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# 3D Finite Element Analysis for Core Losses in Transformer

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## ABSTRACT
The phenomenal growth of power systems has put burden on the transformer industry to supply consistent and cost-effective transformers. Any failure of a transformer or its component will impair the system performance and social setup. The reliability of a transformer is a major concern to users and manufacturers for ensuring a trouble-free performance during service. Magnetic circuit is considered as the most active component of the transformer. It consists of iron core and carries flux associated to the windings. It is important to understand the connection between iron core and leakage flux to get a better design of Transformer. Some of the limitation of using transformer is expenditure by some losses in core. By solving this difficulty it can save more energy. This paper presents a numerical technique for calculating the core losses and its reduction.

## Keywords
Finite Element Method, Transformer, Core Losses.

## 1. INTRODUCTION
A transformer is a multifaceted three dimensional electromagnetic device, which is used extensively in electric power systems to transfer power by electromagnetic induction between the circuits at the same frequency but with different values of voltage and current. Transformers involve transfer of power between circuits through the use of electromagnetic induction. Although transformer is a static most efficient device of the power system but still there are problems associated with the transformers which affects its performance.

Majorly transformer has two types of losses associated with it due to electric current flowing in the windings and the alternating magnetic field in the magnetic core. The losses related with the windings are called the load losses, while the losses related to the core are called no-load losses or core losses [1]. **Load losses** vary according to the load on the transformer. These losses include heat losses and eddy currents in the primary and secondary windings of the transformer. Heat losses or $I^2R$ losses, in the windings share a major part of the load losses. These losses can be minimized using a material with low resistance per cross-sectional area. It is found that copper is the best suitable conductor material when designing transformer considering its parameters like size, weight, cost and resistance. Engineers can also decrease the resistance of the conductor by increasing the cross-sectional area of the conductor. But it increases the cost of the transformer. **No-load losses** are initiated by the magnetizing current required to energize the core of the transformer. These losses are independent of the load on the transformer. They are also called constant losses. Hysteresis losses and eddy current losses contribute about 99% of the no-load losses, whereas stray losses, dielectric losses and $I^2R$ losses are often neglected due to small amount of no-load current [2].

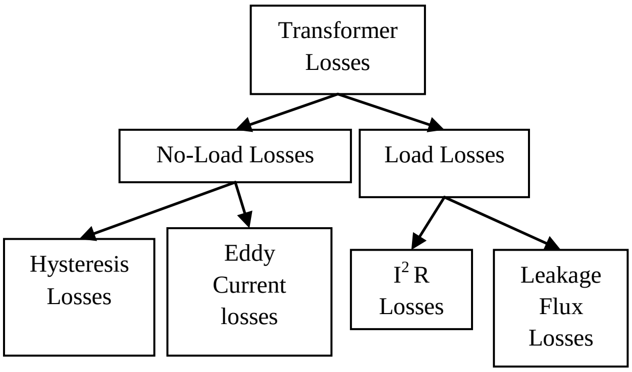



**Fig. 1: Classification of Transformer Losses**

## 2. RECENT TRENDS IN REDUCTION OF TRANSFORMER CORE LOSSES
There has been a secure development of core steel material in the last century from non oriented steels to grain-oriented steels. The reduction in transformer core losses in the last few decades is related to a significant increase in energy costs. One of the best ways to reduce the core losses is to use thinner grades of core steels. But the price of the thinner grades is comparatively higher. Despite these disadvantages, core materials with still lower thicknesses will be available and used in the future.

The new material is amorphous magnetic alloys which is about 30% of cold rolled grain oriented (CRGO) steel materials, because of their high resistivity-and low thickness. The flux distribution in amorphous materials is more uniform in then as compared to the CRGO materials. The assembly of core is an automatic process, due to which the amorphous core transformers are considered as cost-effective with improved performance [3].

## 3. CORE LOSS EVALUATION METHOD
Core loss evaluation is a multi-disciplinary problem, requiring information on Electrical Engineering, Material Engineering and Physics. Several analytical and numerical techniques are used for the computation of electrostatic and magneto static fields in the transformers. Analytical techniques include double-Fourier method, method of images, separation of variables, etc. But due to geometric and material complexities, numerical methods are used for the solution of electrostatic, electromagnetic, structural, thermal problems [4].

In order to improve the performance of transformer design, researchers worked on the characteristic, types and performance of magnetic core materials to reduce core losses [5]. G.W. Swift studied the variables which affect the performance of magnetic cores with respect to core loss and exciting current and investigated the effect of frequency and the effect of series air gaps at the corners [6]. Z. Valkovic compared the characteristics of different cores and determined the building factor to study the influence of corner joint overlap length, the quantity of laminations per stagger level, and the yoke cross-section form [7]. Loffler et al. showed the improvements of multistep-lap (MSL) jointed cores in comparison to single-step-lap (SSL) jointed cores to reduce power losses and concluded that power losses reduces with more homogeneous flux distribution [8].

Girgis et al. carried out an analytical study to determine the magnitude of core production attributes [9]. Albach et al. presented a practical method to predict the core losses in magnetic components for an arbitrary shape of the magnetizing current [10]. Dolinar et al. determined the magnetically nonlinear iron core model of a three phase three limb transformer and compared it with the classical saturated iron core model [11]. Stranges and Findlay described an apparatus that determined the iron losses due to rotational flux [12]. Researchers carried out the experimental study on various samples of iron core to test the different stacking patterns of grain oriented silicon steel laminations and reduced the iron core losses of power transformers [13-15].

A modern method of analysis of transformer performance is Finite element analysis (FEA). It is one of several numerical methods that can be used to solve complex geometries and is the considered as the best method used today. FEA consist five methods that are:

1. Finite Difference Method (FDM)

2. Moments Method (MM)

3. Monte Carlo Method (MCM)

4. Boundary Element Method (BEM)

5. Finite Element Method (FEM)

FEM is a mathematical method for solving ordinary and elliptic partial differential equation. It can use to calculate object with linear or nonlinear. FEM is useful to obtain an accurate characterization of electromagnetic behavior or magnetic components such as transformers [16].

These days, finite element method (FEM) is a very effective numerical tool for the simulation of structural components, material optimization, reliability enhancement, failure analysis, corrective action and verification of new designs under various loading conditions of transformer [17, 18].

## 3.1 Finite Element Method Analysis Of Transformer

Finite element methods used for solving transformer problems includes three stages. At first stage the problem space is meshed into contiguous elements of suitable geometry and appropriate values of the material parameters-conductivity, permeability and permittivity to each element are assigned. In the second stage, the model is excited, so that the initial conditions are set up. Finally, the boundary conditions for the problem are specified. The finite element method has the advantage of geometrical flexibility. It is likely to comprise a greater density of elements in regions where fields and geometry are rapidly [16].

The finite element method is a numerical method of analysis for the explanation of problems described by partial differential equations. The considered field is represented by a group of finite elements. The space discretization is realized by triangles or tetrahedron depending on the problem is 2D or 3D respectively. Therefore, a constant physical problem is transformed into a discrete problem of finite elements. The solution of such a problem reduces into a set of algebraic equations. Therefore, the solution of the 2D or 3D magneto static problem describing the transformer field reduces into the estimation of the magnetic field density at each node of the triangles or tetrahedral of its 2D or 3D mesh, respectively [19].

## 3.2 3D FINITE ELEMENT METHOD BASED MODEL OF TRANSFORMER CORE

In the 2D FEM analysis, the magnetic field calculation is conducted with the use of the magnetic vector potential A. However, in the case of 3D problems, the use of the vector potential results to great complication, due to the great number of unknowns parameters. Therefore, the use of magnetic scalar potential $\Phi_m$ is preferred in the case of 3D magneto static problem solution. In most of the developed scalar potential formulations this calculation of $\Phi_m$ is realized with the help of the following equation:

$$H = Hs - \nabla \Phi_m \qquad (1)$$

Figure 2 shows the outlook view of the 3D FEM model of the transformer active part, comprising the iron core, high and low voltage windings of single phase.

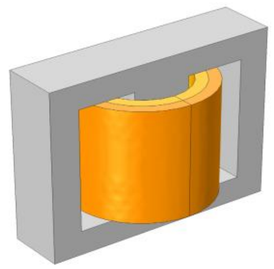


**Fig. 2: 3D FEM Model of Transformer Core**

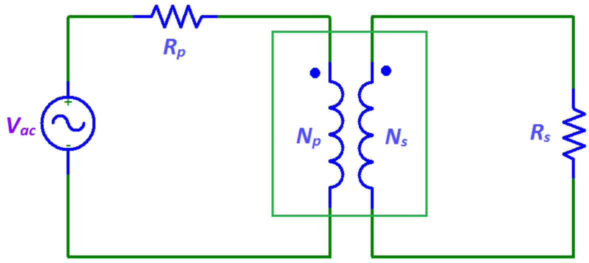
In transformer analysis, because of ferromagnetic materials properties usually the problems appear in nonlinear system. Magnetic permeability u=B/H is not persistent and is a function of magnetic field in each mesh.

The ampere law states that:

$$\nabla \times H = J \qquad (2)$$

H: Magnetic field intensity

J: Total current density




It is a role of magnetic field in each mesh. The B-H curve of ferromagnetic core as shown in Figure 3 is a hysteresis loop.

The hysteresis loop can be used for calculation of short circuit reactance or radial and axial electromagnetic force on the transformer coils but for calculation of flux distribution and losses in transformer core, the B-H loop is used. Nominal voltage of primary winding, the value of B and H can be considered from the following equation:

$E(t) = V(t) - Ri_o = N\, d\text{Ø}/dt$ (3)

And $H = Ni/L$ (4)

$i_o$: no load current

V (t): Terminal voltage in no load circumstance

E (t): EMF

Ø: Flux

R: Resistance of winding

N: Number of turn

L: Mean length

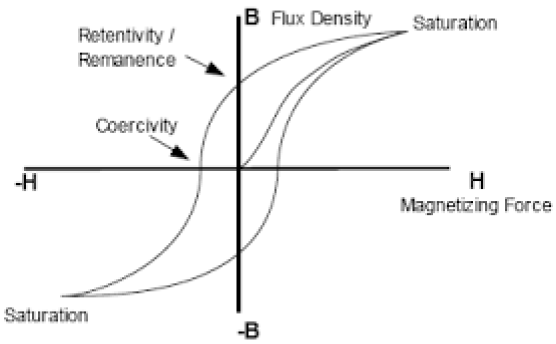



**Fig. 3: B-H Curve (Hysteresis Loop)**

In 3D analysis of transformer we use third order equation, by which permeability of each part can be calculated as a function of B. Core attributes can be predicted by using the third order equation model. 3D model of FEM shows that we can estimate core losses of a transformer with high accuracy and can localized flux distribution in the core. Using 3D FEM model we can also find the hot spots inside the core. The accuracy of the results increased with the increase in number of meshes. The mesh generation of these models is as shown in Figure 4. These types of models show the transformer behavior at the design stage and required parameters can be considered before manufacturing them and thereby reducing the design time and cost [20].

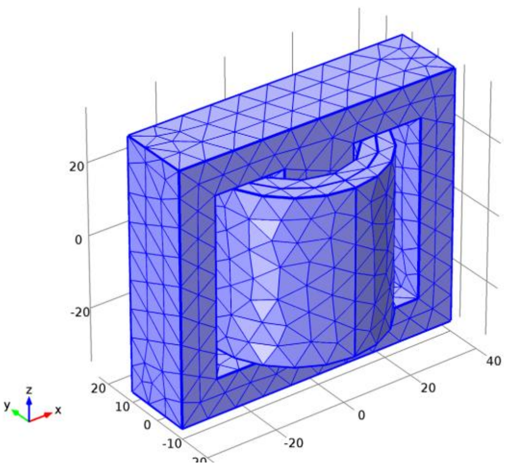


**Fig. 4: 3D FEM Mesh Analysis of Transformer Core**

## 4. CONCLUSION

The finite element method is a numerical technique for obtaining estimate solutions to boundary value problems. Especially it is an important tool to solve electromagnetic problems because of its ability to model geometrically and compositionally complex problems. With the use of advanced computational tools, more efficient, reliable and compact transformer can be designed with minimum core as well as other losses occurring in transforme\

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