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Full Length Research Paper

Thermal Modeling and Electromagnetic Analysis of 1000 kVA Distribution Transformer Based on Electrical –Thermal Equivalent Circuit and FEM

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The importance of transformers in the electricity transmission and distribution systems, is an obvious axiom in the modern day's power systems. The top oil temperature (TOT) and hot spot temperatures (HST) in the transformer oil and windings is a important parameter that affect transformer performance. Accordingly, in order to have a transformer working at optimum level ,many researches and tests have been being performed. This paper studies the Electromagnetic Analysis and thermal modeling of 1000 kVA distribution transformer. The 3-D finite element method is utilized as a Instruments for viewing magnetic flux density on the transformer core .After electromagnetic Analysis and compute the load and no load losses of transformer based on computer simulation according to the use of the FEM that improved in Ansoft – Maxwell, thermal modeling of transformer and its results has been analyzed. Based on ANSI/IEEE C57 standard, the hot-spot temperature values of oil are used to calculate aging parameters which include the aging acceleration factor.

Keywords: Thermal Modeling, 1000 kVA Distribution Transformer, Electrical –Thermal Equivalent Circuit and FEM.

INTRODUCTION

Power transformers are the main parts of the energy system and the most expensive part of investments. Accordingly, it is important to forecast and monitoring the transformers thermal Performance (TOT,HST) limit, since this sets the electro mechanical performance limit. The appearance of TOT and HST is a complicated process in itself ,because of dynamic nature of the load and ambient temperature (Hurterand and Viale, 1984). İn the literature a variety procedures for direct measurements of HST have been presented, such as ,fiber-optic sensors and fluoro-optic thermo meters (Susa et al., 2005) .G. Swift developed an equivalent circuit of a transformer, that consist of Top oil and hot spot model (Swift et al., 2001).To estimate the parameters of thermal circuit a few authors using a genetic algorithm (GA) (Tang et al., 2002)- (Tangand and Wu, 2004).This paper investigates thermal behaviors and electromagnetic analysis in a 1000 kVA , 10/0.4 kv distribution transformer. İn the first section, based on Electromagnetic Analysis and by using FEM , the flux density distribution in transformer core and calculation of load and No-load losses have been investigated. In section 2, Three common thermal model have been used for TOT and HST calculation. Comparisons of this three model are made. In the section 3, by using the results obtained in the previous section the aging acceleration factor have been investigated.

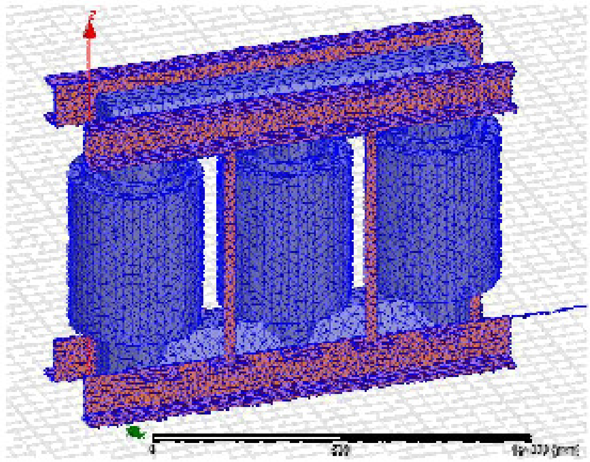

Fig. 1. 3-D mesh operation of studied transformer

TABLE I. ELECTRICAL PARAMETRS OF STUDIED TRANSFORMER

QUANTITY	Value	Unit
Primary voltage	10	KV
Secondary voltage	0.4	KV
Rated power	1000	KVA
No.of primary windingt urns	693	………
No.of secondary winding turns	16	………
Primary winding resistance	2.12	ohm
Secondary winding resistance	0.0007	ohm
Height of LV winding	471	mm
Height of HV winding	431	mm

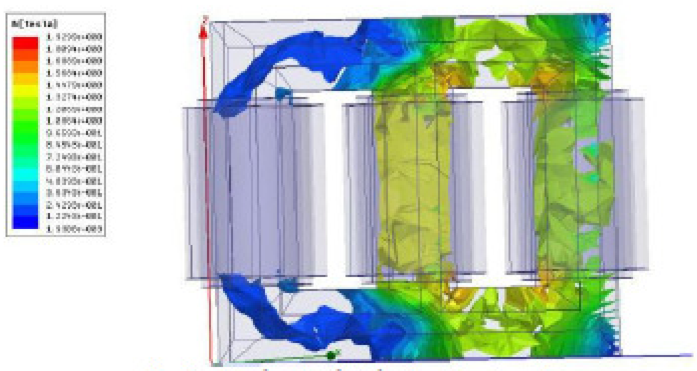

Fig.2 : flux density distributions in a transformer core

Electromagnetic Analysis of Distribution

Transformer via 3-d time domain finite element method

The FEM is a scalar procedure for solving partial differential and integral equations. This technique will either resolve the differential equation and make the problem steady-state or approximate the equations in to a system of common differential equations and afterwards apply the scalar integrating method that provide by the Standard methods such as Euler's, Runge- Kutta methods ,etc. A 3-phase, Dy11, 1000 kVA, 10kV/400V distribution transformer is studied in this paper. Table.1 briefly illustrate the characteristics of the proposed transformer. Fig. 1, demonstrated The Three dimensional modeling of the distribution transformer with core clamp under mesh operation, whereas the tank isn't

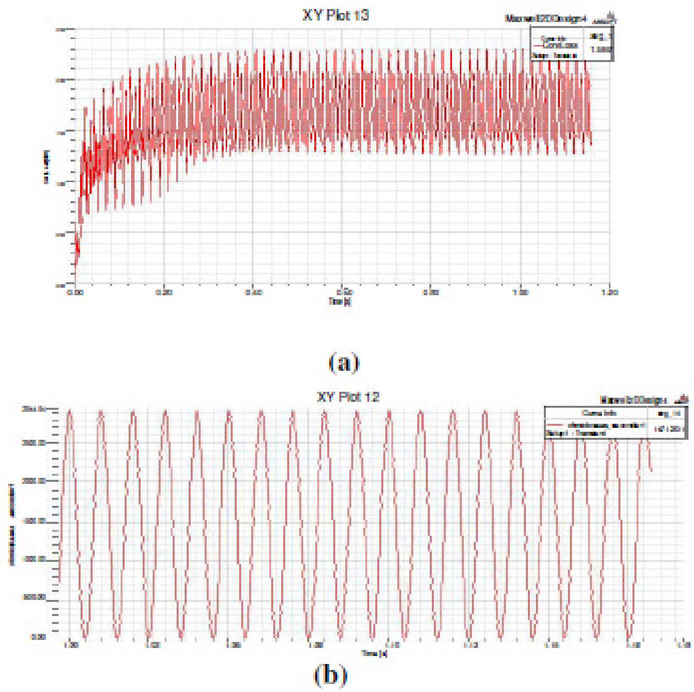

Fig.3 : a) No-load loss b) ohmic losses in each phase of secondary side versus time for studied transformer

TABLE.2: TRANSFORMER LOSSES

	No-load losses(w)	Dc losses(w)	stray losses (w)	Total losses (w)
Measurement	**1562**	**11284**	**1108**	**13954**
FEM	**1595**	**11493**	**1050**	**14138**

shown. All the meshes shapes is tetra hedral. Core clamp made of 25 mm thick steel, and have conductivity of 1.1×10^6 s/m .In order to increase accuracy of analysis ,the number of mesh core, windings and core clamp respectively is 51633 , 40184, 23180. In this paper, for laminations of the transformer core, M5 type silicon alloy steel plates with 0.30 mm thick are used.

By using the complicated form of the magnetic field in the three dimensional model in Cartesian coordinate (x, y ,z), hence:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A}{\partial z}\right)-jw\sigma A+\ J_0 \qquad (1)$$

Fig.2 displayed the flux density distributions in a transformer core. It can be seen in this fig, the maximum flux denstity is 1.92 tesla.

Calculation of transformer losses based on FEM

Commonly, Transformer losses are categorized into no load or core losses and load losses**.** This can be written in equation form:

$$P_T = P_{NL} + P_{LL} \qquad (3)$$

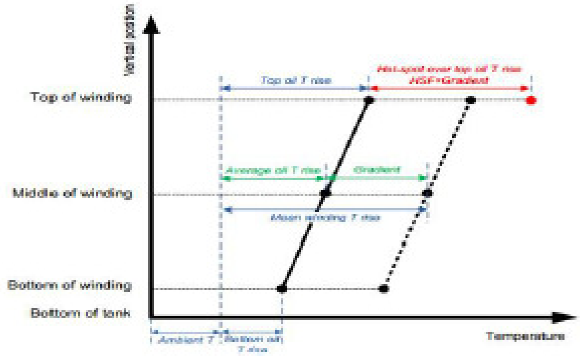

Fig.4: The temperature distribution in the transformer

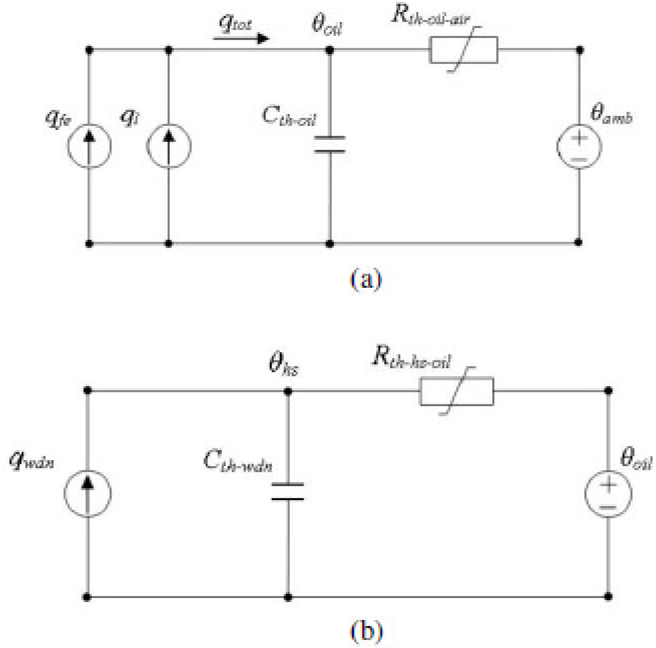

Fig.5 : Thermal model 1, (a) top oil temperature circuit, (b) Hot spot temperature circuit

P_{Core} are the core losses or no load losses Because of the voltage excitation. No-load losses in transformer is consists

of hysteresis and eddy current losses

$$P_{NL}=P_h+P_f \qquad (4)$$

In this Equation p_h(hysteresis losses) is proportion with the Square of flux density and p_f (eddy current losses) is proportion with the Square of flux density and frequency.

$$P_h \alpha f.B^2$$

$$P_e \alpha f^2.B^2$$

P_{LL}, categorize into P_{dc} losses or windings losses and stray losses that because of the electromagnetic fields in the windings, magnetic shields, core clamps, enclosure or tank walls, etc .P_{dc} can be calculated by multiplying the dc resistance of the winding with the square of the load current. The stray losses additionally divided into winding eddy losses and structural part stray losses. Winding eddy losses divided in to eddy current losses and rotating current losses. Other stray losses because of the losses in the clamps, tank or enclosure walls, etc.
Fig. 3(a), shows No- load loss of studied 3-phase , 1000 kva distribution transformer versus time. The average No-load losses is 1595 w. Fig.2(b) indicate ohmic losses in each phase of secondary side of transformer with the average of 1471 w. Table .2 summarized the calculated losses by finite element method.

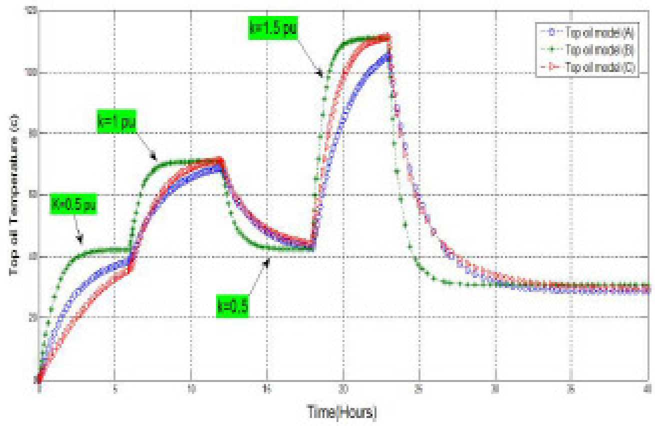

Fig. 6 : Calculation results of TOT temperatures based on three common thermal models

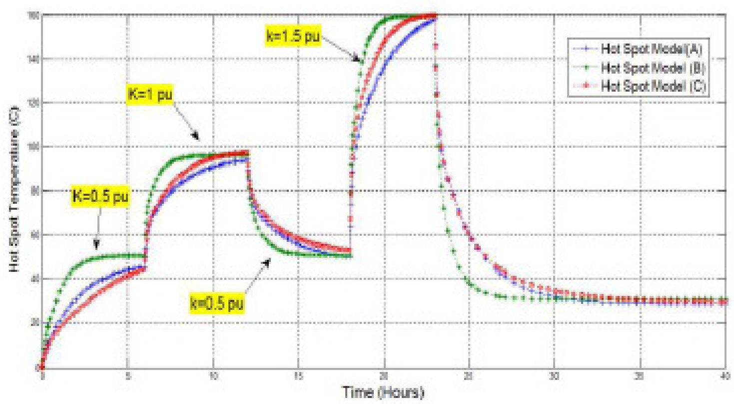

Fig.7 : Calculation results of HOT SPOT temperatures based on three common thermal models

Thermal Modeling Of Distribution

Transformer

The major source of heat in transformer is power losses. The heat generated in transformer via losses, transfer by three different heat transfer mechanism as i-convection ii-conduction and iii-radiation .Fig.4 shows the IEC 345 loading guide for oil immersed transformer in order to calculate the top oil and hot spot temperature. It can be seen in this fig, temperature of oil increase from bottom to top and winding temperature increase linearly from bottom to top with a constant temperature difference (g).
This paper investigates three common thermal model in order to calculation of top oil and hot spot in studied transformer by using lumped parameter theory. The first model (model A) is Based on Modified İEEE model .The second model(model B)is based on swift model. The last model (model c) that studied in this paper is susa
models. Each of these methods is described below and the results of this methods compared with each others.

Thermal Model Based on Modified İEEE model

The improved İEEE clause 7 thermal modeling includes the ambient temperature variation. This improved, allows the top oil temperature to respond daynamically to change in ambient temperatures. The following diffrential equations used to calculate the top oil and hot spot temperatures via modified İEEE model.

$$\Delta\theta_{To} = \left[\Delta\theta_{To,U} - \Delta\theta_{To,i}\right]\left[1 - e^{-\frac{t}{\tau_o}}\right] + \Delta\theta_{To,i} \quad (5)$$

$$\Delta\theta_{H} = \left[\Delta\theta_{H,U} - \Delta\theta_{H,i}\right]\left[1 - e^{-\frac{t}{\tau_o}}\right]. \quad (6)$$

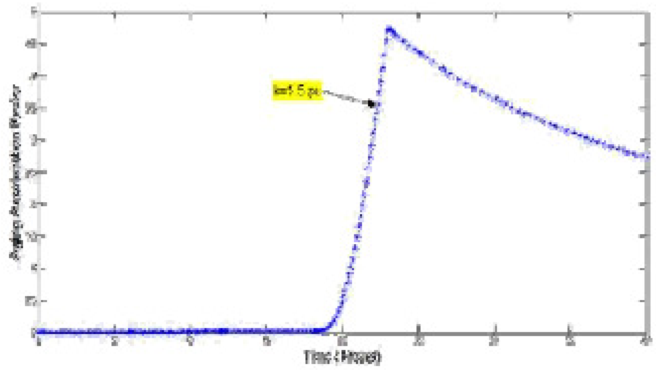

Fig .8: Transformer Aging Acceleration Factor

By solving the above first order differential equations :

$$\tau_{To}\frac{D\Delta\theta_{To}}{dt} = \left[\Delta\theta_{To,U} - \Delta\theta_{To}\right] \qquad (7)$$

$$\Delta\theta_{To,U} = \Delta\theta_{To-R}\left(\frac{1+R.K^2}{1+R}\right)^n \qquad (8)$$

$$\tau_{To}\frac{D\theta_{To}}{dt} = \left[\Delta\theta_{To,U} + \theta_A\right] - \theta_{To} \qquad (9)$$

$$\tau_H\frac{D\Delta\theta_H}{dt} = \left[\Delta\theta_{H,U} - \Delta\theta_H\right] \qquad (10)$$

$$\Delta\theta_{H,U} = \Delta\theta_{H,R}.K^{2m} \qquad (11)$$

Eventually hot spot temperature campute by adding the top oil temperature rise, ambient temperature and hot spot rise temperature.

$$\theta_H = \theta_A + \Delta\theta_{To} + \Delta\theta_H \qquad (12)$$

İn this equations K is the load current per unit, R is the ratio of load to no load losses θ_A is the ambient temperature,

θ_H is the dynamic hot spot temperature, θ_{To} is the dynamic top oil temperature.

A. Model Based on swift model

A thermal circuit based on thermal-electric alanalogy and heat transfer theory in order to calculatethe top oil and hot spot indicate in Fig.5.

This differential equation governing the thermal circuit:

$$q_{wdn} = C_{th-wdn} \times \frac{d\theta_{hs}}{dt} + \frac{\theta_{hs} - \theta_{oil}}{R_{th-hs-oil}} \qquad (13)$$

$$(q_{fe} + q_L) = C_{th-oil} \times \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb})}{R_{th-oil-air}} \qquad (14)$$

İn this equatios $R_{th-oil-air}$, $R_{th-hs-oil}$ is a nonlinear thermal resistance . The equation for the nonlinear thermal resistance is

$$R_{th-hs-oil} = R_{th-hs-oil} = \frac{1}{h \times A} \qquad (15)$$

By replace the thermal resistance in quation (13)&(14) this differential equation is changed to:

$$q_{wdn} \times \left(\frac{\mu^n}{C_1 \times A}\right) = \left(\frac{\mu^n}{C_1 \times A}\right) \times C_{th-wdn} \times \frac{d\theta_{hs}}{dt} + (\theta_{hs} - \theta_{oil})^{n+1} \qquad (16)$$

$$(q_{fe} + q_L) \times \left(\frac{\mu^n}{C_1 \times A}\right) = \left(\frac{\mu^n}{C_1 \times A}\right) \times C_{th-oil} \times \frac{d\theta_{oil}}{dt} + (\theta_{oil} - \theta_{amb})^{n+1} \qquad (17)$$

İn this equatios q_{fe} is the core losses and q_{wdn} is the winding losses .

B. Model Based on susa model

İn this model susa takes oil viscosity changes and loss variation with temperature into account.The change of time constant due to changes in the oil viscosity are also accounted for. This equation used to calculate the top oil and hot spot temperature base on susa model.

$$\Delta\theta_{oil,R}\left[\frac{K^2R+1}{1+R}\right] = \tau_{oil-R}\frac{d\theta_{oil}}{dt} + \left[\frac{(\theta_{oil} - \theta_{amb})^{\frac{1}{n}}}{(\mu_{pu}.\Delta\theta_{oil-R})^{\frac{1-n}{n}}}\right] \qquad (18)$$

$$\{k^2 \times P_{cu,pu}(\theta_{hst})\}\Delta\theta_{hst,R} = \tau_{wind,R}\frac{d\theta_{hst}}{dt} + \frac{(\theta_{hst}-\theta_{oil})^{\frac{1}{m}}}{(\Delta\theta_{hst,R}\cdot\mu_{pu})^{\frac{1-m}{m}}} \quad (19)$$

İn thise quatios $P_{cu,pu}(\theta_{hot})$ is the windings losses μ_{pu}

dependence on the hot spot temperature and is the viscosity variation with temperature .

$$\mu_{pu} = \frac{\mu}{\mu_R} = \frac{1.3573 \times 10^{-6} \times e^{\frac{2797.3}{\theta_{oil}+273}}}{1.3573 \times 10^{-6} \times e^{\frac{2797.3}{\theta_{oil-R}+273}}} \quad (20)$$

$$P_{cu,pu}(\theta_{hst}) = P_{DC,pu}\left[\frac{\theta_{hst}+235}{\theta_{hst,R}+235}\right] + P_{ED,pu}\left[\frac{\theta_{hst-R}+235}{\theta_h+235}\right] \quad (21)$$

IV. Simulation result and comparison

For validate the, three thermal model that described in the previous section, A 1000 kVA distribution transformer (Table 1) is used for calculation of TOT and HST. The required parameters for the models are found to be :

$\theta_{hst,R} = 25.6$ ℃ , $\Delta\theta_{oil,R} = 50.7$℃

$\tau_{win} = 8$ min $\quad \tau_{oil} = 135$ min

The transformer loading cycle is 6h/0.5pu,6h/1pu ,6h/0.5, 6h/1.5pu.The comparison between three thermal model fig, when the load is greater than the nominal value (1.5 pu) the aging acceleration factor increase **.**

RESULT

This paper presents a simulation model designed to calculate the transformer losses and electromagnetic Analysis by using ansoft Maxwell program **.**The results showed that finite element method is a powerful tools in the magnetic analysis of transformer**.** In order to calculate the top oil and hot spot temperature of studied transformers , three common used thermal models are presented in this paper. The results show that Susa model and modified IEEE model are in good consistency while Swift model differs from the other two models.

REFRENCE

Hurterand R, Viale F,(1984). “Thermal aspects of large transformers, test procedures hot spot identification, permissible limits, their assessment in factory tests and service, overload limitations, effect of cooling system”

Presented in the name of study committee-12,” in Proc.CIGRE.12–1330th Session, vol. 1,1984.

Susa D, Lehtonen M, Nordman H, (2005). “Dynamic Thermal Modelling of Power Transformers”,IEEE Trans. Power Delivery, Vol. 20, pp. 197–204, 2005

Swift G, Molinski TS, Brayand R, Menzies R (2001). "A fundamental Approach to transformer thermal modeling. II. Field verification, ",IEEE Trans. Power Delivery, vol. 16, pp. 176 – 180, April 2001.

Tang WH, Wuand QH, Richardson ZJ (2002). “Equivalen the heat circuit Based power transformer thermal model”, IEE Pros-Electr. Powr Appl.,Vol. 149, pp.87-92, 2002.

Tangand WH, Wu QH (2004). “A simplified Transformer Thermal Model Based on Thermal-ElectricAnalogy”, IEEE Trans. Power Delivery, Vol.

19, pp.1112–1119, 2004

Najafi A (2014). Iskender Comparing transformer derating under harmonic load and unbalanced supply voltage based on IEEEc57.110 standard and TESFEM by FHLand K_factor . International Review of Electrical Engineering (IREE).Vol.9 ,No.1 , 226-234 (2014)

Degefa MZ, Millar RJ (2013). “Dynamic Thermal Modeling of MV/LV Prefabricated Substations” IEEE TRANSACTIONS ON POWER DELIVERY, PP:1-8 , 2013

Dongjin K, Kyosun K,” Hot Spot Temperature for 154 kV Transformer Filled with Mineral Oil and Natural Ester Fluid” IEEE Transactions on Dielectrics and Electrical Insulation Vol. 19, No. 3; June 2012

Tang WH, Wu QH (2004)” A Simplified Transformer Thermal Model Based on Thermal-Electric Analogy” IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 19, NO. 3, JULY 2004