Thermal Modeling of Electrical Utility Transformer

by

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Thermal Modeling of Electrical Utility Transformer
Using Finite Element Modeling Technique and Thermal-Electrical Analogy

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Abstract— Heat dissipation is always a problem in large power transformers. Increased market competency demands for accurate determination of the thermal profile across the transformer. This paper presents a thermal model to simulate the thermal behavior of the electrical utility transformers. The thermal model is arrived at using the principle of thermal electrical analogy and the fact that the losses in the transformer are distributed rather than lumped. In this paper, the model is implemented for single phase transformer and the same model can be extended to three phase transformer. Simulation results are presented.

Keywords- FEM; Power transformers; Temperature; Thermal electrical analogy; Thermal modeling; Thermal profile

I. INTRODUCTION

Power transformers represent the largest portion of capital investment in transmission and distribution substations. One of the most important parameters governing a transformer’s life expectancy is the hot-spot temperature value [1], [2]. To the user, temperatures in a transformer are important to determine the amount and duration of over load it can sustain, and to estimate the effects on the life of the transformer by operation at various temperatures. For a designer, prediction of temperatures at all points becomes important to determine the amount of copper to place in the coils, leads and outlet bushings, type of cooling and ducts, position of ducts, insulation class, design and settings of control equipment [3].

A transformer is provided with a cooling system which is designed for normal operations. But actually, the transformer might run on overload for a longer duration or frequently for shorter durations. Further, there are stray losses in transformer, which are usually under estimated [4]. Also, the iron loss may change because of change in grain orientation due to punching and clamping actions [5]. For all these reasons, the losses actually may be larger than the calculated ones. Though safety factors are included because transformer is a remotely installed and frequent maintenance is not feasible, still we cannot go for large safety factor for economic reasons. This results in temperature rise in the transformer beyond normal value.

The consequences of temperature rise may not be sudden, but gradual as long as it is within break down limit. These include deterioration of winding insulations (Law of Insulation ageing – Arrhenius Law), insulating oil changing its chemical properties and causing dissociation of oil, increased pressure in the tank because of the gases formed during the supposed chemical reactions which arise chances of tank explosion and fire hazards, change in the electric and magnetic properties of the core and coil which again result in increased losses and increased heat generation and accelerate the above discussed effects [5]. Among these consequences, insulation deterioration is economically important. Insulation being very costly, its deterioration is undesirable [6] - [8].

II. THERMAL ASPECTS – HEAT BUILD UP IN TRANSFORMER

The process of energy transfer in the case of transformers involves currents in the conductors and fluxes in the ferromagnetic parts. Thus, there are I²R losses in the windings and core losses in the ferromagnetic cores and hence there is heat generation. Larger is the transformer, even larger are the losses and greater is the heat produced. This thermal energy produced during energy transfer causes a rise in temperature of transformer parts above the ambient. This heat must be properly transferred to outside ambient [8].

Coolants are used to aid this heat transfer. Heat transfer in a transformer takes place through conduction and convection assisted by radiation. The heat generated inside various parts of the transformer is transferred to the surface by means of conduction. This heat is transferred to the tank surface by convection. The heat from the tank surface is dissipated to the ambient by means of convection assisted by radiation. The heating up and cooling down of the transformers are exponential in nature with the gradient determined by the heating and cooling time constant respectively [5].

III. THERMAL MODELING – RECENT TRENDS

Thermal Analysis is the study of heat transfer through devices. Thermal modeling is the development of a mathematical model that predicts the temperature profile of an object or device using the principle of thermal analysis. The accuracy of the thermal model depends on the guiding principles used for the design of the model and the accuracy of values used for the parameters.

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The earlier works done in this area are presented in [4], [9]–[22]. The usual practices followed for the temperature calculations and winding hotspot estimations are IEC and IEEE empirical formulae [9], [10] which are insufficient with the market competency these days [11], [12]. Further, simple estimates of temperature rise, which are achieved through 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. In the recent past, fiber optic sensors have significantly improved to the extent that direct measurement of winding temperature is sometimes preferred to measure temperatures than using standard empirical formulae. Compatibility of fragile fiber optic sensor with transformer factory environment, which was a problem, is now resolved with sturdy fiber jackets, proper spooling of sensor during factory work and simplified through-wall connections. But these fiber optic sensors are costly.

With the improved capabilities of computer automations, efforts are being done constantly to derive software based packages for accurate measurement of hot spot temperatures. Improvisation is needed not only in the measurement of temperatures but also in the methods of accurate determinations of eddy current losses, stray losses, cooling mechanism etc. In this direction a two dimensional finite element formulation for calculation of eddy current losses in transformer windings has been given in [13]. For large power transformers, the radial component of the leakage flux becomes appreciable, which is not accounted for in the empirical formulae. An initiative towards accurate determination of this radial component of leakage flux was presented in [13]. 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, so that the resulting losses can be used in conventional models to calculate the hot spot temperatures.

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 basic R-C circuits driven by current source are said to define the total thermal model of a transformer. One is supposed to be the air-to-oil model, which is used to calculate the top oil temperature. This temperature would serve as ambient temperature 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].

The oil flow inside the tank is a complicate process, dependent on the temperature, viscosity and whether the oil flow is natural or forced. Further, the heat transfer is both by conduction and convection and attempts are being made to model the complex oil flow. Attempts are also being made to model for accurate determination of the magnetic properties of the core using FEM packages [18], [19]. These are the recent innovations in finding internal temperature through advance computational techniques. 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.

IV. PROPOSED TECHNIQUE OF THERMAL MODELING

A. Considered Problem Geometry:

A transformer with specifications as 15 KVA, 11KV/250V, single phase 3-limb two winding construction has been considered in this paper. Fig. 1 shows the geometry of the transformer and gives the dimensions of the transformer in SI unit system. The winding is wound on the central limb. The inner winding is LV winding and the outer one is HV winding.

![Considered Transformer Geometry](image)

Figure 1. Considered Transformer Geometry

B. Working Principle:

The proposed model as said above uses distributed values of losses instead of lumping them. The principle is that each point-element in the transformer generates heat because of the loss in it. The heat transferred to that element or from that element depends upon the neighboring elements. The element stores a little amount of heat, which is the cause of temperature rise of that element and dissipates the rest into surrounding medium as long as its temperature is greater than that of the surrounding medium. The temperature of each point-element depends on heat generation in that element and also surrounding elements temperature.

C. Overview of Implementation:

First we divide the transformer geometry into finite number of elements. The flux density in each of the elements is found out using Finite Element Analysis (FEA). An electrical equivalent block simulating the thermal behavior is built for
each element, which when assembled together give the thermal model for the entire transformer geometry. This electrical equivalent of thermal model when solved for potentials at different nodes gives the temperatures at the nodes.

D. FEA Implementation:

The concept of FEA deals with applying the differential equations over smaller sub domains of the main domain and then building up the solution of next layer of sub domains using the already calculated values of field variables of the neighboring domains as boundary conditions [23]. This is extended to transformer problem. The values of field variables are computed for single element (the transformer geometry has been divided into a number of finite elements) using Maxwell’s equations. This serves as boundary conditions for the next layer of elements and computations are made for the next layer of elements. The software used for this purpose is NISA, a comprehensive suite of programs for Computer Aided Design.

E. Development of Thermal Model:

The development of the thermal model is based on thermal electrical analogy [22] presented in Table I. The heat generated by the element is represented by a current source and the heat dissipated by the element is represented by means of resistors connected horizontally and vertically. Thermally modeled elements in this way are connected together in the same way the elements are located in the geometry and this yields the thermal model for single phase transformer.

<table>
<thead>
<tr>
<th>Sl. no</th>
<th>Element</th>
<th>Thermal parameter</th>
<th>Electrical Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Through variable</td>
<td>Heat transfer rate (Power loss) q Watts</td>
<td>Current i ampere</td>
</tr>
<tr>
<td>2</td>
<td>Across variable</td>
<td>Temperature θ °C</td>
<td>Voltage v volts</td>
</tr>
<tr>
<td>3</td>
<td>Dissipation element</td>
<td>Thermal Resistance Rth °C/Watt</td>
<td>Electrical Resistance, Rth Ω</td>
</tr>
<tr>
<td>4</td>
<td>Storage element</td>
<td>Thermal Capacitance Cth J/°C</td>
<td>Electrical Capacitance, Cth Farads</td>
</tr>
</tbody>
</table>

V. FEA IMPLEMENTATION FOR TRANSFORMER

FEA is applied on the transformer to obtain distributed flux densities at various locations in the transformer. Using the electromagnetic module of NISA, we obtain the flux densities at various elements [24]. The numerical values of material properties considered in the model are as shown in table II. The value of flux density in each element is used to calculate the loss and thereby the heat generated in the element. The elemental division of geometry, the flux density plots and leakage flux plots are shown in fig. 2, fig. 3, fig. 4. It is important to note that the color bands in the flux density plot define a range of values; not a single value.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>MATERIAL</th>
<th>MUXX(1/μμr)</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>

In the leakage flux plot, the range of the output has been limited to the maximum value of flux density in the windings.
and tank (leakage flux density). That is why, the rest regions look black.

**Figure 4. Leakage flux plot**

In the process of Finite Element Modeling of the various parts of the transformer, the considerations taken are as given below.

1) The simplifications considered in core modeling are:
   a) Conventional construction of core is assumed instead of mitred core
   b) The core is made of high quality CRGO Si steel.
   c) The clamps and clamping bolts etc are not modeled because this is a two dimensional cross section of the actual core.

2) The simplifications considered in coil modeling are:
   a) Spaces between layers and discs of the coils are neglected. The inter turn insulations, inter winding insulations and the inter disc insulations are neglected.
   b) The coil is considered to be a copper solid lump according to software limitations. The current density will be the Ampere turns of the original winding divided by the cross sectional area of the winding.
   c) The eddy currents produced in the copper winding due to stray flux are neglected.
   d) Secondary winding AT = (Primary AT – Magnetizing AT)

3) The simplifications considered in oil modeling are:
   a) The oil is considered static. Dynamic behavior of oil can be accounted for, using corrective multiplication factors.

4) The simplifications considered in tank modeling are:
   a) The tank construction is assumed to be rectangular.
   b) Cooling employed is assumed to be ONAN. So, no radiators are modeled.

**VI. DEVELOPMENT OF THERMAL MODEL**

The equivalent electrical circuit simulating the thermal behavior of each element is extended to form the thermal model of transformer. Fig. 5 shows the electrical equivalent circuit, which can simulate the thermal behavior of an element. Similar electrical equivalents are built for each element and then assembled to arrive at a total thermal model. The points to be noted in this process are as follows:

1) There are no sources in the case of oil elements, as there are no losses in the oil. Oil is a dissipating medium, and there is no heat that is actually generated in the oil.

2) The heat dissipation from the tank to ambient is represented by means of thermal resistances connecting the outer nodes of the tank to ambient.

3) The ambient is taken as ground in the electrical equivalent circuit simulating the thermal behavior. However, the ground here is not at zero potential. It is at the potential equal to the ambient temperature (refer analogy) i.e., 20°C. In other words, we can say that the thermal model yields the temperature rises above ambient instead of giving absolute temperatures. This is an added advantage that the developed thermal model includes the effects of ambient too.

4) Symmetry is observed in the equivalent circuit and the issue that heat in the transformer is transferred from the centre to the outside in either directions is taken care of accordingly.

**Figure 5. Equivalent electrical circuit simulating the thermal behavior – Original circuit and the steady state equivalent circuit**

The correspondingly built thermal model is shown in fig. 6.

**Figure 6. Thermal Model**

This model now needs to be solved for potentials at all the nodal points which are the temperatures actually. MULTISIM is the software used for solving the circuit shown in fig. 6.
MULTISIM is a user friendly schematic based tool used to simulate electrical and electronic circuits.

VII. CALCULATION OF PARAMETERS

A. Calculation of Source Values:

The sources in the thermal model represent the heat generation in the element because of power loss taking place in that element. So, the value of losses calculated in the core, coil and tank sections are 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 $I^2R$ losses, which are calculated using the current densities in the windings. The losses in the tank and core are the iron losses because of flux lines passing and are calculated using the values of flux density and dimensions of various elements (divisions) of the core and tank with the formulae as given below.

\[ W_h = K_h(B_m)^{1.6}f \text{ Watts/kg.} \] (1)

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

Where, $K_h$ and $K_e$ 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.

Using these formulae and the flux density values in the core and tank, we calculate the iron losses in the core and in the tank (Iron losses occur in the tank because of leakage fluxes) and the calculated losses are given as inputs to the thermal model.

B. Calculation of Thermal Resistances and Capacitances:

We have used a novel approach for calculating the values of thermal resistances. The thermal resistance exhibited by a section of elements is equal to the temperature drop across the section divided by the total amount of heat the section of elements has to dissipate. This value should be equal to the total heat generated by all the elements geometrically enclosed within the section of elements. For this, we divide the transformer into different sections denoted by ‘S *’as shown in the fig. 7. ‘S’ in the fig. 7 represents ‘Section’, while * is the numbering given to the section.

Now, the resistance of an entire section calculated is distributed across the elements of the section. The calculated resistance multiplied by the total surface area of dissipation would be proportional to the specific resistance exhibited by that section of elements. Depending upon the surface area of individual element, this specific resistance value is used to calculate the resistance exhibited by individual element. In this way, the resistances are computed.

The capacitance of each element is calculated by multiplying the specific heat capacity of the material of the element with the mass of the block.

VIII. RESULTS

The circuit when solved in MULTISIM yields potential values at each node. These values are actually the temperature values by analogy.

With the transformer dimensions considered above and with the properties of materials as given in the table II, we have obtained a set of results as shown in fig. 8, which shows the temperature distributions. The results are super imposed on the transformer geometry to assist understanding. This way we have simulated the temperature profile of transformer and the temperature values are quite reasonable. The values denoted is the potential at the nodes of the electrical equivalent circuit, which is actually the temperature rise above ambient.

IX. ADVANTAGES OF THE METHOD

A few advantages of this method of thermal modeling of power transformers and obtaining the temperature profile of the transformer are as follows:

1) It requires no investment or cost of operation except the computational power, which has turned cheap now-a-days. Therefore, this method is very economical.

2) It gives the total thermal profile across the transformer geometry which gives a better understanding of the thermal performance of the transformer. It also provides an idea to what extent the materials must be thermally insulated.
3) Since it considers the distributed losses, this is more accurate than the lumped source model.

4) It doesn’t require any other details except the dimensions and the current density, while material constants are available for any transformer.

5) The proposed model can be built up before the actual transformer is manufactured. Thus, the model can be used to check the thermal feasibility of the design.

X. FUTURE SCOPE OF THIS WORK

This model can be extended to three phase transformers. Also, the elements can be made smaller such that the considered transformer geometry comprises of more number of elements and hence temperatures at more points on the geometry can be obtained. That would give a finer thermal profile of the transformer. Efforts are being made towards arriving at a more compact formula for calculating the thermal resistances exhibited by the elements by generalizing the process and defining the relations in a more organized way. In general, this application of Finite Element Analysis (FEA) to transformer problems (or in general electro magnetic problems) has a lot of future scope and this technique can be used for stray loss evaluation in the transformer, leakage flux calculations, optimal design and location of magnetic shunts to reduce the stray losses, and the design of baffles to direct oil flow etc.

XI. CONCLUSIONS AND DISCUSSIONS

The paper presents a technique of thermal modeling of electrical utility transformers. The losses in the core, which are difficult to accurately compute, are calculated by determining the flux densities using Finite Element Analysis. A thermal model is proposed which uses the calculated values of the losses as heat generating sources, combined with the values of thermal resistance calculated from losses using the temperature drops at various elements. This model gives the temperature profile across the considered transformer’s geometry. The proposed thermal model builds a thermal equivalent electrical model for the transformer, whose parameters are based on the dimensions and specifications of the transformer and simulated temperature profile is presented. This model comes out to be a cheap and effective design tool for predicting temperature rise of electrical utility transformers.

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