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Steady State Temperature Distribution of Cast-Resin Dry Type Transformer Based on New Thermal Model Using Finite Element Method

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Abstract—In this paper, a thermal model of cast- resin dry type transformer is proposed. The proposed thermal model is solved by finite element technique to get the temperature at any location of the transformer. The basic modes of heat transfer such as conduction; convection and radiation are used to get the steady state temperature distribution of the transformer. The predicted temperatures are compared with experimental results reported in this paper and it is found a good agreement between them. The effects of various parameters such as width of air duct, ambient temperature and emissivity of the outer surface were also studied.

Keywords—Convection, dry type transformer, finite-element technique, thermal model.

I. Introduction

In recent years, the variety of transformer types available for use in small and medium power applications has grown considerably [1]. The major types are oil filled transformers, gas insulated transformers and dry type transformers. In oil filled and gas insulated transformers, the oil and gas are acting as insulation and a cooling medium. But the dry type transformer lacks any fluid for cooling [2].

Cast resin type is the most popular kind of dry type transformers. This type of transformers is protected against flammability and moisture attraction [2]. Analytical and experimental investigation of temperature distribution in some types of dry type transformers has been presented in [2-5]. However, no mathematical model gives a detailed data about the transformer. By using finite element technique to analyze the proposed model, more accurate configuration of temperatures is obtained and the location of hot spot in the transformer can be determined. A schematic view of cast resin transformer is shown in Fig. 1 [6].

Three dimension problem is reduced to two dimensional (r and z) as space variable to reduce size and time and time of calculation.

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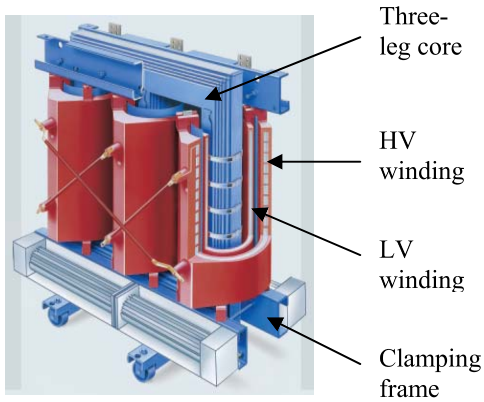

Fig. 1 Schematic view of cast resin transformer

II. Proposed Thermal Modeling

A. Finite Element Analysis

A mathematical model of cast resin dry type transformer is developed to investigate the temperature distribution, using the finite element technique, due to heat generation in the windings and iron core. The effects of heat generation, due to eddy currents, in mechanical parts such as clamps and bolts were neglected. The structure of transformer components is complex, so under accepted assumption, the transformer can be considered as comprised of five major components: iron core, low voltage windings, high voltage windings, air duct and fictitious surface acts as a boundary of the air around transformer as shown in Fig. 2.

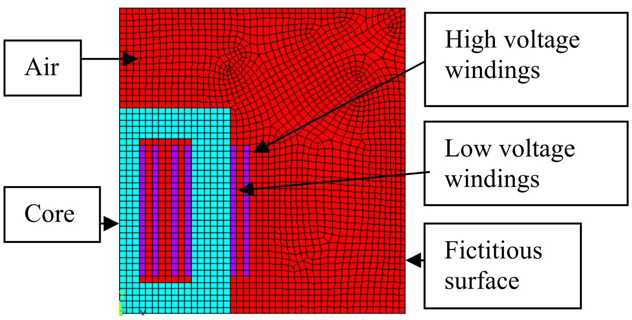

Fig. 2 Schematic of transformer with elements

In the finite–element technique, a complex region is discretized into simple geometric shapes called finite elements as in Fig. 2. The numerical simulation of heat transfer was carried out with **Ansys 10**. A two dimensional cross section of three phase cast resin dry type transformer is used in analysis.

A reflective symmetry around the center line of core was used in the model to reduce the size and time of calculations as in Fig. 2.

The temperatures in 2D cylindrical coordinates are obtained by the heat diffusion Eq.(1) [7]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial Z^2}+\frac{q^\bullet}{k}=\rho c\frac{\partial T}{\partial t} \quad (1)$$

Where T represents the temperature in (K), $q^\bullet$ heat source in (W/m^3), k thermal conductivity (W/m k), ρ density of material in (kg/m^3) and c specific heat in (J/kg K).

To solve Eq.(1), many boundary conditions must be applied on the surfaces of the model. Winding losses, convection and radiation relations are used to get a complete graph of the temperatures at every location in the model.

A. Natural Convection

The heat transfer rate of convection is obtained by Eq.(2)[8]:

$$q''_{conv}=h(T_s-T_{air}) \quad (2)$$

Where q''_{conv} represents heat transfer rate per unit area at the outer surface (W/m^2), h heat transfer coefficient for convection from outer surface (W/m^{2}K), T_s local temperature of surface (K), and T_{air} ambient temperature (K).

The outer surface of high voltage acts as vertical plate so, to get the value of heat transfer coefficient, we use the correlations used in [2] which are given below:

$$h(z)=\frac{Nu_z k_{air}}{Z} \quad (3)$$

$$\mathrm{Nu}_z=\left[\frac{2}{(360)^{1/5}}\right]\left[\frac{\mathrm{Pr}^2}{0.8+\mathrm{Pr}}\right]^{1/5}\mathrm{Gr}_z^{*\,1/5} \quad (4)$$

$$Pr=c\mu/k \quad (5)$$

$$Gr_z^*=\frac{g\beta q'' Z^4}{k\nu^2} \quad (6)$$

Where, Nu_z represents Nusselt number, K_{air} thermal conductivity of air (W/m K), Pr Prandtl number, Gr Grashoff number, g acceleration of gravity (m/sec^2), β volumetric expansion of fluid (1/K) , q'' heat flux at location z (W/m^2), Z vertical distance (m), ν kinematics viscosity of fluid (m^2/sec) and μ dynamic viscosity of fluid (kg/m sec).

The above equations are valid over the Grashoff number in rang $10^5 \le Gr^* \le 10^{10}$ and all the parameters of air are dependent on unknown temperatures [7, 8].

B. Natural Convection in Air Duct

The equations which are used by Pierce [3] will be used in the model to get the heat transfer coefficient between two concentric cylinder (low voltage and high voltage windings) as given below:

$$q''_d=h_d(T_s-T_{air}) \quad (7)$$

$$h_d=\frac{Nu_z k_{air}}{b} \quad (8)$$

For entrance region ($\Phi_z \ge 60$)

$$Nu_z=C_1(1+R)^{1/6}\Phi_z^{1/3} \quad (9)$$

For fully developed flow ($\Phi_z \le 60$)

$$Nu_z=\frac{C_2}{(1+R)\left[\frac{1}{\Phi_z}\left(\frac{24}{1+R}\right)^{1/2}-\frac{9}{27}\right]+\frac{1}{2}} \quad (10)$$

$$\Phi_z=\frac{\left(\frac{b}{z}\right)Gr^* Pr}{\left[\left(\frac{b}{L}\right)Gr^* Pr\right]^{1/2}} \quad (11)$$

$$Gr^*=\frac{g\beta q'' b^4}{k\nu^2} \quad (12)$$

Where, q''_d represents the local convection heat flux in inner or outer cylinder (W/m^2), h_d local heat transfer coefficient for convection from inner or outer wall(W/m^2 K), b width of air duct (m), C_1 and C_2 : 0.697 and 1, L total height of cylinder (m), q'' equal to q_i (heat flux in inner cylinder) and q_o (heat flux for outer cylinder) (W/m^2), and R is equal to q_o/q_i for inner cylinder and q_i/q_o for outer cylinder.

For a rectangular duct b was replaced with B given by the following equation:

$$B=\frac{2(DUCTAREA)}{DUCT\ PERIMETER}=\frac{2ab}{(2a+2b)} \quad (13)$$

Where a is the distance between edges of duct spacers (m).

C. Radiation on the Outer Surface

Radiation heat loss has a considerable effect on the total distribution of temperatures in the model. Radiation heat transfer occurs at outer surface of winding and iron core. It can be calculated as given below [3]:

$$q''_r=\varepsilon\sigma F_{ij}(T_1^4-T_2^4) \quad (14)$$

Where q''_r is the heat transfer rate per unit area by radiation(W/m^2), ε is the emissivity coefficient of surface, σ is the Stephan Boltzman's coefficient (5.67*10^{-8} W/m^2 K^4), F_{ij} is the view factor, T_1^4 is the temperature of first surface (K) and T_2^4 is the temperature of second surface (K) or temperature of air.

III. Validity of Model

The proposed model was verified by comparing the computed results with the measured in [2] (three phase, 50 Hz, 400 V/20 kV, 800 kVA). Fig. 3 shows the contour plot for a nodal temperature distribution of cast resin dry type transformer at full load (800 kVA).

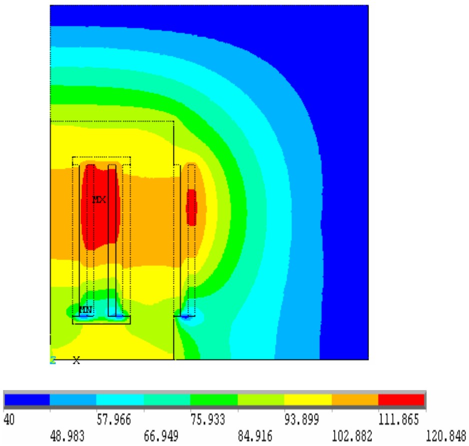

Fig. 3 Calculated temperature distribution at full load 800 kVA

Fig. 4 shows a comparison between experimental data in [2] and the outer surface temperature distribution of the high voltage winding. It can be seen that the modeling is valid with a good accuracy.

The hottest spot for the high voltage located near the top of the winding is 120.8°C. It can be observed the drop of temperature at the top of winding as a result of extra heat loss due to convection.

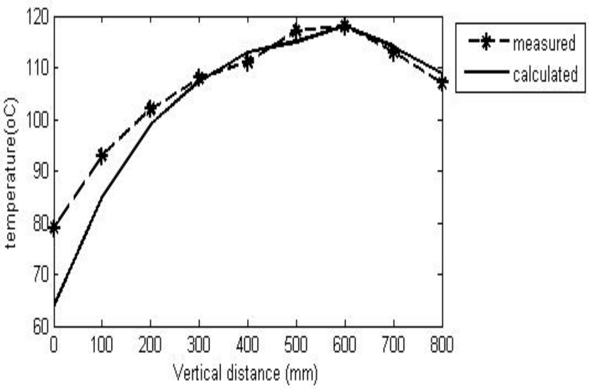

Fig. 4 Comparison measured and calculated temperatures at outer surface

IV. Sensitivity Study

By using the proposed model, the effect of many parameters such as ambient temperature, width of air duct and emissivity of the outer surface are evaluated.

A. *Ambient Temperature*

Fig. 5a, and Fig. 5b and Fig. 5c show a contour plot of temperatures in the transformer at various ambient temperatures (10°C, 30°C, 40°C). Fig. 6 shows the variation of temperature at the outer surface at different ambient temperatures.

It is clear that when the ambient temperature increase, the temperature of high voltage winding and low voltage winding increase but not at same rang because the nonlinearity of relation of convection and radiation.

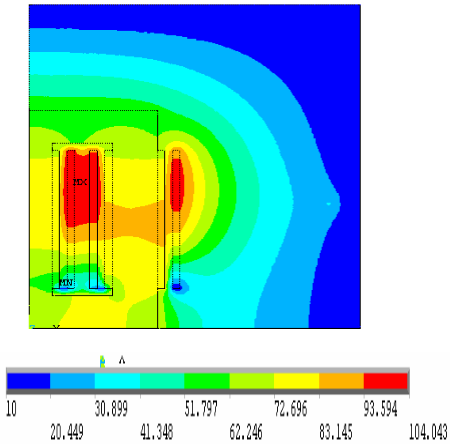

Fig. 5a Calculated temperature distribution at ambient 10°C

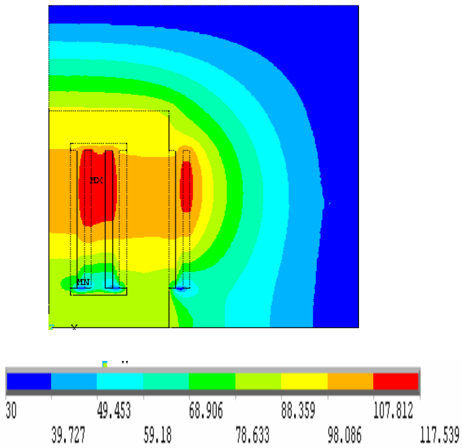

Fig. 5b Calculated temperature distribution at ambient 30°C

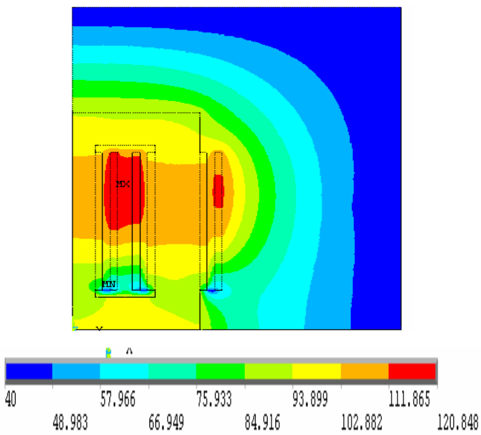

Fig. 5c Calculated temperature distribution at ambient 40°C

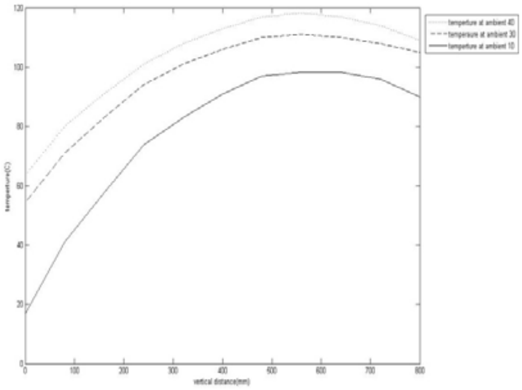

Fig. 6 Variation of temperature at outer surface at different ambient temperature

B. Air Duct

Fig. 7a, Fig. 7b and Fig. 7c show a contour plot of temperatures at different air duct between low voltage and high voltage windings (60mm, 40mm, 20mm).

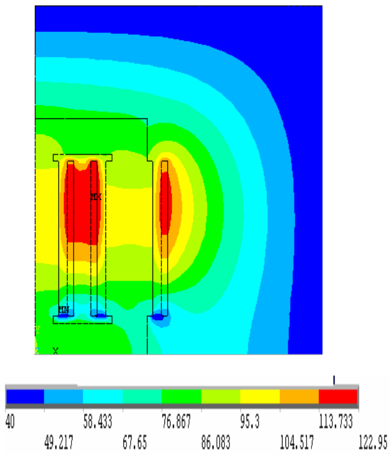

Fig. 7a Calculated temperature distribution at air duct 60mm

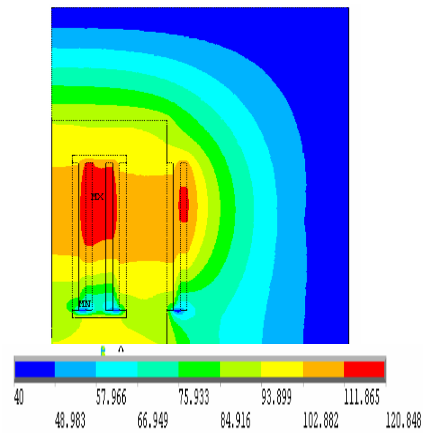

Fig. 7b Calculated temperature at air duct 40mm

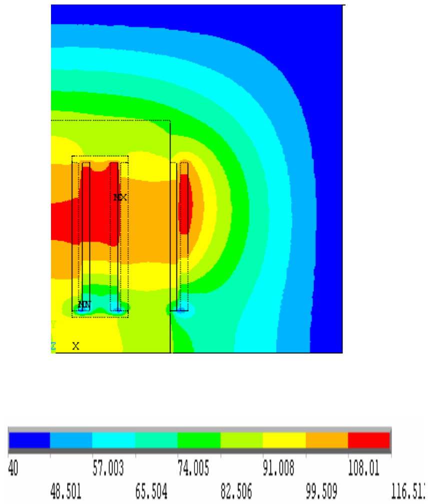

Fig. 7c Calculated temperature at air duct 20mm

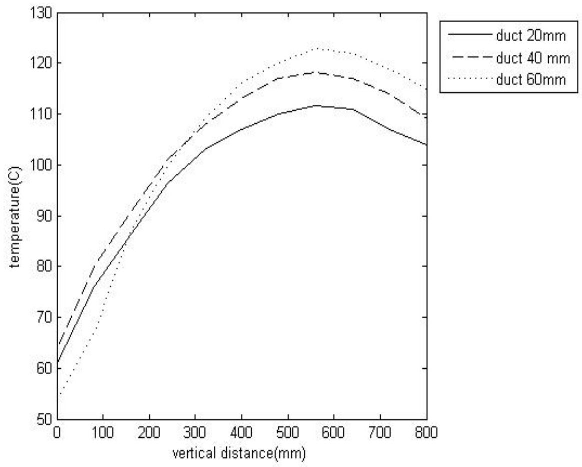

Fig. 8 Variation of temperature of outer surface at different air duct

When the air duct increase the heat loss increase as a result of increasing the length of winding so it is expected that the temperature will increase. But on anther side the convection increase as result of increasing the width of air duct .It can be observed that for small width, the heat loss decrease and has the larger effect but at large air duct the convection will be dominant at the entrance of air duct.

Fig. 8 shows the variation of temperature of the outer surface at different air ducts.

C. Emissivity of Outer Surface

Fig. 9a shows the contour plot of temperature of transformer at different emissivites (0.8 and 0.9).

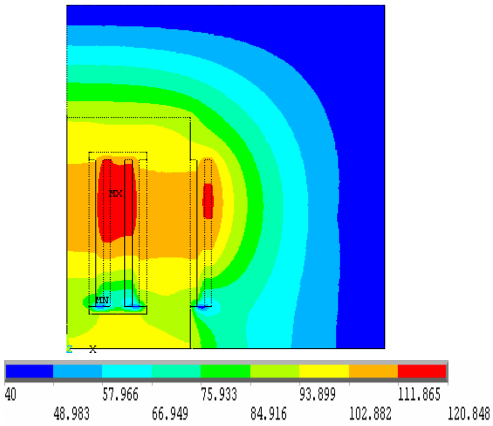

Fig. 9a Calculated temperature at emissivity 0.8

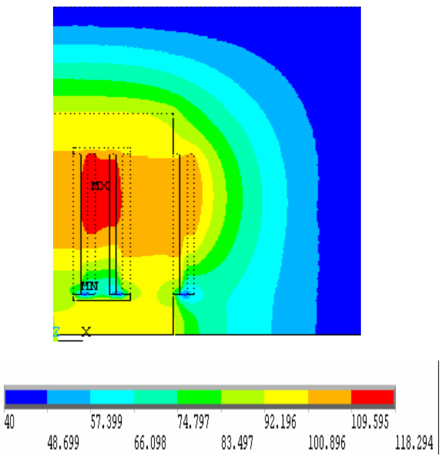

Fig. 9b Calculated temperature at emissivity 0.9

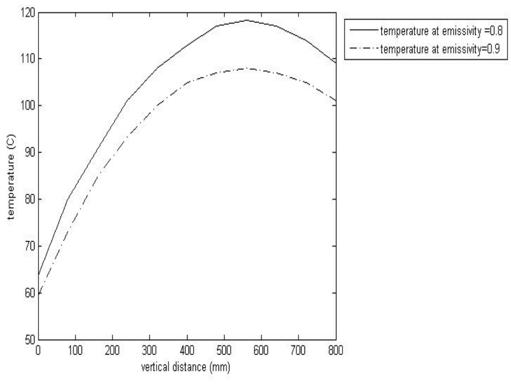

Fig. 10 Distribution of temperature at different emissivites

It is clear that when the emissivity increases the radiation heat loss from the outer surface will increase and the temperature decrease. Fig. 10 shows the distribution of temperature at different emissivity.

V. Conclusion

The thermal model of cast-resin dry type transformer developed in this paper, using finite element technique, gives the distribution of temperature in the transformer. The results of the proposed model were compared with actual measurements and they showed reasonable accuracy. This analysis is more accurate than any other previously developed model because it is possible to predict the value and location of hot spot of transformer. This will be very useful for transformer performance.

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