Predicting Hottest Spot Temperature in Self-Cooled Dry-Type Transformer

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ABSTRACT

In this study, the temperature distribution of a dry-type transformer was determined numerically. Each leg of the transformer that consists of the upper and the lower windings and the core. The solution was carried out for the temperature dependent property fluid. The solution of thermal-fluid equations includes natural convection. The velocity field and the temperature distribution of the windings and the core are obtained by the FEM-based pocket program ANSYS. The level and the location of the hot spot temperature were determined. The agreement between solution obtained and experimental results presented in literature was found to be very good.

I. INTRODUCTION

Transformers are of the main components of the electric distribution systems. The losses in the core and the windings of high efficiency transformers cause an increase in the operating temperature of the transformer. This temperature increase can affect the insulating material used in the windings of the transformer. The life of a transformer is limited by the maximum temperature of this insulating material can stand. Maximum temperature-rise limit depends on the type of the insulating material. Generally, approximate determination of allowable maximum temperature can be experimentally done during which direct current pulses are injected to the windings for a short time while the transformer is operating at the rated power level. The temperature found in the experiment is the average temperature of the windings. In fact, there are points, called hot spot, on the windings where the temperature is above this average value. The insulating material on the windings at these hot spots ages rapidly. This finally causes short circuits between the windings. It's difficult to determine the temperature field and hot spots within the windings by experiment directly. Thermal elements, used windings, disturb normal winding construction and therefore alter the thermal properties of winding. There have been many researches and experiments to find these high temperature points on the windings. There hasn't been enough research to address this important issue. Moreover, the standards about this issue are not clear enough [1,2].

In order to find the location and the temperature level of these hot spots, the temperature distribution of the transformer must be determined. If these hot spots are located the transformer can be safely overloaded, the manufacturing cost can be minimized and it will support of developing to diagnose and detecting faults in power transformers. Rapid development in computer technology makes easier to predict the temperature field by using numerical methods. It's possible to determine the axial temperature distribution of the air and windings as well as the radial temperature distribution within each component [3]. Therefore we obtain much more precise values of the winding temperature and at a known position, the hot spot temperature, the factor governing the ageing and loading of transformers.

In this study, the temperature distribution of a dry-type transformer with thirteen coils was modelled. The level and the location of the hot spot temperature in this model were determined as affected by, the coil geometry, current density, physical properties of conducting and insulating materials and coiling intensity at the coil surface. The flow of air is the principle medium of energy dissipation. A more accurate prediction of air and heat transfer in the air should significantly improve the transformer thermal model. The results of theoretical analysis, obtained by numerical solution of the governing equations, were compared by experiments carried out on a dry type transformer.

II. DRY-TYPE TRANSFORMER MODEL

The model considered here is a dry type self cooled transformer with 13 coils. Each winding is cylindrical and disc type. The upper and lower voltage winding have 537,6.10-3 m height. This configuration of the model is similar to the experimental model studied by [4], for the sake of comparison, which is shown in Figure 1.

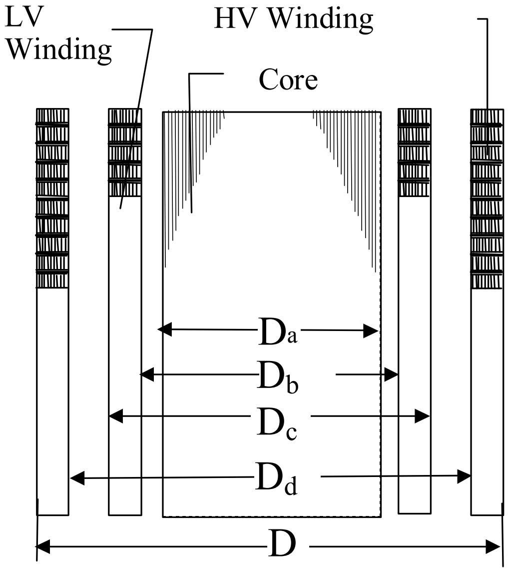

Figure 1. The model geometry

The winding coils made of paper-insulated rectangular copper conductor 1 mm x 8 mm bare, 1,6 mm x 8,6 mm covered (Figure 2.). Windings consist of 13 coils and first four in 13 is made of 3 discs and the left is made of 4 discs. The number of conductors in radial direction is 10 turns and the total number of conductors in upper and lower windings is 480 turns. The winding characteristics of model are given in Table 1.

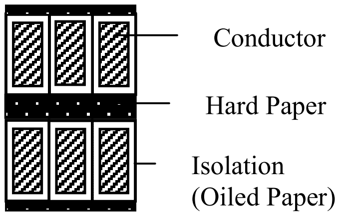

Figure 2. Coil cross-section

Table 1. The winding characteristics

Diameter of core	D_a=157 mm
LV inner diameter	D_b=175 mm
LV outer diameter	D_c=207 mm
HV inner diameter	D_d=271 mm
HV outer diameter	D=303 mm
Winding height	H=537,6 mm
LV and HV winding width	c_1= c_2=16 mm

The conductor in the windings is copper, which is covered oiled paper. Hard paper takes place between the discs. The core is made of a paper-insulated steel core.

III. MATHEMATICAL MODEL

By considering the two-dimensional mass, momentum and energy conservations for this geometry, the temperature distribution of transformer windings, core and surrounding fluid can be obtained [5]. Besides temperature field, the velocity field reveals itself by solving these equations, the adaptation of governing equations for the problem in hand results in the following form;

Continuity equation,

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

The x- and y-momentum equations,

$$\rho(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}) = -\frac{\partial P}{\partial x} + \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) + X \tag{2}$$

$$\rho(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}) = -\frac{\partial P}{\partial y} + \mu(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}) + Y \tag{3}$$

Energy equation:

$$\rho c_p (u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) + \dot{q} + \mu\Phi \tag{4}$$

In this equation ,

T, temperature (K)
P, pressure (N/m^2)
ρ: density of fluid (kg/m^3)
u,v: velocity component of fluid in x and y direction respectively (m/s)
X,Y: body forces in x and y direction respectively (N/m^3)
μ: dynamic viscosity (kg/m s)
c_p: specific heat (Ws/kgK)
k: thermal conductivity for the conductor or insulation material (W/mK)
$\dot{q}$: losses density (W/m^3)
Φ: viscous dissipation (s^{-1})

Dissipation term is as follow,

$$\Phi = 2\left[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2\right] + (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2 \tag{5}$$

Continuity equation is a general expression of the mass conservation requirement. Continuity and Momentum

equations provide a complete representation of conditions in a two-dimensional velocity boundary equation, and the velocity field in boundary layer may be determined by solving these equations.
In the solid part velocity is zero. Thermal conductivity which is defined in equation (4) must depend on directions therefore it is considered different values in each direction.

IV. HEAT GENERATION PER VOLUME IN WINDINGS

The heat losses, due to the electric current through the conductor, were imposed as a volumetric heat generation. Heat generation per volume in windings is as follows,

$$\dot{q} = i^2 . \rho . \eta . 10^6 \qquad (6)$$

where,

i: current density (A/mm^2)
ρ: electrical reistance of conductor (Ω.mm^2/m)
η: filling factor

The lower and upper windings, insulation materials, conductors are considered as a single body. Filling factor (η) allows for the fact that losses occur only in the conductor cross-section; therefore it is defined as follows,

$$\eta = \frac{\text{Total conductor cross - section in coil}}{\text{Total coil cross - section}} \qquad (7)$$

V. EFFECTIVE THERMAL CONDUCTIVITY

Coils in winding consist of conductors and insulating layers. During the development stage of transfer modelling computer capacity and CPU time are two essential restrictions. Therefore, building up a model, having entire dependence on these two restrictions, is needed some simplification and limitations on parameters. it's practical to defined equivalent thermal conductivities due to the windings design complexity. The homogeneity of windings results in calculating horizontal and vertical effective thermal conductivities separately by using constant flux and constant temperature models [6].

VI. SOLUTION PROCUDERE

In order to have numerically effective solution procedure steps given below must be followed.

1. Create the physics environment,
2. Build and mesh the model and assign physics attributes to each region within the model,
3. Establish the boundary conditions for temperature and velocity,
4. Apply boundary conditions and loads,
5. Solve the governing equation (1-6) using the boundary conditions implemented.

The governing equations implemented (1-4) are coupled, so that each equation is solved with intermediate values of already unknown values. All the equations are solved in turn and then the properties and unknown values are updated [7].

The governing equations (1-6) implemented are solved for laminar incompressible flow, including natural convection, and for the steady case, iteratively. Convergence was reached at 950 sweeps, using ANSYS program based on FEM. 2-D Cartesian coordinate system was used with x coordinate in radial direction, y coordinate in vertical direction, 22200 elements were used in order successfully to outline the results. Transport properties own material characteristics of lower, upper winding and core section (ρ, μ, k, c_p) are introduced as known values [8].

The upper voltage winding, lower voltage and the core were taken into account separately. The solution was determined by taking into account the change of fluid properties with temperature. As well as the temperature distribution of the windings and the core,
the temperature distribution and the movement of the surrounding air were also determined.

VII. RESULTS

With the assumptions mentioned above the temperature-rise distribution of transformer windings is shown Figure 3.

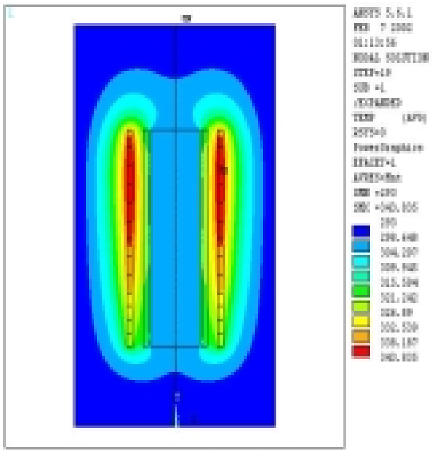

Figure 3. The temperature distribution of transformer windings

Surrounding temperature is 20^{0}C, maximum temperature rise, called hot spot temperature, is found about 50,865^{0}C. From the Figure 3. can easily be seen that the temperature increases from bottom to top of the windings . Hot spot located in the section at 78% of winding height and 33,6 % of winding width. If mid-section temperature of each coil surface is carried on the graphical form, the trend shown in Figure 4. is obtained.

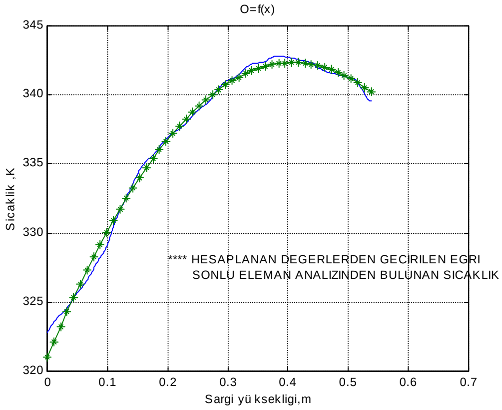

Figure 4. Temperature variation along LV winding height

As depicted in Figure 4. the temperature is continuously increasing and is reaching its maximum value at 74,4% of the winding height.

Continuous movement of fluids, which is moving upper portions of the control volume and then moving down side, during this cyclic movement, heat is continuously removed. However, during this continuous movement of the fluid between two windings, heat produced by the core removed in to the fluid, results in increasing fluid temperature this also brings about turbulent motion. Circular movement of the flow appears about 70% of the winding height.

An appropriate heat model with correct geometrical modelling and boundary conditions, including necessary-given transport coefficients can be solved successfully. By knowing the temperature distribution, it is easy to obtain value and location of hot spot temperature. Comparison of the temperature-rise variation along surface of upper winding-height obtained from experimental data and calculation is shown in Figure 5.

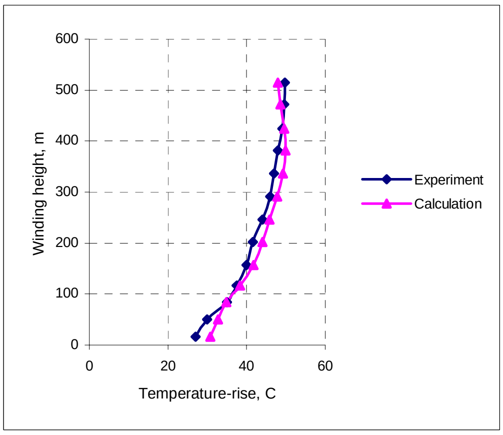

Figure 5. Comparison of temperature-rise variation along surface of upper winding height obtained from experimental data and calculation

Although there is a difference between calculation and measurement, the tendency is almost the same and they are well correlated.

VIII. CONCLUSION

The main objective of this study is to find the temperature distribution and hot spot temperature value and location by which it is possible to determine the life of the transformer and to reduce the material used. Changing in temperature has the dominant effects on transport coefficients as well as on the fluid physical characters. Therefore the field equations of fluid and heat are solved in the coupled form. Surrounding fluid temperature distributions are also obtained. Moreover, upper and lower windings are considered separately and the oil channel cooling effects are also considered, as haven't done in previous studies.

For the future study and further investigations, the heat transfer coefficient can be determined by using this obtained temperature distribution. When the deviation bottom and up portion temperatures reaches over the certain values, turbulence comes up. Therefore, turbulence model is needed for detailed investigation.

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