A Numerical Method to Calculate Winding Temperature Distribution for Oil Immersed Transformers

Xiaoping Su*[1], Li Chen[1], Yu Liu[1], Chong Pan[1], Weigen Chen[2]

1. Chengdu Power Supply Company, Chengdu, 610017, China;
2. State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing, 400044, China;

*e-mail: cqusuxiaoping@gmail.com

Abstract: **Winding temperature distribution is an important characteristic to describe the thermal performance of oil-immersed power transformer. In this paper an alternative numerical approach based on Finite Volume Method (FVM) has been employed to resolve the control equations of flow and heat transfer process in oil immersed power transformer, which in turn to simulate the winding temperature distribution. Moreover, we applied this numerical method to a 100kVA/5kV prototype transformer, the numerical calculated results of winding temperature distribution shows a good consistence with the experiment results. Furthermore, we have also found some flow rolls appeared between the winding top and oil outlets, these complex fluid flow may resulted from the thermal buoyancy within transformer. Thus, this presented numerical method can not only simulate the fluid distribution within power transformer but also calculate winding temperature distribution.**

Index Terms-- **oil-immersed power transformer, finite volume method, winding temperature distribution**

I. INTRODUCTION

As an expensive and difficult to replace equipment in power system, oil-immersed transformers' failure will cause damage to the reliability of the power system and aggravate the service costs. At present, there is an increasing emphasis on keeping transformers in service longer than in past, the basic criterion, which limits the transformer load ability and operation life, is partially determined by the ability of transformer to dissipate the internally generated heat to its surrounding, namely the thermal performance of transformer. Thermal performance is partially characterized by winding temperature distribution and heat transfer within oil-immersed transformer. Therefore, the knowledge of the transformer thermal performance could lead to an improvement of the utilization of transformers. By on-line comparison of a measured quantity (e.g. top oil temperature, hot spot temperature) and a calculated value, which is obtained by means of physic model or numerical model or artificial intelligence algorithm, some rapidly developing failures such as the malfunction of pumps or fans can be detected. Hence, accurately predict the winding temperature distribution can ensure transformers service efficiently and reliably [1-7].

Transformer thermal performance is usually predicted through analytical formulas that use approximations and constants derived through experimental results. Current thermal analysis methods focused on the top-oil temperature prediction and winding hot-spot temperature prediction. The ANSI / IEEE C57.91 Loading Guide for mineral oil immersed transformer suggests means of predicting top oil temperature(TOT) by Using the first derivative model to calculate the top-oil temperature rise over ambient temperature[9]. By considering the top-oil temperature changes with ambient temperature, Lesieutre proposed an improved top oil temperature model and take into account daily variations in ambient temperature[10]. The authors of [11] present a simple equivalent circuit to represent the thermal heat flow equations for oil-immersed transformers, key features of this thermal-electrical analogy models are based on heat transfer theory, application of the lumped capacitance and nonlinear resistances. However, these approaches' accuracy may significantly be affected by an inaccurate estimation of the cooling conditions, and depends much on the consistency between the evaluated parameters and the actual transformers data.

Finite volume method (FVM), due to its enhanced ability in the field of numerical calculation of flow and heat transfer, various implementations of flow distribution are encountered in the technical literature, be widely used in metal forging, ship viscous flow simulation, numerical simulation of mud flows and other areas [12-14].the authors of [12] conducted a detailed finite control volume analysis of the cooling conditions in the windings of transformer. View of the above, taking into account the complexity of oil-solid coupling structure, solving the winding temperature distribution within the transformer can be attributed to an investigation of flow and heat transfer problems between oil flow and solid components (i.e. windings, tank and radiator). In this paper, FVM method will be employed to evaluate the internal temperature fields of the transformer by solving a set of conservation equations, and the simulation results of winding temperature distribution will be verified by a laboratory 100kVA/5kV transformer under different conditions respectively.

II. TEMPERATURE DISTRIBUTION CALCULATION BASED ON FVM

A. Governing equations

The heat transfer in oil-immersed power transformer contains heat conduction and convection (neglecting thermal radiation). The rate of heat generation is assumed as a constant in per unit volume and once the heat generation and dissipation achieved thermal equilibrium, there are no more changes on temperature and velocity all over the transformer in steady state. Convective heat transfer process of the fluid which inside the system is co-dominated by fluid mass, momentum and energy conservation. And its internal temperature and flow field equations are as described in literature [13]:

$$\frac{\partial(\rho\varphi)}{\partial t}+\mathrm{div}(\rho \boldsymbol{U}\varphi)=\mathrm{div}(\Gamma_{\varphi}\mathbf{grad}\varphi)+S_{\varphi} \qquad (1)$$

The above four items represent time terms, convection terms, diffusion terms and source terms, respectively. Where φ is a specific variable, $\Gamma\varphi$, $S\varphi$ represent the corresponding diffusion coefficient terms and source terms, respectively.

For the computational purpose, and taken into account the prototype transformer behaves symmetrical configuration, the three-dimensional model can be simplified as a two-dimensional model, and only a half of the model is considered because the other parts may be as symmetrical to it. For all the above reasons in this investigation, the detail representation of the variable of the above equation as shown in Table I, u and v are represent the velocity component of vector $\boldsymbol{U}$ in x-direction and y-direction, respectively. Similarly, S_{Mx} and S_{My} are momentum components, p is the pressure, μ and λ represent the kinematic viscosity and heat conduct coefficient of the fluid, respectively. In addition, both Φ and S_T are input source item, represent dissipation function and heat resource, respectively.

TABLE I. VARIABLES OF GOVERNING EQUATIONS

Continuity equation	1	0	0
x-momentum equation	u	μ	$\partial p/\partial x+S_{Mx}$
y-momentum equation	v	μ	$\partial p/\partial y+S_{My}$
Energy equation	i	λ	$p.div(\boldsymbol{U})+\Phi+S_T$

B. Boundary conditions

Improper treatment of the boundary conditions can lead to serious errors and perhaps instability. Therefore, analysis of the thermal process within the flow and solid domain is quite necessary. The heat and cooling process in oil-immersed power transformer case, can be expressed as follows: the heat produced by solid (winding) transferred by fluid (hot oil) convection, and then dissipate through the wall of transformer tank and air to achieve a thermal equilibrium, convection boundary conditions along the interface between the core, windings, and insulating oil. The non-homogeneous boundary conditions of generalized fluid-solid coupling system is described by the following equations:

$$-\lambda_1\,\mathrm{div}(T)=f_1(x,y,t)=q \qquad (2)$$

$$-\lambda_2\,\mathrm{div}(T)=f_2(x,y,t)=\alpha(T-T_\alpha) \qquad (3)$$

$$T=F(x,y)\quad t=0,\ v=u=0,\ p=p_0 \qquad (4)$$

Where λ_1, λ_2 represent the thermal conductivity of solid and fluid respectively, $\boldsymbol{T}$ is a function of the space variable (x,y) and time variable t (i.e. $\boldsymbol{T}\equiv F(x,y,t)$). $F(x, y)$ represents the initial function of the heat transfer process, the boundary function f_1 (x,y,t) represents the heat produced by solid (i.e. q), f_2 (x,y,t) characterize the fluid convection with surroundings (i.e. $\alpha(T\text{-}T_\alpha)$), α is heat transfer coefficient; and p_0 is the initial pressure of the finite elements.

C. Parameters

The computational field corresponds to the transformer prototype configuration (i.e contains high-voltage coils, low-voltage coils, core, sleeve and oil flow) is subdivided into finite volumes by grids, each of which encloses a node, and scalar variables such as temperature are evaluated at the grid node. By testing different grids configuration and with corresponding refinement technology, a grid configuration for two-dimensional model with total size equals 253699 is suitable. Additionally, due to the momentum and thermal fields are coupled in buoyancy driven flows, under-relaxation factors are adopted in the segregated solver with first order upwind scheme. Moreover, there is a need to take the properties of the solid(i.e core, winding and tank) and thermal characteristics variation of the fluid(i.e. mineral oil) into account, that is, the transformer oil has thermal characteristics strongly dependent on temperature needs to be considered.

TABLE II. PARAMETERS OF SOLID REGIONS

Properties	HV winding	LV winding	Core	Sleeve	Tank
Density(kg.m^{-3})	8978	8978	7550	1400	7800
Thermal conductivity (Wm^{-1}K^{-1})	387.6	387.6	51.9	0.454	35
Specific heat(Jkg^{-1}K^{-1})	381	381	446	243	502

The detail properties of solid and thermal characteristics of transformer oil are shown in Table II and Table III. Where $f_{\mathrm{den}}(T)$,$f_{\mathrm{cp}}(T)$,$f_{\mathrm{k}}(T)$ and $f_{\mathrm{dv}}(T)$ represent the density, specific heat, thermal conductivity and dynamic viscosity function of temperature, respectively. Once the heat sources in the windings and core area are obtained as well as the boundary functions, the discrete momentum equations can be established and renewed by 'Guess' and 'Correct' process in accordance with the FVM method, and combined with the parameters of the transformer prototype in this investigation (see Table II and Table III), the solution of the differential equations can be obtained which refereed to the temperature distribution within the transformer (i.e $\boldsymbol{T}\equiv F(x,y,t)$).

TABLE III. PARAMETERS OF TRANSFORMER OIL

Variable of transformer oil	Function of oil temperature
Density of oil(kg.m^{-3})	$f_{den}(t)$ =1098.72 - 0.712T_{oil}
Specific heat (Wkg^{-1}K^{-1})	$f_{cp}(t)$ = 807.163+3.58 T_{oil}
Thermal conductivity (Wm^{-1}K^{-1})	$f_k(t)$ = 0.1509-7.101e-5 T_{oil}
Dynamic viscosity (Pa.s)	$f_{dv}(t)$ =0.08467-4e-4 T_{oil} +5e-7(T_{oil})^2

III. RESULTS AND ANALYSIS

To verify the proposed numerical model can calculate temperature distribution of the transformer windings and hot oil region effectively and accurately, A laboratory

100kVA/5kV oil-immersed prototype transformer (rated high voltage current: 20A, rated low voltage current: 250A) was chosen and instrumented with multi-points measurement and monitoring equipment. In order to improve the accuracy of measuring system, a poly measure technology about fiber-optic sensors and thermocouple is carried out. The pre-experiment results show that the probability higher temperature regions are located in the upper half of the vertical winding. Therefore, each disks of the upper halve windings was built 3 sensors and the rest built 1 sensors per disk.in addition, 15 sensors were installed in top surface of the winding, top of the cooling channel, top/bottom tank oil and tank wall. As depicted in figure 3, S0,S1,S2,S3 represent four easy-measured sensors. the heat convection of the transformer has been analyzed and the winding temperature distribution has been simulated by the FVM numerical method. The temperature rise development process under different operating load(K=0.9 p.u., K=1.0 p.u. and K=1.1 p.u.) has been shown in Figure 1, Figure 2 and Figure3. Where (a), (b), (c) represented the temperature contours during three different periods (1 hour, 3 hours and 5 hours) respectively.

A. Temperature field of transformers

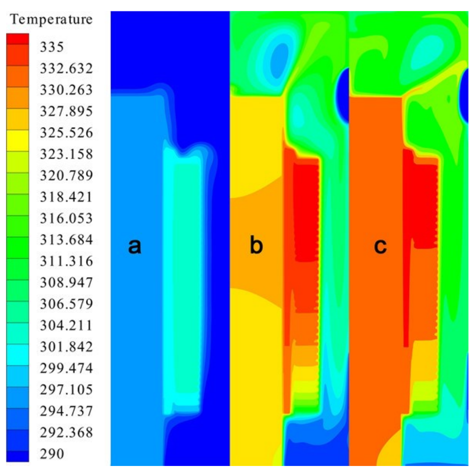

Figure 1 Temperature contour of transformer (K=0.9 pu) versus time. (a) 1hour, (b)3 hours, (c)5 hours.

From Figure 1(a) we can found that with the smaller load factor, the local temperature of transformer oil rise more slowly than transformer winding, and it maintains a lower temperature after one hour heating. The heat generated by winding increased itself temperature much higher than the temperature of core and local oil. Figure 1(b) indicates that local temperature of transformer oil increased slowly after about three hours, and the temperature of the region nearby winding top and bottom shows significant gradient. Figure 1(c) shows that the internal temperature field tends to be stabilized after about five hours, winding temperature distribution have clear gradient, and the highest temperature over surroundings is about 50K. In addition, we have also found some flow rolls appeared between the winding top and oil outlets, these complex fluid flow may resulted from the thermal buoyancy within transformer.

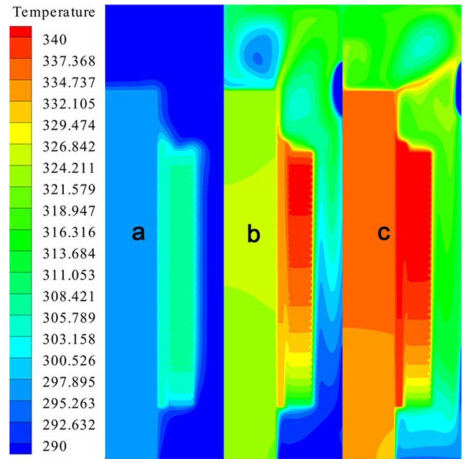

Figure 2 Temperature contour of transformer (K=1.0 pu) versus time. (a) 1hour, (b)3 hours, (c)5 hours.

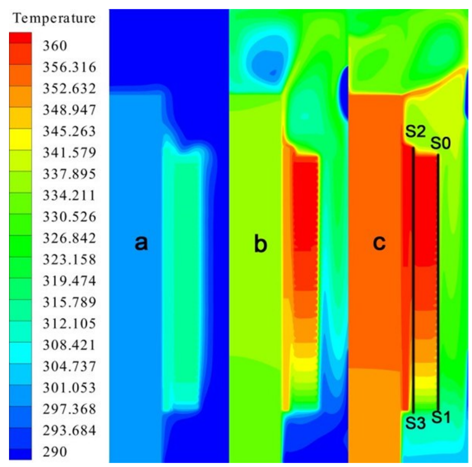

Figure 3 Temperature contour of transformer (K=1.1 pu) versus time. (a) 1hour, (b)3 hours, (c)5 hours.

B. Winding Temperature distribution

As shown in Figure 4, the temperature distribution of high voltage winding under different load profile(K=0.9 p.u., K=1.0 p.u. and K=1.1 p.u.) presents notable regularity, the vertical temperature growth trend is nonlinear with the winding height increases, in line with the physics that the temperature profile gradient along the height caused by natural convection, which driven by thermal buoyancy and gravity, the top temperature over bottom temperature is about 25K, 30K and 40K respectively. The distribution did not presented linearity due to the complex oil-solid coupled structure and oil flow stagnancy. The temperature higher, the velocity of oil flow slower, oil flow fast in low temperature regions, high velocity oil flow squeeze surrounding oil, and which low-velocity filled the blank regions, resulting in an oil circulation to transfer heat from solid surface (e.g. winding and core) to fluid(e.g. oil or air).

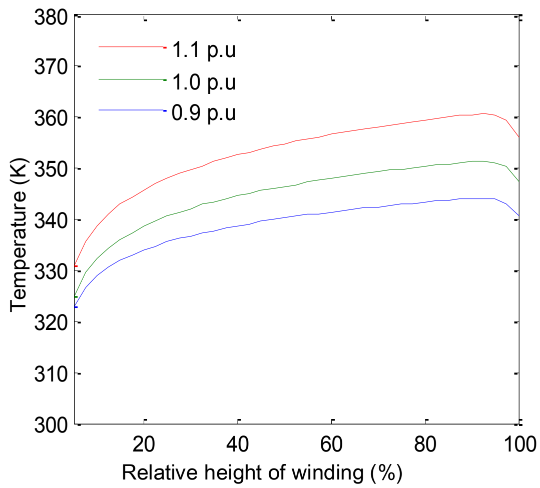

Figure 4 Longitudinal winding temperature distribution of winding.

It may be also observed form figure 4 that the maximum temperature does not occur at the top conduct of the winding, it occurs at about 80%, 84% and 88% height of the winding under loading factor K=0.9 p.u., K=1.0 p.u. and K=1.1 p.u. , respectively. It can be drawn a conclusion that the local hot spot region of the winding located about 80%-88% of height of the winding. Which correspond to the location between the 32^{nd} and 34^{th} disk of the prototype transformer. A good agreement between the numerical results and measurements were verified.

IV. CONCLUSIONS

In this paper, a numerical method for power transformer thermal model based on finite volume method was established. This model could be used to calculate winding temperature distribution and simulate the temperature filed of power transformer. According to the numerical results, the temperature distribution of power transformer high voltage winding under different load profile (K= 0.9 pu, K=1.0 pu and K=1.1pu) have a clear regularity: the vertical temperature growth trend is nonlinear with the winding height increasing, in line with the physics which the temperature profile gradient along the height is caused by natural convection driven by thermal buoyancy and gravity. The local hot spot region of the winding located about 80%-88% of the winding height which corresponding to the 32^{nd} and 34^{th} disk of the prototype transformer. A good consistence between the numerous experimental results and measure value was verified on a 100kVA/5kV oil-immersed prototype power transformer.

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