# Efficient Finite Element Model for Power Transformer Optimization

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***Abstract*-- In this article, an efficient model for the finite element analysis of distribution transformers is presented. In this model, a particular reduced scalar potential formulation is adopted, necessitating no prior source field calculation, reducing significantly the computational effort of the magnetic field sources calculation. This formulation, in conjunction with the detailed modeling of the transformer windings results to a computational tool, which allows the accurate and fast transformer optimization. Comparisons between this method and test values for a number of commercial transformers, prove its validity and accuracy. The model is also used for the magnetic field and transformer characteristics prediction under open circuit test.**

## I. TRANSFORMER MODELING METHODOLOGY

### *A. Particular reduced scalar potential formulation*

The finite element method is a numerical technique for the solution of problems described by partial differential equations. The governing equation in the case of a magnetostatic field is the Laplace equation:

$$\nabla^2 \Phi_m = 0 \tag{1}$$

where $\Phi_m$ is the scalar magnetic potential.

Many scalar potential formulations have been developed for 3D magnetostatics, but they usually necessitate a prior source field calculation by using Biot-Savart's law. This presents the drawback of considerable computational effort.

In the present paper, a particular scalar potential formulation has been adopted, enabling the 3D magnetostatic field analysis. According to this method, the magnetic field strength **H** is conveniently partitioned to a rotational and an irrotational part as follows, [1]:

$$\mathbf{H} = \mathbf{K} - \nabla\Phi \tag{2}$$

where $\Phi$ is a scalar potential extended all over the solution domain, while **K** is a vector quantity (fictitious field distribution), that satisfies Ampere's law and is perpendicular on the subdomain boundary.

A model has been developed based on such a formulation, for power transformer analysis under short circuit test and short-circuit impedance evaluation [2]. In the present paper, this method is extended for considering the detailed winding geometry, including cooling ducts, by defining an appropriate fictitious source field distribution, which is important for geometry optimization. Moreover, accurate no load analysis is performed, by incorporating convenient tensor reluctivities for grain oriented laminations representation.

### *B. Detailed representation of the transformer windings*

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

The construction of the transformer model with detailed winding geometry is realized in two steps: first, an elliptic approximation of the winding corners is considered, while, afterwards, the winding cooling ducts are inserted into the model. This modeling affects the calculation of the fictitious field distribution $K_z$, which must take into account the exact geometry of the coil boundaries as well as the fact that the current density is equal to zero in the ducts area. A division of the HV coil to four subcoils is also realized, enabling the modeling of winding arrangements that produce different primary voltage levels (dual voltage transformers).

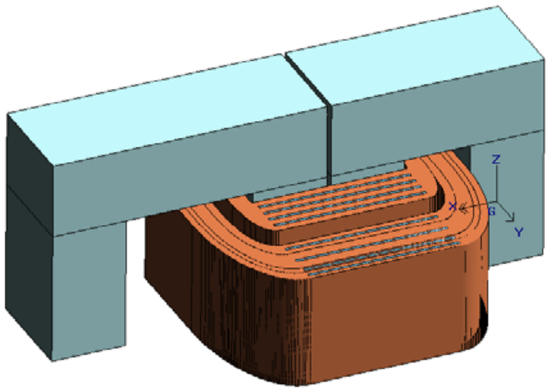


Fig. 1. Perspective view of the active part of the transformer one phase part modeled (detailed winding geometry).

### C. *Computer code for automated optimization of distribution transformers*

For the generalization of the method, a computer code was developed, performing the pre-processing tasks, the finite element calculations and the post-processing of the results.

A process of mesh parameterization was adopted, which modifies the coordinates of initial tetrahedral meshes of various densities in accordance with the geometric data of the examined transformers. This interface has overbalanced another major deficiency that has so far restrained the proliferation of the use of 3D FEM techniques for optimization of transformers by a manufacturing industry. The structure of the computer program is depicted in the flowchart of Fig. 2.

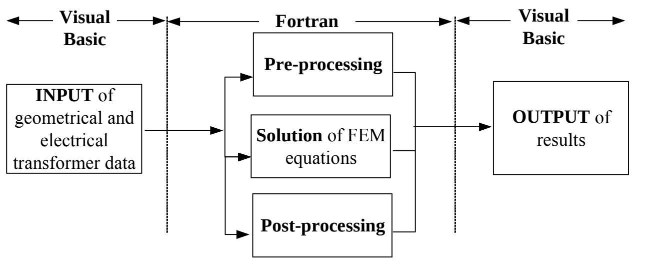


Fig. 2. Structure of the computer code implemented for the application of FEM to distribution transformers.

## II. RESULTS AND DISCUSSION

### A. *Geometry optimization*

The finite element method has been used to determine the optimized geometry transformer short circuit impedance. The results were compared to the ones provided by simplified modeling of the transformer windings and to the actual short circuit impedance measured after the transformer construction in the case of a 630 kVA transformer. The respective results are shown in Fig. 3, proving the ability of the detailed model to provide accurate results with the use of low mesh densities.

### B. *Transformer field under open-circuit test*

Fig.4 shows the resulting magnetic induction variation of the considered transformer under open circuit test, focusing on the iron core, where the magnetic induction distribution appears to be less uniform, especially in the upper part. This can be attributed to the fact that for representation of the core magnetic characteristics, a tensor magnetization is adopted (Fig. 5) consisting of three main axes, taking into account the different characteristics due to the iron laminations and the grain orientation of the considered material [3]. However, such a representation requires additional data for the magnetic permeability along the directions vertical to the grain orientation directions $\mu_x$ and $\mu_z$). The material manufacturers usually provide only the magnetization curve along the grain

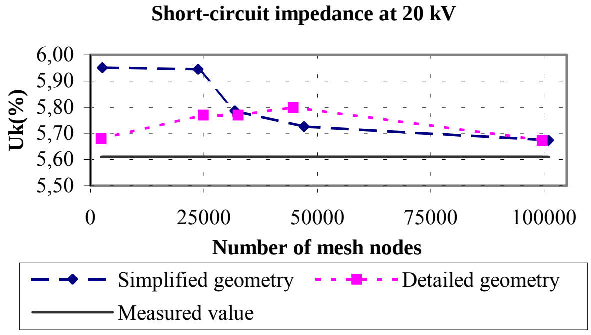


Fig. 3. Short circuit impedance results for simplified and detailed winding geometry of a 630 kVA, 20-15/0.4 kV transformer.

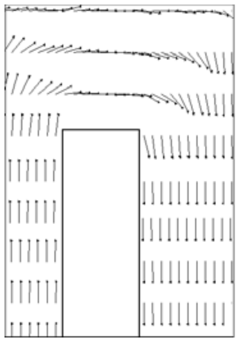

Fig. 4. Magnetic induction distribution during open circuit test, in the right iron core of Fig. 1 (xz-plane).

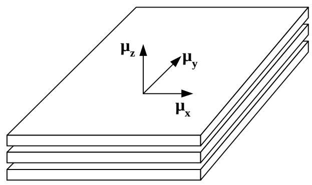


Fig. 5. Magnetization tensor along the sheets of the iron core shown in Fig. 1.

orientation direction ($\mu_y$), which is also used for the other two axes of the magnetization tensor. This fact, along with the use of the experiential value of the lamination stacking factor (influencing the $\mu_Z$ component of the magnetization tensor) results to the inhomogeneity of the induction distribution appearing in Fig. 4.

## III. REFERENCES


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