Transformer Thermal Modelling and Simulation

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ABSRACT: The aim of this paper is to present a transformer thermal model. The model equations are established to predict the top oil and the hot spot temperatures. The model is used to predict the top oil temperature of 2500 kVA foil/wire distribution transformer equipped with thermo-couples. The top oil model parameters are identified using a non-linear least square algorithm and measurements. The model showed good results.

1. Introduction

One of the most important parameters is the transformer operating temperature that has a major influence on the ageing of the insulation and the life time of a unit. There are several models for predicting a transformer hot spot temperature. The commonly used model is described in clause 7 in the IEEE loading guide and IEC 354 [1][2]. The top oil rise equation of clause 7 of the IEEE guide is modified to allow for continuously varying ambient temperature [3].

An alternative method is suggested in Annex G. The method requires the use of bottom oil rise over ambient at rated conditions. The duct oil temperature is introduced which may be higher than the top oil temperature under certain conditions [1].

Another transformer thermal modelling approach in the form of an equivalent circuit based on fundamentals of heat transfer theory is proposed. The top oil temperature is calculated from the oil-to-air model. The top oil temperature becomes the ambient temperature for winding-to-oil model. The top oil temperature model is shown to be valid for a 250 MVA transformer in the field. [4][5]. The hot spot equation which is analogous to the top oil is introduced and the thermal model is shown to be valid for 250 MVA transformer equipped with fibre optic probes and heat run tested according to a load cycle comprising a short time load up to 2.1 pu [6][7].

This paper, presents a transformer thermal model equations. The top oil model is applied to 2500 kVA distribution transformer equipped with thermocouples. A non-linear least square algorithm is used to estimate the model parameters. The hot spot temperature is not included here.

2. Description of the Thermal Model

The thermal model is used to determine the hot spot temperature. The top oil temperature is calculated from the top oil model. The top oil temperature becomes the ambient temperature for the hot spot model. The top oil temperature is often labelled as Liquid temperature and it is traditionally measured at the top of transformer oil. The differential equation used to calculate the top oil temperature is [4]:

$$\frac{1+\beta I_{pu}^{2}}{1+\beta}\cdot\left[\Delta\theta_{O-R}\right]^{1/n}=\tau_{o}\frac{d\theta_{O}}{dt}+\left[\theta_{O}-\theta_{A}\right]^{1/n} \tag{1}$$

The variables and parameters are:

Input variables (Functions of time, *t*)

I_{pu}	is the load current per unit.
θ_A	is the ambient temperature, ° C.

Output variable (Function of time, *t*)

θ_O	is the top oil temperature, ° C.

Parameters (constants)

β	is the ratio of no load to load losses, conventionally *R*.
$\Delta\theta_{O-R}$	is the top oil temperature rise over ambient, K.
τ_O	is the top oil time constant, min.
n	is an exponent which defines non-linearity.

The hot spot temperature is the maximum temperature occurring in the winding insulation system. This temperature represents the thermal limitation of the transformer loading. The hot spot temperature differential equation is [6]:

$$\frac{I_{pu}^{2}\left[K_{\theta}+\frac{P_{EC-R}}{K_{\theta}}\right]}{1+P_{EC-R}}\cdot\left[\Delta\theta_{H-R}\right]^{1/m}=\tau_{H}\frac{d\theta_{H}}{dt}+\left[\theta_{H}-\theta_{O}\right]^{1/m} \tag{2}$$

The variables and parameters are:

Input variables (Functions of time, *t*)

I_{pu}	is the load current per unit.
θ_O	is the top oil temperature, ° C.

Output variable (Function of time, *t*)

θ_H	is the hot spot temperature, ° C.

Parameters (constants)

P_{EC-R}	is the rated pu eddy current losses at the hot spot location.
$\Delta\theta_{H-R}$	is the hot spot temperature rise over top oil, K.
τ_H	is the hot spot time constant, min.
m	is an exponent defines non-linearity.
K_θ	is the resistance correction due to temperature change.

3. Simulation Model

Equations (1) and (2) are modelled in Simulink/Matlab. At each discrete time the top oil temperature is calculated and it becomes the ambient temperature to calculate the hot spot temperature as shown in Fig. 1. The equations are solved numerically using Runge–Kutta method.

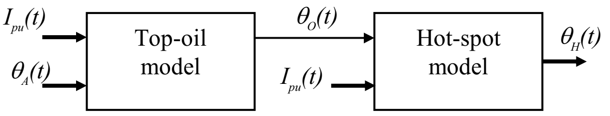

Fig. 1 The Thermal model for hot-spot calculation.

The implemented top oil temperature model is shown in Fig. 2. The study in this paper is limited to the top oil temperature and the hot spot temperature will be considered in future work.

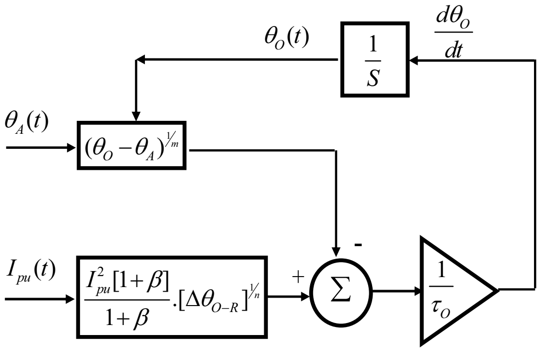

Fig. 2 The block diagram of the top oil model.

4. Tested Transformer

A 2500 kVA 20.5 ± 2 × 2.5%/0.71 kV, ONAN without external cooling Dy11 connected, is equipped with 28 thermocouples. The transformer was heat run tested under load cycle of 1 pu 50Hz/ 300 minutes and 2 pu 50Hz/90 minutes. The thermocouples were installed in different locations to measure characteristic temperatures such as top oil, hot spot, bottom oil and duct oil. Fig. 3 shows part of the thermocouples installed to measure the top oil and the winding hot spot temperature in the transformer. The thermocouples installed to measure the top oil at different locations oil pocket, tank surface and under tank cover. Others installed in the winding hot spot temperature location based on the manufacturer experience. Figs 4-6 show the transformer measured top oil temperature, applied current and ambient temperature respectively for 1 pu load. Fig. 7 shows the measured top oil pocket for the loading cycle. The data was recorded at two minutes intervals.

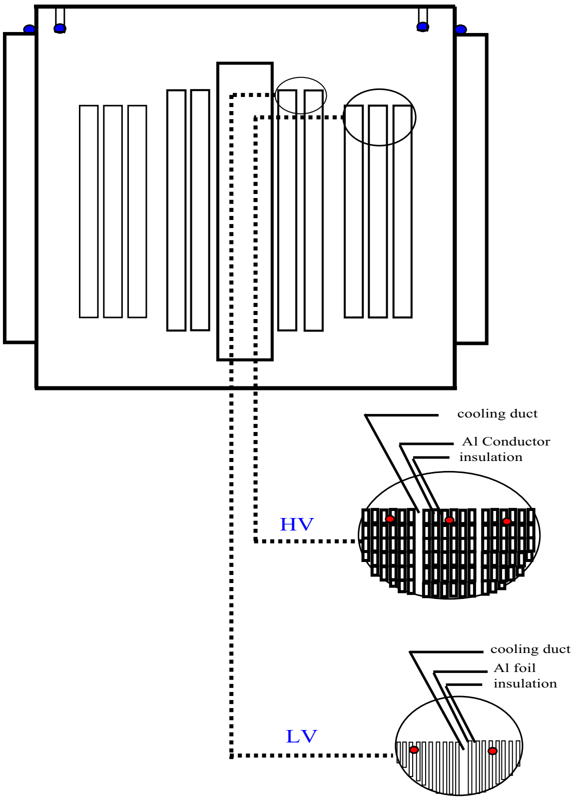

Fig. 3 Transformer under test: A thermocouple to measure top oil ● A thermocouple to measure winding insulation hot spot ●

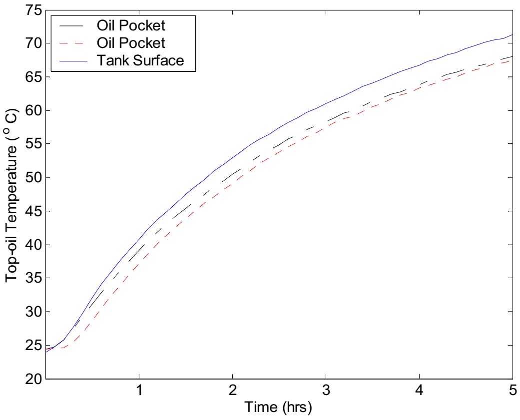

Fig. 4 Measured top oil temperature at different locations

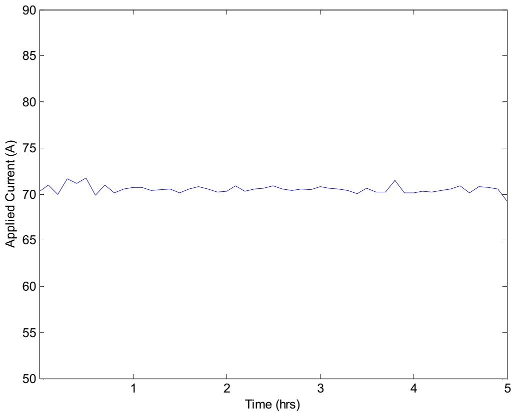

Fig. 5 Applied load current

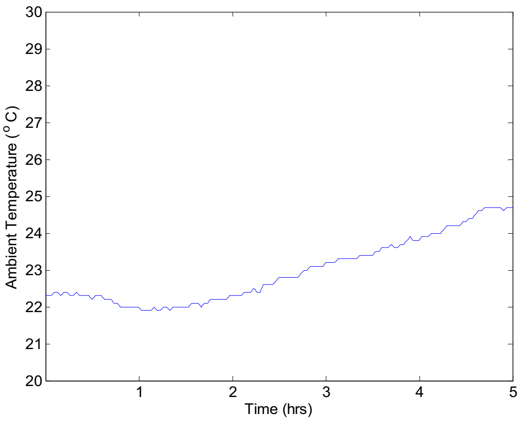

Fig. 6 Measured ambient temperature

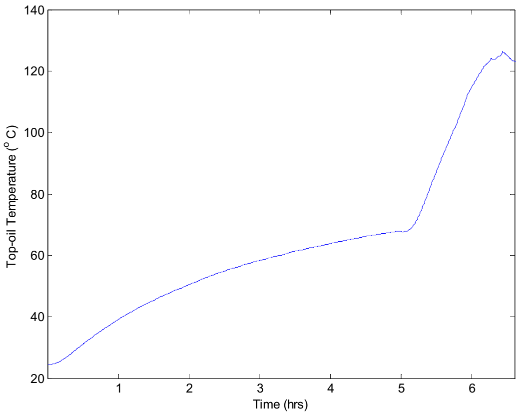

Fig. 7 Measured top oil temperature at 1 pu and 2 pu loading

5. Parameters determination

Some of the thermal model parameters are known accurately from the factory tests. The measurements can be used to determine the unknown thermal model parameters.

$$\min_{x} \; \frac{1}{2}\sum_{i=1}^{l}\left(F(x)_i - y_i\right) \qquad (3)$$

where

$F(x)_i$ is the model calculated temperature at each step.
x are the parameters to be determined.
y_i is the measured temperature at each step.
l is the index over the period.

Using the nonlinear least squares [8], the model equation (1), the parameter values are estimated from the measured data in Figs. 4-6 the corresponding model parameters are found to be:

$\Delta\theta_{o\text{-}R} = 50\ ^{o}\mathrm{C}$, τ_o=130 min, $n = 1$

The parameter n was found to be 1 i.e the heat transfer from the oil in the tank to the outside air is only proportional to the temperature difference between the liquid and the air. This can be due to the fact that the transformer is without external cooling.

Fig. 8 shows the predicted top oil temperature compared with measured the one.

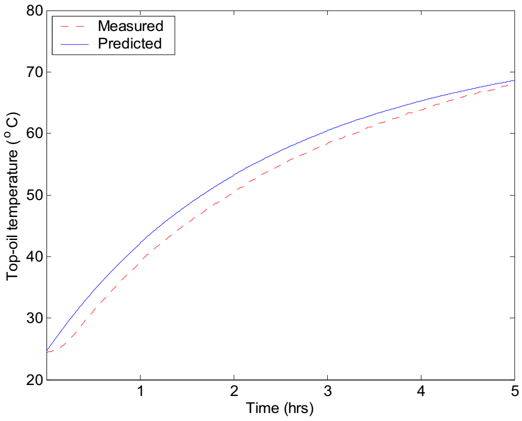

Fig. 8 Predicted and measured top oil temperature for 1 pu load

6. Simulation in Comparison with Factory Heat Run Test

The top oil temperature for any loading can be predicted by inputting the measured pu load, ambient temperature and the optimised parameters into equation (1). The model output and the measured top oil temperature are compared in Fig. 9. It is clear that the prediction does adequately represent the top oil temperature.

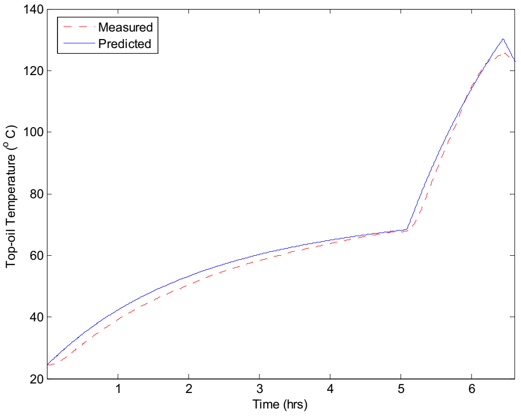

Fig. 9 Predicted and measured top oil temperatures

7. Conclusion

Transformer thermal model equations to predict the top oil and hot spot temperature is presented. The model is employed to calculate the top oil temperature of a distribution transformer. A nonlinear least-square method is utilized to determine the model parameters based on measurements of the load, top oil temperature and ambient temperature. The model is physically based, easy to use in practice, and shown to be valid for a distribution transformer.

Acknowledgement

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