Analysis of effect of core material on the performance of single phase transformer using FEM

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Abstract: The remarkable progress of power systems set liability on the transformer engineering to sources table and economical transformers. Transformer is a complex three dimensional structures built of numerous modules such as core, windings, isolation, chamber, and several other equipments. There are many transformers available with different type of magnetic materials for core. But the Amorphous Magnetic material changes the whole scenario of the market. In this paper E-Core Transformer Finite Element model is simulated using FEM based software for different magnetic materials for core to find the losses of the transformer with same dimensions and supply conditions. The comparative analysis was conducted for different electromagnetic characteristics such as magnetic flux density, current density, magnetic vector potential etc.

Keywords: Finite Element Method, E-Core Transformer, Core Materials, Losses of transformer

1. Introduction

A three dimensional static electromagnetic device, which transfers power among the circuits at the identical frequency by electromagnetic induction, is known as transformer, but it transfers power with varying values of voltage as well as current. Transformer is a complex three dimensional structures built of numerous modules such as core, windings, isolation, chamber, and several other equipment. Besides electric and magnetic fields, physical fields also exist in the transformers [1].

There are many analytical in addition to numerical techniques available for the calculation of electrostatic as well as magneto static fields in the transformers. Analytical techniques such as separation of variables, method of images, Fourier method etc. But numerical techniques are employed for the way out of electrostatic, magneto static, thermal, electromagnetic, physical problems. Currently, finite element method (FEM) is a considered as the most efficient numerical tool that can incorporate the simulation of physical components, analysis of failures, reliability improvement, optimization of core and windings materials, remedial actions and authentication of novel designs of transformers [2].

The magnetic circuit is the most significant dynamic portion of transformer design. It comprises of laminated iron core; the core carries flux that further associated to the windings. The flux linkage between the windings mainly affects the performance of a transformer. So a magnetic path with low reluctance, known as core, is engaged in the transformer in order to have the efficient linking of flux between the windings. Hysteresis and eddy current losses are the main difficulties with the transformer core. Material used for core mainly affects the hysteresis losses. Earlier grades of steel laminations were used but later on with the addition of 4-5% of silicon in the steel, reduced the eddy current and hysteresis losses effectively and hence the performance and efficiency of the transformer
is improved [3,4].

Amorphous magnetic materials have been used in transformers for over 25 years. In the mid-1970s because of the need of energy efficiency improvement, the amorphous materials and their use was of great interest in electrical power distribution systems. But due to high initial cost of amorphous material based energy-efficient transformers, this trend took a reverse direction. Moreover, amorphous materials have lower saturated magnetic induction as compared to silicon steels, that results in increased cost of transformers with large size. However, this short coming can be overcome by keeping the maintenance costs lower for the energy-efficient transformers during their lifespan. These researches done in transformer core materials had a significant effect on global energy-savings struggles and on environmental concerns [5].

Three models of transformer proposed in this paper using different core materials and comparison was conducted for different electromagnetic characteristics using finite element method.

2. Methodology of Finite Element Method

Finite Element Method (FEM) is a numerical technique that helps in solving comparatively compound electromagnetic complications which includes the nonlinearities of materials and anisotropy in analyzed domain. The whole domain is discretized and analyzed in small triangular surfaces, that are known as finite elements. Maxwell’s equations are applied into Finite Elements to calculate the distribution of magnetic field in the electrical devices. Methodology of FEM is shared into three portions: 1. Pre-processing 2. Processing and 3. Post-processing portion. In pre-processing, the geometry of the object and its boundary conditions are well-defined. Materials with its properties are input in model of the object. The entire field such as cross-section of entity is spread into a definite digit of elements to evaluate magnetic vector potential \( A \). Maxwell’s equation needs to be solved for the execution of processing portion and output results of the obtained system. As per equation below, field density \( \mathbf{H} \) and flux density \( \mathbf{B} \) must follow:

\[
\nabla \times \mathbf{H} = \mathbf{J} \quad (1)
\]

\[
\nabla \times \mathbf{B} = 0 \quad (2)
\]

The relation between flux density and field intensity for specific material is given by equation:

\[
\mathbf{B} = \mu \mathbf{H} \quad (3)
\]

Methodology of FEM includes the finding of a field which fulfils equation (1)-(3) by magnetic vector potential. Whereas the relation between flux density \( \mathbf{B} \) and vector potential \( \mathbf{A} \) as given in equation (4):

\[
\mathbf{B} = \nabla \times \mathbf{A} \quad (4)
\]

Whereas

\[
\nabla \times \left[ \frac{\nabla \times \mathbf{A}}{\mu(B)} \right] = \mathbf{J} \quad (5)
\]
A three-phase transformer has no moving parts so it is a static electromechanical device. Balanced electromagnetic field is created by three phase primary windings that are coupled with secondary windings electromagnetically. Conductivity of material in secondary winding will be same as of the conductivity of primary because there are no rotary parts in its construction. Under no-load conditions, the primary winding is delivered with rated voltage while secondary winding is kept open so there is no current flowing. Under no-load the losses occur in the material may be due to following reasons:

i) The material tendency to maintain magnetism and to face any variation in it, which is usually termed as magnetic hysteresis

ii) The $I^2R$ heating that occurs in the material due to voltages and resultant circulatory currents induced because of the time variant flux.

3. Geometry of Model Description

Transformer is constructed on the principle of transferal of power among circuits through electromagnetic induction. A single-phase transformer that consists of a pair of E-cores is considered here and it is the core that transfers flux related to the windings. The flux linkage between the windings mainly affects the performance of a transformer. The primary and secondary coils in the transformer are positioned round the central limb of the core as shown in Figure 1.

![Figure 1: Overview of Transformer Model](image)

In this model, the primary and secondary windings, are wound with thin wire and modeled with features of multi-turn coil. The primary winding is attached to a resistance, $R_p$ and an input voltage source, $V_{ac}$, however, the secondary winding is attached to a load whose resistance is, $R_s$ as shown in Figure 2.

![Figure 2: Electrical Circuit of Transformer with Voltage Source and Resistors](image)
Specifications and Design parameters of the Transformer under Test

| Parameter                        | Value   |
|----------------------------------|---------|
| Supply Voltage (Vac)             | 25V     |
| Supply Frequency (f)             | 50Hz    |
| Primary Side Resistance (Rp)     | 100Ω    |
| Secondary Side Resistance (Rs)   | 10kΩ    |
| Primary Turns (Np)               | 300     |
| Secondary Turns (Np)             | 300     |

4. Simulation Setup description

In this paper three different types of magnetic core materials are examined. The goal of the simulation was to examine distributions of magnetic flux density, magnetic vector potential and current density in the transformer core. The analysis of single phase e-core transformer was done by changing the three different type core material named as Soft Iron (with losses), CRGO Silicon Steel and METGLAS alloy 2605SA1. Effect of material change is expressed in terms of magnetic flux density, magnetic vector potential and current density. In all the three models, the boundary conditions, the excitations and other related parameters are kept alike. The material of the core has been changed in order to acquire maximum efficiency in description with reduced losses. The parameters that are given to all the three models with different core materials are shown in following Table 1:

| Table 1: Parameters of different Core Materials: Soft Iron, CRGO Silicon Steel, METGLAS 2605SA1 |
|---------------------------------|---------------------------------|---------------------------------|
| Core Material                   | Soft Iron (with losses)         | CRGO Silicon Steel              | METGLAS 2605SA1                  |
| Electrical Conductivity (S/m)   | 1.12e7                          | 1.72117                         | 7.6                              |
| Relative permittivity           | 1                               | 1                               | 1                                |
| Curie Temperature (°C)          | 770                             | 750                             | 395                              |
| Saturation Flux Density (T)     | 1.6-2.2                         | 1.5-1.8                         | 1.56                             |
| Resistivity (Ω-m)               | 10x10^-8                        | 45x10^-8                        | 142x10^-8                       |
| Permeability (H/m)              | 1500x10^-7                      | 93x10^-7                        | 125x10^-7                       |

5. The Impact of Different Core Material on Magnetic Flux Density, Magnetic Vector Potential And Current Density

The most fundamental transformer equation is

\[
E = 4.44fNAB_{\text{max}}
\]

where

- \(E\) = Applied rms voltage [volts]
- \(B_{\text{max}}\) = the maximum flux density [Tesla]
- \(f\) = frequency [Hz]
- \(N\) = turns on the primary winding
- \(A\) = Magnetic circuit cross-sectional area [m²]
So therefore, 

\[ B_{\text{max}} = \frac{E}{4.44 f N A} \]

The maximum flux density \( B_{\text{max}} \) depends on the core material used. Finite Element Method is applied to calculate the magnetic flux distribution inside the transformer, with magnetic parameters and geometrical measurements of the transformer. Figure 3 shows the magnetic flux density distribution in the transformer core with amorphous material. In the simulation work, a comparative study has been conducted for flux density due to all the three types of core material, as shown in Figure 4.

![Figure 3: Magnetic Flux Density distribution in Amorphous Core Transformer](image)

Normally, transformer losses are of two types, no-load additionally load losses. No-load losses are further divided into hysteresis power losses, \( P_h \), and eddy current power losses, \( P_e \), at a constant frequency. Eddy current power losses of transformer are given as:

\[ P_e = \frac{\omega^2 \gamma_e \varepsilon^2 B_{\text{max}}^2 V_{\text{core}}}{24} \]

Where
- \( \gamma_e \) = electrical conductivity of magnetic sheets
- \( \varepsilon \) = thickness of the magnetic sheet (m)
- \( V_{\text{core}} \) = effective core volume (m³)
The thickness of the core sheets will be considered constant, within the analyzed power range, and

\[ P_E \propto B_{\text{max}}^2 l^3 \]

For the hysteresis losses on a magnetic circuit of a volume in which the magnetic flux density is everywhere uniform, the empirical Steinmetz expression will be considered:

\[ P_H = \frac{\omega}{2\pi} K_H V B_{\text{max}}^y \]

Where, \( K_H \) = hysteresis coefficient(material characteristics) and this equation can be written as:

\[ P_H \propto B_{\text{max}}^2 l^3 \]

The eddy losses in transformer core can be reduced by using core of high resistivity and thinner laminations. In the simulation work, a comparative study has been conducted for magnetic vector potential and current density due to all the three types of core material, as shown in Figure 5.
Figure 6: Comparison of Current Density

Figure 7: Magnetic Vector Potential in Amorphous Core Transformer

Figure 8: Magnetic Vector Potential in Amorphous Core Transformer
In this paper, attempt has been made to study the flux distribution, vector potential and current density in the transformer core. When the flux density is high, Amorphous type transformer core shows an abnormal anisotropy. In order to study its electromagnetic characteristics, the effects of the anisotropy of the amorphous core material were observed under high flux density conditions. Numerical simulations have been carried out for electromagnetic characteristics to make a detailed comparison with different materials.

6. Conclusion
In this paper, work has been done on the numerical analysis performed in core of single phase transformer. The emphasis was positioned on the improving the accuracy in assessing the losses of the transformer. The considerable benefit of the amorphous metal core transformers during the study of its electromagnetic characteristics is its low losses as compared with the CRGO steel and soft iron. Analysis of three-phase transformers with amorphous material is still in research phase and desires to be reinforced with more research on design, technology and application.

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