Evaluation of Permissible Loading for Indoor Oil-Immersed Distribution Transformers

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Abstract

Failures of power transformers can cause high financial damage. Du to this fact 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, permissible steady state loading of indoor transformers is evaluated from the top-oil temperature rise model. To verify the proposed model experiments are applied for both indoor and outdoor transformers and the results of top-oil temperature rise corresponding to these tests are compared. Since the thermal transfer is different for indoor and outdoor transformers considering their operating conditions, their top-oil temperature rise differs from each other. Due to this fact the permissible loading factors of these two types transformers are different.

1. Introduction

A typical oil immersed transformer layout is shown in Fig. 1. During working under load a transformer is the source of energy losses, the majority of which are located in two fundamental parts, the magnetic core and the windings. In the magnetic core the losses are generated by variation of alternating flux in the magnetic circuit; therefore they are directly related to the induction and hence the applied voltage. The winding losses are primarily due to resistive losses and eddy currents, however, and are related to the load. Losses are also generated in the connections, tap changers and bushings. They can be linked with the losses referred to above, and appear in the same way as in materials with good electrical conductivity. The leakage flux due to the windings, terminals and connections can also create stray losses by inducing eddy currents in neighboring non-active metallic components, such as the fastenings, tank and cover. The manufacturer is required to reduce these to the absolute minimum [2]. All these losses cause heating in the corresponding parts of the transformer and this heat is transferred to the transformer oil by convection and further, from the oil to the cooling medium via a heat exchanger. Though the winding conductor holds its mechanical strength up to several hundred degrees Celsius and the transformer oil does not significantly degrade below about 140°C, the paper insulation deteriorates very rapidly if its temperature exceeds 90°C.

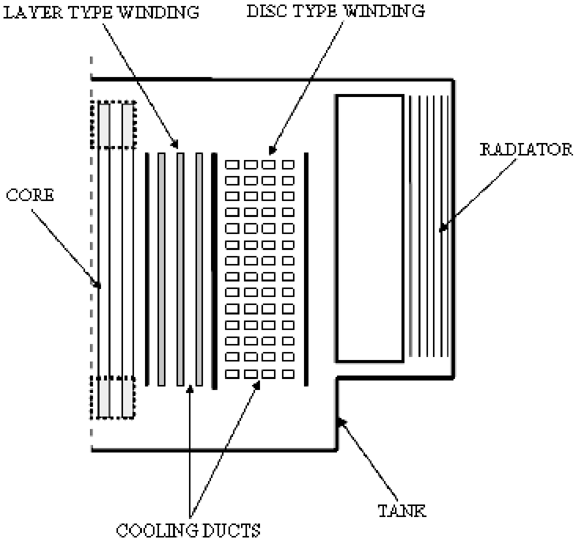

Fig. 1. Cross-sectional view of a typical oil-immersed transformer

In addition, the moisture content, acidity and oxygen content of the oil have a significantly detrimental effect on insulation life [1, 2]. Therefore, the loading capacity of a transformer is defined in terms of the thermal ageing of its insulation and the transformer hot-spot temperature. As it is reported in [1, 2, 4], from 90 to 110°C the tensile strength aging rate is doubled for approximately each 6°C increase in temperature. In other studies like [2], the life of different transformer insulation materials is halved by an increase in temperature ranging from 5 to 10 degrees. Generally, the consensus is that in the temperature range from 80 to 140°C, the life expectancy is halved by each 6°C increase in temperature [1, 3]. According to IEC Publication 76, the rate of ageing of the inter-turn insulation of transformers under the effect of time and temperature is referred to a hotspot temperature of 98°C (i.e., to a value that normally corresponds to a 20°C cooling air temperature under the continuous rated load) [2]. The service life of such a transformer due to ageing is about 30 years. IEC-76 defines temperature rise limits (e.g., top-oil and average winding temperature rises above ambient temperature for different cooling modes) and specifies test methods for temperature-rise measurements [2]. The IEEE standard test code for liquid-immersed distribution, power, and regulating transformers [1], also deals with temperature rises and related test procedures similar to IEC-76 parts 1 and 2 [1, 6].

According to IEEE Standard [1] the normal life (the normal solid insulation life) is as 180,000 hours or 20.6 years. This is the life corresponding to continuous operation at the design hot spot temperature of 110 C. It is related to the loss of tensile strength or degree of polymerization retention of the solid winding insulation (page 10 of the Standard). A nonlinear formula relates the rate of loss of life to other values of hot spot temperature as Table 1.

Table 1. Aging acceleration factor

Hot Spot Temperature ◦ C	Rate of Loss of Life relative to normal
110 (design value)	1
117	2
124	4
131	8
139	16
147	32

The oil has flash point with in 140 ◦C, operation at the 'oil flash point' condition is thought to be OK, for a short time, because the bubbles will redissolve when the oil cools, but operation at hottest-spot temperatures above 140°C for long time, may cause gassing in the solid insulation and the oil. Gassing may produce a potential risk to the dielectric strength integrity of the transformer [1].

The basic criterion which limits the transformer load capabilities is the temperature of the winding and insulation. Several studies to measure the quantitative loss of transformer life due to the effect of thermal ageing have been carried out since 1930. Loading beyond nameplate rating and cumulative loss of transformer functional life have been basic considerations in the well-practiced IEC 354, 161ANSI C 57.92 and NEMA Guides for loading oil-immersed power and distribution transformers with 65ºC average winding temperature rise [1,3,6].

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 steady state rise for the indoor transformers is higher than that of for outdoor transformers. The Dynamic response is difference for two difference situation. Due to this fact permissible loading is also different. For evaluation of permissible loading it is required to calculate thermal behavior of two different transformer [3].

2. 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 composed of resistive losses (windings losses, joint points losses and connectors losses), winding eddy losses and the stray losses [1,3,5].

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 [2,5]

2.1. 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., [5].

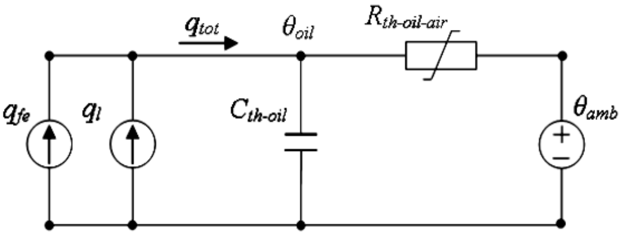

Fig. 2. The equivalent top-oil thermal model

Using Fig. 2, the top-oil temperature rise is obtained as Eqn. 1.

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

Eqn. 2 gives the top-oil thermal model suggested by IEEE [1].

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

Substituting the heat transfer coefficient in Eqn. 2. gives Eqn. 3, [3, 5].

$$(q_{fe} + q_l) \times \left(\frac{\mu^n}{C_1 \times A}\right) = \left(\frac{\mu^n}{C_1 \times A}\right) \times C_{th-oil} \times \frac{d\theta_{oil}}{dt} + (\theta_{oil} - \theta_{amb})^{1+n} \tag{3}$$

where :

β	ratio of load losses to core losses
C_1	oil constant
C_{th-oil}	transformer equal thermal capacitance
q_{fe}	transformer core losses
q_l	transformer load losses
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
$\Delta\theta_{tor}$	top-oil temperature rise over ambient at rated power
τ_{to}	top-oil time constant
n	oil exponent
μ	the oil viscosity

K	load in per unit

2.2. 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 [3].

The thermal model, i.e. the equivalent thermal circuit diagram, is based on the energy balances for the following elements: i- windings ii- oil, core and tank iii- cooling air; iv- door v- walls vi- ceiling. This thermal circuit represents an extension of the widely used thermal circuit with two nodes. The heat generation sources are the power losses inside the transformer – in the winding (copper) q_l and in the iron core and auxiliary constructive parts q_{fe}, and the heat that generated in distribution cabinet from the low voltage side and high voltage cabinets components like bus bars, fuses, disconnectors, switches and etc [3].

The heat transfer between different element existing in the transformer 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

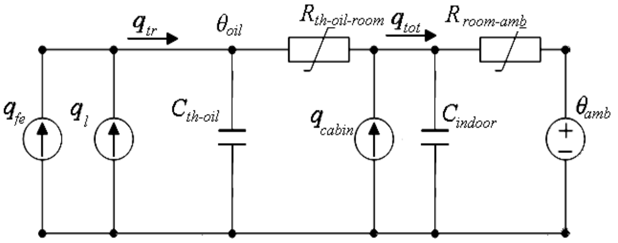

Fig. 3. The top-oil thermal model for indoor power transformers

Air inside the room is cooled by natural ventilation and convection heat transfer from the air to room parts (door, walls and ceiling). The first cooling component, being dominant, is represented by the heat conductance. The initial form of this thermal conductance is derived from the Hoppner formula [3], defining the size of the ventilation [3].

$$q_{fe}+q_l=C_{th-oil}\times\frac{d\theta_{oil}}{dt}+\frac{(\theta_{oil}-\theta_{air-room})}{R_{th-oil-room}} \qquad (4)$$

$$q_{fe}+q_l+q_{cabin}=C_{indoor}\times\frac{d\theta_{air-room}}{dt}+\frac{(\theta_{air-room}-\theta_{amb})}{R_{room-amb}} \qquad (5)$$

where :

C_{indoor}	the thermal capacitance of prefabricate transformer room
q_{cabin}	the components power losses of cabinet
q_{tot}	total power losses at rated power
$R_{th-oil-room}$	thermal resistance between transformer and room environment
$R_{room-amb}$	thermal resistance between room and ambient air
$\theta_{air-room}$	temperature of room air

The thermal model shown in Fig. 3 can be simplified as Fig. 4.

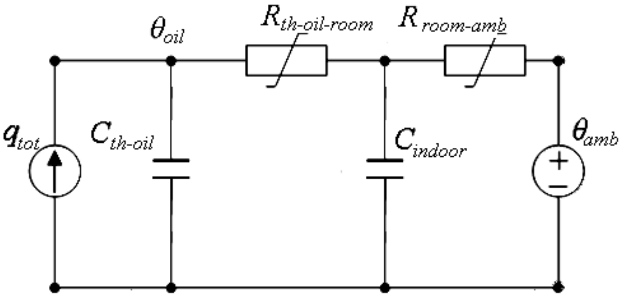

Fig. 4. The equivalent top-oil thermal model for indoor situation

The simplified top-oil thermal models of outdoor and indoor transformer are given in Fig. 5, a-b.[3]

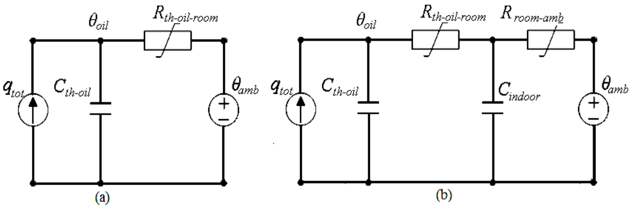

Fig. 5. Comparing thermal models (a) outdoor situation (b) indoor situation

3. Experimental Temperature Rise Tests

To verify models that used for evaluation permissible loading, experiments were carried out using two different cabinets and two different transformers with the specifications given in Table 2.

Table 2. Main characteristics of two oil immersed distribution transformer

	Transformer No.1(TR1)	Transformer No.2(TR2)
Model	TR-1000-33-A1	TSR-1600-33-A1
Nameplate rating	1000kVA	1600kVA
Serial No.	050708	086208
Voltage	33000/400 volt	30000/400 volt
Vector	Dyn11	Dyn11
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

The experimental and theoretical temperature rises results obtained from indoor and outdoor transformer with the same injected power to the primary windings of the transformer (secondary windings are short circuited) [3,7] are shown in Fig. 6 and 7, respectively. It is shown from these figures 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.

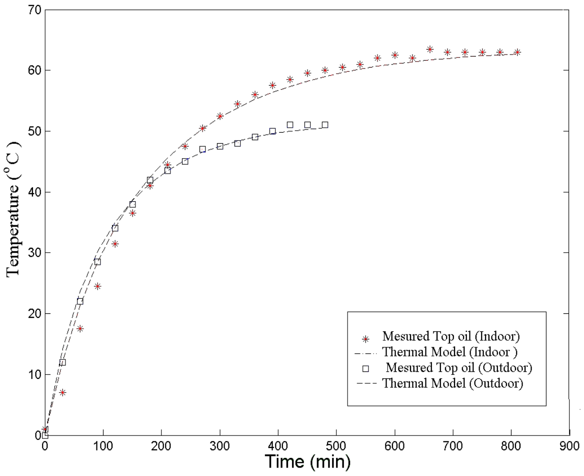

Fig. 6. Comparing experimental and theoretical results of the top-oil temperature rise for transformer No 1 (TR1)

It is seen from Fig. 6 and 7 that there is about ten degree of centigrade over heating in indoor transformer center, cause of ten degree is the criterion and limitation of ten degree in IEC 61330 standard for prefabricate transformer substation [7]. The difference temperature between outdoor and indoor operation (10 deg) is due to the limit given in Prefabricate Transformer Substations Standard. The prefabricated transformer substations manufacturers consider the above mentioned limit during designing.

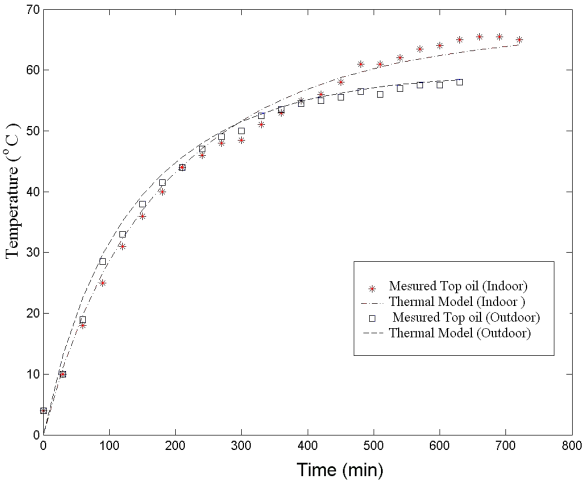

Fig. 7. Comparing experimental and theoretical results of the top-oil temperature rise for transformer No 2 (TR2)

4. Permissible Loading

The hottest-spot winding temperature is the principal factor in determining life due to loading. The temperature cannot be measured directly because of the hazards in placing a temperature detector at the proper location because of voltage.

Distribution transformers may be operated above 110°C average continuous hottest-spot temperature for short periods provided they are operated for much longer periods at temperatures below 110°C. This is due to the fact that thermal aging is a cumulative process. This permits loads above the rating to be safely carried under specified conditions without encroaching upon the normal life expectancy of the transformer. When the ambient temperature is below the 30°C ambient used to establish the transformer's rating, or when the transformer's temperature rises at nameplate rated load, as determined by test, are less than the normal limiting values, some additional load beyond nameplate rating is possible within normal life expectations.

The basic loading of a distribution transformer for normal life expectancy is continuous loading at rated output when operated under usual service conditions as indicated in 4.1 of IEEE Std C57.12.00-1993. It is assumed that operation under these conditions is equivalent to operation in a constant 30°C ambient temperature. The hottest-spot conductor temperature is the principal factor in determining life due to loading. Direct temperature measurement of the hottestspot may not be practical on commercial designs [1]. Due to this fact we use the relationship between top-oil temperature and hot-spot value. Fig. 8. is a transformer thermal diagram that shows the main temperature distribution along the winding height as well as the oil temperature distribution inside the transformer tank.

According to EEE Std. C57.12.00 for 60-65 ˚ C transformers, at 30◦ C of ambient temperature and operating at rated power, the hot-spot value is 110 ˚ C, and then hot-spot value is 20 ˚ C above top-oil temperature [1, 4].

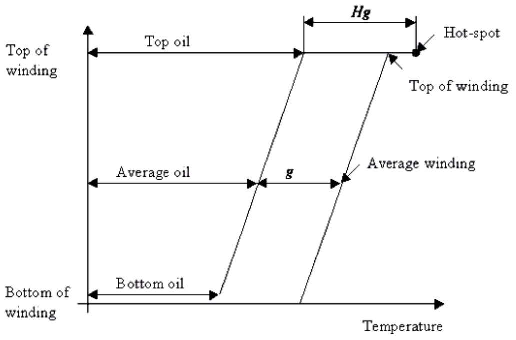

Fig. 8. Temperature rises in different parts of transformers.

The intersection of 110 ˚C ambient temperature with one per unit loadability represents the design condition, that is, the condition under which continuous loading would result in a steady-state hot spot temperature of 110 ˚C.

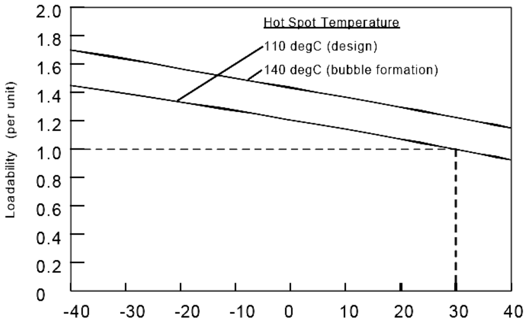

Fig. 9. Outdoor transformers loadability versus ambient temperature

Fig. 9. Show the relation between permissible load and ambient temperature according to IEEE Std. C57.91.1995 and IEEE Std. C57.12.00. [4].

Due to limited ventilation in indoor transformers the top oil temperature rise is higher; considering this fact in order to reach the same life performance the loading in indoor situation, we must load under outdoor situation as have same temparature rise for hot spot temperature . from Fig. 8. hot spot value have linear realashion with top of winding temperature , and top of winding temperature have same relation with top-oil temperature, therefore we can use diference of steady state temparature rise to calculate loadability in indoor situation.

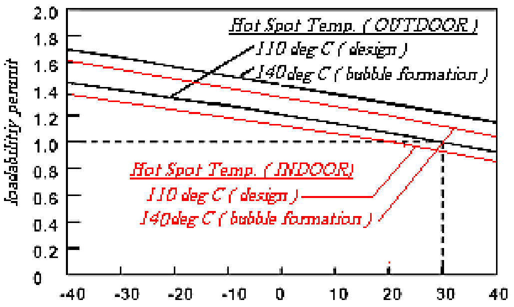

Fig. 10. Indoor transformers loadability versus ambient temperature

Then

$$\Delta\theta_{tou} = \Delta\theta_{tor}\left[\frac{K^2\beta+1}{\beta+1}\right]^n \qquad (6)$$

By using Eqn. 6. permissible load versus ambient temperature shown in Fig. 9. From Eqn. 6. load factor calculated by shifting ten degree of centigrade then the permissible load for indoor transformer will calculated as Fig. 10.

5. Conclusions

According to IEEE Standard C57.91, 1995 extra heating in transformer will accelerate ageing of transformer insulation causing a reduction in transformer life. According to theoretical and experimental results obtained from this study, when a transformer is operating under indoor condition its load should be less than the load of a similar transformer operating under outdoor conditions. In other words, the expectancy life of an indoor transformer operating under nominal load is 0.37 time of the expectancy life of a similar outdoor transformer supplying the same load considering the same ambient temperature. Considering the principal loading profile given in this study will increase the useful life of an indoor transformer.

6. Acknowledgment

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6. References

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