Determining Thermal Life Expectancy Of Power Transformer Under Non Linear Loads Using FEM By ANSYS And MATLAB

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Abstract

Power transformers have immense importance in power system and this should work very efficiently for good results. Hotspot temperature plays a vital role in transformer's life expectancy. Temperature rise in a power transformer due to non linear load current is known to be most important factor in causing rapid degradation of its insulation. Core is one of the parts of transformer where hotspot temperature is effective. Therefore design of transformer should be considered. A non linear load in power systems has reduces transformers life due to additional losses, which is due to harmonics. In this paper, a design of transformer core and parameters of hotspot and top oil with and without harmonics and its life expectancy is discussed. In order to calculate accurate losses, initially flux density is calculated by Finite Element Method (FEM) in ANSYS software and next the hotspot and top oil temperature are calculated by a thermal model of transformer using MATLAB software. According to the ambient temperature and variation of daily load cycle, loss life, efficiency and core design is discussed. This model is applied on ***400KVA, 20KV, ONAF*** *transformer.*

Keywords: transformer, design, flux density, losses, top oil and hotspot, Finite element method

1. Nomenclature

T_{amb} –Ambient temperature.
I_h- Harmonic current
I_R- Rated current
T_{oil} -Top oil temperature.
H -Hot spot factor.
I-Load current.
P_{NL}-No load losses
P_{LL}-Load losses
P_{LL-R}-Rated load losses
P_{EC}-Eddy current losses.
P_{EC-R}-Rated eddy current losses.
P_{OSL}- Stray losses.
P_{LL-H}-losses due to harmonics
T_{oil}-Rated-top oil temperature rise over ambient temperature.
δ-Current density
T_{hs}- Rated-hot spot temperature rise over top oil temperature.
K-Factor depends on type of transformer
B_m-Magnetic flux density.
A_i-Cross sectional area of the core
d -Diameter of core.
K_i-Factor that shows steps of core.
$Q_{3\text{-phase}}$ -KVA per phase
Δ_t-change in temperature
K_w-Window spacing vector.
A_w-Window area.
L-Height of window.
D-Center to center distance of the core.
W-Overall length of yoke.
B-Width of window.
F_{AA}= Aging factor
A = y-Intercept
B = Slope
T= Hot-spot temperature in degrees Kelvin

2. Introduction

Power transformers are the main components and plays crucial role in the power systems. The efficiency of transformer depends on its losses and the core dimensions. Increase in the transformer power losses and hence temperature rises are the primary concern of the impact of harmonics [1]. If this device is damaged it effects the network. Therefore transformer core should be designed in such a way that losses, weight and temperature should be maintained. Loss is the main factor in increasing the top oil temperature and hot spot temperature that leads to rapid thermal degradation[2]. Ideally, the best method is to directly measure the winding hot spot temperature through a sensor [3]. However this may not be practical for existing transformers for some reasons. There are several models for predicting the hot spot temperature. In this paper at the first the calculation of core dimensions is given, then verifying the flux density using ANSYS software, with this accurate losses are obtained. Then by analyzing the total loss, the hot spot and top oil temperature at daily load and ambient temperature cycle will be predicted. Finally aging factor, efficiency, thermal life expectancy are mentioned with and without harmonics.

3. Impact of harmonics

Current harmonics have most significance in power systems. Additional losses will occur due to harmonic current components in the windings and other structural parts. Transformers losses(P_T) are divided in to no load losses (P_{NL}) and load losses (P_{LL}). No load losses are due to the voltage excitation of the core and load losses will occur in winding of the transformer and it is expressed as:

$$P_{LL}= I^2R + P_{EC} + P_{OSL}$$

The total stray losses are determined by subtracting I^2R from the load losses measured during the impedance test and there is no test method to distinguish the winding eddy losses from the stray losses that occur in structural parts[4]. Conventionally, the winding eddy current losses generated by the electromagnetic flux are assumed to vary with the square of the rms current and the square of the frequency (harmonic order *h*) as

$$P_{EC}=P_{EC\text{-}R}= \sum_{h=1}^{h=max} h^2(I_h/I_R)^2$$

The flux magnitude is proportional to the voltage harmonic and inversely proportional to the harmonic order h. the harmonic distortion of the system voltage usually 5% in power systems[5][6]. Therefore neglecting the effect of voltage harmonics and considering P_{NL} by fundamental components only.

4. Selection of core design constants

Much of the transformer core design depends upon proper selection of design constants, flux density B_m, current density δ and window space vector K_w and determining factors A_i, Aw. Therefore, it is worthwhile to select the above parameters in a proper way. Based upon the given specification, main dimension of the frame can be determined. In order to design of core, we should consider following phases.

Phase 1: calculation of e.m.f. per turn

The output in KVA of a transformer can be simply related to e.m.f. per turn as below

$$E_t = K\sqrt{KVA/phase}$$

Phase 2: calculation of net cross sectional area

$$A_i=E_t/4.44fB_m$$

Any number of designs can satisfy the above equation. The flux is roughly a measure of the cross section of the iron core, and (NI) gives the cross section of the winding. The problem before a designer is to relate dimensions and the material in such a way so as to obtain the desired output and performance at the lowest cost.

Phase 3: calculation of core diameter

$$d^2=A_i/K_i$$

The value of K_i shows numbers of the steps of core.

Phase 4: calculation of main cross section window

Each limb wound with both primary and secondary windings of respective phases. i.e.; copper area in each window is :

$$A_{W=}\ Q_{3\emptyset}/ 3.33\, f\, B_m\, \delta\, K_w A_i$$

Phase 5: calculation of overall length of the yoke

$$A_w = L\,(D – d)$$

$$b_w = D – d$$

$$W = 2\,D + 0.9\,d$$

The height of the window can be assumed varying from 2.0 to 4.0 times the width of the window as

$$2.0 \le m = \frac{L}{D\text{-}d} \le 4.0$$

This method is used to determine the core dimensions. by using the proposed method The results of calculation are summarized in table I.

Ratio, m	L (cm)	b_w (cm)	W (cm)
2.7	71.6	26.5	105.9
3.0	75.5	25.1	103.2
3.2	77.99	24.37	96.50
4.0	87.20	21.80	96.5
4.2	89.35	21.27	95.45
4.5	92.42	21.5	94.01

Tabel:1 dimensions of core design

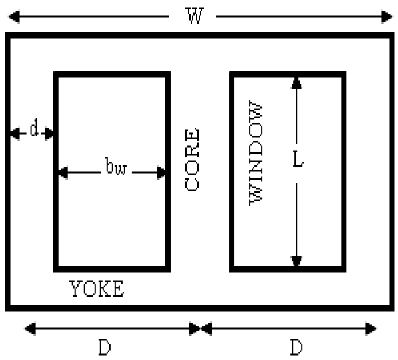


Fig:1 3-phase core transformer

5. Fem analysis in ANSYS software

Calculation of the magnetic flux density using core dimensions and current density as inputs by **FEM** (finite element method model) in **ANSYS software** **[9]** The two dimensional FEM is used to estimate the transformer losses. Using the local flux density obtained from FEM the hysteresis losses and the eddy current losses due to the axial and radial magnetic flux density is calculated for each disc. The finite element method is to subdivide the region to be studied into small sub-regions called finite elements.

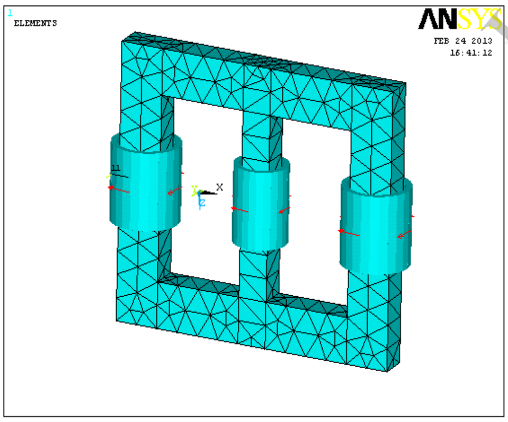


Fig: 2 FEM model of transformer

Fig:2 show the transformer fem model that is meshed using ansys software which divides the transformer's components. The flux density and losses in the windings and core surfaces are shown in below fig:3

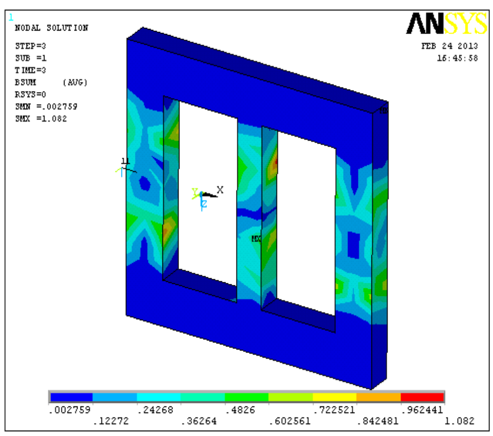


Fig: 3 transformer field solution

6. Top oil and hot spot temperature thermal model

Equations used for estimating the top oil temperature and hot spot temperature are given in below. Same equation can be used for case with and case without harmonics by varying $P_{LL\text{-}H}$ in each case as follows.

$$\text{Top oil temperature(k)} = \frac{\left[\begin{array}{l} T_{amb}\ \Delta t + \left[\dfrac{P_{LL\text{-}H} + P_{NL}}{P_{LL\text{-}R} + P_{NL}}\right]. \\ \theta_{fl}.\Delta t + \left(\dfrac{P_{LL\text{-}R}}{P_{NL}}\right).\text{Top oil temperature(k-1)} \end{array}\right]}{\left(\dfrac{P_{LL\text{-}R}}{P_{NL}}\right) + \Delta t}$$

$$\text{Hot spot temperature(k)} = \frac{\left[\begin{array}{l} \text{Top oil temperature (k)} * \Delta t + \left[\dfrac{P_{LL\text{-}H} + P_{NL}}{P_{LL\text{-}R} + P_{NL}}\right]. \\ \theta_{fl}.\Delta t + \left(\dfrac{P_{LL\text{-}R}}{P_{NL}}\right).\text{Hot spot temperature(k-1)} \end{array}\right]}{\left(\dfrac{P_{LL\text{-}R}}{P_{NL}}\right) + \Delta t}$$

Formula for increased load losses without harmonic

$$P_{LL-H=}\ P.\sum\left(\frac{I_h}{I_R}\right)^2$$

Formula for increased load losses with harmonics

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

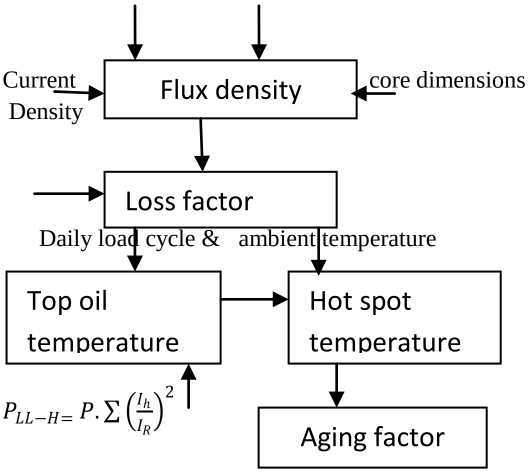


Fig:4 model for thermal life expectancy of transformer

The thermal equations are modeled using Simulink/Matlab the required input parameters for the models are as shown in Table 2. At each step the top oil temperature equation is solved by inputting the variable daily load data and the ambient temperature with the known parameters. The calculated top oil temperature is the input for the hot spot model as shown equation.

Hot spot factor	**1.3**
Top oil time constant	**160**
Hot spot time constant	**6**
I^2R winding losses	**123900**
No load losses	**111**
Other stray losses	**11000**
Temperature base for losses	**75**
Top oil rise over ambient	**50.6**
Transformer KVA	**400**
Winding eddy current losses	**11400**
Cooling mode	**ONAF**
Average oil to average winding	**19.7**
Rated pu P_{EC} at hot spot location	**0.52**

Table: 2 transformer model input parameters

7. Ambient temperature and its influence on loading

Ambient temperature is an important factor in determining the load capability of a transformer since the temperature rises for any load must be added to determine operating temperature. Temperature ratings are based on a 24 hours ambient of 30°C. This is ambient used in guide. Whenever the actual ambient can be measured, such ambients should be averaged over 24h and then used in determining the transformer's temperature and loading capability [11]. The ambient temperature seen by a transformer is the air in contact with its radiators or heat exchangers.

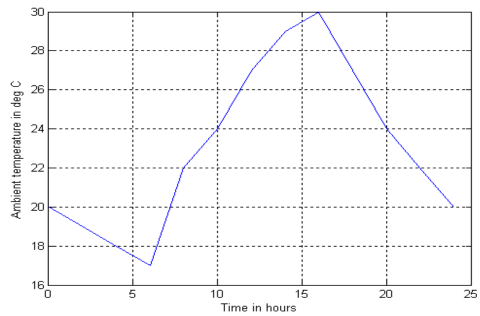
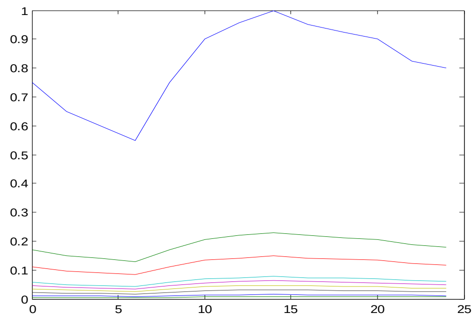


Fig:5 ambient temperatures

8. Method of calculation life expectancy

Assume that the data available for analysis is in the form of a typical daily load cycle showing load variation over a 24- hour period and harmonic distortion for 9 curves which is shown in below Fig. a curve showing the variation of ambient temperature for a period of 24 hours is shown in figure.



Time in hours vs. load current (PU)

Fig.6 Daily load cycle with THD 22% .

The Matlab program proceeds through a series of calculations to convert the power transformer characteristics to constants which are used in determining the transformer winding hot-spot temperatures For each of the input 2-hours of intervals is given to the daily load cycle[12]. Throughout the loading cycle, and translation of the temperature data into corresponding aging data by means of experimentally determined aging curves applicable to the Insulation. These hot-spot temperatures are then used by the program to calculate the per-cent loss of life.

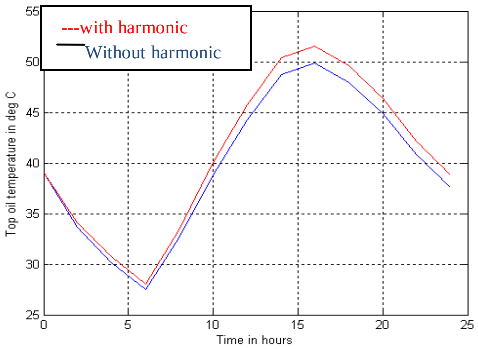


Fig:7 top oil temperature

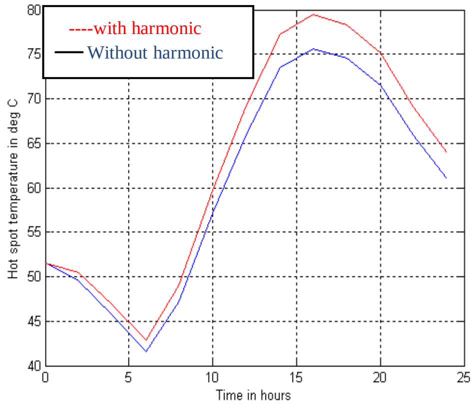


Fig:8 hot spot temperature

9. Aging factor

Aging factors for the transformer were obtained from the curve shown in Fig.9 Aging factor is defined as the rate of aging at any given temperature, relative to the rate of aging at some reference temperature. The aging factor curve . can be described by the familiar Arrhenius Equation:

$$\log_{10} F = A + \frac{B}{T}$$

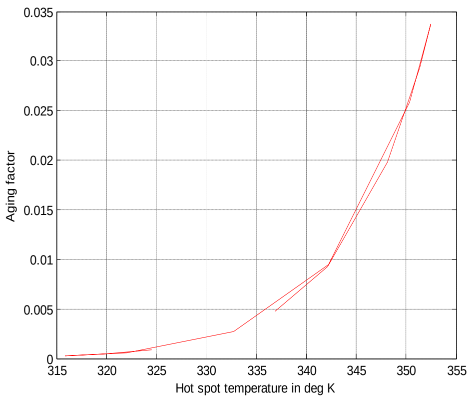


Fig: 9 aging factor

10. Transformer efficiency

A transformer loss is effective on Transformer efficiency. As core loss is the part of transformer losses, therefore core dimension can be effective on the efficiency. The efficiency is obtained as[13]:

$$\eta = 1 - \frac{(P_{NL} + P_{LL})}{S\ X\ \cos\theta}\ X\ 100$$

Where S and $\cos\Theta$ are apparent power and power factor respectively. The below fig 10 shows transformer efficiency.

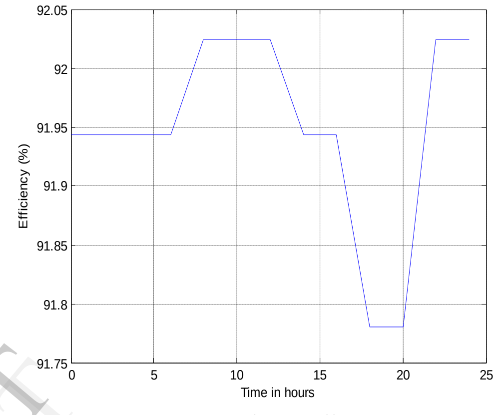


Fig: 10 transformer efficiency

11. Life estimation

The equations that relates the hot spot temperature and aging acceleration factors is given as [14].

$$\text{FAA} = e^{\frac{15000}{383} - \frac{15000}{\theta_h + 273}}$$

To estimate insulation heating effect, the loss of life factor is integrated over a given period of time. Where F_{AA} has a value greater than 1 for winding hottest-spot temperatures greater than the reference temperature 110^o C and less than 1 for temperatures below 110^o C.

Since insulation aging is a cumulative effect ,the percent loss of life per day is the summation of the percent loss of life.

Percentage loss of life=

$$\frac{0.0000285\ X\ aging\ factor\ X\ 100\%}{base\ life}$$

Where $$0.0000285 = \frac{1}{8{,}760\ X\ 4}$$

=years per quarter-hour

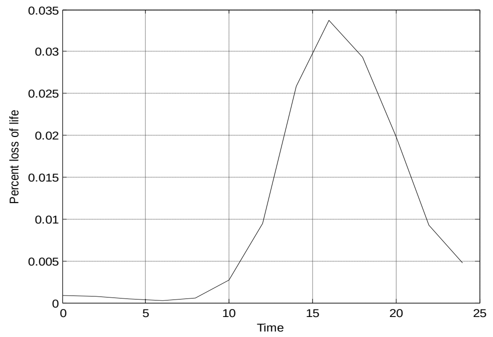


fig: 11 loss of life

Conclusion

Non linear loads injects harmonic currents into power system. Transformers subject to this harmonic currents exhibits additional load losses. Using ANSYS software by finite element method 2D approach the accurate losses are estimated. The novel thermal model has been established to calculate the winding hot spot temperature. The top oil temperature calculated from the top oil equation becomes the ambient temperature for hot spot equation model. To correctly estimate a transformer loss of life the real load and ambient temperature variations should be considered. To evaluate life estimation the aging factor is integrated over a given period of time. Insulation aging is cumulative effect so using this percentage loss of life is predicted from MATLAB.

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