TEMPERATURE DISTRIBUTION IN THE DISC-TYPE COIL OF TRANSFORMER WINDING

Güven Kömürgöz
e-mail:guven@elk.itu.edu.tr
Istanbul Technical University,
Faculty of Electric & Electronics,
Department of Electrical Engineering,
Maslak, 80626, Istanbul, Turkey

İbrahim Özkol
e-mail: ozkol@.itu.edu.tr
Istanbul Technical University,
Faculty of Aeronautics and Astronautics
Department of Aeronautical Engineering,
Maslak, 80626, Istanbul, Turkey

Nurdan Güzelbeyoğlu
e-mail:nurdan@elk.itu.edu.tr
Istanbul Technical University,
Faculty of Electric & Electronics,
Department of Electrical Engineering
Maslak, 80626, Istanbul, Turkey

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ABSTRACT

In this study a series of numerical experiments are conducted so as to develop a new thermal model for oil-immersed transformer windings. A line of eight-disc-coil has been modelled as a series of heat producing sources in a vertical channel. The heat transfer equations for the model in hand were solved by a semi numerical-analytical method to obtain temperature distribution. Also, the results obtained are verified by ANSYS packet program. And the results obtained are in good enough agreement with open literature.

I. INTRODUCTION

Last two decades, there is an increasing trend in modelling interdisciplinary problems, such as heat-flow, heat-electric-flow, to overcome difficulties presented by the feedback actions of dealing fields. Improving product quality, reducing product cost, and shortening the product development cycle have always been critical for all kinds of companies, even including transformer-coil producing companies, to stay competitive. These competitive drivers result in a continuing need to achieve improvements in today's existing brands.

Therefore, the temperature limits permitted in the active parts, influence the constructional design, size, cost, load carrying capacity and operating conditions of the transformers have already been precisely defined. According to IEC publication in 1976, the average temperature-rise permitted of a transformer winding is determined by the resistance method. But this method has some deficiencies to predict temperature distribution in the coil [1].

The structure of insulating materials built into transformer, mainly those based cellulose, is subject to aging. The aging process is mainly due to the effects of heat and oxygen as well as the duration of their influence. Aging modifies the original electrical, mechanical and chemical properties of the insulating paper used. From laboratory experiments on insulating materials, it has found that determinable dangerous temperature limit can be found for the material used in. There is an exponential relation between temperature, duration of thermal effect and the extent of aging of insulating material. The thermal stress reduces the mechanical and dielectric performance of the insulation.

However, well known fact that, from the experimental observations that higher temperatures result in a chemical dissolution. The active mechanisms in the dissolutions are the value of the highest temperature and its acting period. The experiments, which were carried out by Montsinger indicate that when the transformer temperature has the values between 90-110 ^{o}C, 8 ^{o}C increments on these values results in halving the life of the insulation [2].

To determine average heat load and the temperature-rise, many experiments have been still carrying out. However, the point, which should be kept in mind, is the hot-spot temperature over those obtained instantaneously. As well as, obtaining its exact value, the lasted period of this hot spot is important. Therefore, it is quite important from the point of transformer life to know temperature distribution and hot spot temperature [3,4].

At that point invoking the heat transfer, a thermal model must be developed to over come such difficulties. The thermal design of transformer windings has relied on determining temperature distribution. After applying further simplified assumptions, it is possible to determine the axial temperature distribution of the windings as well as the radial temperature distribution within each individual coil. With this approach, it is possible to obtain much more precise values of winding temperature-rise, and at a known position, the hot-spot temperature as well as the factor governing the aging and loading of transformers.

In the most of the studies, experimental results are presented which are not adequate to answer in any changing in the governing parameters. In the others equivalent circuit models or some simplified models are used to predict the temperature distributions for example Preiningerova, [5], carried only the radial direction temperature distribution under the assumptions of equivalent-winding cross section. In addition to that he also assumed the same values of average surface heat transfer coefficients for horizontal and vertical channel sections or, even in some evaluations, predicted these values from the experimental results.

Therefore in this study a series of numerical experiments are implemented by means of a semi numerical-analytical method so as to develop a new thermal model in design of transformers. The determination of the radial and axial temperature distributions have been managed within a single disc-coil. But, actually, the heat transfer coefficient on vertical and horizontal surfaces must be different in point of heat transfer direction and in existence of buoyancy.

The transformer model, which consists of eight-layer disc-type coil, was borrowed from [6]. And same assumptions are used for the radial and axial heat transfer coefficients for the sake of comparisons. The temperature distributions are evaluated by using ANSYS based on FEM.

I. MODEL

For heat transfer analysis, coils with the cross-section shown in Figure 1. are considered. Neclecting the curvature of winding, the covarege of horizontal surfaces by the spacers is assumed to be about 40% of the total convective surfaces. The temperature profiles of the oil in vertical and horizontal ducts around the winding section are fully developed and beyond the boundary layers. The losses in each coil consist of eddy-current and dc losses. The total losses for each coil is 30,90 W/kg. Dimensions of conductors of an eight layer disc-coil and heat transfer surfaces are shown Figure 1.

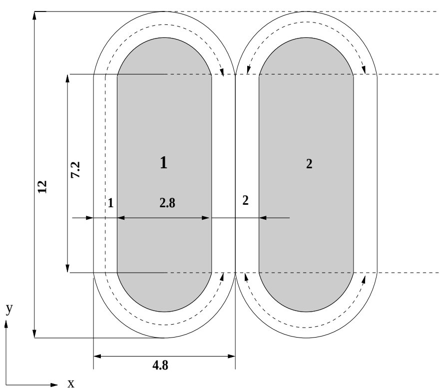

Figure 1. Dimensions of conductors of an eight layer disc-coil

II. HEAT TRANSFER COEFFICIENT

The heat transfer by natural convection inside a cooling duct for a transformer coil is a complicated function of the fluid properties, the coil temperature distribution and duct geometry. This problem has been studied for many years and although a self consistent solution is still not avaible, but many quasi solutions and emprical realitonships are present in literature[7,8,9]. Complicated thermal tests are required to find the true heat transfer coefficient. The coefficient is a nonlineer function of temperature and cooling duct geometry. For long and norrow ducts, temperature varies lineerly along the winding [10]. Heat transfer coefficient can be taken as a costant, since the height of the coil is smaller than the height of the winding.

The heat transfer coefficient can be expressed as an exponential function of heat flux per unit transfer area. The surface heat transfer coefficient can be defined in term of heat flux as follows [6],

$$h = 2.1.q^{0.5} \tag{1}$$

where, q is the heat flux per unit transfer area. This value can be obtained from; dividing the loss of dissipated heat, by outermost layer through convection, by the convection surface of that layer. In the similar manner, for the intermediate layer heat transfer coefficient, which can be obtained by dividing the heat loss to the area it is dissipated.

III. SOLUTION PROCEDURE

Using the thermal circuit, depicted in Figure 2.,it is possible to evaluate heat flow between layers and the flow between the outermost layers and the surrounding fluid.

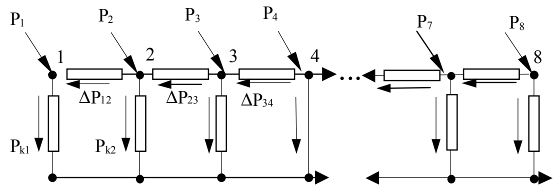

Figure 2. Thermal scheme of an eight-layer disc-coil

As shown by Figure 2., eight nodes correspond to the eight layers, the nodes being marked with serial numbers from 1 to 8. The losses $P_1, P_2 \ldots P_8$ developing in the layers are those given schematically above. The outermost layer on the left hand side obtains a power ΔP_{12} through resistance R_p. The loss developing in the conductor arranged in the 3rd layer is P_3, and the 3rd layer obtains a power ΔP_{34} from the 4th layer and transfers ΔP_{23} to the 2nd layer. From the 1st layer, following powers are transferred to the surrounding fluid,

$$P_{k1} = P_1 + \Delta P_{12} \tag{2}$$

Similarly, same relations can be written between each layer in order to obtain individual temperature-rise, which are denoted by $\Delta\theta_1, \Delta\theta_2, \ldots \Delta\theta_3$

$$\Delta\theta_{\ell} = R_{c+p} P_{k\ell} \tag{3}$$

Where, ℓ is layer number.

R_{c+p} is the the thermal resistance between any layer and fluid is as folows,

$$R_{c+p} = \frac{1}{A_c h} + \frac{\delta}{A_p k_p} \qquad (4)$$

Where, A_c, convection surface area of the outermost layer or any intermediate layer, m^2
A_p, surface area of the outermost layer or any intermediate layer for mean thickness of the paper layer, m^2
k_p, thermal conductivity of insulating paper, W/mK
δ, the thickness of the insulation layer , m.
h, surface heat transfer coefficient, W/m^2K

The temperature drops between adjacent layers can be written, for example, between 1st and 2nd layer

$$\Delta\theta_1 - \Delta\theta_2 = R_{c+p}\Delta P \qquad (5)$$

R_p is thermal resistance of the insulation between any two layers.

$$R_p = \frac{2.\delta}{A_t k_p} \qquad (6)$$

Where, A_t, heat transfer area between any two layers, m^2

With similar assumptions as equation 5 between other layers, seven equations are obtained with seven unknown quantities. The solution of these seven equations yield energy dissipated ($P_{k\ell}$) from intermediate and the outermost layers, the temperature-rise of coil and heat transfer coefficients.

IV. GENERAL EQUATIONS (for Ansys Model)

In this paper the temperature-rise is amount to the difference between the local temperature (T (x,y,z)) and ambient temperature ($T_{Ambient}$). Let the temperature-rise in the windings be defined as,

$$\theta(x, y, z) = T(x, y, z) - T_{Ambient} \qquad (7)$$

The transformer windings thermal analysis may be reduced to the solution of a heat conduction problem related with appropriate convective boundary conditions. Considering the transient conduction of heat transfer process, neglecting convection due to low speed fluid (surrounding fluid) movement around, the governing equation reveals itself as the Poisson equation[11]. Hence,

$$k_x\left(\frac{\partial^2\theta}{\partial x^2}\right) + k_y\left(\frac{\partial^2\theta}{\partial y^2}\right) + k_z\left(\frac{\partial^2\theta}{\partial z^2}\right) + q = \frac{\partial}{\partial t}(\rho c) \qquad (8)$$

Where, θ , temperature-rise ,°C,
x,y,z , spatial coordinates of a Cartesian frame,
c, specific heat, J/kgK
ρ, density , kg/m^3
q, losses density , W/m^3.
k, thermal conductivity for the conductor or insulation material, W/mK

Assuming steady state, then

$$\frac{\partial}{\partial t} = 0 \qquad (9)$$

The increase in winding temperature is generally assumed to increase proportionally with losses. Loss density is given by,

$$q = f_e f_s i^2 \rho_o \qquad (10)$$

Where, f_e, is coefficient for supplementary losses in Winding
f_s is coefficient for the influence of spacers.
i, current density , A/mm^2
ρ_o, the specific electrical resistance of the conductor, $\Omega mm^2/m$

Note that the heat source or loss density exists only in the winding conductors. Then, the governing equation reduce to.

$$k_x\left(\frac{\partial^2\theta}{\partial x^2}\right) + k_y\left(\frac{\partial^2\theta}{\partial y^2}\right) + k_z\left(\frac{\partial^2\theta}{\partial z^2}\right) = 0 \qquad (11)$$

In order to solve equation 8 , boundary conditions for the winding surfaces must be determined as below,

a) at the surface

$$k_p\frac{\partial\theta}{\partial n} + h\theta = 0 \qquad (12)$$

Where n is the direction normal to the surface,

b) at the boundary between insulating layer and conducting part of cross section.

$$k_{cx}\frac{\partial\theta}{\partial x} = k_{px}\frac{\partial\theta}{\partial x} \qquad \text{in the x direction}(13)$$

$$k_{cy}\frac{\partial\theta}{\partial y} = k_{py}\frac{\partial\theta}{\partial y} \qquad \text{in the y direction } (14)$$

where, k_{px},k_{py} is conductivities of insulation material in the radial and axial direction respectively, W/mK
k_{cx},k_{cy} is conductivities of conductor in the radial and axial direction respectively, W/mK

To calculate winding temperature distribution ,

- Find the surface heat transfer coefficient and establish the boundary conditions
- Solve the governing equation 8 using the boundary conditions implemented.

The temperature distribution in the coil is evaluated by using ANSYS program based on FEM. 2-D Cartesian coordinate system was used with x coordinate in radial direction, y coordinate in vertical direction 2220 nodes, 4152 elements were used to successfully outline the results.

V. RESULTS

The results of the calculations, with the assumptions mentioned above, are given Table 1.

Table 1.The results of calculations

Layer Number	Energy dissipated to fluid (W)	Temperature -rise (^{o}C)	Heat Transfer Coefficient (W/m^{2}K)
1-8	13,448	16.769	51,340
2-7	11,070	19.55	56,894
3-6	11,746	20.382	58,6
4-5	11,934	20.611	50,073

By means of the procedure developed, semi analytical numerical, the heat transfer coefficients have been obtained. . In order to find the temperature-distribution, these obtained values introduced into ANSYS program. This distribution is shown in Figure 3.

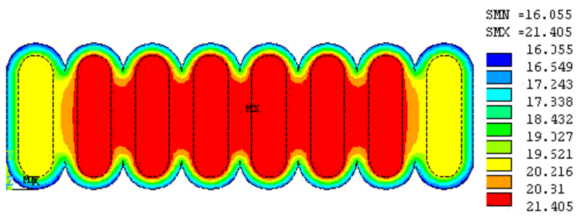

Figure 3. The temperature distribution in disc-coil of transformer winding

The temperature-rise distribution of each coil in axial direction is shown Figure 4. The upper and lower surfaces temperature-rise of coil is symmetrical, since the heat transfer coefficients of upper and lower surfaces are taken equal. The main reason for this equality is fully developed flow field. In the winding channel the coil considered is in the upper portion of the channel, that is the probable section in which hot spot temperature can be exist. If the boundary layer is fully developed, for example at the top of winding , it`s low and the temperature-rise of the fluid in the cooling duct is high, contributing to the hottest spot temperature-rise in the top of the coil [9].

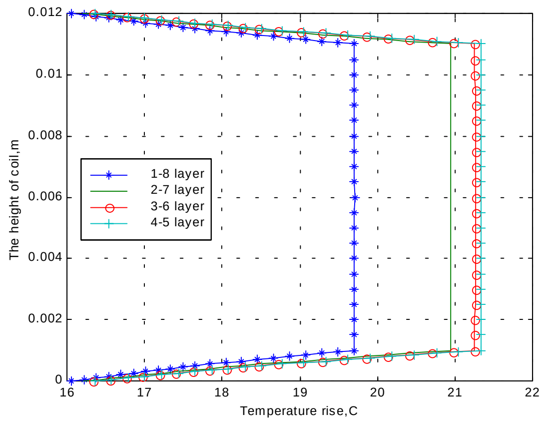

Figure 4. Temperature-rise distribution of coil in axial direction

The temperature-rise distribution of coil in radial direction is shown Figure 5. The difference between the values obtained from ANSYS program and developed analytical method are quite small. This comparision is given in Table 2.

Table 2.Comparision of results

Layer Number:	Temperature-rise (^{o}C)	
	ANSYS Solution	Current Solution
1-8	16.055	16.769
2-7	19.521	19.55
3-6	21.001	20.382
4-5	21.405	20.611

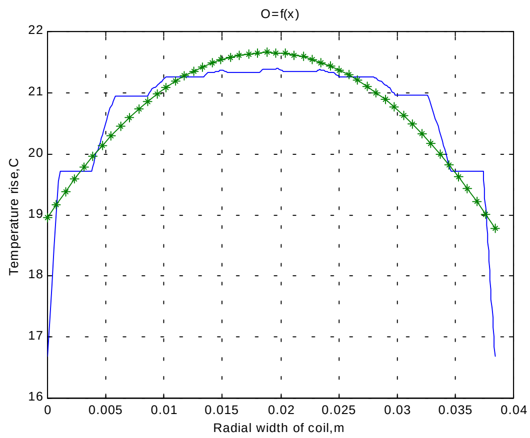

Figure 5. Temperature-rise distribution of coil in radial direction

VI. CONCLUSION

By means of the procedure developed, semi analytical numerical, the heat transfer coefficients both in axial and radial direction have been obtained for the transformer model, which consists of eight-layer disc-type coil. In order to find the temperature distribution, these obtained values introduced into ANSYS based on FEM. Also material proporties, the geometry of the model , heat transfer coefficients for each surfaces are introduced as the input values.

The results obtained from the developed model and ANSYS program have a little discrepancy. That indicates that the developed model can be successfully used for these kinds of analysis.

For the accurate results of the temperature distributions, the exact values of heat transfer coefficients require. However this can be managed by solving the flow field equation by using any means, i.e. numerical methods

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