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Thermal Modeling of Dry-Transformers and Estimating Temperature Rise

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***Abstract*—**Temperature rise in a transformer depends on variety of parameters such as ambient temperature, output current and type of the core. Considering these parameters, temperature rise estimation is still complicated procedure. In this paper, we present a new model based on simple electrical equivalent circuit. This method avoids the complication associated to accurate estimation and is in very good agreement with practice.

***Keywords*—**Thermal modeling, temperature rise, equivalent thermal circuit.

I. Introduction

TEMPERATURE rise is one of the most crucial parameters that affect the transformer lifetime. Temperature rise can easily leads to the serious damages. This makes temperature estimation an important priority for engineers and companies. Different methods have been suggested. Among them, measurement of winding resistance according to IEEE/ANSI standards, usage of Fiber Optic for measurement of Hot-Spot temperature and software's simulations can be mentioned. [1,2,3]

In this study we present a simple model based on parameters that can be calculated using the manufacture data of the transformer. The value of the thermal equivalent resistance is initially extracted from experimental data and to increase the model accuracy, this value is adjusted via simple procedure.

II. Fundamental Model

To analyze the temperature rise inside a transformer, the analogy between thermal and electrical process is employed. A thermal process can be modeled by using energy balance equation:

$$q \times dt = C_{th} \times d\theta + \frac{\theta - \theta_{amb}}{R_{th}} \times dt \quad (1)$$

In this equation, q is the generated heat, C_{th} is the equivalent thermal capacitor, θ is the temperature, R_{th} is the equivalent thermal resistor and θ_{amb} is the ambient temperature.

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The equation can be reformulated as the following:

$$q = C_{th} \times \frac{d\theta}{dt} + \frac{\theta - \theta_{amb}}{R_{th}} \quad (2)$$

This looks similar to famous RC circuit equation; Fig.1 depicts this equivalent circuit. The current equation of this circuit reads as:

$$i = C_{el} \times \frac{du}{dt} + \frac{u}{R_{el}} \quad (3)$$

By comparing the equations 2 and 3, the analogy between the electrical and a thermal process can be obtained as it mentioned in Table I [4,5].

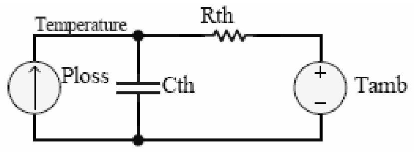

Fig. 1 RC Circuit to Model a heat transfer

TABLE I
ANALOGY BETWEEN A THERMAL PROCESS AND AN ELECTRICAL CIRCUIT

Thermal		Electrical	
Power Loss	Ploss	Current	i
Temperature	θ	Voltage	V
Thermal Resistance	R_{th}	Elec. Resistance	R_{el}
Thermal Capacitor	C_{th}	Elec. Capacitor	C_{el}

III. Optimized Model

Total power loss in a transformer has two elements: the winding loss and the core loss. Winding loss can be easily determined by calculating the primary and secondary resistance while the core loss is calculated by using the Steinmetz relationship ($P_{core} = kf^{x}\Delta B^{y}$) or other models that best fit the experimental data. [6]

Total core loss is scalar summation of these two losses. We modeled this in equivalent circuit by cascading two RC networks, representing each loss process. This is depicted in Fig. 2.

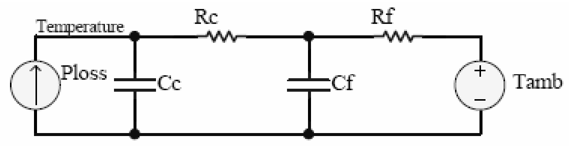

Fig. 2 Optimized Thermal Model for a Dry-Type Transformer

In this circuit *Ploss* is the total transformer power loss, *Rc* is the thermal resistance of winding, *Rf* is the thermal resistance of core, *Cc* is the thermal capacitor of winding and *Cf* is the thermal capacitor of the core.

IV. Value of the Elements

In the presented model, *Ploss* is calculated according to the power loss formula. The value of *Cc* and *Cf* capacitors are directly proportional to the amount of iron and copper used in the construction of the transformer and can be extracted as the following:

$$C_c = m_{cu} \times C_{sp-cu} \text{ (J/K)} \tag{4}$$

$$C_f = m_{fe} \times C_{sp-fe} \text{ (J/K)} \tag{5}$$

In these equations, m_{cu} and m_{fe} are weight of copper and iron that is used for construction of transformer, C_{sp-cu} and C_{sp-fe} are the specific heat capacity of copper and iron. [7]

The current source in the model represents the amount of power loss and due to the fact that thermal time constant is measured in minute, values from formulas (4) and (5) should be divided to 60 before using them in simulations.

Testing ensemble of the transformers, with output power changes from 0.5KVA to 15KVA, the following factor has been defined to indicate a rough estimation of the Hot-Spot temperature rise:[8]

$$\text{Temperature Rise Factor} = \frac{\text{Transformer Total Power Loss}}{\text{Core Volume in } cm^3} \tag{6}$$

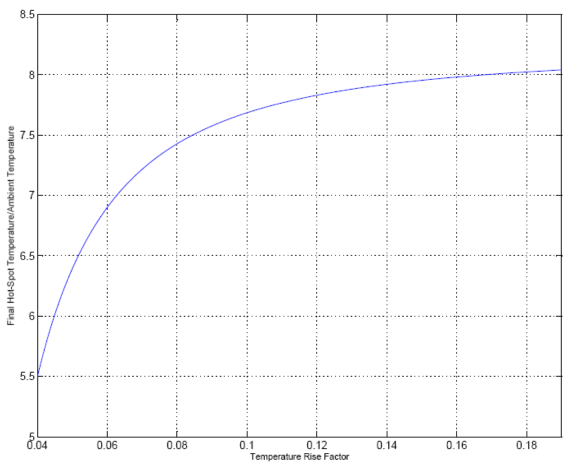

Fig. 3 Dependency of TRF and Temperature Rise

The relation between *Temperature Rise Factor (TRF)* and the value of *Final Hot-Spot Temperature/Ambient Temperature* has been drawn in Fig. 3.

Knowing Hot-Spot temperature rise, the equivalent thermal resistor can be extracted from the familiar formula $\Delta\theta = R_{th}.Ploss$.

Substituting this approximate value for R_{th} in the fundamental model and considering *Cf+Cc* as C_{th}, we end up with the model that can predict the thermal behavior of the transformer with the moderate accuracy. Fig. 4 shows a comparison of this model with the experimental data.

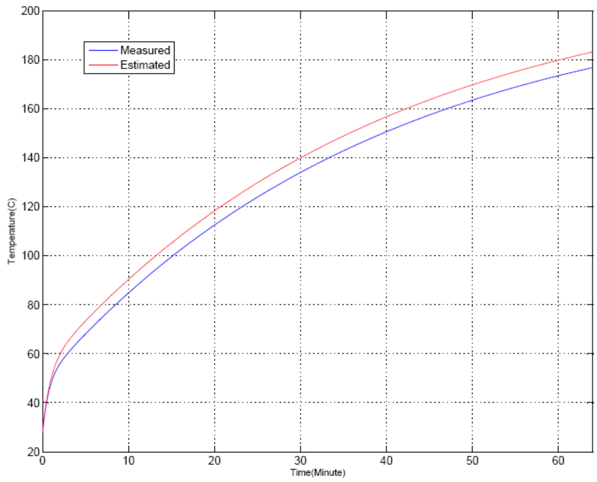

Fig. 4 Comparison between the result of the model and the thermal behavior of a 2KVA transformer

This data can be employed to find an approximate value of the *Rc* and *Rf*.

V. Improving Thermal Resistor Estimation

To improve the accuracy of the model, the value of *Rf* and *Rc* have to be modified using the experimental data. There is no need for tests like short circuit or overload, but measuring the steady state Hot-Spot temperature under a normal load.

Using Laplace Transform, the following equation can be derived for steady state temperature of the Hot-Spot, based on the electrical analysis of the optimized model:

$$\theta_{Steady\ State} = \frac{\theta_{amb}}{s} + \frac{P_{loss}}{s} \times z(s) \tag{7}$$

Where *z(s)* is:

$$z(s) = \frac{R_c R_f C_f s + R_c + R_f}{R_c R_f C_c C_f s^2 + R_c C_c s + R_f C_f s + R_f C_c s + 1} \tag{8}$$

Employing the experimental data and the above equations, an accurate value for *Rc* and *Rf* can be easily found using MATLAB Curve Fitting Toolbox [9,10].

VI. Model Verification

Finding adjusted values for *Rc* and *Rf*, thermal behavior of transformer can be predicted with much better accuracy. Fig. 5 and Fig. 6 compare the result of modified model and experimental data. As they show, there is very good agreement between model result and experiment which justifies our adjusting process.

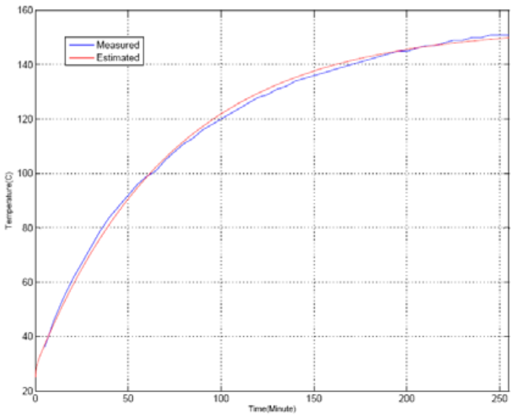

Fig. 5 Comparison between the result of the adjusted model and the thermal behavior of a 5.5KVA transformer

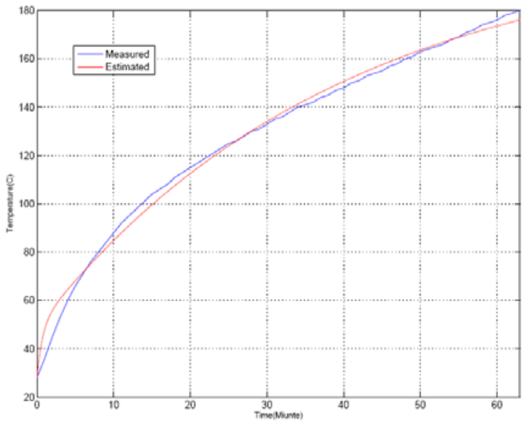

Fig. 6 Modified result for 2KVA transformer

VII. Application and Conclusion

We accomplished good level of accuracy through rather simple model based on equivalent circuit for the heat transfer. This model is also capable to predict thermal behavior for wide range of the loads. For example Fig. 6 shows for how long a 7KVA transformer can supply the different loads with temperature limit of the 180C.

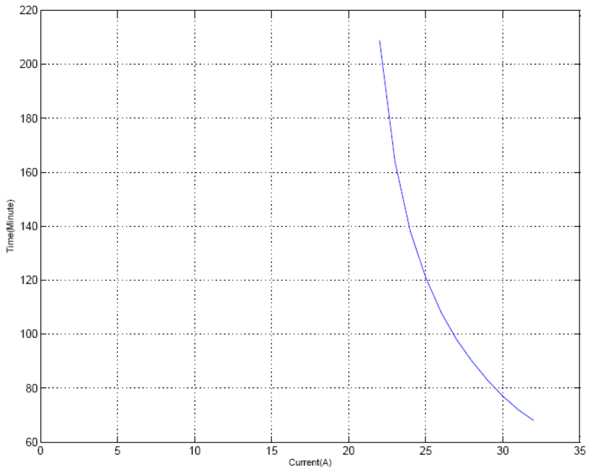

Fig. 7 Time-Current Graph of a 7KVA Transformer

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