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Analyzing and Comparing Thermal Models of Indoor and Outdoor Oil-Immersed Power Transformers

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Abstract-- Transformers are the largest part of the investments of transmission and distribution systems and have a considerable economic impact on the operation of an electrical network. It is advisable to know the insulation condition, operating life, and loading capacitance of transformer to ensure its economical operation and secured service. The most important parameter in transformers life expectancy is the insulation temperature level which accelerates the rate of aging of the insulation. In this study, the top-oil temperature is studied both for indoor and outdoor transformers and the thermal models proposed for them are compared. Since the thermal transfer is different for indoor and outdoor transformers considering their operating conditions, their thermal models differ from each other. In this study, the top-oil temperature is analyzed for indoor and outdoor transformers and the proposed thermal models are verified by the results obtained from the experiments carried out on different operating conditions.

***Index Terms*-- oil immersed transformers, thermal model, indoor, outdoor**

I. NOMENCLATURE

C_{el}	the electric capacitance
C_{fe}	the thermal capacitance of core
C_{th}	the thermal capacitance
C_{tm}	the thermal capacitance of transformer metal component
C_{pri}	the thermal capacitance of primary winding
$C_{\sec}$	the thermal capacitance of secondary winding
C_{oil}	transformers oil thermal capacitance
C_{th-oil}	transformer equal thermal capacitance
c_{oil}	the specific heat capacity of oil
g	is the gravitational constant
h	is the heat transfer coefficient
i	electrical current
K	load in per unit
k	the oil thermal conductivity
L	the characteristic dimension, length, width or diameter
P_l	the power transfer by natural ventilation
q	power
q_{cabin}	the components power losses of cabinet
q_{fe}	transformer core losses
q_{l}	transformer load losses
q_{pri}	transformer primary side resistive losses
q_{sec}	transformer secondary side resistive losses
q_{s}	transformer stray losses
q_{tot}	total power losses at rated power
R_{el}	electrical resistance
R_{th}	thermal resistance
$R_{th-oil-air}$	thermal resistance between transformer and ambient air
$R_{th-oil-room}$	thermal resistance between transformer and room environment
$R_{room-amb}$	thermal resistance between room and ambient air
R_{hyd}	the hydraulic resistance to the air circulation
S	the surface of input, i.e. output ventilation holes
v	voltage
β	ratio of load losses to core losses
β_{oil}	the oil thermal expansion coefficient
ρ_{oil}	the oil density

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θ	temperature
θ_{aex}	temperature difference between inlet and outlet ventilation air
$\theta_{air-room}$	temperature of room air
θ_{amb}	ambient temperature
θ_{tor}	top-oil temperature rise
θ_u	ultimate top-oil temperature
θ_i	initial top-oil temperature for t=0
θ_{oil}	transformer top-oil temperature
$\Delta\theta_{oil}$	the oil temperature gradient
$\Delta\theta_{tor}$	top-oil temperature rise over ambient at rated power
τ_{to}	top-oil time constant
n	oil exponent
μ	the oil viscosity

II. INTRODUCTION

TRANSFORMERS are major apparatus in electric power systems. The power transformer capacity in a power system is about five to eight times of the power transferred in the corresponding system. Aging of insulation is a temporal function of the insulation temperature, the humidity level, and the oxygen included in it [1]. The humidity level and the oxygen included in oil can be taken under control in new designed oil immersed transformers. Therefore, the most important parameter that should be taken under control is the operating temperature of transformer. For this purpose, deriving and study of the thermal model of a transformer is getting more importance. The thermal model of a transformer is also important when it is aimed to manage the load profile of a power transformer [3, 5] and to program its loading.

The variation of the temperature is described by an exponential equation based on the time constant of the transformer top-oil temperature. In the thermal equivalent circuit model, the time constant is equal to multiplication of thermal capacitance and thermal resistance. In power systems the usage of indoor transformer station is preferred due to several reasons such as safety and environmental problems.

In some of the papers published about thermal analyzing of oil-immersed transformers the top-oil temperature characteristics are only studied mathematically [1, 4, 9, 12, 13, 14]. In the recent published papers the studies of thermal analysis are going based on thermal-electrical analogy and this is an easy understandable method from the view point of electrical engineering [2, 3, 5, 8, 10]. In this study, the thermal-electrical analogy method has been used to analyze the top-oil temperature of transformer. In the thermal-electrical analogy proposed in [2] the thermal resistance of top-oil which is a nonlinear parameter depending on the temperature is considered to be constant. In [3] the thermal resistance of top-oil is also constant and the ambient temperature is not included in the model. In [5] the top-oil thermal resistance is not constant but it is estimated using thermal loading data obtained after three months operating of transformer, therefore, the proposed thermal model isn't a general model but is corresponding to a specific transformer. The thermal model given in [8] is simplified model of that given in [3] and has the corresponding drawbacks. In [10] the thermal resistance is taken as a nonlinear parameter and the ambient temperature has also been considered in the proposed model. The drawback of this paper is the inadequate top-oil thermal capacity which only considers the oil thermal capacitance without taking into account the thermal capacitances of winding, core, tank and the other metal components used in inside of the transformer. In addition, almost all the papers published about thermal model of oil immersed transformers study only the thermal model of the outdoor transformers and there is not more information about thermal model of indoor transformers. The reference model [9] is the only study that investigates the thermal model for indoor transformers. In this study also the thermal resistance and thermal capacitance of transformer are considered as constant and the ambient temperature variation is not included in the proposed model. In addition, the thermal model given in [9] is only based on some mathematical expressions without introducing the thermal-electrical analogy. The drawbacks of the above mentioned references are removed in this study by considering nonlinear thermal resistance and taking into account the variation of the ambient temperature. The nonlinear thermal resistance considered in this study in not constant but depends on the operating temperature and the thermal capacitance of the transformer is also investigated in detail and more accurately. Besides these, this paper analyzes both thermal model of indoor and outdoor transformers and compares them.

Since the heat flow diagram is different for indoor and outdoor transformers and also considering the limited ventilation and storing of heat for indoor transformers the thermal resistance and thermal capacitance of these two types of transformers are different. For the same load the temperature rise for the indoor transformers is higher than that of for outdoor transformers.

III. FUNDAMENTAL THEORY OF THERMAL-ELECTRICAL ANALOGY

Heat is a form of energy and is always transferred between two communicating systems, arising solely from a temperature difference. In simple cases, the rate of heat flow can be quantitatively determined by applying the basic principles of thermodynamics and fluid mechanics [7, 9].

Though heat transfer by natural convection is considered to be in efficient in many industrial processes the external forces are used to make the heat transfer more efficient [7].

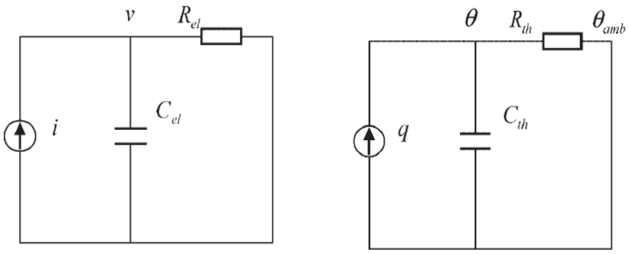
The analogy between thermal and electric process is briefly given below to analyze the thermal behavior of the inside of the power transformer [5, 8]. A thermal process can be defined by the energy balance given in Eqn. 1.

$$q = C_{th}\frac{d\theta}{dt} + \frac{\theta - \theta_{amb}}{R_{th}} \tag{1}$$

Eqn. 2 is similar to Eqn. 1 corresponding to a simple electric RC circuit shown in Fig. 1-a.

$$i = C_{el}\frac{dv}{dt} + \frac{v}{R_{el}} \tag{2}$$

The analogy between thermal and electrical process is shown in Fig. 1. Fig. 1 (a) shows an electrical RC circuit. Fig. 1. (b) shows analogous thermal circuit.



(a) RC circuit (b) analogous thermal circuit

Fig.1. The electric and thermal–electric circuits. (a) electric RC circuit, (b) analogous thermal circuit.

Table 1 shows the parameters obtained from the thermal–electric analogy by comparing Eqns. 1 and 2.

TABLE I
THERMAL – ELECTRICAL ANALOGOUS QUANTITIES.

Variables	Thermal	Electrical
Through Variable	Heat transfer rate, q, watts	Current , i , amps
Across variable	Temperature, θ, degree, ◦C	Voltage, v, volts
Dissipation element	Thermal resistance , R_{th} , deg(C)/watt	Elec. Resistance, R_{el} , ohms
Storage element	Thermal capacitance, C_{th} , joules/deg(C)	Elec. Capacitance, C_{el} ,farads

IV. THERMAL MODELING

Power losses are converted into heat in a transformer. These losses are composed of no-load losses and load losses. The no-load losses are comprised of eddy-current and hysteresis losses of the core. The load losses are comprised of resistive losses (windings losses, joint points losses and connectors losses), winding eddy losses and the stray losses.

The heat generated in a transformer transfers (from heat source to oil, from oil to surface and from surface to external environment) by three different heat transfer mechanism as i-convection ii-conduction and iii-radiation.

The thermal model is based on the energy balances for the windings, oil, core and tank, cooling equipment and cooling environment.

A. Outdoor situation

The thermal equivalent circuit of an ONAN/OFAF (oil natural air natural, oil forced air forced) power transformer includes nonlinear heat resistance, heat capacitor and heat current source. The top-oil thermal circuit of a power transformer is shown in Fig. 2.

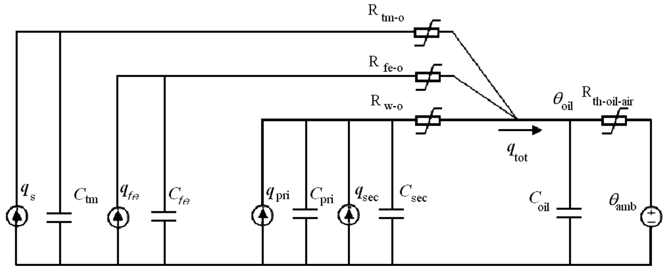


Fig. 2. The top-oil temperature thermal circuit.

In this figure q_s , q_{fe} , q_{pri} , q_{sec} are the heats generated by the stray losses, the core losses, the primary winding losses, and the secondary winding losses, respectively. C_{tm} , C_{fe} , C_{pri} , C_{sec} are the thermal capacitances of the tank including the other metal components, the core, the primary winding conductor, and the secondary winding conductor, respectively. R_{tm-o} , R_{fe-o} , R_{w-o} , $R_{th-oil-air}$ are the nonlinear thermal resistances of the tank including the other metal components to oil, core to oil, the windings to oil, and the oil to air, respectively. θ_{oil} and θ_{amb} are the top-oil and the ambient temperatures, respectively.

The load losses can be considered as sum of resistive and stray losses:

$$q_l = q_{pri} + q_{\sec} + q_s \tag{3}$$

The nonlinear thermal resistances R_{tm-o} , R_{fe-o} , and R_{w-o} which are in range of 5×10^{-5} K/W are very low with respect to $R_{th-oil-air}$ [3, 4]. Therefore, the equivalent thermal model given in Fig. 2 can be simplified as Fig. 3.

The thermal capacitance (C_{th-oil}) of power transformer top-oil equivalent circuit can be written as:

$$C_{th-oil} = C_{tm} + C_{fe} + C_{pri} + C_{\sec} + C_{oil} \tag{4}$$

The top-oil thermal model introduced by IEEE is shown by a first order differential equation as given below [1].

$$\tau_{to}\frac{d\theta_{tor}}{dt} = -\theta_{tor} + \theta_u \tag{5}$$

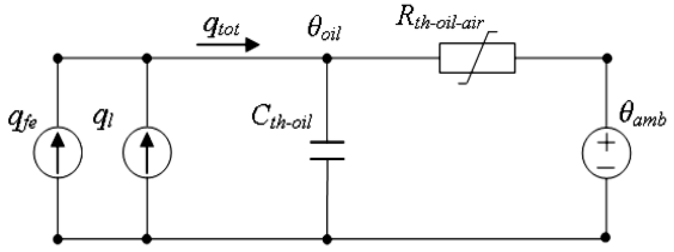


Fig. 3. The simplified equivalent top-oil thermal model

The top-oil temperature rise is obtained from Eqn. 5 as:

$$\theta_{tor} = (\theta_u - \theta_i)(1 - e^{-(t/\tau_{to})}) + \theta_i \tag{6}$$

Eqn. 7 gives the top-oil thermal model suggested by IEEE.

$$\left[\frac{K^2\beta+1}{\beta+1}\right]^n .\Delta\theta_{tor} = \tau_{to}\frac{d\Delta\theta_{tor}}{dt} + \Delta\theta_{tor} \tag{7}$$

where

K is the load factor in terms of per unit.

$$K = \frac{I}{I_{rated}} \tag{8}$$

β is the ratio of load losses to core losses and given as:

$$\beta = \frac{q_l}{q_f} \tag{9}$$

The top-oil time constant at rated power (kVA) is obtained from Eqn. 10.

$$\tau_{to} = C_{th-oil}R_{th-oil-air} \tag{10}$$

The thermal capacitance of power transformer top-oil suggested by IEEE is obtained from Eqn. 11 [1].

$$\begin{aligned} C_{th-oil} &= 0.1323 \text{ (weight of core and coil assembly in kg)} \\ &+ 0.0882 \text{ (weight of tank and fittings in kg)} \\ &+ 0.3513 \text{ (liters of oil)} \end{aligned} \tag{11}$$

The thermal resistance $R_{th-oil-air}$ is given by Eqn. 12.

$$R_{th-oil-air} = \frac{\Delta\theta_{tor}}{q_{tot}} = \frac{1}{h \times A} \tag{12}$$

Due to variation of oil thermal parameter by temperature the thermal resistance $R_{th-oil-air}$ is not constant and varies with temperature variation. Using the Nusselt number (Nu), Prandtle number (Pr), and Grashof number (Gr) [7,10] Eqn. 13 is obtained as:

$$\frac{h \times L}{k_{oil}} = C \times \left[\left(\frac{c_{oil} \times \mu}{k_{oil}}\right) \times \left(\frac{L^3 \times \rho_{oil}{}^2 \times g \times \beta_{oil} \times (\Delta\theta_{oil})}{\mu^2}\right)\right]^n \tag{13}$$

The density of oil varies with temperature according to Eqn. 14 [10].

$$\rho_{oil}(\theta) = 1098.72 - 0.712\theta \tag{14}$$

The oil thermal conductivity varies with temperature change according to Eqn. 15 [10].

$$k_{oil}(\theta) = 0.1509 - 7.101E - 0.5\theta \tag{15}$$

The specific heat capacity of oil varies with temperature according to Eqn. 16.

$$c_{oil}(\theta) = 807.163 + 3.5\theta \tag{16}$$

The oil thermal expansion coefficient varies with temperature according to Eqn.17 [10].

$$\beta_{oil}(\theta) = 8.6 \times 10^{-4} \tag{17}$$

The viscosity of oil varies with temperature according to Eqn. 18 [10].

$$\mu(\theta) = 0.08467 - 0.0004\theta + 5E - 7\theta^2 \tag{18}$$

The variation of viscosity with temperature is much higher than the variation of other transformer oil physical parameters with temperature ($\rho_{oil}, c_{oil}, k \ , \beta_{oil}$) [10]. Substituting of Eqns. 14,15,16,17,18 in Eqn. 11 gives Eqn. 19.

$$h = C_1 \times \left(\frac{\Delta\theta_{oil}}{\mu(\theta)}\right)^n \tag{19}$$

C_1 is given in Eqn. 20 and can be taken constant.

$$C_1 = C \times \left[\rho_{oil}{}^2 \times g \times \beta_{oil} \times k^{\left(\frac{1-n}{n}\right)} \times L^{\left(\frac{3n-1}{n}\right)} \times c_{oil}\right]^{(n)} \tag{20}$$

The transformer top-oil thermal model given in Fig. 3 is derived from the thermal-analogy and heat transfer theory. The differential equation corresponding to Fig. 3 is as Eqn. 21.

$$q_{fe} + q_l = C_{th-oil} \times \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb})}{\dfrac{1}{h \times A}} \tag{21}$$

Substituting the heat transfer coefficient (h) (h is obtained by substituting C_1 from Eqn. 20 into Eqn. 19) in Eqn. 21 gives Eqn. 22.

$$(q_{fe} + q_l) \times \left(\frac{\mu^n}{C_1 \times A}\right) = \left(\frac{\mu^n}{C_1 \times A}\right) \times C_{th-oil} \times \frac{d\theta_{oil}}{dt} + (\theta_{oil} - \theta_{amb})^{1+n} \tag{22}$$

$R_{th-oil-air,rated}$ which is the non-linear thermal resistance at rated power is obtained from Eqn. 23.

$$R_{th-oil-air,rated} = \frac{1}{C_1 \times A} \times \left(\frac{\mu_{rated}}{\Delta\theta_{oil,rated}}\right)^n \tag{23}$$

B. Indoor situation

The heat flow diagram is different for indoor and outdoor transformers. Due to limited ventilation in indoor operation the thermal resistance and thermal capacitance of indoor and outdoor transformers are different. For the same load the temperature rise for the indoor transformers is higher than that of for outdoor transformers.

The thermal model, i.e. the equivalent thermal circuit diagram for indoor transformer, is based on the energy balances for the following components: windings, oil, core, tank, cooling air, ventilation holes, walls, and ceiling (Fig. 4). The heat generation sources comprised of the power losses inside the transformer (load losses, q_l and core and auxiliary constructive losses, q_{fe}) and the heat generated in the distribution cabinet (losses corresponding to cabinet components like bus bars, fuses, disconnectors, switches and etc, q_{cabin}).

The heat transfer between bodies is as follows:

1. From winding to oil – conduction through the solid winding insulation and convection from outer solid insulation surface to the oil.
2. From oil to surrounding air – convection heat transfer from the transformer tank to the surrounding air

predominantly determines this heat transfer component

3. Air inside the room is cooled by natural ventilation and convection heat transfer from the air to room parts (door, walls and ceiling).

4. The heat transfer through the door

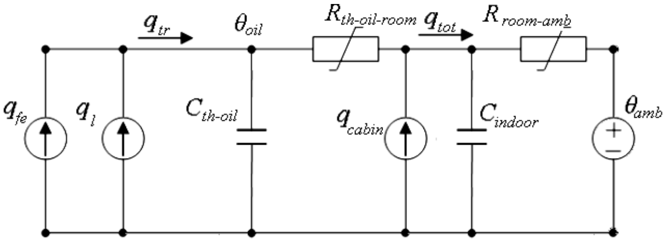


Fig. 4. The top-oil thermal model for indoor power transformers

The cabinet air inside the room is cooled by natural ventilation and convection heat transfer from the cabinet air to components existing in the cabinet like door, walls and ceiling. The first cooling component which is dominant is represented by thermal resistance of room to ambient, $R_{room-amb}$. The initial form of this thermal resistance is derived from the Hoppner formula [9]. This formula (Eqn. 24) gives the relationship among P_l (power transferred by natural ventilation), R_{hyd} (hydraulics resistance of air circulation), H (cabinet height), and θ_{aex} (temperature difference between inlet and outlet holes).

$$S=\sqrt{\frac{13.2P_l^2R_{hyd}}{\theta_{aex}^3H}} \tag{24}$$

From Eqn. 24, P_l is derived in terms of the other parameters as given in Eqn. 25. For the given ventilation hole area, cabinet height, and hydraulics resistance of air circulation the expression under the root sign is constant and the Eqn. 25 can be simplified as Eqn. 26.

$$P_l=\sqrt{\frac{H}{13.2Rhyd}}S\ \ \theta_{aex}^{1,5} \tag{25}$$

$$P_l=c_{con}\ \ \theta_{aex}^{1,5} \tag{26}$$

where $c_{con}=\sqrt{\dfrac{H}{13.2Rhyd}}S$

using $\theta_{aex}=R_{room-amb}\times P_l$ given in [9] we obtain Eqn. 27.

$$R_{room-amb}=1\Big/c_{con}\sqrt{\theta_{aex}} \tag{27}$$

C_{indoor} is equal to 0.22 times of weight of the cabinet as given in [9].

From solving thermal model given in Fig. 4 the following equations are derived.

$$q_{fe}+q_l=C_{th-oil}\times\frac{d\theta_{oil}}{dt}+\frac{(\theta_{oil}-\theta_{air-room})}{R_{th-oil-room}} \tag{28}$$

$$q_{fe}+q_l+q_{cabin}=C_{indoor}\times\frac{d\theta_{air-room}}{dt}+\frac{(\theta_{air-room}-\theta_{amb})}{R_{room-amb}} \tag{29}$$

The thermal model shown in Fig. 4 can be simplified as Fig. 5.

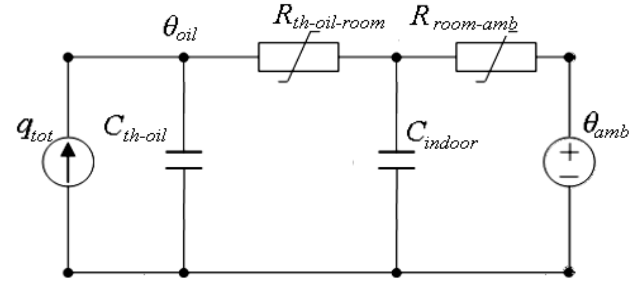


Fig. 5. The equivalent top-oil thermal model for indoor situation

The simplified top-oil thermal models of outdoor and indoor transformer are given in Fig. 6, a-b.

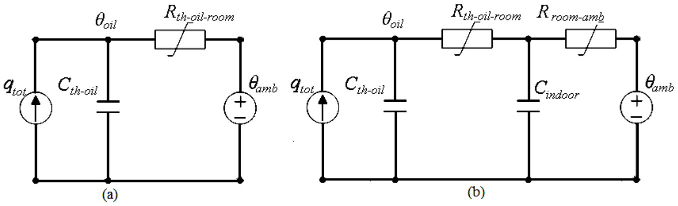


Fig. 6. Comparing thermal models (a) outdoor situation (b) indoor situation

V. EXPERIMENTAL WORKS

To verify the models derived for outdoor and indoor transformers the experiments were carried out using two different cabinets and two different transformers with the specifications given in Table II. Firstly, load and no-load losses were measured by carrying out the routine tests at rated values at principle tapping according to IEEE Standard std. C57.12.00.2006 [6, 11]. The measured losses were corrected according to the reference temperature. Then, the temperature rise tests were carried out according to *IEC 60076* and the results of temperature rise were recorded.

During temperature rise tests the secondary windings were short circuited and the voltage applied at primary was adjusted such that the generated losses were equal to total load and no-load losses at rating values.

The temperature was measured from six different points using six thermocouples. Two thermocouples were mounted at top of the transformer to measure the top-oil temperature and the next four thermocouples were used to measure the ambient temperature at four different points which have one meter distance from the transformer corners.

During experiments E-type thermocouples were used due to their advantages as: i-higher sensitivity (the highest millivolt output per degree of temperature change), ii- non-magnetic properties (they aren't affected by the magnetic fields existing around the experimental set up). The outdoor

TABLE II
MAIN CHARACTERISTICS OF TWO OIL IMMERSED DISTRIBUTION TRANSFORMER

	Transformer No.1(TR1)	Transformer No.2(TR2)
Model	TR-1250-33-A1	TSR-1600-33-A1
Nameplate rating	1000kVA	1600kVA
Serial No.	050708	086208
Voltage	33000/400 volt	30000/400 volt
Connection Vector	Dyn11	Dyn11
Type of cooling	ONAN	ONAN
No Load losses	1724 watt	2188 watt
Load losses $q_{tm} + q_{pri} + q_{\sec}$	10458 watt	18110 watt
Total rated losses	12182 watt	20298 watt

and indoor situations during tests are shown in Fig. 7-a and 7-b, respectively.

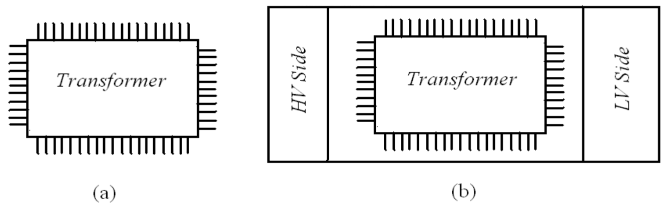


Fig. 7 Testing in indoor and outdoor conditions (a) outdoor condition (b) indoor condition

The experimental results obtained for outdoor and indoor transformers are compared with the theoretical results obtained from Eqn. 22 (for outdoor transformer) and Eqns. 28 and 29 (for indoor transformers). The top-oil temperature rise is obtained by subtracting the ambient temperature from the temperature measured at the top of transformer.

Fig. 8 shows the measured and theoretical results of the top-oil temperature rise for indoor transformer No 1.

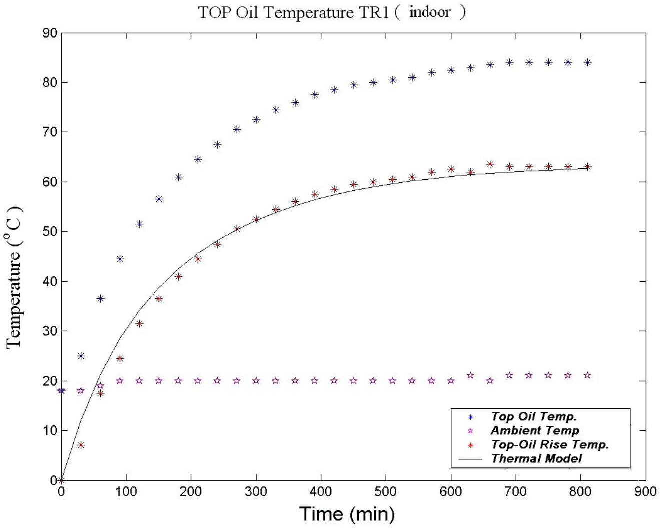


Fig. 8 Experimental and theoretical results of the top-oil temperature rise for transformer No 1 at indoor condition (TR1)

The measured and theoretical results of the top-oil temperature rise for outdoor transformer No 1 are shown in Fig. 9.

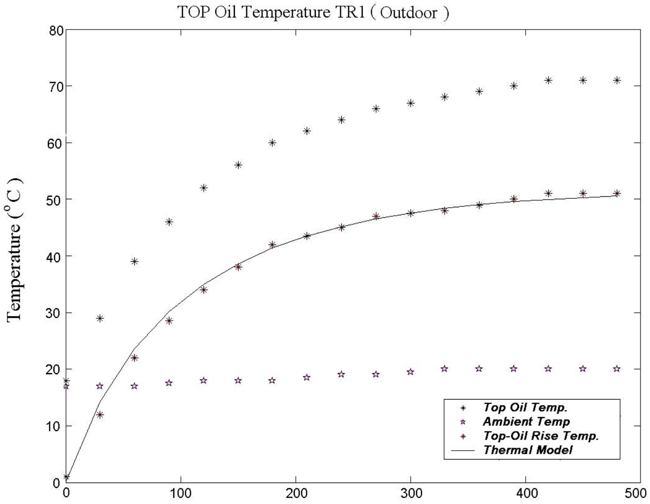


Fig. 9 Experimental and theoretical results of the top-oil temperature rise for transformer No 1 at outdoor condition (TR1)

The experimental and theoretical temperature rises results which obtained from indoor and outdoor transformer with the same injected power to the primary windings of the transformer (secondary windings are short circuited) are shown in Fig. 10. It is shown from this figure that the steady-state top-oil temperature of indoor transformer is higher than that for outdoor transformer. This means that for the same load and the same conditions the top-oil temperature of indoor transformer is higher than the top-oil temperature of outdoor transformer.

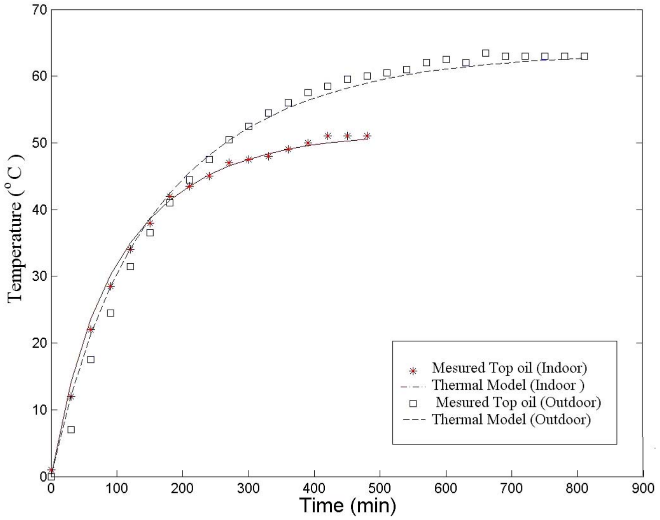


Fig. 10 Comparing experimental and theoretical results of the top-oil temperature rise for transformer No 1 (TR1)

Therefore, for the same temperature rise for the same transformer for two different conditions of indoor and outdoor condition the indoor loading level will be less than the loading level of outdoor condition. It is also shown that the top-oil temperature rise of outdoor transformer (for the first 140 minutes) is higher than that for indoor conditions. This is due to effect of the thermal capacity of the cabinet with the components existed inside it.

The measured and theoretical results of the top-oil temperature rise for indoor transformer No 2 are given in Fig. 11.

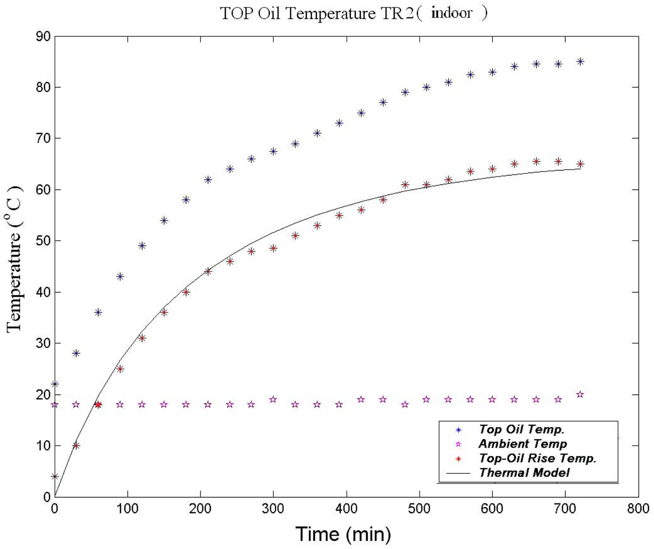


Fig. 11 Experimental and theoretical results of the top-oil temperature rise for transformer No 2 at indoor condition (TR2)

The measured and theoretical results of the top-oil temperature rise for transformer No 2 for outdoor condition are shown in Fig. 12.

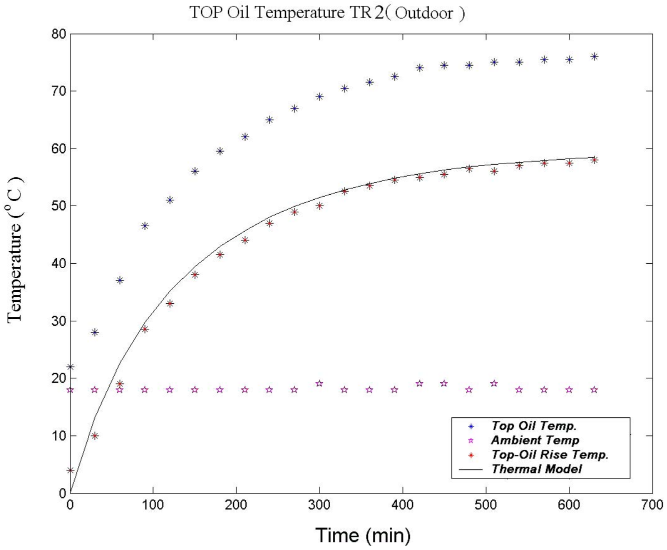


Fig. 12 Experimental and theoretical results of the top-oil temperature rise for transformer No 2 at outdoor situation (TR2)

The experimental and theoretical temperature rises results which obtained from indoor and outdoor transformer with the same injected power to the primary windings of the transformer (secondary windings are short circuited) are shown in Fig. 13. It is also shown from this figure that the steady-state top-oil temperature of indoor transformer is higher than that for outdoor transformer.

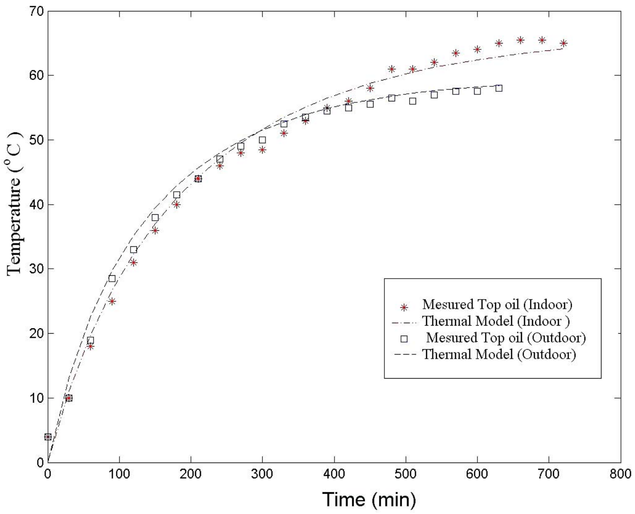


Fig. 13 Comparing experimental and theoretical results of the top-oil temperature rise for transformer No 2 (TR2)

VI. CONCLUSION

The top-oil thermal model of oil immersed power transformer was derived considering nonlinear thermal resistance and the adequate value of thermal capacitance. The ambient temperature change was also considered in deriving the thermal-electric analogy model. The top-oil thermal model for indoor transformer was also derived based on the thermal-electric analogy theory. This model is the first top-oil thermal-electric analogy model proposed for indoor transformers. The experimental results are in a good accordance with the theoretical results both for indoor and outdoor transformers. The dynamic and steady-state responses of indoor and outdoor transformers are different. The steady-state top-oil temperature corresponding to indoor transformer is higher than that of for outdoor transformer (about 10 degrees of centigrade). This should be taken into account in load managing and operation policy. According to IEEE Standard C57.91, 1995 extra heating in transformer will accelerate ageing of transformer insulation and this will reduce life of transformer.

VII. ACKNOWLEDGMENT

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