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Layer-Type Power Transformer Thermal Analysis Considering Effective Parameters On The Temperature Rise

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ABSTRACT

Since large power transformers belong to the most valuable assets in electrical power networks it is suitable to pay higher attention to these operating resources. Thermal impact leads not only to long-term oil/paper-insulation degradation; it is also a limiting factor for the transformer operation. Therefore, the knowledge of the temperature, especially the hottest spot (HST) temperature, is of high interest. This paper presents steady state temperature distribution of a power transformer layer-type winding using conjugated heat transfer analysis, therefore energy and Navier-Stokes equations are solved using finite difference method. Meanwhile, the effects of load conditions and type of oil on HST are investigated using the model. Oil in the transformer is assumed nearly incompressible and oil parameters such as thermal conductivity, special heat, viscosity, and density vary with temperature. Comparing the results with those obtained from finite integral transform checks the validity and accuracy of the proposed method.

KEYWORDS

Power transformer; Layer-Type Winding; Thermal Analysis; Conjugated Heat Transfer; Finite difference method.

1. INTRODUCTION

In a power transformer a part of the electrical energy is converted into the heat. Although this part is quite small comparing to total electric power transferred through a transformer, it causes significant temperature rise, which represents the limiting criteria for possible power transfer through a transformer. That is why the precise calculation of temperatures in critical points (top oil and the hottest solid insulation spot) is of practical interest. Thermal impact leads not only to long-term oil/paper-insulation degradation; it is also a limiting factor for the transformer operation [1], [2]. Therefore, the knowledge of the temperature, especially the hottest spot temperature, is of high interest. If the temperature rise goes beyond the permissible value, the load of transformer must be reduced or an auxiliary transformer is used in order to preserve the insulation from deterioration. For an oil-immersed transformer, the oil surrounds the transformer body. Oil is a nearly incompressible fluid and density changes due to temperature rise, therefore oil moves in the transformer. The heat transferred by convection is the most important method of heat transfer.

Hottest spot temperature must not exceed the prescribed value in order to avoid insulation faults. Furthermore, an accurate computation of the HST helps in a realistic estimation of the reliability and remaining life of the transformer winding insulation. The classical approach has been to consider the hottest-spot temperature as the sum of the ambient temperature, the top-oil temperature rise, and the hottest-spot-to-top-oil temperature gradient. A hottest spot temperature calculation is given in the International Standards [3]-[5]. The algorithm for calculating the hottest spot temperature of a directly loaded transformer using data obtained in a short circuit heating test is given in [6]. Heat transfer theory results from winding to oil are exposed in [7], [8]. The structure of a transformer winding is complex and does not conform to any known geometry in the strict sense. Under general conditions, the transformer windings can be assumed cylindrical; hence, a layer or a disc winding is a finite annular cylinder. The thermal and physical properties of the system would be equivalent to a composite system of insulation and conductor.

In this paper, author has proposed a procedure for obtaining the temperature distribution in the power transformer and the effects of load conditions and type of oil are investigated using the model. For this reason energy and Navier-Stokes equations are solved using finite difference method. Therefore, a code has been provided under MATLAB software. The model can be used for temperature calculation on the arbitrary change of current and outside air temperature. In the paper, thermal model, energy, and Navier-Stokes equations are given in section 2. Results and discussion of the proposed work have been provided in section 3.

2. THERMAL MODEL

Energy equation for Newtonian incompressible fluid (or nearly incompressible fluid) such as oil in two dimensions is [9]

$$\rho \cdot (V_x \frac{\partial (C_p \cdot T)}{\partial x} + V_y \frac{\partial (C_p \cdot T)}{\partial y}) = \frac{\partial}{\partial x}(k \cdot \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k \cdot \frac{\partial T}{\partial y}) \qquad (1)$$

Where T is temperature, V_x is velocity in x direction, V_y is velocity in y direction, k is thermal conductivity, ρ is density and C_p is special heat of the oil in the transformer. In equation (1), oil properties vary with temperature [1], [10], [11]. The temperature dependence of oil properties are given as follows:

$$\mu = a_1 \cdot \exp(\frac{a_2}{T+273}) \qquad (2)$$

$$C_p = a_3 + a_4 \cdot T \qquad (3)$$

$$\rho = a_5 + a_6 \cdot T \qquad (4)$$

$$k = a_7 + a_8 \cdot T \qquad (5)$$

$$\beta = a_9 \qquad (6)$$

Where μ: is viscosity and β is volumetric expansion coefficient. The nine constants for transformer oil and silicon oil have been listed in Table 1 [3, 4]. It is generally valid for all types of transformer oil that the variation of the oil viscosity with temperature is much higher than the variation of other oil properties [11]. Thus, all oil physical properties except the viscosity can be replaced by a constant. However, the variations of all oil properties with temperature have been considered in this paper.

Table1. Oil constants

Oil constant	Transformer oil	Silicon oil
a_1	0.0000013573	0.00012127
a_2	2797.3	1782.3
a_3	1960	1424
a_4	4.005	2.513
a_5	887	989
a_6	-0.659	-0.870
a_7	0.124	0.138
a_8	-0.0001525	-0.00009621
a_9	0.00086	0.00095

In (1) velocity is unknown, and then we must solve Navier-Stokes equations. Navier-Stokes equations in two dimensions for Newtonian incompressible fluid are [9]

Continuity Equation:

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} = 0 \tag{7}$$

Momentum Equations:

$$\rho.(V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y}) = -\frac{\partial P}{\partial x} + (\frac{\partial}{\partial x}(2 \cdot \mu \cdot \frac{\partial V_x}{\partial x}) + \frac{\partial}{\partial y}(\mu \cdot \frac{\partial V_x}{\partial y} + \mu \cdot \frac{\partial V_y}{\partial x})) \tag{8}$$

$$\rho.(V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y}) = -\frac{\partial P}{\partial y} + (\frac{\partial}{\partial x}(\mu \cdot \frac{\partial V_x}{\partial y} + \mu \cdot \frac{\partial V_y}{\partial x}) + \frac{\partial}{\partial y}(2 \cdot \mu \cdot \frac{\partial V_y}{\partial y})) + \rho_0 \cdot g \cdot \beta \cdot (T - T_{ref}) \tag{9}$$

Where P is pressure and g is gravitational acceleration .The heat conduction equation for core and windings is written [10], [11]

$$k_x \cdot \frac{\partial^2 T}{\partial x^2} + k_y \cdot \frac{\partial^2 T}{\partial y^2} + Q = 0 \tag{10}$$

Where k_x and k_y are thermal conductivity in x and y directions respectively. The term Q is the volumetric heat source function and has been modified here to take care of variation of electrical resistance of copper with temperature. The heat source term Q can be of the form

$$Q = Q_0 \cdot [1 + \alpha_c \cdot (T - T_{ref})] \tag{11}$$

Where α_c is the temperature coefficient of electrical resistance of copper wire. With this representation, the function Q becomes temperature dependent, distributed heat source. Thermal conductivities are unequal in different directions. Thermal conductivity has been treated as a vector quantity, having components in both radial and axial direction. Resultant thermal conductivity of the system is [10]

$$K = \sqrt{k_x^2 + k_y^2} \tag{12}$$

Where

$$k_x = \frac{\log \frac{r_n}{r_1}}{\left(\frac{\log \frac{r_2}{r_1}}{k_1} + \frac{\log \frac{r_3}{r_2}}{k_2} + \ldots + \frac{\log \frac{r_n}{r_{n-1}}}{k_n}\right)}$$

$$k_y = \frac{k_{cu} \cdot k_{in} \cdot (t_{cu} + t_{in})}{t_{in} \cdot k_{cu} + t_{cu} \cdot k_{in}}$$

Term K represents resultant thermal conductivity of insulation and conductor system. In this paper, the bottom oil temperature rise over ambient temperature has been calculated as

$$\theta_u = \theta_{fl} \cdot \left(\frac{I_r^2 R_l + 1}{R_l + 1}\right)^n \tag{13}$$

Where θ_u is the bottom oil temperature rise over ambient temperature, θ_{fl} is the full load bottom oil temperature rise over ambient temperature obtained from an off-line test, R_l is the ratio of load loss at rated load to no-load loss. The variable I_r is the ratio of the specified load to rated load.

$$I_r = \frac{I}{I_{rated}} \tag{14}$$

The exponent n depends upon the cooling state. The loading guide recommends the use of n=0.8 for natural convection and n=0.9-1.0 for forced cooling.

3. RESULTS AND DISCUSSION

A code has been provided for finite difference solution of energy and Navier-Stokes equations using MATLAB 7.1. Figure 1 shows cross section of a 50KVA, 20KV/400V power transformer in two dimensions. Dimensions and specifications of the power transformer have been summarized in Table 2. Table 3 shows the power transformer losses.

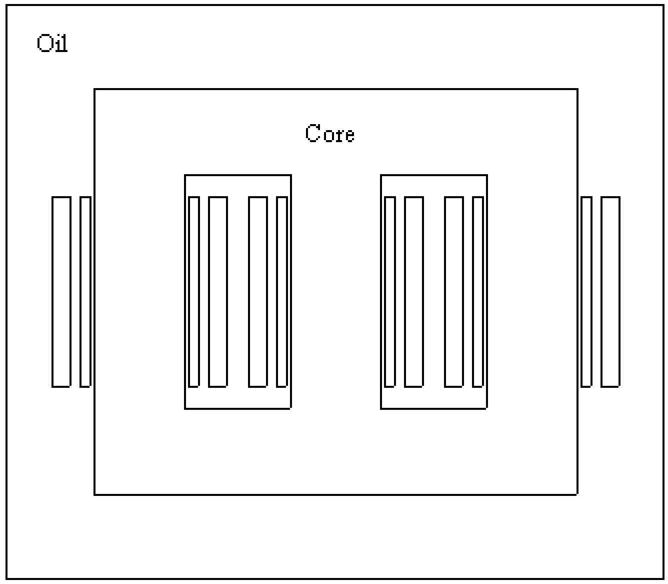

Figure1. Three phase power transformer in two dimensions

Table2. Dimensions and specifications of the proposed power transformer

Core diameter (cm)	10
Width of each window (cm)	12
Height of window (cm)	28
Thickness of LV winding (cm)	1.2
Thickness of HV winding (cm)	2
Rated power	50KVA
HV voltage	20kV
LV voltage	400V
HV current	1.44A
LV current	72A

Table3. Power transformer losses

Losses (w)	Value
Core	158
DC of LV windings	384
DC of HV windings	534
Eddy currents of LV windings	64
Eddy currents of HV windings	-

We assume that inlet oil temperature is the temperature base. Therefore, we have

$$\Delta T = \frac{T - T_{b,oil}}{T_{b,oil}} \times 100 \tag{15}$$

Where $T_{b,oil}$ is the bottom oil temperature. Figure 2 shows temperature distribution from LV winding (axis symmetry in height direction) in one per unit (p.u.) load with oil natural cooling (ON). It can be pointed out that for LV winding, maximum temperature location is around 80% of winding height from the bottom and at about 50% of radial thickness of the layer. Temperature distribution from HV winding has been shown in figure 3. It can be observed that the maximum temperature occurs in the neighborhood of 55% of the axial and 50% of the radial thickness of the layer.

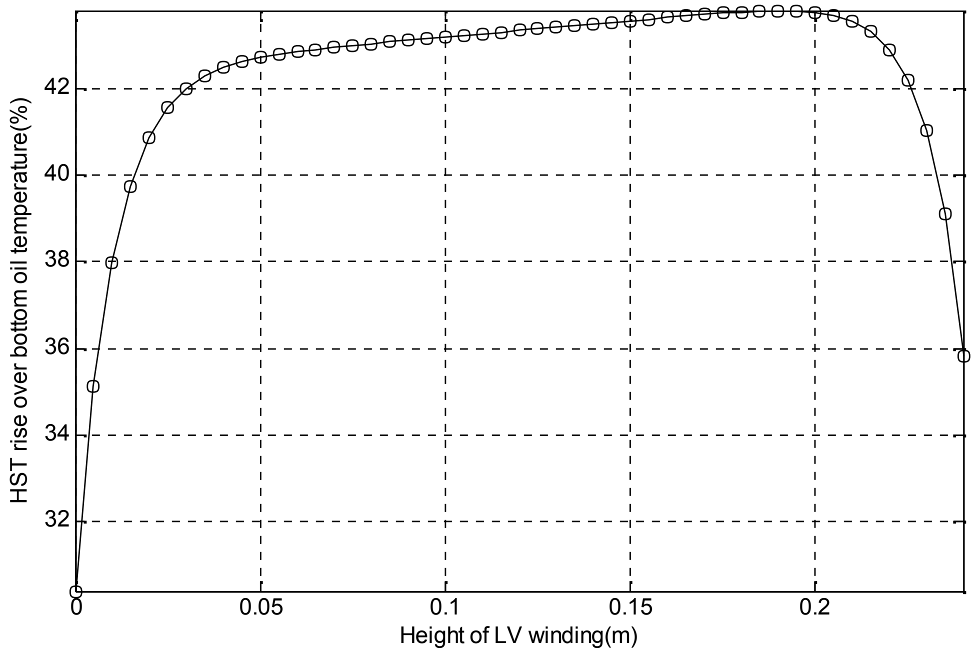

Figure2. Temperature distribution in height direction of LV winding with transformer oil natural cooling

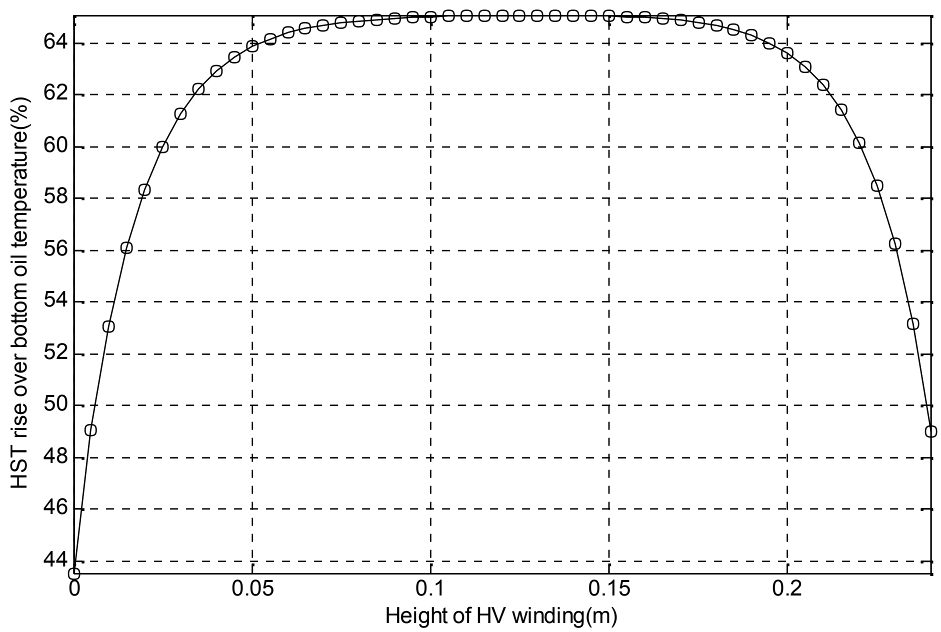

Figure3. Temperature distribution in height direction of HV winding with transformer oil natural cooling

Figure 4 shows HST rise over bottom oil temperature versus load for two types of oils and figure 5 shows HST versus load at T_{amb}=25(°C).

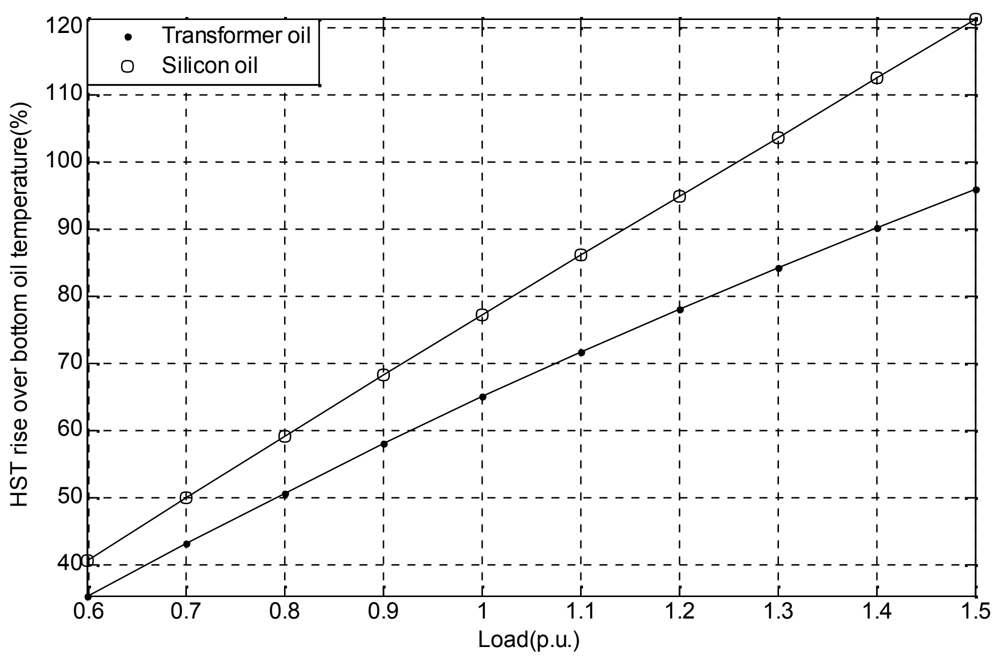

Figure4. HST rise over bottom oil temperature versus load at T_{amb}=25(°C) with oil natural cooling

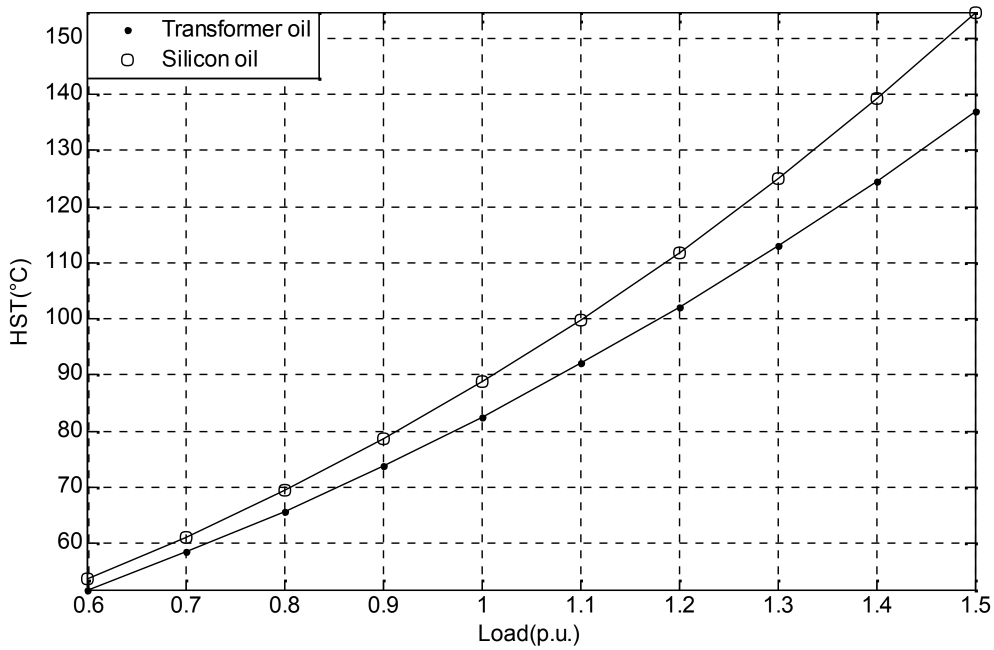

Figure5. HST versus load at T_{amb}=25(°C) with oil natural cooling

It can be pointed out from figures 4 and 5 that the HST value is low when the transformer oil is used for cooling, therefore the transformer oil is better than silicon oil in the cooling of the power transformer when load changes. Table 4 shows comparison of the proposed method with finite integral transform used in [10] for power transformer oil. HST locations at different loading are given in Table 5.

Table4. HST (°C) magnitudes at T_{amb}=25(°C)

Load (p.u.)	Proposed	Analytical [10]
0.6	51.72	53
0.7	58.35	56
0.8	65.71	66
0.9	73.78	75
1.0	82.54	80
1.1	91.99	93
1.2	102.15	101
1.3	113.01	115
1.4	124.59	125
1.5	136.91	139

Table5. HST locations at T_{amb}=25(°C)

Load (p.u.)	Proposed (radial thickness%-height%)	Analytical [10] (radial thickness%-height%)
0.6	50 / 54.17	44 / 52
0.7	50 / 54.17	45 / 53.5
0.8	50 / 54.58	46 / 54
0.9	50 / 54.58	48 / 54.5
1.0	50 / 55	50 / 55
1.1	50 / 55	50 / 55
1.2	50 / 55.42	50 / 55
1.3	50 / 55.42	50 / 55
1.4	50 / 55.42	50 / 55.5
1.5	50 / 55.42	50 / 55.5

Reference [10] has proposed an analytical method based on boundary value problem of heat conduction in power transformer winding using finite integral transform techniques. This technique uses Fourier transform and Hankel transform and finds temperature based on polynomials with infinite order (sequential series) of space variables and time, and then approximates temperature with finite order. Analytical method in [10] is suitable for cylindrical winding with rectangle cross-section, but this limitation is not for finite difference method. In the other hand, if we assume that we can increase order of polynomial, solution time will rise and analytical method will not differ with numerical method.

4. CONCLUSION

A numerical study was conducted to investigate temperature distribution in layer-type power transformer for a variety of load conditions and type of oil. On the other hand, an attempt has been made to suggest a method to improve the accuracy of prediction of the temperature of the hottest spot in power transformer. Heat transfer partial differential equations were solved numerically with finite difference method. The heat source function has been taken as temperature dependent and has been directly incorporated in the heat conduction equation for core and windings. The purely numerical approach followed in this paper seems to correspond reasonably well with results of analytical calculations [10]. In addition, it can be pointed out that transformer oil is better than silicon oil in cooling of the power transformer when load changes.

NOMENCLATURE

C_p : specific heat of oil ($J.kg^{-1}.K^{-1}$)
g: gravitational acceleration ($m.s^{-2}$)
I_r: ratio of the specified load to rated load
k: thermal conductivity of oil ($W.m^{-1}.K^{-1}$)
K: equivalent thermal conductivity ($W.m^{-1}.K^{-1}$)
k_{cu} : thermal conductivity of copper ($W.m^{-1}.K^{-1}$)
k_{in} : thermal conductivity of insulation ($W.m^{-1}.K^{-1}$)
k_x : thermal conductivity in x direction ($W.m^{-1}.K^{-1}$)
k_y : thermal conductivity in y direction ($W.m^{-1}.K^{-1}$)

n : temperature rise exponent due to bottom oil
P: pressure ($N.m^{-2}$)
Q : volumetric heat source function ($W.m^{-3}$)
Q_0: reference volumetric heat source ($W.m^{-3}$)
r_i's : radius of insulation and conductor layers (m)
R_l : loss ratio = load loss/no load loss
T: temperature (K)
T_{ref} : reference temperature (K)
$T_{b,oi}$: bottom oil temperature (K)
t_{cu}: thickness of conductor (m)
t_{in} : thickness of insulation (m)
V_x: velocity in x direction ($m.s^{-1}$)
V_y: velocity in y direction ($m.s^{-1}$)

Abbreviations

HST: hottest spot temperature
HV: high voltage
LV: low voltage
ON: oil natural cooling
p.u.: per unit

Greek symbols

β : coefficient of volumetric expansion of oil (K^{-1})
θ_u : bottom oil temperature rise over ambient temperature (K)
θ_{fl}: bottom oil temperature rise over ambient temperature at rated load (K)
ρ : density of oil ($kg.m^{-3}$)
ρ_0: reference density of oil ($kg.m^{-3}$)
α_c : temperature coefficient of electrical resistance (K^{-1})
μ : viscosity of oil ($kg.m^{-1}.s^{-1}$)

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