THERMAL MODELING AND AGEING OF TRANSFORMER UNDER HARMONIC CURRENTS

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ABSTRACT

Transformers are normally designed and built up for use at rated frequency and linear load current. The hot spot temperature determines the potential risk of releasing gas bubbles during a severe overload condition. This increases the importance of knowing the hot spot temperature at each moment of the transformer during operation at different loading conditions and variable ambient temperature. The paper begins with background information on the thermal models of transformer feeding linear loads according to IEEE guide, an improved top oil temperature model and dynamic thermal model. According to the IEEE model for loading mineral-oil-immersed transformers, the hot spot temperature (HST) varies instantaneously with varying the top oil temperature (TOT). The TOT varies instantaneously with varying the ambient temperature. The variation of the TOT rise and HST rise are described by an exponential equation based on a time constant. According to an improved top oil temperature model, the TOT will naturally delay behind the daily cycle of ambient temperature changes. According to dynamic thermal model, the HST doesn't vary instantaneously with varying the TOT. The heat flow is more than proportional to the temperature difference across the transformer tank wall as the hotter air near to the wall will be moving faster due to its lighter weight, i.e., the convection will be greater. The result is that the proportionality is not linear.

The HST and the TOT are verified in MATLAB by linear loads variations according to the dynamic thermal model. It is applied on a 2.5 MVA, liquid filled transformer, FA cooling type. The transformer is equipped with thermocouples and tested at varying loads. The measured temperatures are compared with the predicted temperatures of the dynamic thermal model.

A non-linear load on a transformer causes additional losses, equipment heating & loss of life. Normal life expectancy will result from operating continuously with hottest-spot conductor temperature. The devastation effects caused by the HST are usually taken into consideration, upon investigating of the ageing process. The ageing acceleration factor is usually taken to be a good indicator of transformer loss of life. In this paper, the impacts of harmonics on the normal life of transformer are analyzed. The HST and TOT are computed under harmonic conditions according to the dynamic thermal model. It is verified using simulation in MATLAB and considered harmonic load currents and ambient temperature. It is applied also on 2.5 MVA, liquid filled transformer, FA cooling type. The TOT, hot HST, and ageing acceleration factor with and without harmonic loads are calculated. The results show that the TOT, HST, and ageing acceleration factor with harmonic current is greater than without harmonics. Finally, an algorithm is used to determine the loading capability of transformer in the presence of non-linear load currents. After using the suggested algorithm, the ageing model is verified again using simulation in MATLAB.

INTRODUCTION

Transformer can be overloaded due to contingency outage of various system elements of the power system or due to extra capacity is needed especially during hot summers. Transformers may be overloaded, while still maintaining transformer integrity, to keep continuity of the load for economical or reliability reasons [1]. Hence, it is necessary to predict the thermal behavior of a transformer during normal cyclic loadings and particularly in the presence of overload conditions.

The hottest spot temperature (HST) of transformer winding represents the most important parameter for determining the capability of the transformer to feed any load and life time expectancy of the transformer. Hence, the prediction of the (HST) of transformer winding is necessary [2].

Utilities can operate the transformer more closely to its thermal limits by using more accurate thermal models. The unused capacity in security margins would be readily available for utility usage. To reduce the security margin, the credibility and the accuracy of the thermal modeling technique need to be improved [3].

This paper presents the dynamic thermal model equations as in [4]. The transformer is equipped with thermocouples and tested at varying loads according to IEC 60076-7 [5]. The HST and TOT are recorded during the varying load current test and will be plotted.

To determine the loading capability of a transformer, ambient temperature should be taken into consideration. As the operating temperatures of the transformer is dependent on the temperature rise for any load and the ambient. In this paper, the impacts of harmonics on transformers are discussed and a thermal dynamic model to predict a transformer HST is presented. It is verified using simulation in MATLAB and considered harmonic load currents and ambient temperature. The TOT and HST with and without harmonic loads are calculated.

TRANSFORMER LOADING GUIDE

IEEE Top Oil Temperature Rise Model

The model for TOT rise over ambient temperature shows that any increasing in the transformer loading current leads to additional losses. The additional losses cause increasing in TOT rise. This temperature variation is dependent on the top oil time constant [6].

The prediction of the TOT rise can be calculated as: [6]

$$T_o \frac{d\Delta\theta_{To}}{dt} = -\Delta\theta_{TO} + \Delta\theta_{ou} \tag{1}$$

Where $\Delta\theta_{ou}$ is the ultimate TOT rises, T_o is the top oil time constant, t is time referenced to the time of the load current change, and $\Delta\theta_{T0}$ is the top oil temperature rise.

IEEE model shows that the ultimate temperature rise is dependent on the load current and it can be obtained by the following expression:

$$\Delta\theta_{ou} = \Delta\theta_{fl}\left(\frac{K^2R+1}{R+1}\right)^n \tag{2}$$

Where $\Delta\theta_{fl}$ is the full load TOT rise over ambient, n is a cooling constant if the movable fluid is air, R is the ratio of load loss at rated load to no-load loss, and K is the ratio of the specified load to rated load:

$$K = \frac{I}{I_{rated}} \tag{3}$$

IEEE Hot Spot Temperature Rise Model

In IEEE loading guide Std C57.91-1995, a model to estimate the HST rise over TOT was discussed [7]. An increase in the transformer loading current leads to an increasing in TOT rise over ambient temperature. The model for predicting the HST rise over TOT obtained by the following equation: [8]

$$T_H \frac{d\Delta\theta_H}{dt} = \Delta\theta_{HU} - \Delta\theta_H \tag{4}$$

Where $\Delta\theta_{HU}$ is the final (ultimate) temperature rise, T_H is the hot spot time constant, t is time referenced to the time of the loading change and $\Delta\theta_H$ is the hot spot temperature rise over top oil temperature variable [8].

$$\Delta\theta_{HU} = \Delta\theta_{H-R}[K]^{2m} \tag{5}$$

Where $\Delta\theta_{H-R}$ is the rated hot spot temperature rise over top oil temperature and m is an empirically derived exponent that is dependent on the cooling method [8].
The hot spot temperature obtained by adding the ambient temperature, the top oil temperature rise, and the hot spot temperature rise: [7]

$$\theta_H = \theta_A + \Delta\theta_H + \Delta\theta_{To} \tag{6}$$

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IMPROVED TOP OIL TEMPERATURE MODEL

IEEE/ANSI thermal model assumed that the top oil temperature rise is dependent on the loading current of the transformer but, $\Delta\theta_{To}$ is constant without varying in the loading current. The ambient temperature variation plays an important role for dissipation the generated heat. Hence, if the current doesn't vary, the top oil temperature rise over ambient temperature would vary. This effect is not considered in IEEE/ANSI model but is important for a transformer located in an environment with daily variations in ambient temperature [6]. The model for predicting the TOT can be expressed as: [9]

$$T_o \frac{d\theta_{To}}{dt} = -\theta_{To} + \Delta\theta_{ou} + \theta_A \tag{7}$$

Where θ_{To} is the top oil temperature, $\Delta\theta_{ou}$ is the final (ultimate) temperature rise, and T_o is the thermal time constant.
The hot spot temperature can be obtained by adding the top oil temperature and the hot spot temperature over top oil temperature [9].

$$\theta_H = \Delta\theta_H + \theta_{To} \tag{8}$$

DYNAMIC THERMAL MODEL

Dynamic Top Oil Thermal Model

The dynamic top oil thermal model enhanced the improved TOT model. It shows that the rated TOT rise over the ambient temperature without fans (OA cooling type) is higher than that with fans (FA cooling type). This effect is not taken into consideration in the IEEE and improved TOT model [4].

The following differential formula is used to predict the TOT: [4]

$$\frac{{I_{pu}}^2\beta+1}{\beta+1}.\left[\Delta\theta_{T0-R}\right]^{1/n} = T_o\frac{d\theta_{To}}{dt} + \left[\theta_{T0} - \theta_A\right]^{1/n} \tag{9}$$

Where β is the ratio of q_{cu} to q_{fe} at rated load ($I_{pu} = 1$), T_o equals to $R_{oilR}.C_{oil}$, $\Delta\theta_{To}$ equals to $\theta_o - \theta_A$, R as an appended subscript indicates rated load, steady-state, θ_A is the ambient temperature, $\Delta\theta_{T0-R}$ is the rated top oil temperature rise.

Dynamic Hot Spot Thermal Model

The dynamic hot spot thermal model shows that the HST varies with time constant with TOT variations and also the cooling effect on the rated HST rise is taken into consideration [4].

The following differential formula is used to predict the HST: [10]

$$\frac{I^2[1+P_{EC-R(pu)}]}{[1+P_{EC-R(pu)}]}.[\Delta\theta_{H-R}]^{1/m} = T_H\frac{d\theta_H}{dt} + [\theta_H - \theta_{To}]^{1/m} \quad (10)$$

Where θ_H is the hot spot temperature, $P_{EC-R(pu)}$ are the rated eddy current losses at the hot spot location, $\Delta\theta_{H-R}$ is the rated hot spot rise, T_H is the winding time constant at the hot spot location.

MEASUREMENTS BY THREMOCOUPLES

We installed thermocouples in only the lower voltage winding, which is usually next to the core [11]. The transformer is tested according to IEC 60076 under load cycle as shown in Fig.(1) [5]. This transformer is equipped with 28 thermocouples as in [11].

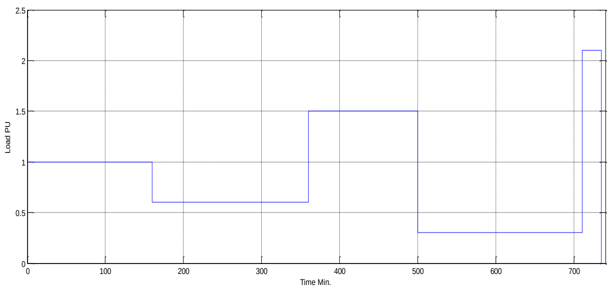

Figure 1. The loading current cycle (IEC 60076-part7) [5].

THE SIMULATION RESULTS

The measured temperatures are compared with the predicted temperatures of the dynamic thermal model as shown in Figs. (2, 3). It is shown that the thermal model generally yields results that match well with measured results.

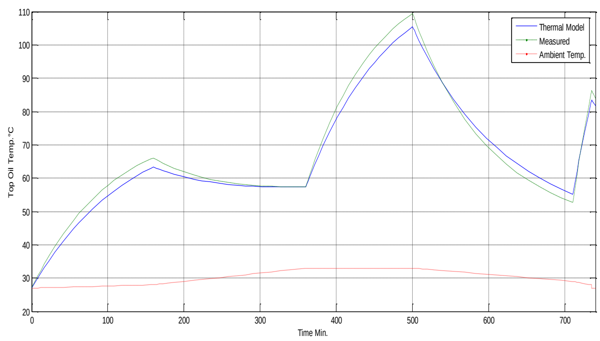

Figure 2. The predicted and measured TOT.

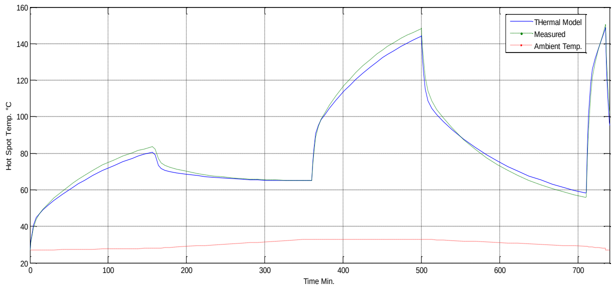

Figure 3. The predicted and measured HST in the LV winding.

TRANSFORMER THERMAL AGEING

It is supposed that insulation failure may be modeled as a pu value for a reference temperature of 110 °C. The ageing acceleration factor can be expressed as: [12]

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} \quad (11)$$

When the hot spot temperature was 117°C, F_{AA} would be doubled. The transformer real life is half of its normal life.

DYNAMIC THERMAL MODELING OF THE TRANSFORMER IN THE PRESENCE OF NON-SINUSOIDAL LOAD CURRENTS

The harmonic impacts on the transformer are increasing the temperature rise of the transformer and deterioration of the insulation.

The harmonic impacts on the TOT model are presented by the following differential equation [13]:

$$\frac{\frac{P_{LL-H}}{P_{NL}}+1}{\frac{P_{LL-R}}{P_{NL}}+1}.[\Delta\theta_{T0-R}]^{1/n} = T_o\frac{d\theta_{To}}{dt} + [\theta_{To} - \theta_A]^{1/n} \quad (12)$$

$$P_{LL-H} = P.\sum_{h=1}^{h\max}\left(\frac{I_h}{I_R}\right)^2 + P_{EC}.\sum_{h=1}^{h\max}h^2\left(\frac{I_h}{I_R}\right)^2 + P_{OSL}.\sum_{h=1}^{h\max}h^{0.8}\left(\frac{I_h}{I_R}\right)^2 \quad (13)$$

Where P_{LL-H} is load losses due to harmonics, P_{LL-R} is rated load losses, P_{NL} is no load losses, P is ohmic losses at rated current, $\Delta\theta_{T0-R}$ is rated top oil temperature rise over ambient, T_o is top oil time constant, θ_{To} is top oil temperature.

The harmonic impacts on the HST model are presented by the following differential equation [13]:

$$\frac{\sum_{h=1}^{h\max}\left(\frac{I_h}{I_R}\right)^2 K_\theta + \sum_{h=1}^{h\max}h^2\left(\frac{I_h}{I_R}\right)^2 . P_{EC-R(pu)}/K_\theta}{1+P_{EC-R(pu)}}.[\Delta\theta_{H-R}]^{1/m} = T_H\frac{d\theta_H}{dt} + [\theta_H - \theta_{To}]^{1/m} \quad (14)$$

Where θ_H is hot spot temperature, P_{EC-R} is pu eddy losses at rated load and hot spot location, $\Delta\theta_{H-R}$ is rated hot spot rise, T_H is hot spot time constant.

The TOT and HST are calculated under constant harmonics load as shown in Table 1[14].

Table 1: Non-sinusoidal input current load [15]

h	1	5	7	11	13	17	19
I_h/I_R	0.978	0.171	0.108	0.044	0.028	0.015	0.0098

Figures (4, 5, 6) show the predicted TOT and HST and the transformer thermal ageing with & without harmonics load respectively.

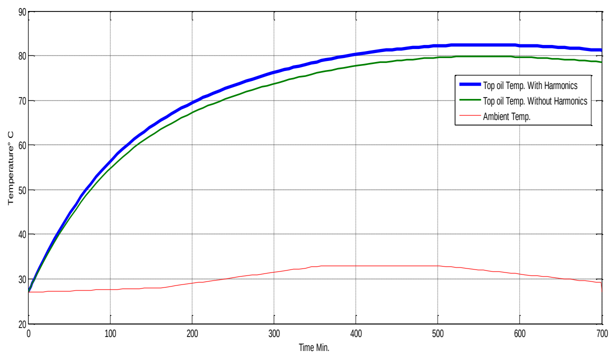

Figure 4. The predicted TOT with & without harmonics load.

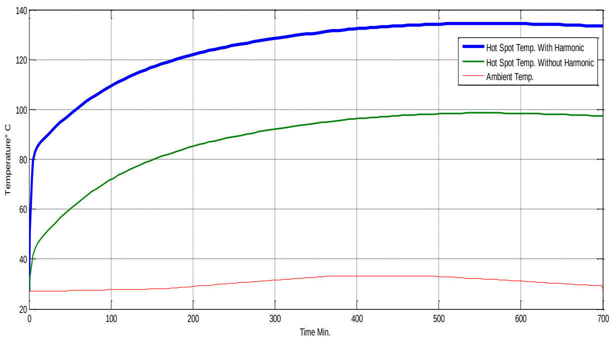

Figure 5. The predicted hot spot temperature with & without harmonics load

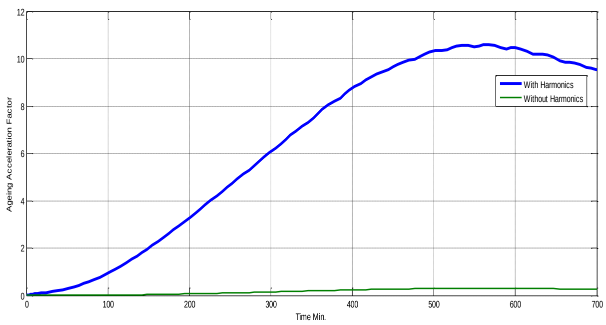

Figure 6. The transformer thermal ageing with & without harmonics input load

In Figs. (4, 5) the TOT and HST with and without harmonic loads are calculated under constant load that shows the TOT and HST in transformer with harmonic current is greater than without harmonics. In Fig. 6, when the winding HST of the transformer with harmonic loads is greater than the reference value of 110 °C, the ageing acceleration factor is greater than one which means that its life is less than normal life. Without harmonic loads, the ageing acceleration factor is less than one which means that it works on its normal life.

THE LOADING CAPABILITY OF TRANSFORMER IN THE PRESENCE OF NON-SINUSOIDAL LOAD CURRENTS

The simulation result has shown, the presence of harmonic loads increases transformer loss of life. Hence, the transformer needs to be derated to reduce the transformer thermal ageing. In order to determine the loading capability of transformer, a suggested flowchart is shown in Fig. 7. If the hot spot temperature limit is exceeded, the harmonic load should be decreased by 2%. Otherwise, work with current load. Then, the transformer thermal ageing is calculated.

The normal life expectancy at a continuous hottest spot temperature of 110 °C is 180,000 h (1 per unit). Thus, if transformer ageing acceleration factor equal to one, it works on its normal life (180,000 h) [12].

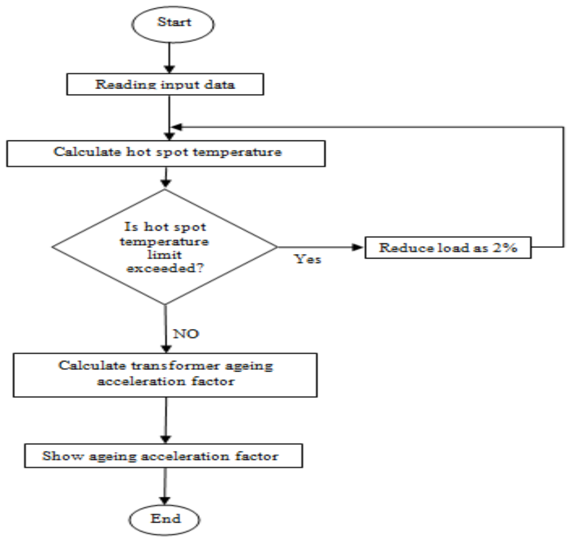

Fig. 7. Flow chart to determine the loading capability of transformer under harmonic conditions

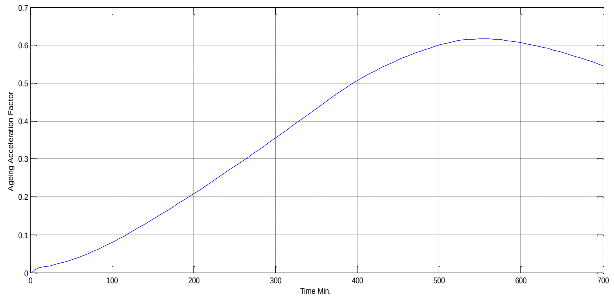

Fig. 8. The transformer thermal ageing acceleration factor in the presence of non-sinusoidal load currents with derating the transformer current loading.

The simulation results show that to avoid the higher losses, early fatigue of insulation, premature failure, and reduction of the useful life of the transformer. The non-linear loads must be derated with 26% of its current loading without exceeding the hot spot temperature limit. As shown in Fig. 8, the thermal ageing acceleration factor is less than unity. Therefore, the transformer is capable to maintain its normal life.

CONCLUSION

A dynamic thermal model succeeded in predicting TOT and HST for liquid-filled transformers. The suggested thermal model is applied at varying load and the results are compared to results obtained by actual measurement in laboratory. The contribution of this research is verification the dynamic thermal model by performing a comprehensive test program on a liquid-filled transformer. During the test program, it was observed that the calculated TOT and HST generally yield results that match well with measured results.

A thermal model of transformer temperature rise and thermal ageing in the presence of harmonic load currents has been established to determine the transformer loading capability. The simulations results show that the presence of harmonic loads increases the HST and transformer loss of life. To maintain the transformer life in normal limitation, a new loading is applied. Furthermore to determine the new loading, a flowchart is presented.

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