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A2-101

Session 2004

Thermal analysis of oil cooled transformer

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Abstract
Thermal design of oil cooled transformers is generally done by empirical lumped parameter methods. Although these methods and correlations provide quite reliable and safe designs, they have limitations and the safety factor has to be kept large in order to account for various approximations, particularly while developing new designs. There are some thermal design procedures in the literature for winding rise prediction with simple network approach. This paper discusses methodology of thermal predictions by considering the transformer as a whole. It takes into account the change of oil properties with temperature at each node in network. It allows variable spacing between discs; variable electrical losses in each disc; number of discs per pass; presence or absence of oil guiding washers; different number and dimensions of spacers at ID and OD; effect of fans and pumps if any etc. It calculates oil flow between discs and can indicate whether oil flows in reverse direction in any duct. Predictions are made for Average Winding Rise, Top oil rise and Hot spots in ONAN, ONAF and OFAF modes of cooling. These predictions are more accurate than conventional method. This paper discusses the methodology and improvement in accuracy.

Keywords
Thermal analysis – Transformer – Winding rise – Top oil rise

Nomenclature

Symbols

Ra	Raleigh number
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
A	Area
f	Friction factor
h	Heat transfer coefficient
H	Height

K	Thermal conductivity
l	Length

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D	Hydraulic diameter
U	Overall heat transfer coefficient
r	Fouling factor
v	Velocity
V	View factor
Q	Rate of heat transfer
ΔP	Pressure difference
t	Thickness
T	Temperature
ε	Emmisivity
σ	Stefan-Boltzman's constant
ρ	Density
g	Gravity
M	Mass flowrate

Subscripts

avg	average
h	header
o	outside area
p	pipe
foul	fouling
conv	convection
rad	radiation
w	wall
amb	ambient
f	fin
w	winding
th	thermal
bot	bottom

1. Introduction

Insulation in oil cooled transformer is susceptible to degradation when it is subjected to temperatures beyond its temperature class. It is said that the life of insulation is the life of transformer. Because of the complicated geometry of the winding, non-uniform distribution of losses and a complex cooling circuit, the temperature distribution is non-uniform inside the transformer. Mostly, the thermal design of transformers is done based on empirical relations and past experience. These relations are based on simplified thermal models of transformer parts and have limitations. With changed practices in transformer design manufacturing, they tend to get unreliable. Past experience may not help in designing a new type of transformer.

On the other hand, thermal analysis based on CFD takes long time for modeling, meshing, applying boundary conditions, solving and post processing. Designers often will not have the time for such analysis. Also it needs a lot of computer resources, costly softwares and dedicated manpower.

To overcome these problems, a software has been developed to do thermal analysis of transformers. Though it also uses some empirical relations, it predicts performance more accurately and can be extended to new designs without the need for prototyping.

In the past, network models for disc winding were analysed by Oliver A. J [1], Nakadate etal. [2]; by considering pressure drop by friction and bends or by friction and gravity. Kamath R. V. and Bhat G. [3] have numerically studied the effects of spacing between two discs and discs per pass. The authors have carried forward this work [4] to predict the thermal parameters analytically. This paper considers pressure drop due to friction, bends and gravity. It takes into account the variation of oil temperature and properties from duct to duct.

2. Modeling of transformer

Windings considered here were Disc and crossover windings. They are modeled as discs with varying heat generation per disc and gaps between discs. Heat is generated within one or more windings due to the current flow and also in the core and surrounding frame due to core loss and stray loss. Radiator fins are modeled as flat vertical plates with heat dissipation from both surfaces by convection and radiation. Tank walls are modeled as flat vertical plates and tank top and bottom as horizontal plates.

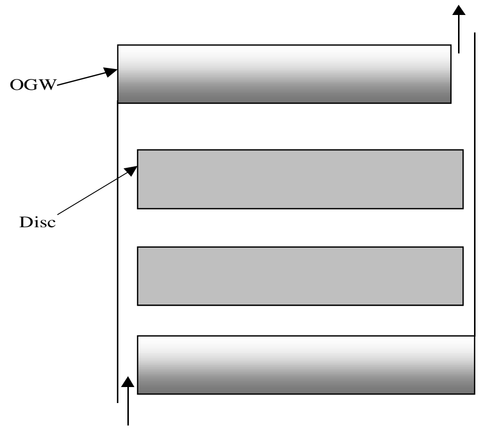

Fig. 1 Sectional view of disc winding

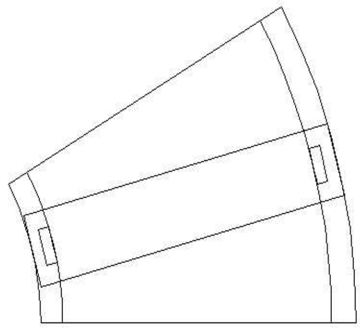

Fig. 2 Top sectional view of disc winding

Fig.1 is a sectional view of disc winding. The discs are arranged one above the other with ducts between them. The ducts are created by placement of horizontal spacers between two discs and vertical spacers at ID, OD or inbetween the winding. The windings have oil guiding washers (OGW) within them to direct the oil flow in a zigzag manner. The group of discs between successive washers is known as a pass. Oil enters at the bottom of winding, flows through vertical and horizontal ducts and leaves from the top. Top view of winding is shown in Fig. 2. It shows the horizontal and vertical spacers that support the discs. They however reduce the cross sectional area for oil flow and surface area for heat transfer from the windings.

Radiator consists of number of fins. Each fin has a number of flutes and flat surfaces joining them. Fins provide a path for oil to flow and vertical surface for rejecting heat to ambient air. There can be one or more radiators each with a number of fins. Oil gets heated in the transformer. It travels upwards and flows into fins from top header. During its downward travel within the fins, it gets cooled and goes back into transformer tank through bottom header. The flow of oil can be natural circulation or forced by a pump. Similarly, air flow over the fins can be by natural convection or forced by a fan. Cooling modes considered here are oil natural air natural (ONAN), oil natural air forced (ONAF) and oil forced air forced (OFAF). ONAN mode of cooling is generally used for lower ratings whereas ONAF and OFAF modes are used for higher ratings. Heat transfer from winding to oil is by convection. Heat transfer from oil to air takes place by convection and radiation.

3. Methodology

The temperatures of interest are top oil rise, average oil rise, average winding rise and hot spot. Inputs to the program are data of transformer winding, radiator and tank geometry; losses and flow from fans and pumps (if any). Geometrical parameters like tank area, radiator area, area of cross section for oil flow etc. are then calculated. Area of cross section and hydraulic diameter can be different for each horizontal duct and electrical losses for each disc. For oil-cooled windings, thermal interaction within phases and windings is negligible [5]. Heat transfer to air takes place by two modes viz. convection and radiation. Both these modes are non-linear functions of temperature. Temperatures of the surfaces are iteratively calculated. From the individual disc temperatures, the average winding rise and hottest disc is found out.

3.1 Calculation of average oil rise

Since heat flux from transformer tank and fins by convection are small, they are assumed to be isothermal surfaces. Fig. 3 shows a flowchart for average oil rise calculation.
For heat transfer from vertical isothermal surfaces i.e. tank walls and fin surfaces [6],
For Ra < 10^9

$$Nu = 0.68 + \frac{0.67Ra^{0.25}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{0.5625}\right)^{(4/9)}} \quad \text{... (1)}$$

For Ra > 10^9

$$Nu = \left(0.825 + \frac{0.387Ra^{(1/6)}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{0.5625}\right)^{\left(\frac{8}{27}\right)}}\right)^2 \quad \text{... (2)}$$

For heat transfer between colder fluid over horizontal plate or hotter fluid below horizontal plate [6],

$$Nu = 0.54Ra^{\text{¿}} 25 \quad \text{... (3)}$$

and for heat transfer between colder fluid below horizontal plate or hotter fluid over horizontal plate [6],

$$Nu = 0.15Ra^{0.25} \quad \text{... (4)}$$

Heat transfer coefficient is calculated from Nu

$$h = Nu\, K / D \quad \text{... (5)}$$

If there is a fan, air flow over the fins is laminar flow in the initial portion of fin where Reynolds no. is less than 5×10^5 followed by turbulent flow. For entire fin [6],

$$Nu = (0.036\, Re^{0.8} - 836)\, Pr^{\frac{1}{3}} \quad \text{... (6)}$$

Since oil flow is laminar, Nusselt no. for oil is constant i.e. 5.0 for given cross section of flute. Considering fouling, the overall heat transfer coefficient is known to be

$$\frac{1}{U_o} = \frac{1}{h_{air}} + \frac{1}{h_{oil}} + r_{foul} \quad \text{... (7)}$$

Heat transfer by convection calculated by

$$Q = U_o A\, \Delta T \quad \text{... (8)}$$

Heat transfer by radiation is calculated by

$$Q_{rad} = \epsilon\, \sigma\, AV\, \left((T_w + 273.15)^4 - (T_{amb} + 273.15)^4\right) \quad \text{... (9)}$$

Here the view factor for intermediate fins is calculated by modeling fins as vertical surfaces of given dimensions and given spacing.
Total heat transfer becomes

$$Q = Q_{conv} + Q_{rad} \quad \text{... (10)}$$

An initial guess is made for T_w. Heat transfer from transformer is calculated for this temperature and compared with heat generated in transformer. This is iterated till the heat input and output are matched within a tolerance.

$$T_{avg} = T_w + \frac{Qt}{K_w A} \quad \text{... (11)}$$

3.2 Calculation of top and bottom oil rises

In upwards flow of oil in tank, its pressure keeps decreasing. When it comes down through fins, pressure keeps rising. For calculating the oil flow due to heating, the pressure drop and increase are matched [7].

$$\Delta P_{rise} = ((H_{th} - 0.5H_f + 0.5H_w)\, \rho_{top} + (H_f - H_w)\, \rho_{avg} - (H_{th} + 0.5H_f - 0.5H_w)\, \rho_{bot})\, g$$

..(12)

Pressure drop per bend in header cooling pipe [1]

$$\Delta P_{drop} = \frac{7000}{Re} \frac{\rho v^2}{2} \quad \text{... (13)}$$

The calculation for oil rise is illustrated in Fig. 4

Initial guess is made for M_{oil}. Pressure rise and pressure drop are calculated for this. Difference of Pressure rise and drop is used as a correction factor with underrelaxation to make new guess for $M_{oil.}$ Guess is refined till they match within a tolerance.

In case of OFAF, the total flowrate of oil is calculated from pumping capacity. T_{top} and T_{bot} are calculated using

$$T_{top} - T_{bot} = \frac{Q}{M} cp_{avg} \quad \text{... (14)}$$

$$T_{avg} = \frac{T_{top} + T_{bot}}{2} \quad \text{... (15)}$$

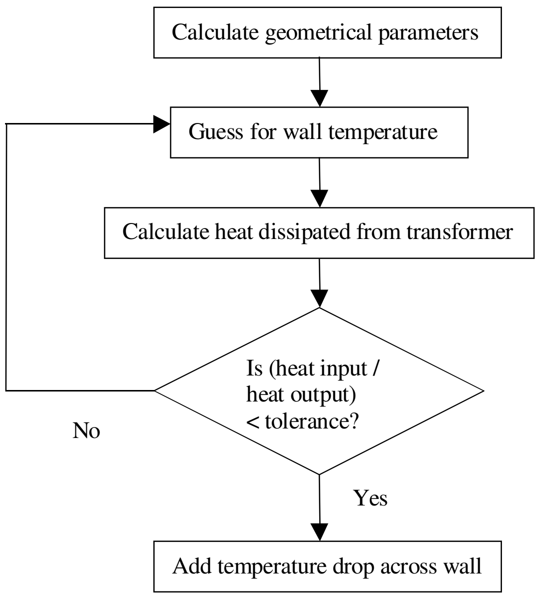

Fig. 3 Flowchart for Average oil rise

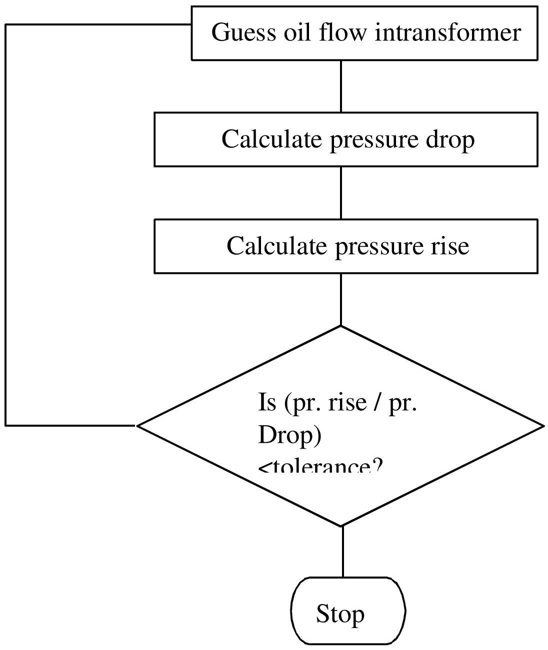

Fig. 4 Flowchart for top and bottom oil rise

3.3 Calculation of average winding rise

Network analysis is used to calculate the flow distribution within the each pass of the winding. Flow inside the windings can be visualised as a network of nodes inside horizontal and vertical ducts around each disc. The nodes are connected to each other by bends and tee joints. Pressure drop due to bends, tee joints, friction and motion against gravity offers resistance to the flow [8]. The flow network can be represented as network of resistances as shown in Fig. 5.

Flow occurs through the winding because of buoyancy and pump (if any). Pressure drop between two nodes is caused by gravity, friction and bends.

Pressure drop by gravity [6]

$$\Delta P_{gravity} = (H_d + H_{SP})\,\rho\, g \qquad \text{... (16)}$$

Pressure drop by friction [9]

$$\Delta P_{friction} = \frac{f\, l\, \rho\, v^2}{2\ D} \qquad \text{... (17)}$$

Pressure drop by 90 degree bend [1]

$$\Delta P_{bend} = \frac{7000}{Re}\frac{\rho\, v^2}{2} \qquad \text{... (18)}$$

Pressure drop by `Tee' [1]

$$\Delta P_{Tee} = \frac{4200}{Re}\frac{\rho\, v^2}{2} \qquad \text{... (19)}$$

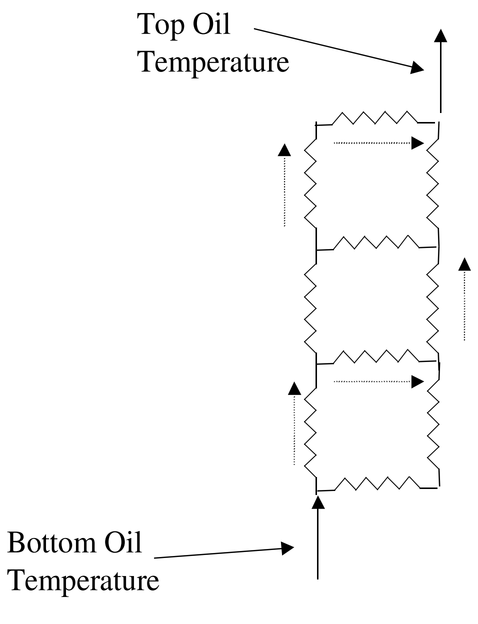

Fig. 5 Network representation of disc winding

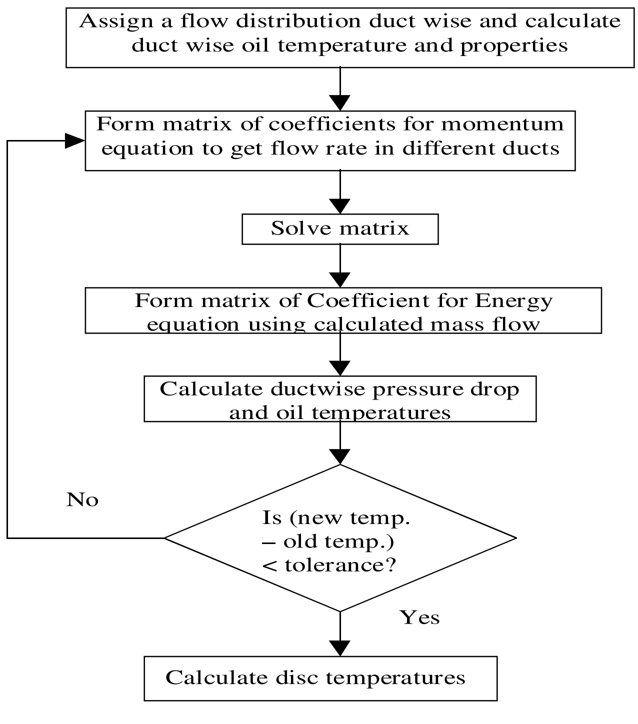

Fig. 6 Flowchart for winding temperature

For each winding, calculation is started from the bottom pass and proceeds vertically upwards. It is iteratively calculated as shown in Fig. 6. Properties of oil, especially viscosity vary greatly with temperature and that too in nonlinear manner. Pressure drop between two nodes depends on temperature and flow rate of oil between the nodes. The solution thus requires iterations. Literature suggests parabolic distribution of velocities in the horizontal ducts along the height of the pass [1] and is taken as the initial guess.

Flow of oil through horizontal and vertical ducts is thus calculated by mass balance. Heat from each disc is taken up by surrounding oil. Energy balance is carried out to calculate nodal temperatures. Oil properties are calculated at these temperatures. Pressure drops and flowrates are calculated based on these properties. Temperatures and flows are calculated iteratively till variation in them reduces within tolerance.

Usually the oil fed at one end flows in same direction through all horizontal ducts. This supplies oil at temperature slightly more than inlet temperature to all discs. If there are large number of discs in a pass (say 20 or more), there is a possibility of reversal of oil flow in some ducts. This was verified with the help of CFD package. Fig. 7 shows a situation in which there is reversal of oil flow in a duct. In this case, hot oil from one vertical duct mixes with colder oil and increases the inlet temperature of oil in all ducts above it within that pass. This in turn gives rise to higher average winding rise. Iterative solution discussed above identifies this problems and helps the designer in correcting the situation.

Temperature of oil surrounding a disc is taken as the average of temperatures at nodes surrounding the disc. Oil properties at these temperatures and velocities at nodes are used to calculate local heat transfer coefficient. Since width of disc is much larger than the disc height, heat transfer to oil mainly occurs from top and bottom surfaces. Heat transfer from vertical surfaces is small and taken into account only while calculating oil temperatures and not disc temperature.

For top surface equation 3 and for bottom surface equation 4 can be used. Insulation causes a temperature difference between surface of the insulation and the conductor. In case of crossover winding or bunched conductors in disc winding, this effect is more prominent. Program models this as an array of heat generating elements with effective thermal conductivity calculated from that of conductor and insulator. Temperature of each conductor is obtained by solving heat conduction equations by Gaussian elimination [10,11].

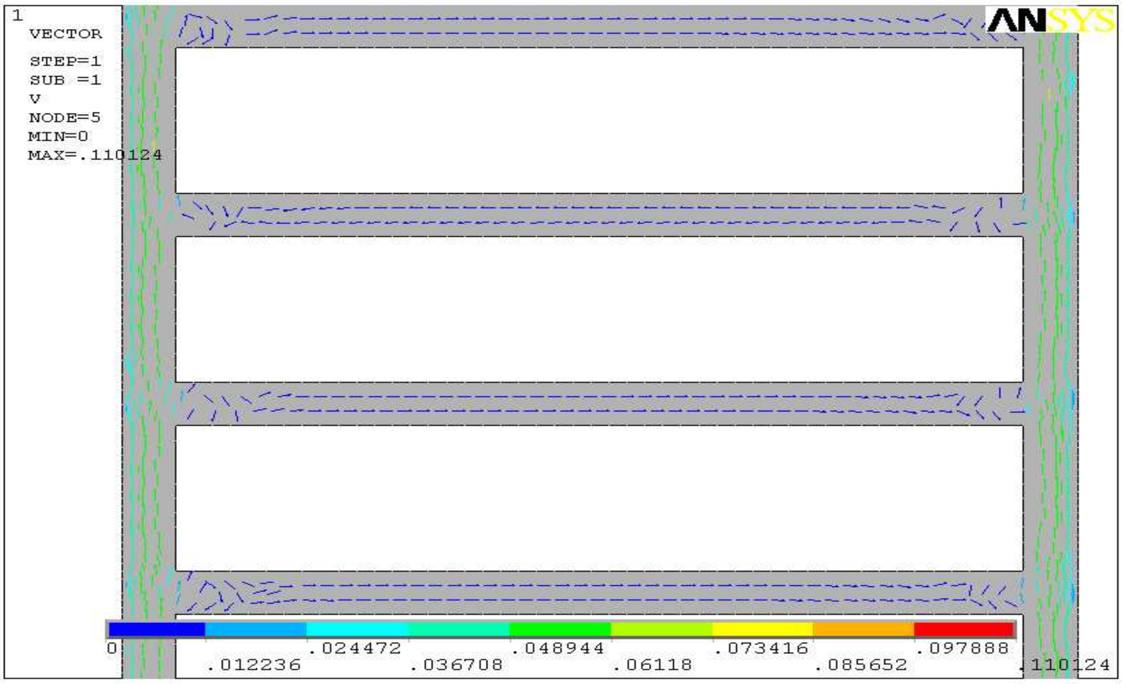

Fig. 7 Reversal of flow in winding

The average winding temperature and hot spot in the winding are calculated from the disc temperatures. This procedure is repeated for all windings.

4. Results and discussion

Standards define maximum operating oil and winding temperatures in terms of top oil rise and average winding rise. Transformers are designed and tested for guaranteed values of these. Measured values for various transformers with different sizes and designs were compared with old design values and prediction by new methodology.

The comparison of error bands for 99% confidence interval of new method and conventional method is shown in Table 1.

Table 1: Comparison of predictions by new and conventional methods

	Error band for 99% confidence interval (°C)	
	Conventional method	New Method
ONAN Average Winding rise	9.8	8.0
ONAN Top Oil rise	11.8	8.4
ONAF Average Winding rise	18.5	9.0
ONAF Top Oil rise	14.9	7.3
OFAF Average Winding rise	13.7	8.2
OFAF Top Oil rise	14.2	5.0

It was observed that when the ratio of disc width to duct height exceeded 35 in case of ONAN and 50 in case of ONAF and OFAF, sufficient oil was not reaching upto middle of disc width. Measured winding rise was higher than predicted in such cases. In case of OFAF, the flow through windings gets enhanced by forced circulation. This effect could not be predicted accurately. Further work in these areas is necessary to improve predictions.

5. Conclusion

The methodology has the following features:

* It is applicable for power transformers with disc, helical and crossover type of winding.
* Predictions from this software are more accurate than conventional method.
* Design with this software is much more convenient, time saving and less prone to human errors compared to CFD and still helps in optimisation.
* It facilitates the designer to evaluate various design parameters. It gives designer some warning messages like oil flow in reverse direction or insufficient thermal head.
* It predicts hottest disc in the winding and its temperature, placement of fiber optic probe for monitoring hot spot is made more reliable.
* Disc windings with different heat generation in each disc; different duct heights can be analysed. Number of spacers, width of spacers can be different in each vertical duct.

The pressure balance technique developed in this project is used for thermal analysis of cast resin dry type transformer with layer and foil windings.

6. Acknowledgments

The authors thank management of Crompton Greaves Limited for their support for this project and permission to publish this paper.

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