CFD Analysis of Temperature Characteristics and Fiber-Optic Temperature Sensor Using a Temperature Rise Experiment of 154kV Transformers

Ji-Ho Kim[1], Hyang-Beom Lee[1]
[1]Department of Electrical Eng., Soongsil Univ., Seoul 156-743, Korea, magnetic1@ssu.ac.kr

Abstract — The purpose of this study is to predict the temperature distribution in the 154kV 15/20MVA single phase separated power transformer by applying electromagnetic-thermal coupled analysis method. For analysis of heat flow, numerical methods were conducted by using SIMPLE algorithm as a method, which combines continuity equation with momentum equation. For checking the appropriateness in interpreting the results, the test results was compared with those of the temperature rise test using power transformer with fiber optic temperature sensors.

I. INTRODUCTION

Transformer life depends on temperature on specific parts, rather than the general thermal property of transformer interior itself. Especially when hot spot temperature rises beyond the allowable range, the corresponding lower dielectric strength may abruptly shorten transformer life. In this regard, cooling effect by transformer oil is supposed to plays a very important role in deciding performance quality of transformer. Accordingly, prediction of temperature distribution and hot spot temperature in transformer can be a prerequisite to solve these problems related to the transformer life [1][2][4].

In this paper, heat flow analysis was conducted to raise the accuracy of electromagnetic-thermal coupled analysis method. For the prediction of temperature distribution in oil immersed power transformer in consideration of natural convection, power loss was assumed as a heat source in heat flow analysis. To satisfy preconditions of heat flow analysis, velocity and pressure were calculated using momentum equation and continuity equation respectively [1][4]. However, pressure is not included in continuity equation, solution could be extracted from the equation combined with momentum equation. Therefore, Patankar-Spalding's SIMPLE (Semi-Implicit Method for Pressure-Linked Equation) algorithm was resorted to for combination of continuity equation and momentum equation. A 154kV 15/20 MVA transformer was manufactured to attain sufficient data for verification of the interpretation of temperature distribution measurements, as well as of cooling design. Fiber optic temperature sensors were inserted at fifteen spots in this transformer. The results were compared with those from temperature rise test, for verification of appropriateness of numerical analysis[1].

II. THERMO-FLUID ANALYSIS METHOD

In governing equation for fluid dynamics applied to interpretation of heat flow problem, continuity equation denoted as equation (1), momentum equation denoted as equation (2) and partial differential equation composed of energy equations denoted as equation (3) should be simultaneously considered, and the essential point could be the combination of these three equation : energy equations, momentum equation and continuity equation[4].

$$\nabla \cdot \rho \vec{v} = 0 \tag{1}$$

$$\rho \frac{D\vec{v}}{Dt} = \rho \vec{g} - \nabla p + \mu \nabla^2 \vec{v} \tag{2}$$

$$\rho c_v \frac{DT}{Dt} = \frac{\partial Q}{\partial t} + \nabla^2 (kT) + \Phi \tag{3}$$

Where, ρ is density (kg/m^3), $\vec{v}$ is flow velocity (m/s), $\vec{g}$ is acceleration due to gravity (m/s^2), p is pressure (N/m^2), μ is viscosity ($kg/m \cdot s$), c_v is specific heat ($kJ/kg \cdot K$), T is temperature (K), Q is unit volume is supplied from outside the heat source (W/m^3), k is thermal conductivity ($W/m \cdot K$), and Φ is energy dissipation.

Control volume based FVM(finite volume method) was used for numerical analysis of the governing equation. Staggered grid arrangement was applied as grid layout, and convection schemes were proceeded applying hybrid numerical method. In this context, discretized equation was induced from integration of control volume including grid points of variables[4].

As pressure is supposed to be indirectly extracted under the conditions satisfying momentum equation and continuity equation at the same time, this study used SIMPLE method, which is able to correct pressure and velocity to meet continuity equation, after interpretation of momentum equation under an assumed level of pressure. The discretized equation was solved using line-by line method according to TDMA (Tri-Diagonal Matrix Algorithm). Convergence condition was decided as value of residual and also tested for convergence with the range between 0.1 and 1% of the maximum.

III. VERIFICATION OF ANALYSIS METHOD

A. Analysis model

Fig. 1 depicts the transformer model applied to this study. The model was designed as a half size of interpreted model, so as to reduce time for interpretation and raise convergence property. The model shows only parts of core, winding and tank out of the whole model. The coil was designed as one block, simplifying the structures of a conductor, which is a coil, and insular papers surrounding the coil. LV(Low Voltage) and HV(High Voltage) windings, where the maximum temperature distribution might appear, were separated into four and six layers, with borders of flow. $k-\varepsilon$ model was used as the turbulence model for heat flow analysis[3][4].

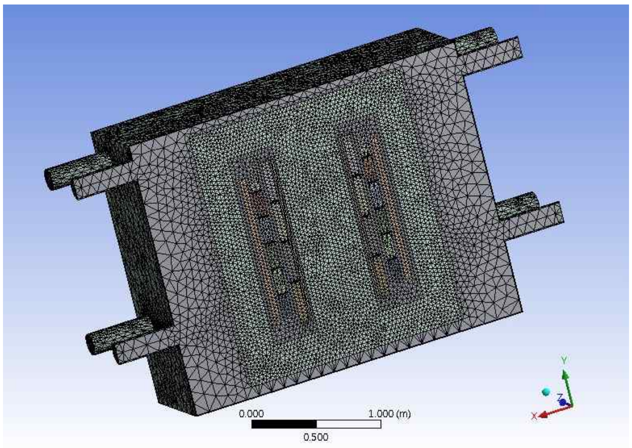


Fig. 1 3D modeling of power transformer

B. *Temperature rise experiment of transformer*

A 154kV 15/20MVA single phase power transformer was manufactured for the test and verification of temperature characteristics of analysis model. Fiber optic temperature sensors were inserted for special temperature rise test. The temperature measurement equipment was composed of fifteen sensors, two couplers and a set of measuring equipments. To specify hot spot point, the sensors were attached at eight spots in the HV windings, six spots in the LV windings and one spot in the core respectively. For the tank and flow, general purpose thermometers were used. Fig. 2 depicts the composition of temperature measurement equipments.

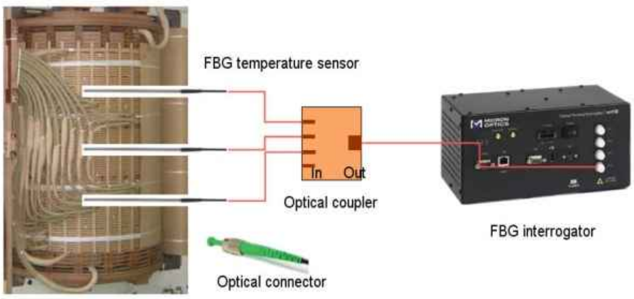


Fig. 2 Overview of measurement equipment structures

C. *Results*

Fig. 3 shows temperature measurement values respectively under the loads of 30, 50, 75, 100 and 120% at the point of hot spot temperature, the center and the bottom parts of LV windings top oil as well as the upper part of core. The resulting values are observed as higher by 5~7℃ in centigrade than the expected values.

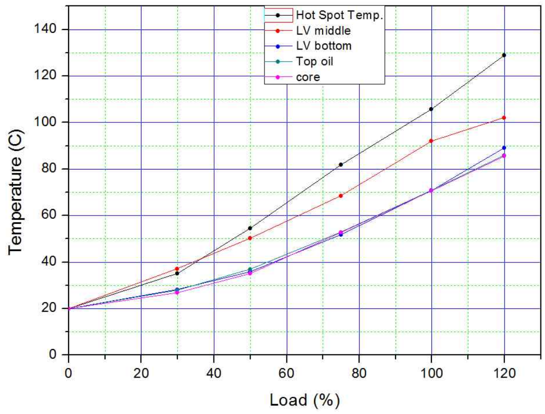
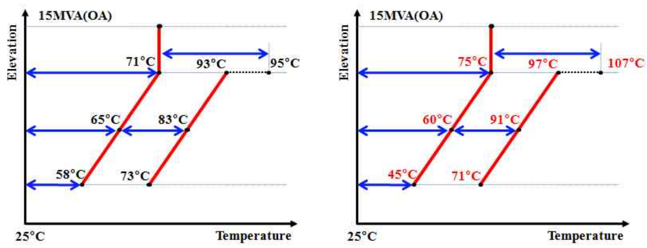


Fig. 3 Temperature measurements according to the load

Fig. 4 illustrates the comparison between the temperature design value from interpretation result and the actual measuring values using fiber optic sensors. On windings, the actual measurements were higher than designed value, and the hot spot temperature was also higher by 10℃.



(a) temperature design value (b) temperature measurement value

Fig. 4 Temperature distribution of 100% load

IV. CONCLUSION

This study predicted the temperature distribution in power transformer by applying CFD analysis. For the verification of the results, the experiment was conducted using a transformer designed and actually manufactured for the test. The comparison results between prediction and actual measurement are supposed to be applied to the design for improvement of cooling performance of transformer.

V. REFERENCES

[1] Preis,K, “Thermal-electromagnetic coupling in the finite element simulation of power transformers,” *IEEE Trans.on Magn.,* vol.42, no.4, pp. 999-1002, 2006.

[2] E.G.teNyenhuis, “Calculation of core hot spot temperature in power and distribution transformer,” *IEEE Trans. Power Delivery.*, vol.17, no.4, pp. 991-995,2002.

[3] Marina A. Tsili, “Hybrid Numerical-Analytical Technique for Power Transformer Thermal Modeling,” *IEEE Trans.on Magn.*, vol.45, no.3, pp. 999-1002, 2009.

[4] Farahmand.F, “Temperature Rise and Free-Convection Heat-Transfer Coefficient for Two-Dimensional Pot-Core Inductions and Transformers,” *IEEE Trans.on Industry Applications.*, vol.45, no.6, pp. 2080-2089, 2009.