Thermal Modeling of Electrical Transformers

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Abstract- Thermal modeling of transformer is necessary to ensure the optimal design and cost of manufacture of transformer. Either of the empirical formulae available from the standards and practical measurement techniques used in the industries as an alternative to the formulae will not be able to answer the problem exactly and hence the development of software based thermal modeling techniques that use the advantages of today’s computational power and produce a quicker as well as best solution is the need of the day. A good number of thermal models are available for thermal modeling of transformer, which are based on lumped values of losses. This paper presents a thermal model based on FEM technique and circuit modeling that can calculate the thermal profile across the transformer geometry at any instant, given the input of the loading conditions at that instant. The model has been tested on an industrial transformer and the results obtained are compared with the practical measured data for that transformer.

I. INTRODUCTION

The life of the transformer and the reliability of its operation is very crucial in a power system network, as transformers cater to a major portion of capital investment. The life of a transformer is majorly governed by its thermal limitations. [1] - [2]. Measurement of the transformer interior temperatures is very important to the user as well as designer [3]. But with the increasing demands as well as efforts to make the existing power system network efficient and smart, this will not be the only requirement. The transformer temperatures must be dynamically measurable, i.e. at the desired instant of time at the desired loading conditions and at the desired location inside the transformer. The transformer is provided with cooling systems to aid the heat dissipation and insulations which are thermally strong and sustain high electrical transients. Still, a transformer’s thermal stability is at stake for the following reasons. Firstly, the transformer losses, especially, the magnetic losses are not estimable exactly and are always under estimated [4]. The copper losses which include stray losses also vary with load.

Though a safety factor is usually taken while designing the cooling system and insulation, such that, the temperatures in the transformer interior at any possible case of operation will not exceed the permissible limits, still, that might not totally suffice but choosing very large safety factor would also be obviously uneconomical. Secondly, there are chances that the iron loss may change because of change in grain orientation due to punching and clamping actions [5]. There are chances that this variation is large and hence the estimated safety factor is insufficient. Thirdly, even, if the losses are slightly varying within permissible limits, the insulation might get deteriorated because of ageing (Law of Insulation ageing – Arrhenius Law) as well as chemical reactions that might happen in the oil [5]. Insulation being very costly, its damage or deterioration is a very undesirable event inside the transformer [6-8]. Further, this might cause an undesirable event inside the transformer like a short circuit of insulation, at a lower temperature than the thermal limit temperature.

Therefore, it can be stated that the pre-commission testing of transformer and the design values of temperatures obtained from tests as well as empirical formulae will not be enough to estimate the condition as well as life of the transformer, because the properties of the insulation, oil, windings and core change with time because of continuous heating inside the transformer due to losses. Hence, a regular monitoring of these parameters has to be done to estimate the running condition and future life of the transformer. This is possible only if the transformer interior temperatures can be predicted at desired instant.

Thermal monitoring can be explained as calculating the transformer internal temperatures at desired instant of time or periodically in order to facilitate such further studies. This is not so easy, pertaining to the complex nature of the properties of various materials inside the transformer. Further, this cannot be done by lumping the total transformer detail into a small equivalent circuit, which is done in many thermal modeling research attempts [1], [4]. Those models might give the value of maximum temperatures with better accuracy, but will not be able to give a thermal profile across the transformer. In this paper, we have made an attempt to apply the FEM technique to the problem of transformer to find the magnetic flux distribution. The transformer thermal model is then built using an electrical equivalent circuit where focus of model being the thermal profile of the transformer and not a single maximum temperature.

II. THERMAL MODELING OF TRANSFORMERS – RESEARCH PROFILE

This section presents an insight of various research attempts being made since long to address the problem of thermal modeling of transformer. Ref. [4], [9]-[22] present the earlier work done in this area of thermal modeling of transformers. The usual practices followed for the temperature calculations and winding hotspot estimations which are the IEC and IEEE empirical formulae [9], [10] are insufficient with today’s market competency [11], [12]. Further, simple
estimates of temperature rise, which are done through the standard empirical formulae even now-a-days, are not a good proxy for direct measurement or simulation of temperature. In an attempt to improve the accuracy, IEEE and IEC loading guides are being revised with more sophisticated models aiming at a better representation of oil temperature inside the winding, considering variations in the winding resistance, oil viscosity and oil inertia.

As a result of continuous improvement in technology, in the recent past, fiber optic sensors have significantly improved to answer the problem of direct temperature measurement in transformer interiors. Compatibility of fragile fiber optic sensor with factory environment was achieved with the use of sturdy fiber jackets, proper spooling and simplified through-wall connections, but they are costly. In order to make the transformer thermal measurements economical as well as accurate, researchers have been trying to utilize the improved capabilities of computer automations to derive software based packages for accurate measurement of transformer interior temperatures. To start with, Ref. [13] presents a finite element formulation to calculate the radial component of leakage flux, which becomes appreciable for larger transformers and effects the eddy current losses. Also owing to the fact that under estimation of the stray losses is the reason for hotspots, evaluation of stray loss is an essential aspect to calculate the hot spot temperatures. In this direction, an approach has been made in [14], [15] to apply FEM to the accurate calculation of losses in the windings.

Regarding the development of thermal models, [4] presents a thermal model of power transformer in the form of an equivalent circuit based on the fundamentals of heat transfer theory. Two R-C circuits driven by current source are said to define the thermal model of a transformer. One is the air-to-oil model, which is used to calculate the top oil temperature. This temperature would serve as reference for the second R-C circuit, which is the winding-to-oil model. This approach uses the lumped values of capacitance and resistance. Based on this approach, a model which considers the non-linear thermal oil resistance has been introduced by Susa, which accounts for oil viscosity changes [1], [16], [17]. Attempts are being made to model the oil flow, which turns complicated because of effects of temperature, viscosity and whether the oil flow is natural or forced and the amount of convection. Attempts are also being made to model the magnetic properties of the core using FEM packages [18], [19].

In this paper, we have made an attempt to use values of distributed losses and thermal conductance instead of taking the lumped values of losses so that the total thermal profile across the transformer is obtained instead of single hot spot temperature. The proposed model is implemented on single phase transformer and same can also be extended to a three phase transformer.

III. PROPOSED MODEL OF THERMAL MONITORING

We start the model with the principle that the losses in the transformer are distributed rather than lumped. Each point element inside the transformer generates heat because of the loss produced in it, of which, a little amount is stored and the rest is dissipated to the surrounding elements, which are at a lower temperature. In this way heat is transferred from the center of the transformer towards the outer ambient. The temperature of an element is determined by the amount of heat generated by it as well as amount of heat stored and dissipated by it, which in turn depend upon the properties of the material, like thermal conductivity, electrical conductivity and the specific heat capacity. As long as the element’s temperature is higher than that of the neighboring elements, the heat flows from the element to the neighboring ones. Thus, heat flow is determined by the temperatures of neighboring elements also.

Firstly, a two-dimensional finite element model is proposed to determine the flux distribution and thereby to have a plot of the core loss which has got a non uniform distribution. Once the losses are calculated in each block, an equivalent thermal model based on the above principles is built for each block, a theoretical diagram of which is shown in Fig. 1.

Fig. 1. Equivalent electrical circuit simulating the thermal behavior

The current source in Fig. 1 represents heat generated in the element, which is the loss in watts. The resistances in horizontal and vertical directions represents heat flow in X and Y directions respectively. The capacitor represents the heat storage inside the element. This representation of elemental circuit is based on the thermal electrical analogy, which states that the thermal quantities of heat flow, temperature, thermal resistance and heat storage are analogous to the electrical quantities of current, voltage or potential difference, resistance and capacitance [22]. Solving the final thermal model formed by connecting single elemental blocks gives the temperature at each node.

IV. IMPLEMENTATION OF THE THERMAL MODEL

The implementation of the proposed thermal model is explained by considering an industrial transformer. The rating of the considered transformer is 25 KVA, 33KV/250V, with single phase core type construction. Fig. 1 shows the geometry of the transformer and gives the dimensions of the transformer in SI unit system. The winding is divided into two halves. Each limb contains a half of the LV winding over which a half of HV winding is wound on. The implementation is started with dividing the transformer geometry into finite number of elements. The size of each element can be taken according to
the accuracy level desired and the ability of the processing tool as well as our convenience. Next is the application of Finite Element Analysis (FEA) to the geometry to calculate the flux distribution.

V. FINITE ELEMENT ANALYSIS OF THE TRANSFORMER

FEA deals with applying point form of governing equations over a sub domain of the main domain and calculating the values of desired parameters through governing equations. These calculated values of field variables serve as the boundary conditions for the neighboring elements. For the outer most layer elements with which the calculations are started, boundary conditions are to be specified by the user or taken as zero [23]. This concept is extended to transformers in our problem. The software used for the implementation is NISA. Table I gives the values of material properties used in the analysis.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>MATERIAL</th>
<th>MUXX(1/μ₀μ₆)</th>
<th>SIXX(1/ρ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Copper</td>
<td>795800</td>
<td>58000000</td>
</tr>
<tr>
<td>2</td>
<td>Transformer oil</td>
<td>795800</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>CRGO steel</td>
<td>400</td>
<td>4000000</td>
</tr>
<tr>
<td>4</td>
<td>Structural steel</td>
<td>800</td>
<td>4000000</td>
</tr>
</tbody>
</table>

Table I

Table I gives the values of material properties used in the analysis.

Secondary winding AT = (Primary AT – Magnetizing AT)

The losses in the tank and oil due to leakage fluxes are neglected. Convection in oil is accounted for by suitable multiplicative factors. The tank is assumed to be rectangular which is valid for most of the transformers. The cooling system employed is supposed to be ONAN. All the above assumptions are valid for most of the transformers.

Fig. 3 gives finite element division of transformer geometry. Fig. 4 is the finite element model, a representation of fig. 3 in software. Fig. 5 and 6 show the main and leakage flux density distributions respectively. The colors shown in the plot define a range of values and not a single value. In the process of modeling, certain assumptions are made, without affecting the accuracy of the results, to make the analysis simple. Regarding the modeling of core, the clamps, bolts etc are not modeled owing to the fact that the model is a two dimensional one. The coils are modeled as solid copper lumps, whose properties were determined accordingly considering the various spacings inside. The current density will be the Ampere-turns of the original winding divided by the cross sectional area of the actual winding. Also, the eddy currents produced in the copper winding due to stray flux are neglected. The secondary winding Ampere turns are calculated based on the primary winding ampere turns and magnetizing ampere turns required by the core.
Now, using the output file, the values of flux densities for each block comprising the core are calculated. The core losses are calculated using the formulae given below.

\[
W_h = K_h (B_m)^{1.6} f \text{ Watts/kg},
\]

\[
W_e = K_e (K_f x B_m)^2 f^2 t^2 n \text{ Watts/kg}.
\]

Where, \(K_e\) and \(K_h\) are material constants that are found out experimentally, \(f\) is the frequency of the alternating flux, \(B_m\) is the maximum value of operating flux density, \(K_f\) is the form factor of the ac wave form, \(t\) is the thickness of each lamination of the core and \(n\) is the number of laminations in the core. The sum of \(W_h\) and \(W_e\) give the value of core losses.

VI. DEVELOPMENT OF THERMAL MODEL

Once the loss in each core block is obtained, we proceed towards building the thermal model. As given in fig. 1, we built the equivalent circuit for each block of the finite element model. Only the blocks corresponding to the core and coils contain current sources, as they are the heat generating elements. Resistances and capacitances are present in all elements. In this way, electrical equivalent block simulating the thermal behavior is built for each element, which when interconnected together give the thermal model for the entire transformer geometry. This electrical equivalent of thermal model which when solved for potentials at different nodes gives the temperatures at the nodes. We used MULTISIM, a user friendly schematic based tool used to simulate electrical and electronic circuits. Fig. 7 shows the thermal model built for the considered transformer.

The following points are to be understood while building up the thermal model.

1. The tank outer surface acts as a heat sink to ambient and hence is modeled accordingly.

2. Ambient is taken as ground and hence the obtained thermal profile shows the rise in temperatures above the ambient.

3. Symmetry is observed in the equivalent circuit to ensure the heat flow from the center of the transformer towards the tank.

This model now needs to be solved for potentials at all the nodal points which are the temperature rises actually.

VII. CALCULATION OF PARAMETERS OF THE THERMAL MODEL

A. Calculation of Source Values:

The sources in the thermal model represent the heat generation in the element. So, the value of losses calculated in the each block is used as the source values in the thermal model. There is no heat generated in the oil and therefore there are no sources in the oil blocks in the thermal model. The losses in Copper are IR losses, which are calculated using the current densities in the windings. The total losses in the LV or HV copper are calculated and since the copper losses are symmetrically and evenly distributed (which is a very valid assumption), it is distributed equally in the four blocks representing the corresponding coil. The losses in the core blocks are calculated using the values of flux density with the formulae given in equations (1) and (2).
B. Calculation of Thermal Resistances:
The thermal resistance of an element represents the opposition offered by the element to the flow of heat through it in either direction, which is represented by resistors. The value of thermal resistance of each element depends on the material property of thermal conductivity in Watts/mK. Fig. 8 shows such an individual element. If \( x \) and \( y \) are the dimensions of the element in X and Y directions respectively, \( z \) is the Z-direction depth, which is the core thickness, same for all the blocks and \( \rho \) is the thermal conductivity of the material, \( R \) is calculated according to the formula given below.

\[
R_{\text{horizontal}} = \frac{\rho}{x \cdot yz}
\]

(3)

\[
R_{\text{vertical}} = \frac{\rho}{x \cdot z}
\]

(4)

\[
\text{Fig. 8. Single element representation with dimensions}
\]

C. Calculation of Thermal Capacitances:
Thermal capacitance of an element represents its capacity to store the heat, which causes a rise in its temperature. It is calculated by multiplying the value of specific heat capacity of the material of the element with the mass of the block.

VIII. RESULTS
The thermal model when solved in MULTISIM yields potential values at each node which are the temperature rise values above the ambient. For the considered transformer, the parameters used in building the model are shown in table II, the results of which are presented in fig. 9. The values of coefficients \( K_h \) and \( K_e \) of the core are 0.005 and 2.523 respectively. The value of form factor \( K_f \) is taken as 1.1 while the thickness of lamination \( t \) was 0.27mm. The weight of the core was 76.75 kg. The results are super imposed on the transformer geometry to assist understanding. This way we have simulated the temperature profile of transformer and a comparison of the temperature values with those of design values is also presented in table III. The values denoted is the potential at the nodes of the electrical equivalent circuit, which is actually the temperature rise above ambient.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity</th>
<th>Specific Heat Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRGO core</td>
<td>26 W/mK</td>
<td>450 J/kg°C</td>
</tr>
<tr>
<td>Copper winding</td>
<td>400W/mK</td>
<td>386 J/kg°C</td>
</tr>
<tr>
<td>Transformer Oil</td>
<td>0.72W/mK</td>
<td>2060 J/kg°C</td>
</tr>
<tr>
<td>Structural Steel tank</td>
<td>45W/mK</td>
<td>400 J/kg°C</td>
</tr>
</tbody>
</table>

TABLE II
VALUES OF THERMAL RESISTIVITY AND CAPACITANCES USED

\[
\begin{array}{|c|c|c|}
\hline
\text{Material} & \text{Thermal conductivity} & \text{Specific Heat Capacity} \\
\hline
\text{CRGO core} & 26 W/mK & 450 J/kg°C \\
\text{Copper winding} & 400W/mK & 386 J/kg°C \\
\text{Transformer Oil} & 0.72W/mK & 2060 J/kg°C \\
\text{Structural Steel tank} & 45W/mK & 400 J/kg°C \\
\hline
\end{array}
\]

\[
\text{Fig. 9. Temperature profile across the transformer geometry}
\]
This shows that the model developed is sufficiently accurate enough to predict the transformer interior temperatures.

IX. CONCLUSIONS AND DISCUSSIONS

A thermal model that can monitor the thermal profile of the transformer has been successfully presented.

The paper proposes a technique of thermal modeling of electrical utility transformers, which calculates the losses in the transformer from Finite Element Analysis of the transformer geometry in two dimensions. A thermal model, which uses these losses as heat sources and the values of thermal conductivities and specific heat capacities of the transformer materials is proposed and the heat flow paths as well as heat distribution in the transformer geometry is studied. The thermal profile is obtained by solving this model similar to solving an electrical pi-network using the analogy between the thermal and electrical systems.

The proposed model is built and tested on a practical transformer for which the results were good and some of the advantage of this model has also been discussed. This model comes out to be a cheap and effective design tool for predicting temperature rise of transformers.

X. REFERENCES

[7] Indrajit DasGupta, Design of Transformers
[20] Oluwaseun A. Amoda, Student Member, IEEE, Daniel J. Tylavsky, Senior Member, IEEE, Gary A. McCulla, Member, IEEE, and Wesley A. Knuth, Member, IEEE, “A New Model for Predicting the Hottest Spot Temperature in Transformers”
[24] Software Manuals of NISA and MULTISIM