

Finite Element Methodology for the Accurate Prediction and Minimization of No Load Loss in Power Transformers

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Abstract—In this article, a finite element model, suitable for power transformer representation, is used for the evaluation of transformer no load loss. The adoption of an efficient two dimensional (2D) finite element formulation, in conjunction with the proper representation of the core material characteristics and geometrical configuration, provides good agreement between calculated and measured loss values. Therefore, the model can be used by the transformer designer to accurately predict the performance characteristics of each design, in order to select the one that minimizes the no load loss.

Key words—Finite Element Method, No Load (Iron) loss, Power Transformer, Design Optimization.

I. INTRODUCTION

The process of electric utilities restructuring, privatization, and deregulation has created a competitive, global marketplace for energy. In this new and challenging environment, there is an urgent need for more efficient use of transformer materials, reduction of size and overall material costs and development of design methods that decrease the manufacturing time. On the other hand, the ability to comply with customer requirements as well as the efficiency and reliability of the produced transformers must not be compromised. Transformer efficiency is improved by reducing load and no load (iron) losses. Transformer reliability is mainly improved by the accurate evaluation of the leakage field, the short-circuit impedance and the resulting forces on transformer windings under short-circuit, since these enable to avoid mechanical damages and failures during short-circuit tests and power system faults.

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As competition continues to accelerate in the electric utility industry, many utility companies are developing business plans for operating in a new and uncertain future. Utilities are finding that an optimal plan requires balancing a set of seemingly conflicting goals: reducing operating costs, improving the quality and reliability of customer service, and continuing to improve environmental performance. Utility planners find that, all too often, actions to further succeed one goal come at the expense of one or both of the remaining two. High-efficiency distribution transformers are a welcome exception to this general rule. Moreover, the need for no load loss reduction in power transformers becomes more vital nowadays, in terms of a global environmental policy that requires the increase of the power systems energy efficiency.

The most common method used by manufacturers for the prediction of no load loss is based on empirical formulas and involves design constants extracted through measurements to constructed transformers. Although this method presents a satisfactory accuracy for typical designs, it is bound to result to significant deviations in cases of non-standard designs and core materials. Thus, the research for more accurate tools of iron loss prediction focuses on different methods of analysis, which can be divided in the three following categories:

- i. *Equivalent circuits*, which consist more complicated versions of the classical transformer equivalent circuit, with appropriate modifications of the iron core representations, [1-6]. Most of these models represent the core geometrical configuration, the leakage flux and the resulting loss as intrinsic parameters calculated through measurements on the examined transformers. Despite their efficiency and simplicity, compared to other analytical methods, these models cannot represent correctly operating conditions that have not been analyzed experimentally. Moreover, the effort to incorporate as much constructional characteristics as possible to these models might render them quite complicated and difficult to incorporate in an automated design process.
- ii. *Numerical methods*, which are able to offer great accuracy, mainly due to their ability to represent in detail the real geometry of the transformer core. These methods combine the solution of the differential equations describing the transformer magnetic field along with data for the loss and

magnetization characteristics of the core material, provided by measurements on its laminations. In the development of these models, special consideration must be given to factors such as the local flux distribution in the core, [7], or the flux circulating between the core laminations, [8-10].

- iii. *Artificial intelligence methods*, such as genetic algorithms or neural networks, [11, 12], which are very promising in the field of no load loss prediction, as it consists a problem of a rather stochastic nature.

The present paper concerns the study of power transformers with the use of two-dimensional (2D) finite element method (FEM) for the evaluation of the transformer no load loss. Its main objective relies on the development of an arithmetic model which can accurately and systematically predict the no load losses of power transformers. The 2D FEM is a reliable and efficient tool for the study of electromagnetic fields and can be used instead of a three-dimensional representation for the no load loss prediction, [13], providing the same degree of accuracy with the advantage of the computational efficiency, resulting from the less number of unknowns involved in a 2D representation. The proposed method is applied in various cases of transformers, of different rated power and the results are being compared with the loss value measured by the manufacturer during the open-circuit test.

This model can constitute the basis for an optimization of transformer design process and therefore can be used by the transformer designer to accurately predict the performance characteristics of each design in order to examine the optimum geometrical configuration of the cores that minimizes the no load loss and increases the performance and reliability.

The paper is organized as follows: Section II is devoted to the importance and necessity of energy efficiency maximization while pointing out the contribution of transformer loss minimization to the improvement of power systems energy efficiency. Section III presents the finite element model developed for the transformer no load loss prediction, while the results of its application and its incorporation to the design process of a manufacturing industry are depicted in Sections IV and V, respectively. Finally, Section VI concludes the paper.

II. IMPACT OF TRANSFORMER LOSS IN POWER SYSTEMS ENERGY EFFICIENCY

A. Energy Efficiency

For slightly over a century, the fortunes of most electric utilities have risen and fallen with their output: when they sold more kilowatthours, they made more profit. However, over the last decades, this principle poorly serves densely populated regions in industrialized nations, where for social and political reasons power plants are now more costly or even impossible to build. From an environmental viewpoint, more kilowatthours mean more tons of carbon dioxide, sulfur dioxide, and nitrogen oxides in the atmosphere and more environmental degradation. For the above reasons,

governments all over the world have adopted regulations enabling utilities to profit as much as possible, by convincing their customers to cut their electricity use by relying on more technologically advanced, energy-efficient lighting, equipment and appliances. The net benefits of this policy are defined as the utility's monetary savings accrued by generating, transmitting, and distributing less electricity (by purchasing less fuel, for example), minus what it costs the utility to bring about the savings (the costs of rebates to customers who buy more efficient appliances, for example, and money spent on promotional campaigns for the programs). The net benefits could be substantial, in both monetary and environmental terms.

Also, the costs are much less if better insulation, more efficient appliances and equipment, and even sensors to monitor and control energy use. While such programs will encourage the use of high-efficiency appliances in certain areas, federal standards that could make a national impact are finally on the way, [14].

Although efficient technologies have made significant gains in market penetration in recent years, there is plenty of room for improvement. The most successful technologies typically take off because of their general merit, not because of an efficiency advantage. Often, what these technologies have in common is their ability to meet consumer needs better than existing technologies do, [15].

B. Energy Efficient Transformers

There are many ways to save electrical energy in an industrial and commercial facility, including adjustable speed drives, automation, more efficient motors, and efficient lighting. But there is one way of saving electrical energy that results in both the utility and the industrial and commercial customer saving money: energy-efficient transformers.

Transformers consist a universal link in the power system of any new or existing construction. Whether a factory, office building, subway, or shopping center, electricity will need to be stepped down from transmission voltages to usable voltages and transformers will be employed to do the job. Because this function is so vital, transformers are often viewed in terms of strictly technical performance and overlooked as an energy-saving opportunity.

Conventional transformers today are very efficient devices (99.6-99.8 percent efficiency), but they represent a mature technology with little room for significant improvements in energy and performance efficiency. These transformers have electrical-steel cores, copper or aluminum windings, and are filled with oil that provides cooling and electrical insulation.

The fact that transformers are energized 24 hours per day, every day, means that substantial energy is consumed in the core of the transformer, a term referred to as core loss. Since core loss is such a predictable quantity over the operational life of the transformer, typically 20-30 years, it is of special interest to energy managers who continually seek such predictable and sustainable sources of energy savings. Of all the available choices for core materials, amorphous metal

clearly offers the lowest core loss, often 75 percent lower. It is important to note that transformer conductors introduce the other component of transformer loss, which can be called conductor (coil or load) loss.

Transformers have a significant impact on the losses of a utility's transmission and distribution system. The transformer manufacturers improve the efficiency of transformers by reducing load and no-load losses, the two components of energy losses in a transformer. No-load losses include hysteresis and eddy current losses, are constant in the energized core, regardless of whether the transformer is supplying energy or not, and occur 24 hours a day, 365 days a year. Load losses are primarily the resistive losses in the windings, occurring in the copper conductor, are temperature dependent, and vary with loading conditions, as the current squared. The transformer design engineer reduces no-load losses by reducing the size of the core, reducing the thickness of the core, or using a type of core steel that is energy efficient, like amorphous metal or laser-etched silicon steel. The transformer designer reduces load losses by increasing the size of the conductor, reducing the length of the conductor, and by reducing the transformer temperature, like with superconducting transformers, [11,12].

It is therefore obvious that the design of efficient low-loss transformers is an iterative process involving a tradeoff of materials and design choices. The materials selected are chosen to reduce total cost, to satisfy customer specifications, and to meet any performance or safety standards, [16]. In this context, the ability to accurately predict no load loss with the use of reliable and flexible tools becomes vital not only for transformer manufacturers but for electric utilities as well, as it enhances their ability to upgrade the quality of the components used in their electrical networks.

III. TRANSFORMER MODELING WITH 2D FINITE ELEMENT METHOD (FEM)

The considered transformer is a three-phase, wound core, distribution transformer (Fig. 1). Its magnetic circuit is of shell type and is assembled from two small and two large wound iron cores. The Low Voltage (LV) winding (secondary winding) comprises layers of copper sheet, while the High Voltage (HV) winding (primary winding) consists of copper wire, [17].

Fig. 2 shows the 2D FEM model of the transformer one phase part modelled, while Fig. 3 indicates the section of the active part (one fourth of the actual geometry) that is represented in model of Fig. 2. This section comprises the windings of one phase as well as the core parts that surround them, while it takes advantage of the symmetries of the active part.

For the calculation of no load loss, the transformer magnetic field during open-circuit test must be evaluated. In the case of open-circuit test, the magnetic flux mainly traverses the cores area. Therefore, the detailed representation of this area in the finite element model is crucial for the accuracy of the results.

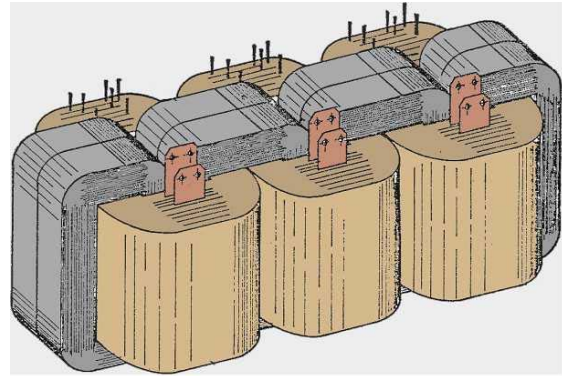


Fig. 1. Real geometry of a three-phase, wound core, distribution transformer

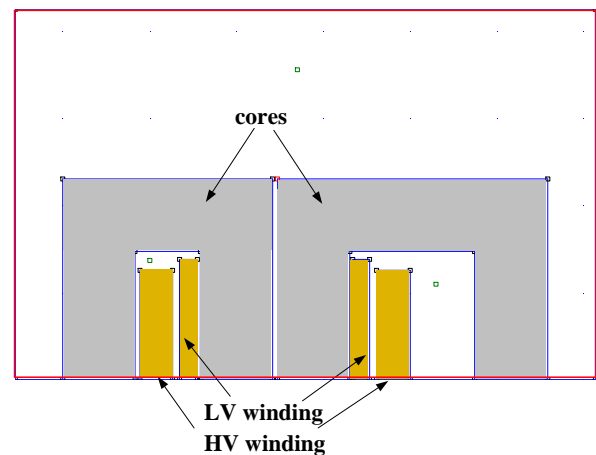


Fig. 2. 2D FEM model of transformer one phase part.

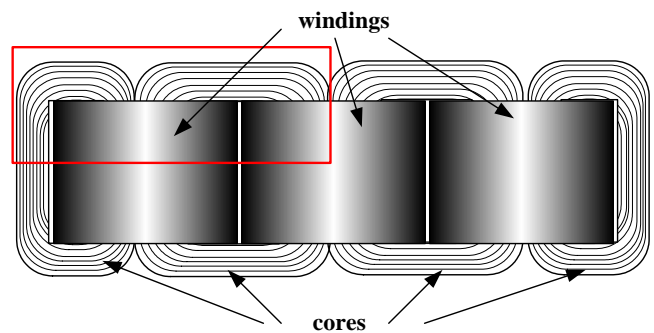


Fig. 3. Active part section corresponding to the one phase model of Fig. 2.

The mesh construction in the case of open-circuit test was conducted taking special care of the mesh density and homogeneity in the cores area. For the transformer magnetic field simulation, the active part is represented by a triangular finite element mesh, illustrated in Fig. 4. It is one of the densest meshes that were used for the evaluation of the transformer field under open-circuit test, illustrating the difference between the density in the cores and coils area, [17].

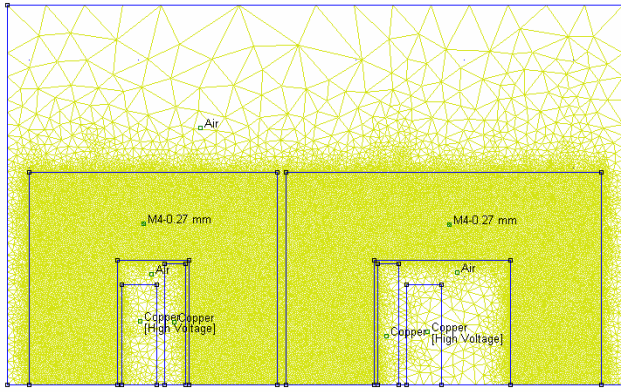


Fig. 4. 2D finite element mesh for the transformer 400kVA.

Fig. 5 illustrates the magnetic induction magnitude distribution along open-circuit test, as it was calculated with the use of a dense mesh and adoption of a tensor magnetization. Fig. 5 confirms the expected distribution under no load conditions, consisting of the main part of the flux in the transformer core area, while the flux in the coils area is particularly negligible.

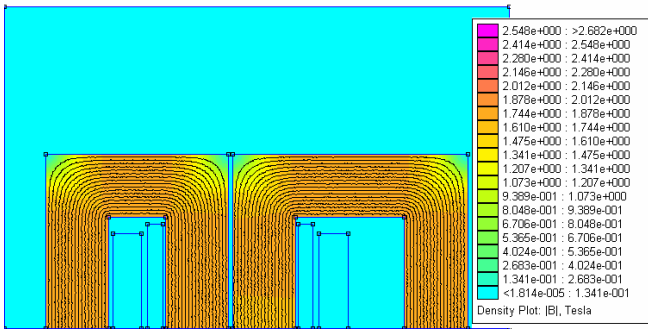


Fig. 5. Magnetic induction distribution under open-circuit test, for the 400kVA, 20-15/0.4 kV transformer considered.

IV. RESULTS AND DISCUSSION

The finite element method was used to evaluate the transformer no load loss. The method was applied in various cases of transformers, of different rated power and the results were being compared with the loss value measured by the manufacturer during the open-circuit test.

This Section presents the results of the evaluation of the no load loss of a 400 kVA transformer with rated primary voltages 20 and 15 kV (dual primary voltage 20–15 kV), rated secondary voltage 400 V, and their comparison to the actual loss value measured after the transformer construction. In order to perform a sensitivity analysis of the impact of the mesh density in the accuracy of the no load loss evaluation, various mesh densities were employed, consisting up to 150000 nodes, approximately. Fig. 6 illustrates the variation of the computed no load loss value with the increase of mesh density.

According to the diagram of Fig. 6, the no load loss predicted by the FEM model exhibits an underestimation for low mesh density (1500 nodes), which decreases as the number of mesh nodes increases and an overestimation after

an intermediate density of 30000 nodes. Moreover, the variation of the error with the number of nodes becomes practically stable after a density of 100000 nodes approximately. The variation of the error in Fig. 6 indicates that the proposed model is able to provide satisfactory accuracy at medium mesh densities, thus reducing its complexity and facilitating its adoption in an automated design procedure.

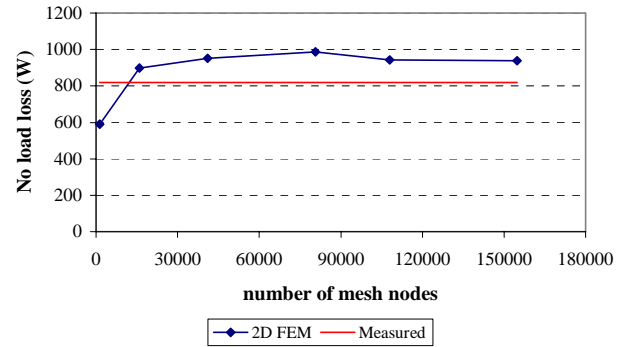


Fig. 6. No load loss results for the FEM model of a 400 kVA, 20-15/0.4 kV transformer.

V. INTEGRATION OF FINITE ELEMENT METHOD IN THE INDUSTRIAL TRANSFORMER DESIGN PROCESS

The model presented in Section III was integrated in the transformer design process of a manufacturing plant. More specifically, it was linked to the existing design software in order to accurately predict the iron loss of each design and examine the optimum geometrical configuration of the cores that minimizes the no load loss and increases the performance and reliability.

For the implementation of the transformer study phase, the manufacturing industry has developed a computer software, using an optimal solution searching algorithm. The design engineer introduces the data in the computer program and the program calculates whether acceptable solutions can derive from the specified data, [18]. Using this program, and giving enough alternative values to the design variables, enough candidate solutions are made. For each one of the candidate solutions, it is checked if all the specifications (limits) are satisfied, and if they are satisfied, the cost is estimated and the solution is characterized as acceptable. On the other hand, the candidate solutions that violate the specifications are characterized as non-acceptable solutions. Finally, from the acceptable solutions, the transformer with the minimum cost is selected which is the optimum technical and economical transformer, [19].

The FEM model is used for the calculation of the no load loss of each candidate solution examined, in order to verify whether the current solution satisfies the technical specifications. In this way, a compound study software (using analytical formulas and numerical model) has derived, taking advantage of the accuracy provided by the FEM calculation.

The embedding of the finite element model is described in

the flowchart of Fig. 7. The symbol n_{loops} appearing in this figure corresponds to the number of candidate solutions examined by the software. The technical specifications related to transformer manufacturing involve the electrical characteristics, i.e. transformer loss and short-circuit impedance. The specification IEC 60076 (1–2–3–5) describes the electrical characteristics and the transformer tests that are related with the transformer dynamic, thermal and electrical strain. The DIN specification defines the transformer losses and accessories, while the CENELEC specification combines data of various specifications.

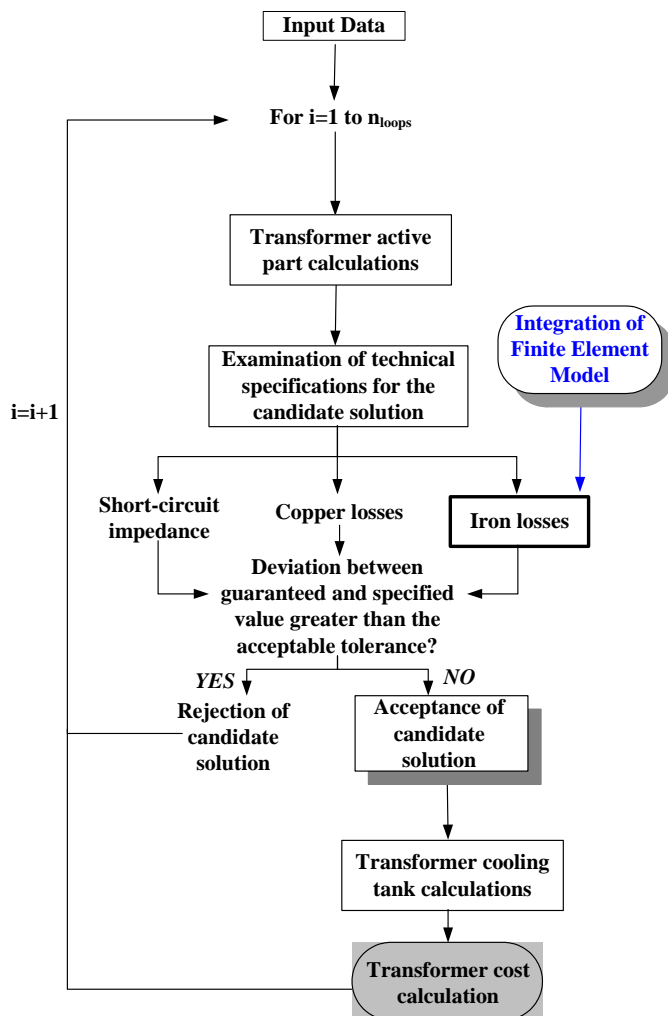


Fig. 7. Integration of finite element model to the transformer design process of a manufacturing plant for the no load loss prediction.

The incorporation of the finite element model to the existing manufacturer design process results to improvement of the design methodology, by providing a proper analysis and optimization tool. With this tool, the designer is no longer obliged to rely on empirical formulas and intuition, thus avoiding possible inadequacies leading to penalties involving equipment weight, efficiency and other performances. Moreover, it offers important increase in the accuracy of the

no load loss calculation, especially in cases of transformers that do not fit into large scale standardized constructions. In these cases, experiential ways of predicting the transformer loss (based on correction coefficients and simplifications of the real geometry) present significant deviations from the actual values, as they concern particular geometries. On the other hand, 2D FEM enables the detailed representation of the transformer geometry, which is crucial for the acquisition of reliable results.

VI. CONCLUSION

In this paper, an efficient 2D FEM model for power transformer optimization has been presented. The model has been employed for the development of an arithmetic model which can accurately and systematically predict the no load losses of power transformers. It is a reliable and efficient tool for the study of electromagnetic fields, which is applied in various cases of transformers, of different rated power and the results are being compared with the loss value measured by the manufacturer during the open-circuit test.

This model can constitute the basis for an optimization of transformer design process and therefore can be used by the transformer designer to accurately predict the performance characteristics of each design in order to examine the optimum geometrical configuration of the cores that minimizes the no load loss and increases the performance and reliability.

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