HOTTEST SPOT AND LIFE EVALUATION OF POWER TRANSFORMER DESIGN USING FINITE ELEMENT METHOD

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ABSTRACT

Power transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network. One of the most important parameters' governing a transformer's life expectancy is the hot-spot temperature value. Due to under estimation of stray losses in power transformer hot spots are formed. So the stray loss evaluation is an essential aspect to calculate hot spot temperature. The stray losses in transformer is caused by the time variable leakage flux which induces emf's & circulates eddy currents in the winding conductors and other conducting parts of transformer like tank wall, core, clamps etc.. Evaluation of stray losses can be done more accurately by Finite Element Method (FEM). This paper presents the new and more accurate temperature calculation methods taking into account the above mentioned findings to estimate life of transformer form hot spot temperature.

Keywords: *Finite element method – Hotspot - Power transformer - Stray losses - Thermal model*

1. INTRODUCTION

POWER transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network. One of the most important parameters' governing a transformer's life expectancy is the hot-spot temperature value [1]. Due to under estimation of stray losses in power transformer [2, 3] hot spots are formed. So the stray loss evaluation is an essential aspect to calculate hot spot temperature. the stray losses in transformer is caused by the time variable leakage flux which induces emf's & circulates eddy currents in the winding conductors and other conducting parts of transformer like tank wall, core, clamps etc.. Evaluation of stray losses can be done more accurately by FEM.

The classical approach has been to consider the hot-spot temperature as the sum of the ambient temperature, the top-oil temperature rise in tank, and the hot-spot-to-top-oil (in tank) temperature gradient When fiber optic probes were taken into use to record local hot-spots in windings and oil ducts, it is noticed that the hot-spot temperature rise over top-oil temperature due to load changes is a function depending on time as well as the transformer loading (overshoot time dependent function). It has also been noticed that the top-oil temperature time constant is shorter than the time constant suggested by the present IEC loading guide, especially in cases where the oil is guided through the windings in a zigzag pattern for the *ONAN* and *ONAF* cooling modes [9]. This results in winding hottest spot temperatures higher than those predicted by the loading guides during transient states after the load current increases, before the corresponding steady states have been reached [4 -8].

This paper presents new and more accurate temperature calculation methods taking into account the losses including the chief cause for hot spot i.e. stray loss [10 – 12], which is evaluated by using finite element method (FEM). The models are based on heat transfer theory, application of the lumped capacitance method, the thermal-electrical analogy and a new definition of nonlinear thermal resistances at different locations within a power transformer. The methods presented in this paper take into account oil viscosity changes and loss variation with temperature. The changes in transformer time constants due to changes in the oil viscosity are also accounted for in the thermal models. In addition, the proposed equations are used to estimate the equivalent thermal capacitances of the transformer oil for different transformer designs and winding-oil circulations.

Here, an important and crucial part of transformer losses i.e. stray loss, which decides the hot spot, evaluation is explained in section II, where as section III is to focus about the thermal modeling of transformer. The results are discussed in section IV and section V gives the conclusion.

II. STRAY LOSS EVALUATION USING FEM

A. Stray loss / Eddy current evaluation using FEM

Equations defining magneto dynamic fields are

$$\nabla X H = J \;\; ; \; \nabla X E = -\frac{\partial B}{\partial t} \;\; \text{and} \;\; \nabla . B = 0$$

For magneto-dynamic fields, the flux density is time variant. The problem then becomes, in general, 3 dimensional. The magnetic flux density B, and the electric field intensity due to the flux density variation [12],

$$\nabla X E = -\frac{\partial B}{\partial t} \;\text{(or)}\qquad \int_J \overline{E}.\overline{dl} = -\oint_S \frac{\partial \overline{B}}{\partial t}.d\overline{S} \qquad \text{(or)}$$

$$\oint_S \nabla X\overline{E}.\overline{dS} = -\int \frac{\overline{\partial B}}{\partial t} d\overline{S}$$

$$\nabla X H = J_I \; ; \qquad J_I = J_S + J_e$$

where Ji is the total current density. Also, let $\gamma = \frac{1}{\mu}$, we get,

$$\nabla X \gamma \nabla X A = (J_S + J_e); J_e = \sigma E$$

where E is the induced electric field intensity in the piece p.

The above equation after arranging in a format,

$$\nabla.(\gamma \nabla A(t+\Delta t)) - \sigma \frac{A(t+\Delta t)}{\Delta t} + \sigma \frac{A(t)}{\Delta t} + JS(t+\Delta t) = 0$$

Applying weighted residual,

$$= -\frac{\gamma}{2D}\begin{bmatrix} q1q1+r1r1 & q1q2+r1r2 & q1q3+r1r3 \\ q2q1+r1r2 & q2q2+r2r2 & q2q3+r2r3 \\ q3q1+r3r1 & q2q3+r2r3 & q3q3+r3r3 \end{bmatrix}\begin{bmatrix} A1 \\ A2 \\ A3 \end{bmatrix}^{(t+\Delta t)}$$

$$-\frac{\sigma D}{12\Delta t}\begin{bmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{bmatrix}\begin{bmatrix} A1 \\ A2 \\ A3 \end{bmatrix}^{(t+\Delta t)} + \frac{\sigma D}{12\Delta t}\begin{bmatrix} A1+0.5A2+0.5A3 \\ 0.5A1+A2+0.5A3 \\ 0.5A1+0.5A2+A3 \end{bmatrix}^{(t)}$$

$$+\frac{Js(t+\Delta t)}{6}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = 0$$

Let us express the above equation in the following matrix form.

$$SA(t+\Delta t)) = Q$$

where, $A(t+\Delta t)) = \begin{bmatrix} A1 \\ A2 \\ A3 \end{bmatrix}^{(t+\Delta t)}$ and

$$Q = \frac{\sigma D}{12\Delta t}\begin{bmatrix} A1+0.5A2+0.5A3 \\ 0.5A1+A2+0.5A3 \\ 0.5A1+0.5A2+A3 \end{bmatrix}^{(t)} + \frac{Js(t+\Delta t)}{6}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

is the right hand side vector, containing source terms resulting from applied currents, and induced currents at the previous time step. In the left hand side of the equation we have,

$$S = -\frac{\gamma}{2D}\begin{bmatrix} q1q1+r1r1 & q1q2+r1r2 & q1q3+r1r3 \\ q1q2+r1r2 & q2q2+r2r2 & q2q3+r2r3 \\ q1q3+r1r3 & q2q3+r2r3 & q3q3+r3r3 \end{bmatrix}$$

$$-\frac{\sigma D}{12\Delta t}\begin{bmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{bmatrix}$$

$$= -\frac{\gamma}{2D}\begin{bmatrix} S^1{}_{11} & S^1{}_{12} & S^1{}_{13} \\ S^1{}_{21} & S^1{}_{22} & S^1{}_{23} \\ S^1{}_{31} & S^1{}_{32} & S^1{}_{33} \end{bmatrix}$$

$$-\frac{\sigma D}{12\Delta t}\begin{bmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{bmatrix}$$

If Js =0 and $\sigma = 0$, the above equation reduces to $[s_{ij}][A] = 0$ Generally, Js is the time dependent. An initial solution $A(t+\Delta t)$ =0 may be used to initial solution procedure. The matrix equation must be solved iteratively to obtain the solution at every t. an essential criterion for obtaining an accurate solution is that Δt should sufficiently small.

B. Simulation and Results

Here, a finite element method (FEM) based commercial package namely ANSYS [13] is used to determine stray losses in a transformer. In this further the method of finding stray losses are "magnetic harmonic analysis" is used. This is well explained in electromagnetic field analysis guide. The following case study is solved using the same to find the stray losses in various conducting parts of the transformer.

The example considered here is a concentric wound transformer along with its stray fittings as shown in fig. 1(a) below. Here shielding is provided along the tank wall CRGO material .this problem is analyzed using ANSYS to determine the stray loss in tank walls, clampings, flitch plates, etc[13]. The respective flux density and flux plots are shown in fig. 1(b) and fig.1 (c).

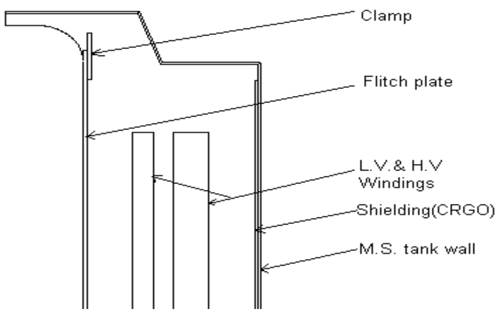

Fig. 1(a). Transformer Model

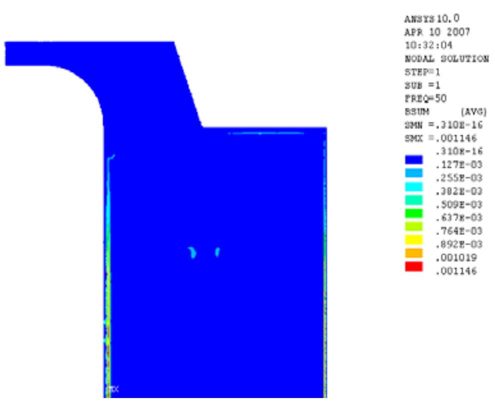

Fig.1 (b). Flux density plot of Model shown in fig.1

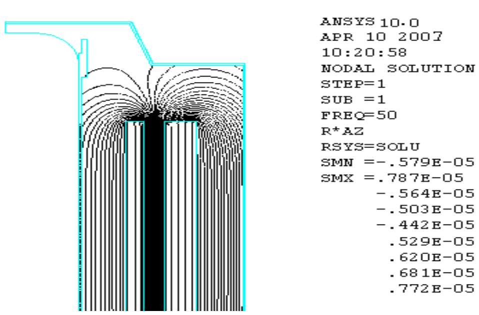

Fig.1 (c). Flux plot of Model shown in fig.1

From the above analysis the total stray loss in various stray parts of the transformer is found and this value is used in the hot spot and life estimation calculations, which is illustrated in the further sections.

III. THERMAL MELING OF TRANSFORMER

The winding hot spot temperature is considered to be the most important parameter in determining the transformer loading capability. It determines the insulation loss of life and the potential risk of releasing gas bubbles during a severe overload condition. This has increased the importance of knowing the hot spot temperature at each moment of the transformer operation at different loading conditions and variable ambient temperature. Thus the appropriate thermal model to determine hot spot temperature has become the designer's challenge. In this paper a novel and advanced thermal model is proposed in view of variations in hot spot temperature at each moment of the transformer operation at different loading conditions and variable ambient temperature[15].

A. Thermal model based on electrical -thermal equivalent circuit

A thermal model of a power transformer in the form of an equivalent circuit based on the fundamentals of heat transfer theory has been suggested by Swift. The proposed thermal model was established to determine the hot spot temperature. The top oil temperature was calculated from the air-to-oil model. The top oil temperature becomes the ambient temperature for the winding to oil model. Based on this approach a model which considers the non-linear thermal oil resistance has been introduced by Susa. The oil viscosity changes and loss variation with temperature were included in the method. The model was shown to be valid for different transformer units. The model is analogous to the top oil model equation. The losses used in the model are the estimated highest losses that generate the heat at a specific location in the LV or HV winding. The model is easy to implement and is validated by comparison with measured results.

In transformers, oil is typically used as the coolant. The heat generated by losses in transformers is taken up by the oil and carried into a heat exchanger, which in most cases is an oil-air cooler. The cooler dissipates heat to the surroundings by natural or forced flow[16].

The non linear thermal resistance is related to the many physical parameters of an actual transformer. The exponent defining the non linearity is traditionally *n* if the moving fluid is air and *m* if it is oil.

B. Top oil thermal model

The top oil thermal model is based on the equivalent thermal circuit shown in fig.2 (a) and (b). A Simple RC circuit is employed to predict the top oil temperature.

In the thermal model all transformer losses are represented by a current source injecting heat into the system. The capacitances are combined as one lumped capacitance. The thermal resistance is represented by a non-linear term. The differential equation for the equivalent circuit is

$$q_{Tot} = C_{th-oil}\frac{d\Theta_{oil}}{dt} + \frac{1}{R_{th-oil}}\left[\Theta_{oil} - \Theta_A\right]^{1/n}$$

where,

q_{Tot} is the heat generated by total losses, W

C_{th-oil} is the oil thermal capacitance, W_{min} $/^0$ C

R_{th-oil} is the thermal resistance

Θ_{oil} is the top oil tempetature, ^{0}C

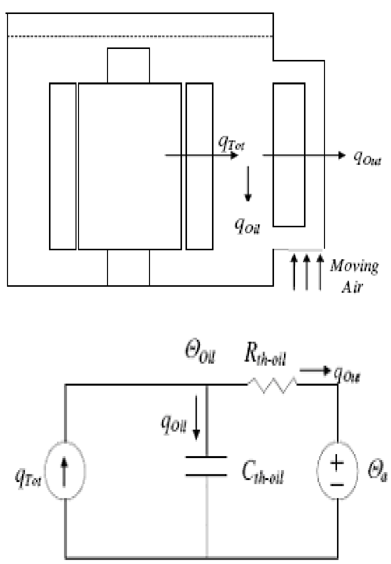

Fig. 2 (a) & (b) Thermal Model for top oil temperature

C. Winding hot spot thermal model

In the thermal model the calculated winding losses generate the heat at the hot spot location. The thermal resistance of the insulation and the oil moving layer is represented by a non-linear term. The exponent defining the non linearity is traditionally *m*. The typical value used for *m* is 0.8. The hot spot thermal equation is based on the thermal lumped circuit shown in Fig. 3 (a) & (b).

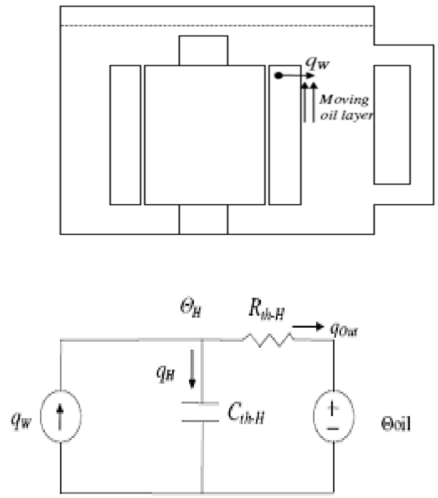

Fig. 3 (a) & (b) Thermal Model for hot spot temperature

The differential equation for the equivalent circuit is

$$q_W = C_{th-H}\frac{d\Theta_H}{dt} + \frac{1}{R_{th-H}}\left[\Theta_H - \Theta_{oil}\right]^{1/m}$$

where,

q_W is the heat generated by the losses at hot spot location, W

C_{th-H} is the winding thermal capacitance at the hot spot location

R_{th-oil} is the thermal resistance at the hot spot location, ^{0}C/ W

Θ_{oil} is the top oil temperature at the hot spot location, ^{0}C

The above equation is reduced to

$$\frac{I_{pu}^2\left[1+P_{EC-R(pu)}\right]}{1+P_{EC-R(pu)}}\cdot\left[\Delta\Theta_{H-R}\right]^{1/m} = \tau_H\frac{d\Theta_H}{dt} + \left[\Theta_H - \Theta_{oil}\right]^{1/m}$$

where

$P_{EC-R(pu)}$ are the rated eddy current losses at the hot spot location

$\Delta\Theta_{H-R}$ is the rated hot spot rise over ambient, K.

τ_H is the winding time constant at hot spot location, min.

The variation of losses with temperature is included in the equation above using the resistance correction factor.

IV. SIMULATION RESULTS

The transformer input parameters needed for the thermal model is shown in Table 1.

Table 1: Input parameters of thermal model

Rated top oil rise over ambient	38.3^0 C
Rated hot spot rise over top oil	20.3^0 C
Ratio of load losses to no load losses	6.20^0 C
pu eddy current losses at hot spot location, LV	0.65
pu eddy current losses at hot spot location, V	0.3
Top oil time constant	170 min
Hot spot time constant	6 min
Exponent n	0.9
Exponent m	0.8

The following fig.4 (a) and (b) represents the top oil temperature model of 250 MVA Transformer and its temperature graph.

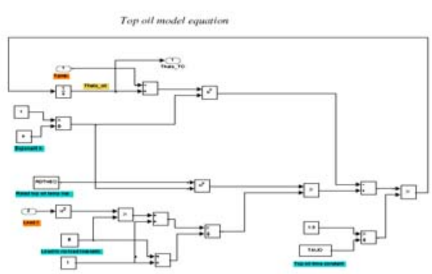

Fig. 4(a) Top oil equation model

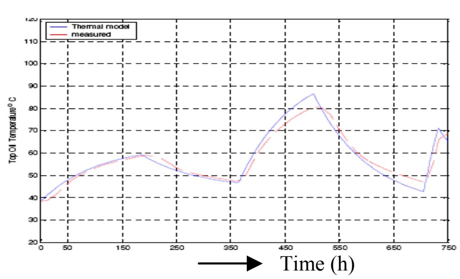

Fig. 4(b) Calculated top oil temperature graph

The following fig. 5(a) and (c) shows the Thermal model of 250 MVA Power Transformer and hot spot plot for the in put load cycle of current shown in fig. 5 (b).

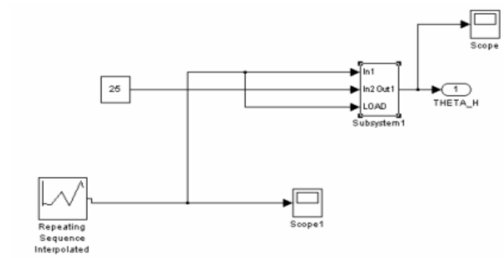

Fig. 5 (a) Thermal model

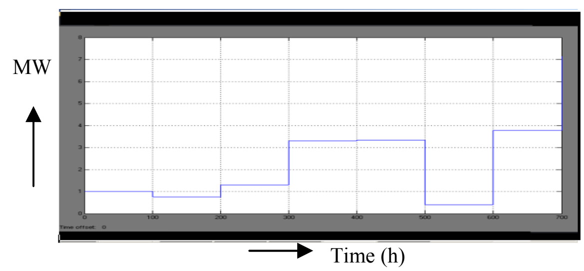

Fig. 5(b) Input load cycle for thermal model

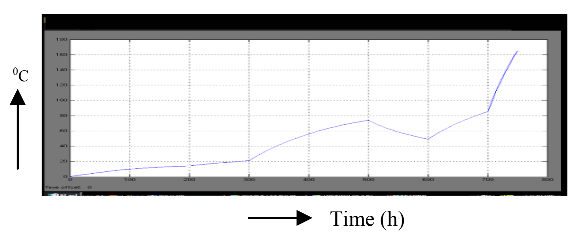

Fig. 5 (c) Hot spot temperature

From the above plot it is clear that for a given load cycle the hot spot temperature rises from rated temperature to a high enormous value.

V. CONCLUSION

The thermal models are fully dependent on accurately defined steady-state temperature rises. Therefore, it will be important to develop a steady-state calculation method, especially because most installed transformers are not heat-run tested. However, further research and development is needed to improve the existing monitoring systems and introduce new solutions that include the transformer thermal models and their real-time application. Utilizing thermal models allows both transformer manufactures and users to run different loading and ambient scenarios and, by analyzing the results, improve the transformer design (costs size and load carrying capacity)[17-

18]. An electromagnetic analysis using a finite element model has been adapted to predict transformer winding losses. This can be used to calculate the eddy losses in individual turns/discs to enable location of the winding losses that cause the hot spot and to predict the hot spot factor *H*.

In this paper a novel thermal model has been established to determine the hot spot temperature. The top oil temperature is calculated from the top oil equation. The top oil temperature becomes the ambient temperature for a hot spot equation model. The equations are modeled in Simulink and validated using transformer data from measurements in the factory, thus a real time online monitoring system can be developed and used.

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