,rated}$ is given by Equation (8).

$$\Delta\theta_{oil,rated} = (q_{fe} + q_{cu})_{rated}.R_{oil,rated} \tag{8}$$

The definition of top-oil time constant τ_{oil} is obtained according to Equation (9).

$$\tau_{oil} = R_{oil,rated}C_{oil,rated} \tag{9}$$

The R constant is known as the ratio of load losses at the rated current to the no load losses which is determined according to Equation (9).

$$R = \frac{q_{cu}}{q_{fe}} \tag{10}$$

The K constant is known as the ratio of the load current to the load current and is calculated according to Equation (11).

$$K = \frac{I}{I_{rated}} \tag{11}$$

Finally, Equation (6) is reduced to Equation (12) which is the final form of the TOT model.

$$\frac{1+R.K^2}{1+R} \cdot \Delta\theta_{oil,rated} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_a)^{1+n}}{\Delta\theta_{oil,rated}{}^{n}} \tag{12}$$

For testing the alternative thermal model constant, *n* is obtained from (Susa et al., 2005) which mainly depends on the cooling method. For the oil time, constant τ_{oil} is obtained from the thermal parameter model in IEC 60076-7. If the mass of fluid is known, τ_{oil} can be calculated using the equations in (Susa et al., 2005).

RESULTS AND DISCUSSION

Table 2 and Table 3 show the load test and input data used for running the alternative thermal model. The thermal model results are also compared with the exponential model in IEC 60076-7 and the Clause 7 model in IEEE C57.91-1995. Figure 6 shows the computed TOT obtained by the alternative thermal model agrees well with the measured values as compared to the other thermal models. It is because of the alternative TOT model have only one constant *n* which controls the sensitivity of TOT value. In order to obtain the ideal value of *n*, case studies related to estimating the value of n that satisfied all results need to be done. The TOT obtained from the IEC 60076-7 exponential model overshoots for an increased load factor, especially for a transformer unit at 250 MVA ONAF. Since the exponential model in IEC 60076-7 consists of the constant k11 and an exponent *x* which controls the sensitivity of the TOT model, due to this condition, the shape of the rise and fall of the exponential function is difficult to control. The TOT obtained by the IEEE C57.91-1995 Clause 7 model was closer to the alternative thermal model.

Table 2
Performed load test (Standard) (Susa et al., 2005)

Transformer Units	Varying load Current
250 MVA ONAF	1.00pu/3h+0.60pu/3h+1.50pu/2h+0.30pu/3h+2.10pu/0.33h
400 MVA ONAF	1.00pu/5h+0.65pu/5h+1.60pu/3h

Table 3
Input data for Thermal Model (Standard) (Susa et al., 2005)

Quantity	Transformer / Winding	
	250/118	400/120
KVA base	250 000	400 000
P_w/W	411 780	637 100
P_E/W	29 469	59 778
P_S/W	43 391	65 772
$\Delta\theta_{oil,rated}$/K	38.3	38.0
Mfluid/kg	73 887	91 397
$\theta_{oil,i}$/°C	38.3	30.9

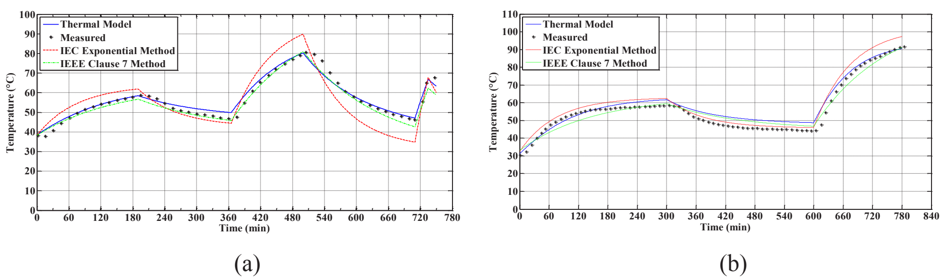

Figure 6. Top-oil temperature of (a) 250MVA ONAF; (b) 400MVA ONAF transformers

CONCLUSION

Based on the heat transfer theory which is the application of the NTR and LC method, the thermal-electrical analogy equivalent circuit was formed. The main factor of the alternative TOT model is the approximation of the convection coefficient h which eliminates the needs of information such as viscosity. Then, all the input parameters for running the alternative TOT model are tied with the parameters of normal heat run test report. The alternative TOT model was developed and tested on two different transformer units. The TOT obtained by the alternative TOT model agrees with the measured values compared with the IEC 60076-7 exponential model. The alternative TOT model results are also closer to IEEE C57.91-1995 Clause 7 model. Thus, the TOT model is fit for online monitoring system, for instance, dynamic loading and ambient temperature.

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