Estimation of No-Load Losses in Distribution Transformer Design

Finite Element Analysis Techniques in transformer design

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***Abstract*—The core losses account for about 70% of the total transformer losses, which makes it a fundamental consideration when designing transformers. This paper presents the utilization of an efficient approach to determine the magnitude of no-load losses by applying Finite Element Analysis (FEA) software techniques. The AC magnetics simulation of the transformer core and winding was done in FEA software and the simulated no-load losses were compared with practical measurement result. It showed that the simulated result deviated by 10% decrease in no-load loss to that of the measurement. Hence, choosing the FEA techniques in transformer design can improve the no-load loss optimization.**

Keywords—Distribution Transformers, Finite Element Analysis, Eddy Current loss, Hysteresis loss, No-load loss

I. INTRODUCTION

No-load loss assessment in designing of distribution transformers is essential not to be neglected. According to Mihail et al [1];

> "The major contributor to the overall transmission and distribution systems losses is the distribution transformer. Its losses can span up to 50% of the overall systems' losses, while its core losses can rise up to 70% of the total transformer losses."

A more realistic firm estimation strategy to simplify the core loss through precise predetermination of the impact of different design parameters on its losses is crucial for transformer manufacturers. Slight eccentricity of the core loss estimate during the design juncture can lead to a financial consequence for the manufacturer [1,2].

Numerous analyses have been performed for the three- phase three-limb core loss optimization. For instance, Valkovic [3,4] investigated the effect of core geometry, core material, joint design and induction on core losses, mainly on three-phase three-limb cores transformers. Valkovic and Rezic [5,6] also analyzed the consequence of the step lap joint improper design on core losses.

Mairs et al [7], investigated the same scenario of transformer losses from over- voltages point of view.

Chen and Neudorfer [8], with an interest in transformer ferro-resonance, were motivated to develop a transient model for the five-limb transformer as a measure to analyze and mitigate such abnormal effects.

The work of teNyenhuis et al [9], proposed flux distribution and magnetic losses in the structure using 2-D FDM (finite difference method), nevertheless the proposed technique needs significant degrees of processing ability [10].

However, a larger percentage of losses of transmission and distribution networks are the continuous losses of transformers which exist in the no-load state. Such losses take place in iron/core part, (which comprise of hysteresis losses and eddy current losses in the core) which is constant regardless of the load[11,12].

Implementation of an improved core design technique has a greater effect in minimization of core losses, despite using superior core materials [11,13]. Hence it is of utmost significance for the transformer manufacturers to adopt a precise design technique that can give accurate dimensions of the core to determine the impact of the design parameters on the core losses [14].

In this paper an effective method is used to predict the magnitude of the no-load loss by applying Finite Element Analysis (FEA) software techniques. To calculate the losses at each element of the transformer core, an equation proposed for winding and magnetic losses are used [15,16]. The AC magnetics simulation of the anisotropic and the non-linear behaviour of the magnetic core material of the power transformer were done in FEA and the results were then compared with measurement results of operational distribution transformer of the same specifications.

II. METHODOLGY

A. Transformer Design Basics

Transformer design steps mostly begin with the selection of suitable core material. The selection criteria are based on the frequency of operation, size, and cost and efficiency spectrum. The cost effectiveness is a priority. Certain constraints may dominate depending on type of transformer and its application, while other parameters effects may be ignored to achieve the most desirable design.

According Mihail et al [1];

> "It is quite impracticable to optimize all parameters in a single design due to their interaction and interdependence. Nevertheless, reduction in weight and volume may still be possible by selecting a more efficient core material, but, at the consequence of increased cost. Thus, judicious trade-offs must be affected to achieve the design goals."

i. *Flux Density Constraint*

The flux (Φ) as being represented by the number of field lines (in fig. 4.) is sometimes called lines of magnetic flux. The closer together the lines of flux, the stronger the field, that is, the strength of the field represented by the density of the lines of flux, called the magnetic field strength (B) or the magnetic flux density. In order words, the concentration of the flux per unit area of the core (A_c) is the magnetic flux density given as;

$$B = \frac{\phi}{A_c} \tag{1}$$

Flux density $\boldsymbol{B}(t)$ is related to the applied winding voltage according to Faraday's Law. From Faraday's law, the peak value of the ac component of flux density is;

$$B_{pk} = \frac{V_{rms}.10^8}{4.44 fNA_c} \quad (2)$$

where,

B_{pk} = Peak AC flux density (gauss)
V_{rms} = RMS AC Voltage (volts)
A_c = Cross-sectional area of the core (cm^2)
N = Number of turns (t)
f = Operating frequency (Hz)

The factor of 10^8 is due to the B_{pk} conversion from tesla to gauss (1 tesla = 10 gauss) and the cross-sectional area (A) conversion from m^2 to cm^2 ($m^2 = 10^4$ cm^2). The change in constant from 4 to 4.44 is due to the form factor of a sine-wave. Since the form factor is equal to the rms value divided by the average value for a half-cycle, the form factor for a sine-wave is 1.11 ($\pi/(2\sqrt{2})$. Under this condition, the core experiences a total peak-to-peak AC flux density swing (ΔB) that is twice the value of peak AC flux density (B_{pk}) calculated with the above formulas.

Increase the peak value of the ac component of flux density (**B_{pk}**) of the component of **B**(t), causes core loss to increase swiftly [21]. It then implies that the core dimension should be well designed in such a way as to make sure that **B_{pk}** is as low as required.

ii. *Winding properties and copper loss constraint*

The next important aspect of the design consideration is the copper loss, which depends on the electrical properties of the winding and the window area, which should be allocated between windings in an optimum manner [17].

The regulation and power rating of a transformer is related to its core geometry, K_g. The area product, A_p, of a core is the product of the available window area, W_a, of the core in square centimeters, (cm^2), multiplied by the effective, cross- sectional area, A_c, in square centimeters, (cm^2), which may be stated as [17,21];

$$A_p = W_a A_c \quad (3)$$

The current density of conductors is related to core area product, A_p, by an equation which may be stated as [21];

$$J = \frac{P_t.10^4}{4.44 K_u B_{pk} A_p f} \quad (4)$$

From (4), factors, such as peak value ac flux density, (B_{pk}), frequency of operation, (f), area product, A_p, and window utilization factor, K_u, define the current density of the copper conductors, which increases with increase in choice of the power rating, (P_t) of the transformer.

iii. *Core loss Constraint*

The magnetizing current needed to energize the core of the transformer causes core losses. It is independent of the transformer load [12]. They can be categorized into five components [17]; hysteresis losses in the core laminations, eddy current losses in the core laminations, I^2R losses due to no-load current, stray eddy current losses in core clamps, bolts and other core components, and dielectric losses. Hysteresis losses and eddy current losses contribute up to 98% of the no- load losses, while stray eddy current, dielectric losses and I^2R losses due to no-load current are small and successively often neglected.

iv. *Hysteresis loss*

Hysteresis loss contributes more to no-load losses. It comes from the molecules in the core laminations resistance, being magnetized and demagnetized by the alternating magnetic field. This resistance by the molecules causes friction that result in heat. The Greek word, hysteresis, means, "to lag" and refers to the fact that the magnetic flux lags behind the magnetic force. Choice of size and type of core material reduces hysteresis loss [17]. Hysteresis as the major contributor of no-load losses depends on the transformer frequency of operation, the type of core material and maximum flux density as described in (5) [18];

$$P_{hys} = K_h f B_{pk}^{1.6} \quad (5)$$

where P_{hys} is the hysteresis loss and K_h is the hysteresis constant.

Typically, this accounts for 50% of the constant core losses for CRGO (cold rolled grain oriented) sheet steel with normal design practice [17].

v. *Eddy current loss*

Eddy current losses occur whenever the core material is electrically conductive. Eddy current loss is inversely proportional to the square of the number of laminations. Iron losses should be between about one and eight watts per kilogram at 50 Hz and 1.5 T for good transformer steel. Thinner lamination of the core steel reduces eddy current losses [19].

Eddy current losses are given with following equation [18,19]:

$$P_{ed} = K_{ed} B_{pk}^2 f^2 d^2 \quad (6)$$

where;

K_{ed} = the eddy current constant
f = frequency (Hz)
B_{pk} = maximum flux density (T)
d = thickness of lamination strips (mm)

For reducing eddy current losses, higher resistivity core material and thinner (typical thickness laminations of 0.35 mm) lamination of core are used [1, 18].

B. The Finite Element Analysis Technique

According to Mohammad et al [17], FEA is a classical tool commonly used by engineers, scientists and researchers to resolve engineering problems arising from various physical fields such as AC Magnetics, transient, electromagnetic, thermal, structural, fluid flow, acoustic and others. Presently the FEA is absolutely the dominant numerical analysis method for simulation of physical field distributions, without being paralleled by any other numerical method.

In essence, FEA finds the solution to any engineering problem that can be described by a finite set of spatial partial derivative equations with appropriate boundary and initial conditions. It is used to solve problems for an exceedingly wide diversity of static, steady state and transient engineering applications in different scientific areas such as automotive, aerospace, nuclear and biomedical etc. [17,19].

vi. *AC magnetics simulation*

FEA in AC magnetic problems' formulations uses complex values that represent the real world quantities sinusoidally changing with time [21, 22]. The integral values appear as quadratic values pulsing around its mean value with double frequency. The mean square flux density, which has the characteristics of quadratic value, is given as [19];

$$B_a^2 = \frac{1}{V}\int_v B^2.dv \tag{7}$$

The coefficient (1/V) represents the reciprocal of the volume of the core. The complex vector of the magnetic flux density B = curl A. and A is the complex amplitude of vector magnetic potential. For x-y symmetry, where the third dimension is considered infinite in extent, the vector potential $A_z(x,y)$ only has a z-component and is described by [19];

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_y}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu_x}\frac{\partial A_z}{\partial y}\right)=-j+\left(\frac{\partial H_{cy}}{\partial x}-\frac{\partial H_{cx}}{\partial y}\right) \tag{8}$$

H_{cx} and H_{cy} are the x- and y-components of the coercive force vector $\boldsymbol{H_c}$, being the corresponding magnetization surface current on the boundary describing a region of continuous magnetization. The flux density mechanism can be obtained from [19];

$$B_x = \frac{\partial A_z}{\partial y}; B_x = -\frac{\partial A_z}{\partial x} \tag{9}$$

vii. *The solution steps of FEA*

The basic steps in setting up, solving and analyzing problem results in FEA software include specifying the problem type, designing the geometrical model and assigning material properties and boundary conditions. Finally, the problem is solved and the results are analyzed [23].

Electromagnetic field problems are solved in FEA by applying Maxwell's equations in a finite region of space with suitable boundary conditions and/or user-specified initial conditions in order to obtain a solution with definite exceptionality. The four Maxwell equations are given as [24];

$$\oint_c E.dl = -\frac{d}{dt}\iint_s B.dS \quad \text{(Faraday's law)} \tag{10}$$

$$\oint_c H.dl = \frac{d}{dt}\iint_s D.dS + \iint_s J.dS \quad \text{(Maxwell – Ampere's law)} \tag{11}$$

$$\oiint_s D.dS = \iiint_v \ell^{dv} \quad \text{(Gauss's law)} \tag{12}$$

$$\oiint_s B.dS = 0 \quad \text{(Gauss's law – magnetic)} \tag{13}$$

E = electric field intensity (volts/meter)
D = electric flux density (coulombs/meter^2)
H = magnetic field intensity (amperes/meter)
B = magnetic flux density (webers/meter^2)
J = electric current density (amperes/meter^2)
ℓ = electric charge density (coulombs/meter^3).

According to Maxwell, [24];

> "Equations (10)-(13) are the fundamental equations guiding the actions of electromagnetic fields. They are applicable in all circumstances despite of the medium and the shape of the integration volume, surface, and contour."

The geometry of the problem is discretized automatically into tetrahedral elements to obtain the set of algebraic equations to be solved. The model parameter dimensions are meshed by mesh operation. The assemblage of all tetrahedral is known as the finite element mesh of the model or simply the mesh. The unknown characteristics for the field being calculated are represented as polynomial of second order in each tetrahedron. Thus, in regions with rapid spatial field variation, the mesh density has to be increased for high precision [17, 21].

C. Total No-Load loss Determination by FEA

The overall no-load losses (P_{NL}) from FEA approach is given by [20,22];

$$P_{NL} = P_w + P_{core} \tag{14}$$

The winding losses (P_w) at no-load is normally neglected due to its infinitesimal value when compared to hysteresis and eddy current losses as shown in table 1. This is why a no-load is often referred to as core losses. The winding (electric) losses density is given as [20];

$$P_w = J^2/\sigma \equiv I^2R \tag{15}$$

Where σ is the electrical conductivity and J *is* the current density. The magnetic core losses (P_{core}), which comprises majorly, the hysteresis and eddy current losses are given by [22,23];

$$P_{core} = P_{hys} + P_{ed} \tag{16}$$

The hysteresis loss (P_{hys}) and eddy current loss (P_{ed}) are calculated together as overall magnetic core losses from FEA software as seen in table 2. For the core (magnetic) losses density of the transformer, the equation for the magnetic power loss (P_{core}) is given by [23];

$$P_{core} = C_m(f/50)^{\alpha}(\Delta B)^{\beta}\rho \tag{17}$$

In FEA approach, the average value of the mean square flux density (B_a^2) is related to the peak value of the ac component of flux density (Δ**B)** by the equation;

$$(\Delta B)^{\beta} = \left(\frac{B_a}{1.5}\right)^2 \tag{18}$$

Standard value of β for the chosen core material is 2. C_m represents the material properties of the core, f is the rated frequency and ρ is the resistivity of copper wire in **Ω**-cm.

According to Erickson [21];

> "About 0.5% of the total output power should be the permissible transformer total power loss."

III. THE TRANSFORMER SPECIFICATION

The transformer under study is a three phase (three-leg core type, oil immersed) medium distribution transformer with vector group of Dyn11. The rated data of the transformer are: S_n = 500 kVA; HV/LV = 11/0.42 kV; I_1/I_2= 26.24/687.32 A; %impedance = 4.5. f_n = 50 Hz. The dimensions of the transformer are: Length = 1140 mm; width = 880 mm; height = 1450 mm. The oil weight and the total weight are 320 kg and 1690 kg respectively. The measured no-load loss is 710 W.

IV. RESULTS AND DISCUSSION

The procedure adopted is after completion of pre-processor stage and transformer discretization in FEA, the model is ready for processing. AC-Magnetics simulation was done on the transformer at no-load to assure the transformer rating and the magnetic power losses. Fig. 1, shows the momentary flux lines interactions between the windings and core in AC- Magnetics simulation. Fig.

3, shows the pure sinusoid result of transient simulation of the model in 0.04 s.

The electrical losses at no-load is quite insignificant to be ignored but the per-phase and the overall results are shown in table I. The A, B and C characters represent the transformer phases while the subscript p and s are the primary and secondary windings respectively. It can be seen (from table I), that the values of the currents in secondary sides are almost zero due to no-load at the secondary terminals.

The utilization of the $\left(B_a^2\right)$ value for the determination of core losses is crucial since it is the only variable parameter in table II. The core design in FEA software was targeted to yield the desired value of $\left(B_a^2\right)$ for appropriate magnetic power loss result.

The summary of the no-load losses in the transformer after calculation of distributions of magnetic flux density and volumetric density of core losses in the process are also shown in Table III, together with the measured losses. It is therefore seen that the core is the major contributor of losses in a transformer at no-load.

V. SUMMARY AND CONCLUSION

The Necessity of a calculation tool to accurately determine the impact of design parameters on the core loss optimization seems inevitable for transformer manufacturers. In this paper an effective method is proposed to predict the magnitude of the no-load loss densities by applying Finite Element Analysis (FEA) software techniques. The anisotropic and the non- linear behaviour of the magnetic core material of the power transformer are simulated in AC magnetic mode of FEA and the results are then compared with measurement results of operational distribution transformer of the same specification. The electrical losses at no-load is seen to be insignificant to be ignored. It is therefore seen that the core is the major contributor of losses in a transformer at no-load.

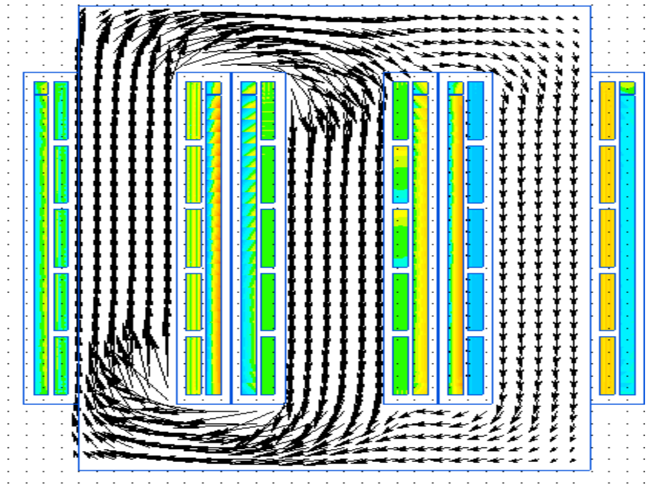

Fig. 1. The momentary flux lines interactions between the windings and core in AC-Magnetics simulation.

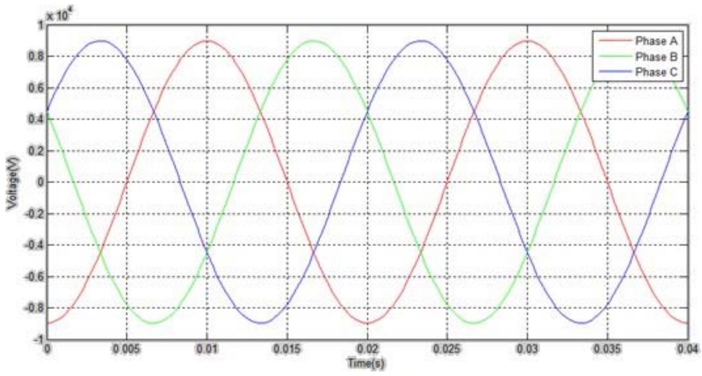

Fig. 2. Pure Sinusoidal output wave form of the transformer

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TABLE I. DETERMINATION OF THE NO-LOAD WINDING LOSSES

Windings	Conductivity (g [S/m])	Area of Conductors (S [mm²])	No-Load Currents (I [A])	No-Load Current Density (J [A/mm²])	No-Load Electrical Losses (P_e [W])
A_p	5.60x10^7	25	0.21	0.0086	1.31
B_p	5.60x10^7	25	0.18	0.0072	0.93
C_p	5.60x10^7	25	0.18	0.0074	0.98
A_s	5.60x10^7	658	2.12x10^{-4}	3.22x10^{-7}	1.85x10^{-9}
B_s	5.60x10^7	658	2.12x10^{-4}	3.22x10^{-7}	1.86x10^{-9}
C_s	5.60x10^7	658	2.12x10^{-4}	3.22x10^{-7}	1.85x10^{-9}
Total Electrical Losses (P_e)					**3.21**

TABLE II. DETERMINATION OF THE (CORE) MAGNETIC LOSSES

Core (Hysteresis and eddy current losses)	Mass density of core material (ρ [kg/m^3])	Material properties of the core (C_m [W/kg])	The power frequency (f [Hz])	Mean square flux density average (B^2 [T^2])	Magnetic Power loss (P_m [W])
	7850	1.5	50	0.12117	**634.12**

TABLE III. SIMULATED NO-LOAD VALUE VERSUS MEASUREMNT

Transformer rating (kVA)	Simulation	Measurement	Relative deviation	Deviation (%)
	560	500	+60	12
No-load losses (W)	637.33	710.00	-72.67	10.23

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