Mathematical Modeling of Disc Type Winding Of Transformer

Sandeep Patel

R.G.P.V. BHOPAL

ABSTRACT

Power transformers are heart of electrical system network. Reliability and serviceability of power transformers depends on the cooling performance of transformer winding. To produce high quality power transformers that conform with various national and international standards manufacturers of power transformers such as Crompton Greaves Ltd.The present thesis focuses on development of a mathematical tool for prediction of oil flow and temperature distribution as well as hot spot in disc type winding with oil guiding washers based on network modeling method. In order to achieve this network modeling method was studied and network model for the said winding type was understood. A MATLAB programme was written with top down approach to solve hydraulic and thermal network of the said winding. A simplified heat conduction model was developed and implemented in MATLAB code for prediction of hot spot in a conductor of a disc. The coupled thermo-hydraulic network model studied was then implemented in a simple MATLAB code that used functions to solve hydraulic network, thermal network and conductor heat conduction model.

INTRODUCTION

As aptly mentioned by American engineer and pioneer William Stanley Jr. transformer is "heart of alternating current". With the advent of electricity as a source of power, it became necessary to transmit electricity over longer distances by conducting cables. It was discovered that losses due to transmission are proportional to square of current hence lower is the current lesser are the losses. To transmit same power through electrical lines at lower current level voltage level is to be increased and brought back to same level for low voltage application at user. This was achieved by using alternating current.A device was designed and perfected over several decades in 19th century by several of European and American engineers that used principals of electromagnetic induction for voltage manipulations. It was called Transformer. By the end of 19th century 3 phase transformers had came to existence in its form that is used till date.

  Crompton Greaves (CG) is a part of the US$ 4 billion Avantha group, a conglomerate with an impressive global footprint, operating in over 10 countries. In transformer division, the capacity of transformer manufactured ranges from 25 kVA to 600 MVA and 11 kV to 765 kV class whereas reactors from 10 MVAr and 33 kV to 765 kV class.

Motivation

In the design process of power transformer prediction of hot spot, temperature and oil flow distribution in winding is very critical because the manufactured transformer must conform with the given specifications and prescribed standard by end user of transformer. Thus focus of any engineering analysis in transformer thermal modeling is mainly winding of transformer. There are two

configurations in cooling duct design of winding namely, oil directed (with oil guiding washer) and oil non directed (without oil guiding washer). Thermal analysis of oil directed type of winding is typical due to its characteristic zigzag oil flow path and thus is subject for most of the research in this field.

Currently detailed thermal analysis of transformer winding is performed in 2D or 3D modeling by FVM based commercial CFD software packages such as Ansys Fluent and CFX. The time required in modeling and simulation is large and systems only with large memory storage as well as faster processing (multi-core processor) are capable to support these simulations.

Literature Review

With relation to prediction of oil flow and temperature distribution in large power transformer and prediction of hot spot along with its location two methods are largely discussed in literature. This literature review primarily focuses on development in this regard since 80's of last century. Various articles from journal and conferences were studied which included latest developments in the modeling methods. Thermal modeling methods studied in this literature review are:

- Computational Fluid Dynamics (CFD)

- Network modelling (NM)

Computational fluid dynamics (CFD)

Kranenborg et al. (2008) [4]:The effect of hot streaking and various regimes of convection on thermal performance of disc type transformer winding wasdescribed through CFD modeling in 2D. Conclusion made was consideration of buoyancy in modeling changes the mass flow distribution and temperature distribution in winding .

LeeJ.Y. et al. (2010) [5]: Cooling design for zigzag winding was studied in this research paper. Correlation for heat transfer coefficient and pressure loss in terms of non dimensional numbers was developed for a winding design which was modeled using commercial CFD software for different geometry, operational and ambient parameters.

TorrianoF. et al. (2010) [6]:A detailed 2D CFD study on a single pass of the 26.4 kV LV winding of a natural oil cooling 66 MVA transformer was presented in this research paper. It was concluded that buoyancy plays key role in flow distribution and heat transfer but the approximation of solid domain, that is the considering disc as homogenous copper blocks is sufficient for calculation accuracy.

TorrianoF. et al. (2012) [7]:The effect of spacers and inter-stickswas demonstrated with a 3D model of same winding studied by authors in their earlier work. In this work conjugate heat transfer analysis of the studied winding geometry was done. CFD simulation for both uniform and non uniform heat loss in winding was performed in 2D as well as 3D and hot spot predictions were compared.

Network modeling (NM)

Zhang J. and Li X. (2004) [12,13]:Network model for transformer winding was developed considering pure axis symmetry based on winding geometry by Szpiro and compared the result with Szpiros' experimental result and numerical prediction. The winding design parameter optimization was carried out for different inlet outlet configurations, mass flow rate and oil channel dimensions. Effect of various parameter changes on flow distribution and pressure loss was demonstrated.

RahimpourE. et al. (2007) [14]:Network model for disc type winding with directed flow was

developed and validated with experimental results. Effect of various parameters such as consideration of eddy losses, spacer numbers, spacer width, cooling system height and duct height on temperature distribution in winding was studied.

RadakovicZ. L. et al. (2010) [15] A comprehensive model for optimization of cooling circuit of transformer based on network modeling approach was formulated in this research paper. The quantity and consequences of oil bypass was studied and it was shown that OD is more beneficial than OF cooling.

Weinläder A. et al. (2012) [16]: The effect of junction pressure loss on oil flow distribution was demonstrated in this research paper. CFD calibrated junction pressure loss equations were deployed and flow distribution along with pressure drop across winding was compared with CFD as well as experimental results.

Based on the literature reviewed to develop network modeling tool for prediction of oil flow and temperature distribution in disc type winding with oil guiding washer following conclusion are drawn.

Methodology

In order achieve the said objectives set following steps are to be taken.

1. Development of code in MATLAB

A code is to be developed in MATLAB to solve any general case of disc type winding with directed flow of oil which can be used as the said mathematical tool in purpose of this thesis. The formulation of equation and solution algorithm described in research paper authored by Oliver is to be implemented in this code. Various parameters and variables are to be identified and

input/output method is to be determined accordingly. The approach used for programming will be top down in which various functions will be defined to operate on the data given.

2. Validation of network model

Validation of code is required because solution accuracy of network modeling mainly depends on the accuracy of empirical equations used to calculate friction pressure losses, junction pressure losses and convective heat transfer to oil in ducts. Some empirical equations that have been used in published literature to describe above mentioned entities, are selected and applied in developed code. Two general cases are selected for this purpose.

3. Parametric study

Finally developed tool is to be tested. For this purpose multiple sets of simulations are performed by changing below mentioned parameters one at a time for said winding with 78 disc in previous section.

- Varying heat dissipation in disc

- Inlet mass flow rate

- Height of horizontal duct

- Width of vertical duct

- Duct spacers in the winding

POWER TRANSFORMERS

Introduction of power transformers

A power transformer is the electrical device which is used to change the voltage of AC in power transmission system. The first transformer in the world was invented in 1840s. Modern large and medium power transformers consist of oil tank with oil filling in it, the cooling equipment on the tank wall

and the active part inside the tank. As the key part of a transformer, the active part consists of 2 main components: the set of coils or windings (at least comprising a low voltage, high voltage and a regulating winding) and the iron core, as Figure 2.1 shows. For a step-up transformer, the primary coil is low voltage (LV) input and the secondary coil is high voltage (HV) output. The situation is opposite for a step-down transformer. The iron core is the part inducing the varying magnitude flux. Nowadays, transformers play key roles in long distance high-voltage power transmission.
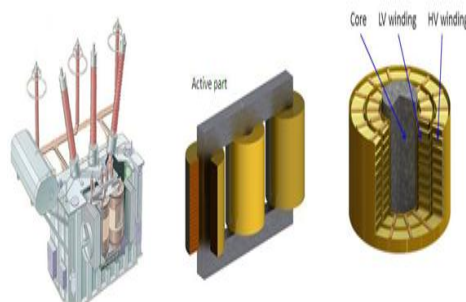

Figure

Structure of Power transformer

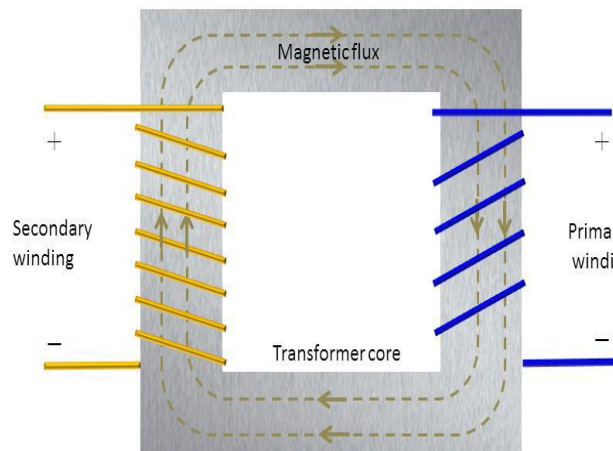**Operating principle of transformer**

Figure Operating principle of transformer

A general operating process of a transformer is that a varying magnetic flux is created in the core due to the changing of the current of the primary coil. Then, a voltage at the secondary coil is induced by this varying magnetic flux. As Figure 2.2 shows, wires are wrapped around each side of the core frame which is made of materials with high magnetic permeability. The left winding is the primary winding and the right winding is the secondary winding. When an AC is connected the left, the magnetic flux will be induced in the core. The magnetic flux will pass through the secondary winding in the right side and induces voltage. This principle is basing on the Faraday's law of induction or the induction law shown in Eq. (2.1).

$$V_{secondary} = N_{secondary} \frac{d\emptyset}{dt}$$
(2.1)

In an ideal transformer, there is a relation between the voltages and the number of coils on both sides as shown in Eq. (2.2). This equation indicates that the ratio of output voltage to the input voltage is defined by the ratio of the primary coils number to the secondary coils number. By this law, within a certain power capacity, transformer can be selected according to the output voltage.

$$\frac{V_{primary}}{V_{secondary}} = \frac{N_{primary}}{N_{secondary}}$$
(2.2)

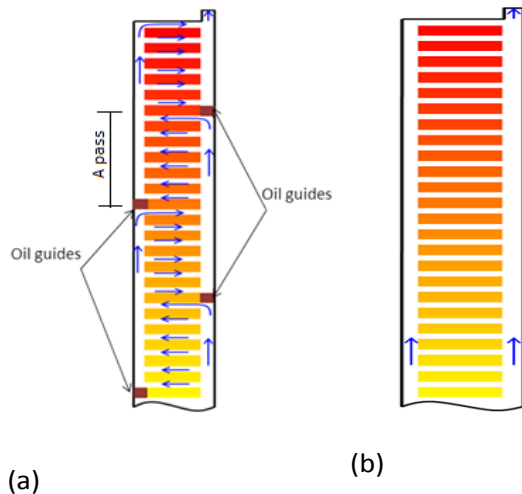**Oil guided and non-oil guided disc windings**

(a)

(b)

Figure 2D cross-sectional images of disc windings

Oil guided and non-oil guided windings are proposed in disc windings transformers. In the active part, as shown in Figure 2.1, between winding and core, LV windings and HV windings, and windings and outer casing, there are insulation board layers. Then, a closed space can be formed for each layer of windings. Figure 2.5 shows the 2D cross sectional area of one layer of disc windings. As Figure 2.5a shows, the guides are set in vertical ducts every 6 discs are oil guides. The purpose of setting oil guides is to improve the natural convection capability of the oil flow by avoiding the stagnation of the oil inside ducts. It can be seen from Fig. 2.4, cold oil come in the windings from the bottom and the go through the vertical and horizontal ducts, the oil guides would change the oil flow direction and make the global oil distribution even. This enhances the global heat transfer coefficient.

CONCLUSION

Use of CFD in the analysis of cooling duct design of disc type winding with oil guiding washers yields thorough understanding of heat interactions and flow patterns of oil in winding but it requires high computational efforts. Network modeling is developed and

used for transformer in thermal analysis of disc type winding since 1980s' which is well balanced between calculation speed and accuracy of results. To obtain general idea of flow pattern and fair estimates of temperature distribution in winding development of mathematical tool based on network modeling was summoned in Crompton Greaves Ltd which is one of the major international manufacturer of power transformer.

The development of mathematical tool based on network modeling of disc type transformer winding with oil guiding washer was initiated with studying theory of network modeling and understanding the requirements for accurate prediction of oil flow and temperature distribution in winding. The various parameters and variables in network modeling of the winding were identified and a method to give input to the MATLAB code was devised using excel template. Then three functions were developed ,

1. To solve hydraulic network,

2. To solve thermal network and

3. To solve conductor temperature

References

[1] Mufuta J. and Van den E., "Modelling of the mixed convection in the windings of a disc-type power transformer," Applied Thermal Engineering, vol. 20, pp. 417-437, 2000

[2] Yeon-Ho Oh, Ki-Dong Song, Jong-Ho Sun, Kyeong-Yup Park, and Bong-Hee Lee, "The thermal analysis of natural convection cooling type transformer," , vol. 1, pp. 358-360, 2003.

[3] Wakil N. E., Chereches N., Padet J., Numerical study of heat transfer and fluid flow in a power transformer, International Journal of Thermal Sciences 45 (6), pp.615-623, 2006.

[4] Kranenborg E. J., Olsson C. O., Samuelsson B. R., Lundin L-A., and Missing R. M., "Numerical study on mixed convection and thermal streaking in power transformer windings," 5th European Thermal-Sciences Conference, The Netherlands, 2008.

[5] Lee J.Y., Lee S.W., Woo J.H., and Hwang I.S.. "CFD analysis and experiments of a winding with zigzag cooling duct for a power transformer," Hyundai Heavy Industries Co., Ltd. Korea. CIGRE 2010.

[6] Torriano F., Chaaban M., and Picher P., "Numerical study of parameters affecting the temperature distribution in a disc-type transformer winding," Applied Thermal Engineering, vol. 30, pp. 2034-2044, 2010.

[7] Torriano F.,Chaaban M., and Picher P., "Numerical investigation of 3D flow and thermal effects in a disc type transformer winding", Elsevier Journal of applied thermal engineering, volume 40, pp. 121-131, 2012.

[8] Oliver A. J., "Estimation of transformer winding temperatures and coolant flows using a general network method," Proc. Inst. Elect. Eng. C, vol. 127, pp. 395- 405, 1980.

[9] Yamaguchi M., Kumasaka T., Inui Y., and Ono S., "The flow rate in a self-cooled transformer," IEEE Transactions on Power Apparatus and Systems, vol. PAS-100, pp. 956-963, 1981.

[10] Yamazaki H., Takagi I., Sakamoto T., and Kawashima K., "Basic Cooling Characteristics of Perfluorocarbon Liquid Immersed Windings for Nonflammable Transformers. Part I, Disk coil cooling for large-capacity forced circulating transformers," *Heat Transfer − Japanese Res.*, vol. 20, pp. 656-667, 1992.

[11] Declercq J. and Van der W., "Accurate hot spot modeling in a power transformer leading to improved design and performance," Transmission and Distribution conference, IEEE, Vol.2, pp.920-924vol.2, 1999.

[12] Zhang J. and Li X., "Coolant flow distribution and pressure loss in ONAN transformer windings. Part I: Theory and model development," PowerDelivery, IEEE Transactions on, vol. 19, no. 1, pp. 186-193, 2004.

[13] Zhang J. and Li X., "Coolant flow distribution and pressure loss in ONAN transformer windings. Part II:

Optimization of design parameters,"
PowerDelivery, IEEE Transactions on,
vol. 19, no. 1, pp. 194-199, 2004.