ISTANBUL UNIVERSITY ENGINEERING FACULTY
JOURNAL OF ELECTRICAL & ELECTRONICS
YEAR : 2002 **(505-512)**
VOLUME : 2
NUMBER : 2

DETERMINATION OF TEMPERATURE DISTRIBUTION IN THE DISC-TYPE COIL OF TRANSFORMER WINDINGS VIA NUMERICAL-ANALYTICAL METHODS

[1]Güven KÖMÜRGÖZ KIRIS **[2]Ibrahim ÖZKOL**

[1]Istanbul Technical University, Department of Electrical Engineering,
80626, Maslak,, Istanbul-TURKEY
[2]Istanbul Technical University, Department of Aeronautical Engineering,
80626, Maslak,, Istanbul-TURKEY

[1]e-mail:guven@elk.itu.edu.tr [2]e-mail:ozkol@.itu.edu.tr

ABSTRACT

In the study presented a new efficient thermal model has been implemented to the coil in oil-immersed transformer windings. In order to show thermal model efficiency eight-disc-coil has been modeled. The governing equations of the model developed were solved by a numerical-analytical method to obtain temperature distribution. The heat transfer coefficients for the convection processes are evaluated for an accurate prediction of the hot spot temperature location. The governing equations were solved in both radial and axial directions. All the evaluations used the model developed are verified by using Finite element-based packet program ANSYS. Both results obtained are in good enough agreement with open literature.

Keywords: *Transformer, coil, temperature, heat transfer coefficient.*

ÖZET

Bu çalýþmada, yaðlý tip transformatör sargý bobinleri için ýsýl model geliþtirilmiþtir. Isýl modelin etkinliðinin gösterilmesi için sekiz diskten oluþan bir bobin modellenmiþtir. Sýcaklýk daðýlýmýnýn bulunmasý için, geliþtirilen modelin bünye denklemleri sayýsal-analitik yöntem kullanýlarak çözülmüþtür. Bobinde sýcak nokta sýcaklýðýnýn yerinin ve deðerinin belirlenmesi için konveksiyona karþý gelen ýsý transfer katsayýlarý belirlenmiþtir. Bünye denklemleri hem radyal hem de eksenel yönde olmak üzere iki boyutta çözülmüþtür. Kullanýlan model için elde edilen analitik hesap sonuçlarý Sonlu Elemanlar Yöntemine dayanan ANSYS paket programý ile karþýlaþtýrýlmýþtýr. Analitik ve ANSYS paket programýndan elde edilen sonuçlar literatürle uyum içerisindedir.

Anahtar Kelimeler: *Transformatör, bobin, sýcaklýk, ýsý transfer katsayýsý*

1. INTRODUCTION

There is a great need to optimize the design and application of transformers. Manifacturers and utilities try to improve product quality by reducing the capital and operational costs of transformers. The temperature limits permitted in the active parts, influence the constructional

Received Date : 19.3.2002
Accepted Date: 28.5.2002

design, size, cost, load carrying capacity and operating conditions of the transformers have already been precisely defined.

The losses in the coils of transformer cause an increase in the operating temperature of the transformer. It is quite important from the point of transformer life to know temperature distribution and hot spot temperature [1,2]. The temperature distribution of transformer at every point should be known to operate it safety and for a long time. The temperature increase can affect the insulating material used in the coils of the transformer windings. The life of a transformer is limited by the maximum temperature rise limit depends on the type of the insulating materials. In fact, there are points on the windings where the temperature is above this average temperature. There have been many researches and experiments conducted to find these high temperature points on the windings. There hasn’t been enough research to address this important issue. The thermal design of oil-immersed transformer windings has for many years relied on determining the mean temperature rise and even difficulties and some degree of uncertainty. Moreover, the standards about this issue are not clear enough. According to standards, the average temperature-rise permitted of a transformer winding is determined indirectly using the resistance method. But this method has some deficiencies to predict temperature distribution accurately in the coil [3,4].

The temperature affects the insulations. The structure of insulating materials using in transformer, mainly those based cellulose, is subject to aging. 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. 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 [5].

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 load capability of transformers.

In some of the studies, experimental results are presented which are not adequate to answer in any changing in the governing parameters. As the CAD (Computer aided Design) tools improve rapidly, it makes it easier to determine accurate temperature distribution in the power transformers by using numerical methods. In the others some equivalent circuit models or some simplified models are used to predict the temperature distributions for example Preiningerova, [6,7], 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 other 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 reliable and adequate thermal model in the 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 view and in the care of existence of buoyancy. Heat transfer coefficients are obtained by a numerical-analytical method.

The transformer model, which consists of eight-layer disc-type coil, was borrowed from [8]. And the 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.

2. MODEL

For heat transfer analysis, coils with the actual cross-section shown in Figure 1. are considered. Neglecting 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 in Figure 1.

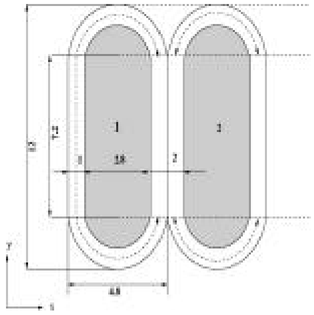

Figure 1. Dimensions of conductors of an eight layer disc-coil

3. SOLUTION PROCEDURE

By 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.

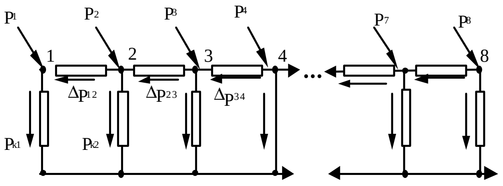

Figure 2. Thermal scheme of an eight-layer disc-coil

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,

$$P_{k1} = P_1 + \text{Ä}P_{12} \tag{1}$$

Similarly, same relations can be written between each layer in order to obtain individual temperature-rise, which are denoted by $\text{Äè}_1, \text{Äè}_2, \ldots \text{Äè}_3$

$$\Delta \text{è}_\ell = R_{c+p} P_{k\ell} \tag{2}$$

Where, ℓ is layer number.

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

$$R_{c+p} = \frac{1}{A_c h} + \frac{\boldsymbol{d}}{A_p k_p} \tag{3}$$

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^{2}K

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

$$\Delta\theta_1 - \Delta\theta_2 = R_{c+p}\Delta P \quad (4)$$

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

$$R_p = \frac{2.\boldsymbol{d}}{A_t k_p} \quad (5)$$

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 unknowns. The solution of these seven equations yields energy-dissipated rate for individual layer ($P_{k\ell}$) from intermediate and the outermost layers, the temperature-rise of coil and the loss of dissipated heat for, by outermost and intermediate layer through convection. Then, heat transfer coefficients are determined for coil walls.

4. HEAT TRANSFER COEFFICIENTS

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 presented in literature [9,10,11,12]. Complicated thermal tests are required to find the true heat transfer coefficient. The coefficient is a nonlineer function of temperature, cooling duct geometry and flow velocty etc. For long and norrow ducts, temperature varies nearly lineer along the winding [13]. Heat transfer coefficient can be taken as a costant, since the height of the coil is smaller than the height of the winding. In fact, the values of heat transfer coefficients differ slightly. The surface heat transfer coefficients for horizantal surfaces are generally different, those for the lower surfaces are being higher then those for the upper ones, and both being lower than that for a vertical surface.

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 [8],

$$h = 2.1.q^{0.5} \quad (6)$$

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.

In the model, only main values of heat transfer cofficients are evaluated by distinguishing the values for different sides of the coil. Therefore, in the present calculations, the heat transfer coefficients used aren’t also uniform over the whole perimeter. The temperature of the oil in the vertical and horizantal ducts around the winding section beyond the boundary layer, is also considered uniform. The surface heat transfer coefficient for upper horizantal surfaces, already presented in earlier study, is taken as 0.8 time the value for vertical surfaces and the surface heat transfer coefficient for upper horizantal surfaces is taken as 0.95 time for lower horizantal surfaces [8].

5. MODEL EQUATIONS

In this study the temperature-rise is amount to the difference between the local temperature (T (x,y,z)) and ambient temperature ($T_{Ambient}$). If θ(x,y) is denoted as temperature-rise in the coil, then

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

The transformer windings thermal analysis may be reduced to the solution of a heat conduction problem related with appropriate convective boundary conditions. A two dimensional approach was used in coil geometry. A cartesian coordinate system was used with x coordinate in a horizantal direction along the radial, and the y coordinate in the vertical direction. 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 [14]. Hence,

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

Where, θ , temperature-rise ,°C,

x,y, spatial coordinates of a Cartesian frame,

c, specific heat, J/kgK

ρ, density , kg/m^3

q, loss density , W/m^3.

k, thermal conductivity for the conductor or insulation material, W/mK

Assuming a steady state case 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 coil

f_s is coefficient for the influence of spacers.

i, current density , A/mm^2

ρ_o, the specific electrical resistance of the conductor, Ωmm^2/m

Note that the heat source or loss density exists only in the winding conductors. 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 sections.

$$k_{cx}\frac{\partial\theta}{\partial x}=k_{px}\frac{\partial\theta}{\partial x}$$

in the x direction (13)

$$k_{cy}\frac{\partial\theta}{\partial y}=k_{py}\frac{\partial\theta}{\partial y}$$

in the y direction (14)

where, k_{px},k_{py} are conductivities of insulation material in the radial and axial directions respectively, W/mK

k_{cx},k_{cy} are conductivities of conductor in the radial and axial directions respectively, W/mK

To calculate winding temperature distribution,

- Create the physics environment,
- Build and mesh the model and assign physics attributes to each region within the model,
- Find the surface heat transfer coefficient and establish the boundary conditions,
- Apply boundary conditions and loads,
- 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 in order successfully to outline the results.

6. RESULTS

The results of the calculations, under the assumptions mentioned above, are given in Table 1. and Table 2.

Table 1.The results of calculations

Layer Number:	Energy dissipated to fluid (W)	Temperature-rise (°C)
1-8	13,448	16,769
2-7	11,070	19,550
3-6	11,746	20,382
4-5	11,934	20,611

By means of the procedure developed, analytical- numerical, the heat transfer coefficients have been obtained. The heat transfer coefficients are given in Table 2.

Table 2.Heat transfer coefficients

	Layer Number:	Heat Transfer Coefficient (W/m^{2}K)
Upper Horizantal Surfaces of Coil	1-8	46,626
	2-7	55,432
	3-6	57,095
	4-5	57,557
Lower horizantal surfaces of Coil	1-8	49,080
	2-7	58,350
	3-6	60,100
	4-5	60,587
Vertical Surfaces of Coil	1	58,296
	8	58,296

In order to find the temperature-distribution, these obtained values are introduced into ANSYS program.

The result of this distribution is shown in Figure 3.

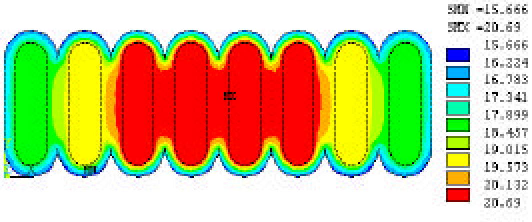

Figure 3. The temperature distribution in disc-coil of transformer winding

The temperature-rise distribution of each coil in axial direction is shown in Figure 4. The upper and lower surfaces temperature-rise of coil aren't symmetrical, since the heat transfer coefficients of the upper and the lower surfaces are taken to be different. The surface heat transfer coefficient for upper horizantal surfaces is taken as 0.8 time the value for vertical surfaces and the surface heat transfer coefficient for upper horizantal surfaces is taken as 0.95 time for lower horizantal surfaces.

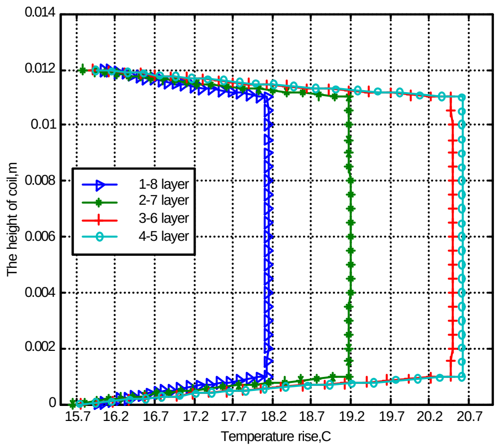

Figure 4. Temperature-rise distribution of coil in axial direction

A carefull inspection of Figure 4. reveals that the upper partion of the coil is hotter than lower part of it at most 0,254 K. In other words temperature rises from bottom to top. In most of the studies the heat transfer coefficients are taken equal, since solutions of governing equations reduces to simple case [7]. But actually, these aren't equal to each other.

The temperature-rise distribution of coil in radial direction is shown in Figure 5. Hot spot temperature of the coil is just in the midlle of the radial width. The differences between the values obtained from ANSYS program and developed method are quite small. This comparision is given in Table 3.

Table 3.Comparision of results

Layer Number :	Temperature-rise (^{o}C)	
	ANSYS Solution	**Current Solution**
1-8	18,151	16.769
2-7	19,191	19.550
3-6	20,491	20.382
4-5	20,625	20.611

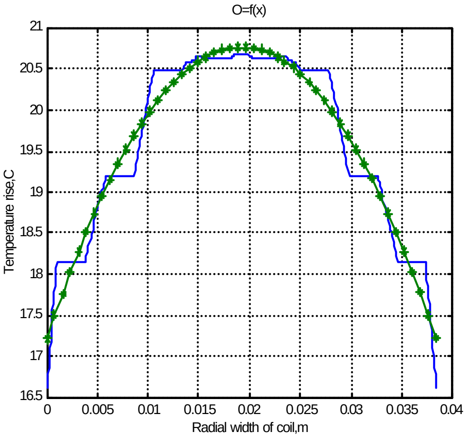

Figure 5. Temperature-rise distribution of coil in radial direction

7. 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 are 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 are required. However this can be managed by solving the flow field equation by using any means, i.e. numerical methods, analytical methods.

REFERENCES

1. Pierce, L., W., “Hottest Spot Temperatures in Ventilated Dry Type Transformers”, IEEE Transactions on Power Delivery, Vol. 9., No. 1., pp. 257-263, January 1994.
2. Pierce, L., W., “Specifying and Loading Cast-Resin Transformers”, IEEE Transactions on Industry Applications, Vol. 29., No. 3., pp. 590-599, May/June, 1994.
3. ANSI, 1981. American National Standard-Guide for Loading Mineral-Oil Immersed Overhead and Pad-Mounted Distribution Transformers,c57,91.
4. CEI-IEC354 International Standard, 1991. oading Guide for Oil-Immersed Power Transformers.
5. Gotter, G., “Erwärmung und Kühlung Elektrischer Maschinen”, Springer-Verlag, 1954.
6. Preiningerova, S.V., Pivrnec, M., “Temperature Distribution in the Coil of a Transformer Winding”, Proccedings of the IEE, Vol. 124, No.3, pp. 218-222, March 1977.
7. Kömürgöz, G., Özkol, Ý., Güzelbeyoðlu, N., “ Temperature Distribution in The Disc-Type Coil of Transformer Winding”, ELECO’2001, Second International Conference on Electrical and Electronics Engineering , pp. 67-71, 2001.
8. Karsai,K., Kerènyi, D., Kiss, L., “Large Power Transformers”, Elsevier,1987.
9. Lobenstein, G., “Zur Heißpunktbestimmung in großen Transformatorenspulen”, Electrie 44, pp. 34-36, 1990.
10. Lobenstein, G., “Die Darstellung des Wärmeübergangskoffizienten im Öltransformator mit kriteriellen Potenzfunktionen”, Electrie 33, pp. 218-220, 1979.
11. Pierce, L., W., “Predicting Hottest Spot Temperatures in Ventilated Dry Type Transformer Windings”, IEEE Transactions on Power Delivery, Vol. 9., No. 2., pp. 1160-1171, April 1994.
12. Pierce, L.W., 1992. An Investigation of the Temperature Distribution in Cast-Resin Transformer Windings, IEEE Transactions on Power Delivery, Vol.7, No.2, 920-926.
13. Hwang, M.D.,Grady, W.M., Sanders, H.W., “Calculation of Winding Temperatures in Distribution Transformers Subjected to Harmonic Currents”, IEEE Transactions on Power Delivery, Vol. 3, No. 3., pp. 1074-1079, July 1988.
14. Incropera, F.P., DeWitt, D.P., “Introduction to Heat Transfer”, John Willey&Sons, 1996.

Biography

Güven Kömürgöz was born in Malatya, 1969. She received the B.S.E.E., M.S.E.E in Electrical Engineering Department from Istanbul Technical University in 1990, 1994. She is interested in Design of Transformer and Heat Transfer. She has been working as a research assistant in the Faculty of Electrical and Electronics of ITU since 1991.

Ýbrahim Özkol was born in Ýzmir, 1962. He received the B.S.E.E., M.S.E.E in Aeronautical Engineering Department from Istanbul Technical University in 1985 and 1988 respectively. He got his Ph.D. degree from Istanbul Technical University, Faculty of Aeronautics and Astronautics in 1992. He is interested in Heat Transfer, Fluid Mechanics, Advanced Dynamics, Genetic Algorithms and Optimization Techniques. He has been working as an associate Professor in the Faculty of Aeronautics and Astronautics of ITU since 1995.