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Finite Element Method (FEM) based Design and Simulation of Practical Transformer with Nano-Crystalline Core Using ANSYS

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Abstract

Transformer is the main apparatus of the power system for both transmission and distribution of electrical energy. It is the important component of electrical engineering because of its high efficiency and helps in step up and step down the voltage, impedance matching and circuit isolation. Team of designers, engineers and building owners struggled for high-performance in order to maximize the transformer efficiencies. Design and selection of material to construct a transformer core is a significant process. The purpose of this study is to model and simulate a practical 12.5MVA, 66/11kV, three phase power transformer with Nano-crystalline materials like FINEMET and VITROPERM using ANSYS. The study also put some light on the usage of these materials for core as they shows reduced losses in transformer.

Keywords: 3Phase Transformer, ANSYS, Electromagnetism, FEM, Nano Crystalline Materials

1. Introduction

A transformer is fundamentally an electromagnetic static apparatus which is based on the source of Faraday's law of electromagnetic induction. A transformer basically comprises of a magnetic core, shielded silicon steel laminations, upon which are coiled groups of coils fittingly situated with respect to each other and designated as primary and secondary windings. This type of grouping may be employed to develop a voltage of higher or lower value. To the primary winding, supply voltage is functional and to the secondary winding, load is attached [1].

It is the main apparatus of the power system for both transmission and distribution of electrical energy. Voltage must be stepped up to Extra High Voltage and Ultra High Voltage so as to minimize the transmission losses occurring while generating power through long distance transmission lines from generating stations to consumer. Nowadays power is transmitted proficiently with voltages in the range of 100-500 kV and also with a higher value of 765kV. Further these high voltages are incompatible for harmless practice in houses and factories. For this reason transformer is integrated in electrical network to reduce the voltage level compatible for consumers [2].

Along the distribution path, transformer is also necessary at respective point where a transformation in voltage is required. Power generated at a power plant will alter voltage many times using transformer afore it reached the end user today. Team of designers, engineers and building owners struggled for high-performance in order to maximize the transformer efficiencies. Once a transformer is positioned in a construction and energized, it actuates consuming energy and by no means is turned off. Even while a structure is deserted and all loads on the transformer are turned off, it continues to consume energy all day [3,4]. All the failures that happen in transformer with their percentage of happenings are stated as shown in Figure 1.

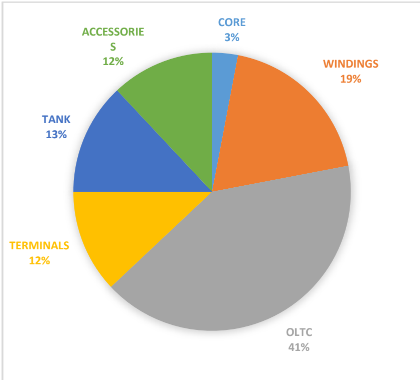

Figure 1: Internal Faults within Transformers

The design of transformer is not only a process to comply customer requirement but also to meet the requirement of national and international standards like IS, IEC, BS and IEEE etc. Over time, both industry and government regulatory Agencies-National Electrical Manufacturers Association (NEMA) and U.S. Dept. of Energy (DOE), respectively-have functioned in cycle to progress the productivity of transformers. The study publicized that on an average, low-voltage dry-type transformers are loaded to only 35% of the maximum rating. NEMA criteria define minimum efficiency levels, but do not define a maximum no-load loss factor. Standards and regulations for transformers explain minimum efficiency levels comprising percentage of maximum loading and temperature. During set-up in the real world, these parameters are not permanent because the load will change as devices are switched on and off. The efficiency will decline as the load varies in proportion to the percentage of maximum rating for which it ensured optimally designed [5].

With the rapid development of digital computers, the designers are free from the drudgery of routine calculations. Computers are widely used for optimization of transformer design. In very less time, computers can work out a number of designs (by varying flux density, core diameter, current density, etc.) and come up with the best possible design as per our requirement. The real benefit due to computers is in the area of analysis. Using commercial two dimensional (2-D) and three dimensional (3-D) field computation software any kind of engineering analysis (electrostatic, electromagnetic, structural, thermal, etc.) can be performed for optimization and reliability enhancement of transformers [4].

This paper deals with Nano-crystalline core materials characteristics and its influence on the losses of transformer. This paper consists of various sections. Section 1 explains the introduction while Section 2 deals with the finite element method for electromagnetics and the steps involved in the process of FEM, Section 3 explains the FEM applied to transformer in order to calculate losses and materials associated with core. Section 4 is 3-D design and simulation of a real transformer core using Nano-crystalline materials and losses obtained. Section 5 presents results derived from the losses obtained and its related discussions. Finally the last section is about conclusion and future scope.

2. Finite Element Method for Electromagnetics

There are different methods that have been useful in the recent past for articulating many electromagnetic problems. As the number of these problems is varied, there can be numerous types of methods that have been found to give reasonable results since their time of occurrence. Earlier researchers employed analytical methods for designing the transformers and carrying their performance analysis. These methods have certain limitations and cannot be applied to complex geometries. For problems involving complex geometries, material properties and boundary conditions, the designer depends on numerical methods which give sufficiently accurate solutions. The finite-element method originated from the need for solving complex elasticity and structural analysis problems in civil and aeronautical engineering [6-8].

The finite element method is utilized for designing the power transformer and their comparison with magnetic circuit theory have been discussed by researcher's respective work. Finite element method is utilized for thermal analysis, structural analysis, leakage field calculations, short circuit forces calculations, fault analysis, losses evaluation and life expectancy in transformer [7, 11]. There are three stages in the process of FEM as shown in Figure 2.

- **Pre-processor**: The problem to be devised is prepared at this stage, in provisions of the known variables, finite nodes and their consequent nodal equations. At the conclusion of pre-processing stage, the problem is all set to be processed.
- **Processor Stage:** Various processing techniques available are employed in this stage so as to compute the field variables at the individual nodes. The techniques at the disposal are currently the special software packages.
- **Post-processing Stage:** The results attained by the processing stage are at this moment compared with experimental or analytical results using various experimental or analytical formulas. The analysis claims to some degree, the consistency of the obtained results with the desired results.

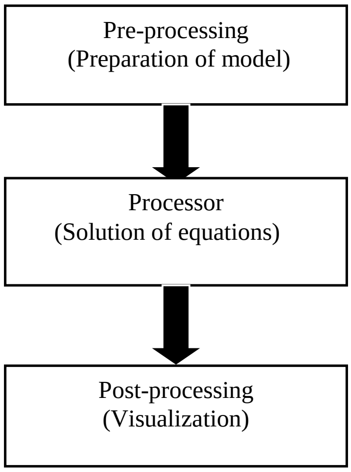

Figure 2: Solution process using FEM

3. FEM for Transformer Losses and its Reduction with Magnetic Core Material

Transformer is a static device that is it transfers electrical energy without any moving parts as in the case of rotating electrical machines so it has higher efficiency and low maintenance cost. Core of the transformer has a very important role in energy transfer. There are continuous advances and starters of better grades of core material.

The important stages of core material development are non-oriented silicon steel, hot rolled grain oriented silicon steel, then cold rolled grain oriented (CRGO) silicon steel. Out of these materials CRGO is improved version of silicon steel. Saturation flux density for CRGO has stayed more or less constant about 2.0 Tesla. There is a continuous progress in watts/kg and volt-amperes/kg features in the rolling trend [9,10].

The core material progresses are controlled by big steel industries. Transformer designers work on the optimization of performance of the core by using effective design and manufacturing skills. The core structure skill has improved from the non-mitered to mitered and then to the step-lap structure. The improved grades of core steel reduce the core losses and also help in reducing the level of noise by few decibels. Amorphous steel used for transformer cores results in one-third core loss as compared to CRGO silicon steel. Because of its brittle property, this material is not very much familiar for use in transformers [12, 13].

Nano-crystalline type of material is very demanding these days for preparing high stability in designing and development of the transformer material. The material arrangement is 84% iron with stability of the silicon quantity, boron, copper, molybdenum, and nickel. These types of material are man-made and completed in an amorphous phase. It is re-crystallized in terms of precise amorphous mixture and on strengthening nano-crystalline segments gives the sensible magnetic belongings [14, 15].

Researchers presented the role of new nanotechnology techniques for the enhancement of transformer cores magnetic characterization [16]. Some work has been reported in literature about the analysis of design of Nano-fluid power transformers for the estimation of distribution of temperature [17]. The benefits of Nano-powder transformer core is also enlisted in the research work [18].

4. 3-D Design and Simulation of Practical Transformer with Nano-Crystalline Core

While dealing with the transformer problems, simulated environment is being set to find the solution as experimental setup involve huge time and money. The pre-requisite of simulated environment is a mathematical model that represents the physical system of the transformer. The transformer can be modeled with the application of boundary conditions and a set of partial differential equations in terms of Maxwell's field equations.

The choice of the material and optimization is one of the essential steps in the designing of the transformer. In the proposed work, various configurations are used for the simulation i.e. Maxwell equations, type of connection, voltage, frequency, number of turns, FEM procedure etc. for reduction of losses at the designing and development stage of the transformer. The whole simulation is done in AUTOCAD and ANSYS. The transformer geometry is achieved using AUTOCAD as shown in Figure 3 which is then incorporated in the ANSYS software as given in Figure 4. The complete geometry is divided into number of elements called mesh elements. These elements are generally triangular in shape, where A is estimated by a simpler function. 3D model created mesh of finite elements is presented in figure 5.

The proposed 3-D analysis is compared with the practical transformer losses. The whole simulation is done in ANSYS Maxwell simulation tool.

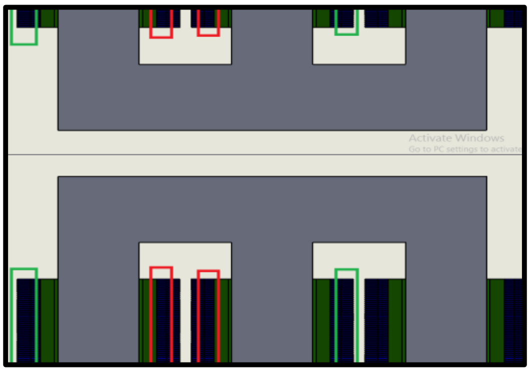

Figure 3: Geometry of Transformer

The proposed work has been prepared to get the excellent performance outcomes of a three-phase power transformer by adopting nano-crystalline materials. Viable grades of these alloys are currently available in market as FINEMET, produced by Hitachi Metals Ltd. in Japan and VITROPERM produced by Vacuumschmelze GmbH in Germany.

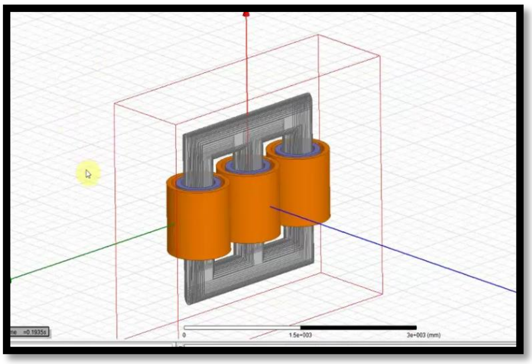

Figure 4: 3-D Model of Transformer in ANSYS

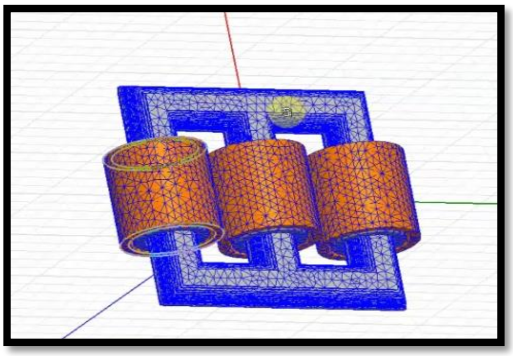

Figure 5: 3D Model Created Mesh of Transformer

The magnetic and electrical properties of these materials are given in Table 1[19].

Table 1: Nano-Crystalline Material Characteristics

Parameters	**FINEMET Properties**	**VITROPERM Properties**
Composition	Fe73.5 Si13.5 B9 Cu1 Nb3	Fe73.5 Si15.5 B7 Cu1 Nb3
Mass Density	7300 kg/m3	7500 kg/m3
Frequency	50 Hz	50 Hz
Thickness	0.01778 mm	0.02286 mm
Conductivity	833330 S/m	833330 S/m
$\mathbf{K_h}$	0.353808 w/m3, 4.84669e-005w/kg	0.0748235 w/m3, 9.97647e-006w/kg
$\mathbf{K_c}$	0.00043334 w/m3, 5.93617e-008	0.000716338w/m3, 9.55117e-008
$\mathbf{K_e}$	0.00846094, 1.15903e-006	0, 0

Nano-crystalline material saturates earlier at a value of 1.2 T instead of 1.5 T as for the case of amorphous material as shown in B-H curves of these materials in Figure 6 and 8. The Core Loss curve (B-P curve) of FINEMET and VITROPERM materials illustrate in Figure 7 and 9. The B-H and B-P curves of Nano-crystalline materials were obtained from the MagWeb database.

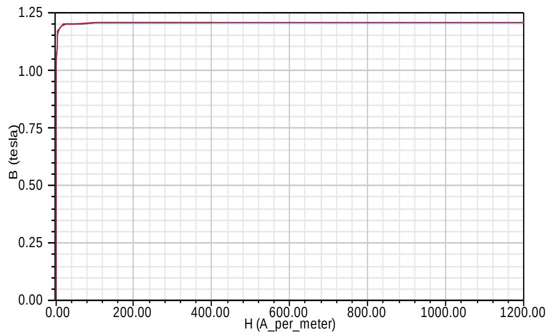

Figure 6: B-H Curve of FINEMET Material

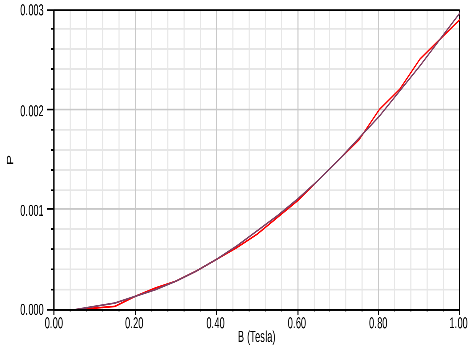

Figure 7: B-P Curve of FINEMET Material Calculated at 50 Hz

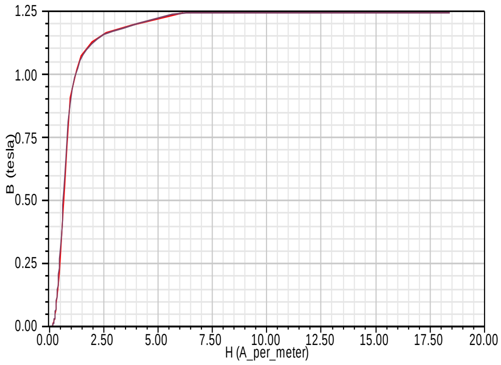

Figure 8: B-H Curve of VITROPERM Material

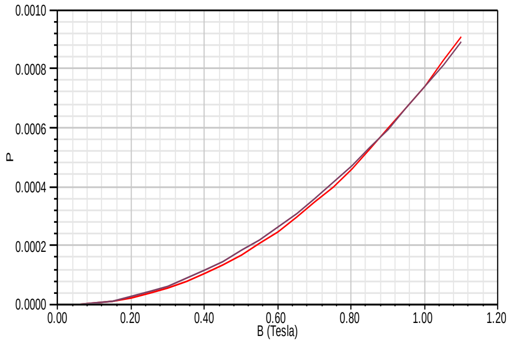

Figure 9: B-P Curve of VITROPERM Material Calculated at 50 Hz

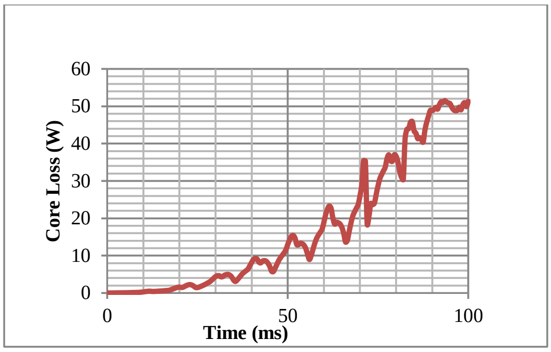

Figure 10: Core Losses of Transformer due to FINEMET Material

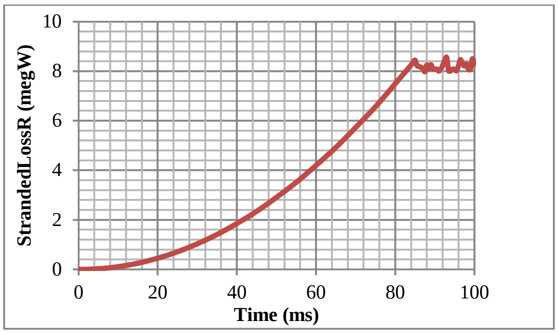

Figure 11: StrandedLossR of Transformer due to FINEMET Material

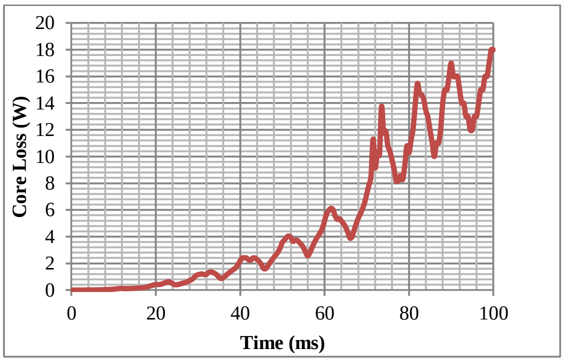

Figure 12: Core Losses of Transformer due to VITROPERM Material

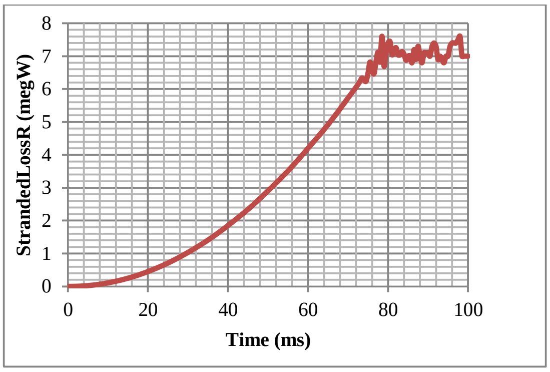

Figure 13: StrandedLossR of Transformer due to VITROPERM

5. Results and Discussions

In the present work Nano-crystalline based materials has been selected for transformer core and substantial results have been obtained with these materials. The BH curves given in Figure 6, 8 are loaded on the material library of the ANSYS. This is done to identify the best core material for which transformer performs efficiently due to reduced losses as shown in Figure 10, 11, 12 and 13. The core material possesses some electric and magnetic properties due to which its retentivity and coercivity diverges. The corresponding B-P curves describe the core loss properties of respective materials as can be visualized from Figures 7 and 9. The proposed work is able to achieve high performance in terms of low losses and efficient design materials.

Nano-crystalline materials are well suited for the performance in terms of low losses in the designing and development of the transformer. It can be noticed that the FINEMET and VITROPERM has minimum losses for achieving high performance in terms of generating high power in the 3-phase transformers.

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6. Conclusion

All the design parameters have their own importance and these add in the performance evaluation of the transformer. The present work described the implementation of finite element method in the accurate design analysis of three phase power transformer by using Nano-Crystalline material. For transformer losses management, a Nano-crystalline model has been proposed that includes reduction in losses and hence increases the efficiency of transformer. As the efficiency of transformer increases, it also increases the life span of the transformer.

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