INCORPORATION OF ADVANCED NUMERICAL FIELD ANALYSIS TECHNIQUES IN THE INDUSTRIAL TRANSFORMER DESIGN PROCESS

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ABSTRACT

The present paper describes the incorporation of finite element method (FEM) for the calculation of transformer equivalent circuit parameters (leakage inductance, short-circuit impedance) in the existing design process of a manufacturing industry. The benefits of the application of FEM are extensively analysed, consisting mainly in the accomplishment of high accuracy in the prediction of transformer characteristics, reduction of the industrial cycle and the overall production cost.

1. INTRODUCTION

In the context of a highly competitive energy market, the need for decrease of delivery time is of primary importance for a transformer industrial plant, [1]. On the other hand, the quality of the produced transformers must not be compromised since high-quality, low-cost products are the key to survival, [2]. Decrease of the transformer delivery time can be accomplished by reduction of the study-design-production time (industrial cycle), while transformer reliability is improved by accurate estimation of its characteristics (short-circuit impedance, no load losses, load losses). These objectives can only be achieved by the adoption of transformer study methods incorporable to an automated design process, able to provide accurate results.

Numerical modeling techniques are now-a-days well established for power transformer analysis and enable representation of all important features of these devices. Techniques based on finite elements present interesting advantages for nonlinear characteristics simulation. Key works adopting this approach are provided next. In [3], eddy current loss in transformer tank walls is analyzed and in [4] finite element models with varying degrees of complexity are used for the computation of short-circuit forces in single phase shell type power transformers. A finite element model is used to simulate foil windings of a three-phase core type transformer in [5], while in [6] minimized magnetic energy and voltage equilibrium are combined with the finite element method for the calculation of leakage field problems coupled with an unknown ampere-turn distribution. In [7], two-dimensional (2D) and three-dimensional (3D) finite element analysis is conducted in three-phase shell type transformer for leakage flux and force calculation. Other works in this category propose the finite difference method as a means of leakage field calculation as in [8] where this method is applied to one-phase and three-phase core type transformers.

In the present paper, a particular 3D scalar potential formulation is adopted for the development of a FEM model for three-phase, wound core, distribution transformers. The method is used for the calculation of the transformer leakage field and short-circuit impedance. The model is incorporated to the automated design process of a transformer manufacturing industry, increasing the accuracy in the prediction of the transformer operational characteristics and reducing the overall industrial cycle.

The paper is organized as follows: Section 2 describes the mathematical formulation of the 3D FEM formulation used for the transformer leakage field evaluation along with the developed 3D FEM model. Section 3 describes the transformer industrial cycle and the integration of the FEM model to the existing design process. In Section 4, the benefits from the adoption of the numerical model are analyzed. Finally, Section 5 concludes the paper.

2. TRANSFORMER MODELING WITH THE FINITE ELEMENT METHOD

2.1 Mathematical formulation

The finite element method is a numerical technique for the solution 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 tetrahedra if the problem is two or three-dimensional respectively. Therefore, a continuous physical problem is converted into a discrete problem of finite elements with unknown field values in their vertices nodes. The solution of such a problem reduces into a system of algebraic equations and the field values inside the elements can be retrieved with the use of calculated values in their indices. Therefore, the solution of the 3D magnetostatic problem describing the transformer field reduces in to the calculation of the magnetic field density at each vertex node of the tetrahedra of its 3D mesh. In most of the developed scalar potential formulations this calculation is realized with the use of the following equation:

$$\vec{H} = \vec{H}_s - \nabla \Phi_m \quad (1)$$

where Φ_m is the scalar magnetic potential satisfying Laplace equation:

$$\nabla^2 \Phi_m = 0 \quad (2)$$

and H_s is the source field density given by Biot-Savart's Law:

$$\vec{H}_s = \frac{1}{4\pi} \int_V \frac{\vec{J} \times (\vec{r} - \vec{r}')}{\left|\vec{r} - \vec{r}'\right|^3} dV \quad (3)$$

However, the above calculation presents the drawback of considerable computational effort, due to the prior source field calculation with the use of (3). In the present paper, a particular scalar potential formulation is adopted [9]: according to this method, the magnetic field strength H is conveniently partitioned to a rotational and an irrotational part as follows:

$$\vec{H} = \vec{K} - \nabla \Phi \quad (4)$$

where Φ is the scalar potential extended all over the solution domain while $\vec{K}$ is a vector quantity (fictitious field distribution), defined in a simply connected subdomain comprising the conductor, that satisfies Ampere's law and is perpendicular on the subdomain boundary.

2.2 Representation of the transformer configuration

Fig.1 shows the active part of the three-phase, wound core, distribution transformer considered. Its magnetic circuit is of shell type and is assembled from two small and two large wound iron cores. Fig. 2 illustrates the perspective view of the one-phase transformer part modeled, comprising the iron core, low and high voltage windings.

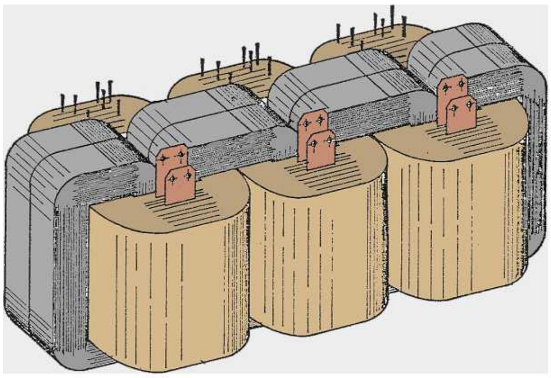

Fig. 1. Active part configuration of the three-phase wound core distribution transformer considered.

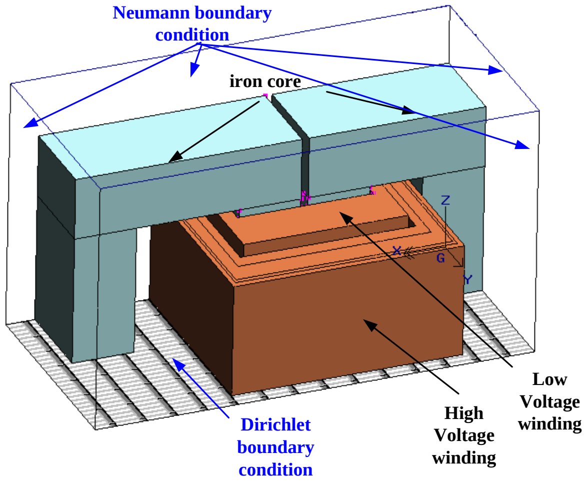

Fig. 2. Perspective view of the one phase transformer part modeled.

The use of this one phase model instead of the whole three-phase transformer model was conducted for the following reasons:

i) The smaller model size enables the construction of more dense tetrahedral finite element mesh without great computational cost (given that the exact representation of the transformer magnetic field requires great accuracy which is dependent on the mesh density and the total execution time of the finite element calculations).

ii) The representation of one phase of the active part does not affect the accuracy of the equivalent circuit parameters calculation.

Due to the symmetries of the problem, the solution domain was reduced to one fourth of the device (although there is a slight disymmetry due to the terminal connections in one side). These symmetries were taken into account by the imposition of Dirichlet boundary condition (Φ=0) along xy-plane and Neumann boundary condition ($\frac{\partial \Phi}{\partial n}$=0) along the other three faces of the air box that surrounds the transformer active part.

As shown in Fig.2, the High Voltage winding area is divided into four subcoils. This division was made in order to take into consideration the winding connection which gives the second high voltage level (i.e. 15 kV). In particular, in the case of the first connection (20 kV) all the subcoils are considered to undergo the nominal current, while in the second one, two of them are connected in parallel, therefore half of the nominal current flows through them. Each subcoil consists of the respective number of turns which are given by the manufacturer.

The finite element mesh of the transformer active part is shown in Fig. 3. The density of the mesh is greater in the windings area, which is crucial for the leakage inductance evaluation under short-circuit test. Moreover, special consideration has been given to the homogeneity of the overall mesh, as it consists an important factor for the accuracy of the finite element calculations.

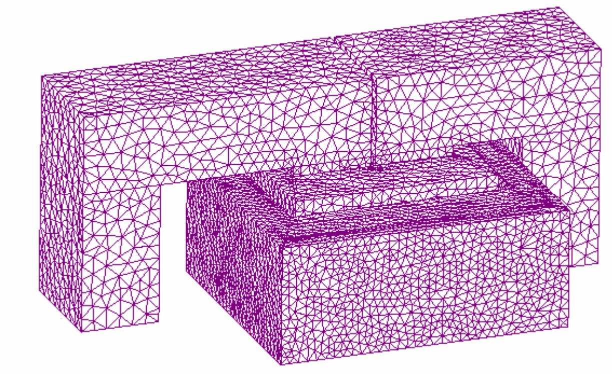

Fig. 3. Three-dimensional finite element mesh of the transformer active part.

3. INCORPORATION OF FINITE ELEMENT METHOD IN THE TRANSFORMER INDUSTRIAL CYCLE

3.1 Description of the industrial cycle

The transformer industrial cycle consists mainly in the study, design and construction phases, [1]:

The transformer study is implemented, based on data that are included in the customer specification (rated power, primary and secondary voltage, short-circuit impedance, losses, required accessories).

Next, the study data sheets are created using a suitable computer program. After that, the study data sheets are send to the Industrial Drawings Department and this Department creates the transformer constructional drawings (using the AUTOCAD environment) and the bill of materials.

Next, the study data sheets, the constructional drawings and the bill of materials are send a) to the Purchasing Department in order to manage the required materials for the construction, and b) to the Transformer Production Department in order to proceed to transformer construction.

After the completion of the production, the Quality Control Department subjects the transformers to various tests and, after confirming that the transformers fulfill the specifications, they are delivered to the customer.

3.2 Transformer study process

3.2.1 Technical specifications. In the transformer study phase, the design engineer must satisfy the customer need for one specific transformer type, producing a design that fulfills the customer requirements and the international technical specifications. The specifications related to transformer manufacturing are shown in Table 1. These specifications are related with the electrical characteristics and the accessories of transformers. 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.

Table 2 presents the tolerances according to IEC 60076-1 to be applied to certain rated quantities when they are the subject of manufacturer's guarantees.

3.2.2. Transformer study software. 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.

During the development of the software, special consideration has been given to the data input procedure. More specifically, there are seven groups of variables for the design of a three-phase distribution transformer:

- *Description variables* (e.g., rated power, rated LV and HV, frequency, material of LV and HV coil, LV and HV connection, …)

- *Variables that rarely change* (e.g., LV and HV BIL, core space factor, turns direction space factor, short-circuit factor, …)

- *Variables with default values* (e.g., LV and HV taps, guarantee and tolerance fields for load loss, no-load loss and impedance, …)

- *Cost variables* (e.g., cost per weight unit for LV and HV conductor, magnetic steel, oil, insulating paper, duct strips, corrugated panels, …)

- *Optional variables* (e.g., variables that either can be calculated by the program or defined by the user)

- *Various parameters* (e.g., type of LV and HV conductor, number of LV and HV ducts, LV and

HV maximum gradient, maximum ambient temperature, maximum winding temperature, …)

- *Variables for conductor cross-section calculations* (LV and HV conductor cross-sections can be defined by the user or can be calculated using current density, or thermal short-circuit test)

- Solution loop variables (e.g., LV turns, dimensions of core, magnetic induction, LV and HV cross-section)

TABLE 1. Transformer specifications

Specification	*Description*
IEC 60076 - 1	Power transformers - general
IEC 60076 - 2	Power transformers - temperature rise
IEC 60076 - 3	Power transformers - insulation levels and dielectric tests
IEC 60076 - 5	Power transformers - ability to withstand short-circuit
IEC 60137: 2003	Bushings for alternating voltages above 1000 V
IEC 60354: 1991	Loading guide for oil-immersed power transformers
IEC 60076-11	Dry-type power transformers
IEC 60905: 1987	Loading guide for dry-type power transformers

Using this program, and giving enough alternative values to the loop 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.

Giving n_{LV} different values for the turns of the low voltage coil, n_D values for the core's dimension D (width of core leg), n_{FD} tries for the magnetic flux density, n_G different values for the core's dimension G (height of core window), cs_{LV} different values for the calculation of the cross-section area of the low voltage coil and cs_{HV} different values for the calculation of the cross-section of the high voltage coil, the total candidate solutions (loops of the computer program), n_{loops}, are calculated from the following equation:

$$n_{loops} = n_{LV} * n_D * n_{FD} * n_G * cs_{LV} * cs_{HV} \qquad (5)$$

TABLE 2. Tolerances according to IEC 60076 – 1

QUANTITY	***TOLERANCE***
a) Losses	
a_1) Total losses (Fe+Cu)	**+10%** of the guaranteed total losses (Fe+Cu)
a_2) Fe losses (Cu losses)	**+15%** of Fe losses (Cu losses), provided that the tolerance for total losses is not exceeded
b) Voltage ratio	
b_1) Voltage ratio on principal tapping	The lower of the following values: a) **±0.5%** of guaranteed voltage ratio b) **±1/10** of the measured impedance on the principal tapping (U_k%)
b_2) Voltage ratio on other tappings	To be agreed with the customer
c) Short-circuit impedance (transformer with two windings)	
c_1) Principal tapping	**±7.5%** of the guaranteed impedance, when the impedance is ≥10%
	±10% of the guaranteed impedance, when the impedance is <10%
c_2) Any other tapping	**±10%** of the guaranteed impedance, when the impedance is ≥10%
	±15% of the guaranteed impedance, when the impedance is <10%
d) No-load current	**+30%** of the guaranteed no-load current

The solution algorithm of the technical and economical optimum transformer is presented in the followings:

for i:=1 to n_{LV}

for j:=1 to n_D

for k:=1 to n_{FD}

for l:=1 to n_G

calculate volts per turn and thickness of core leg

for m:=1 to cs_{LV}

for n:=1 to cs_{HV}

calculate layer insulation

calculate coil dimensions

calculate core dimensions and losses

calculate short-circuit voltage and load losses

calculate coil length

calculate tank dimensions

calculate Cu-oil gradient

if transformer is acceptable then:

calculate dimensions of panels

calculate dimensions of insulating material

calculate weight of duct strips

calculate weight of oil

calculate transformer cost

3.3 Integration of finite element method in the transformer study software

The finite element model presented in Section 2 was incorporated to the transformer design process by integration in the existing study software. The model is used for the calculation of the short-circuit impedance of the candidate solutions, 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. 4.The interaction between the transformer study software and the finite element model is illustrated in Fig. 5.

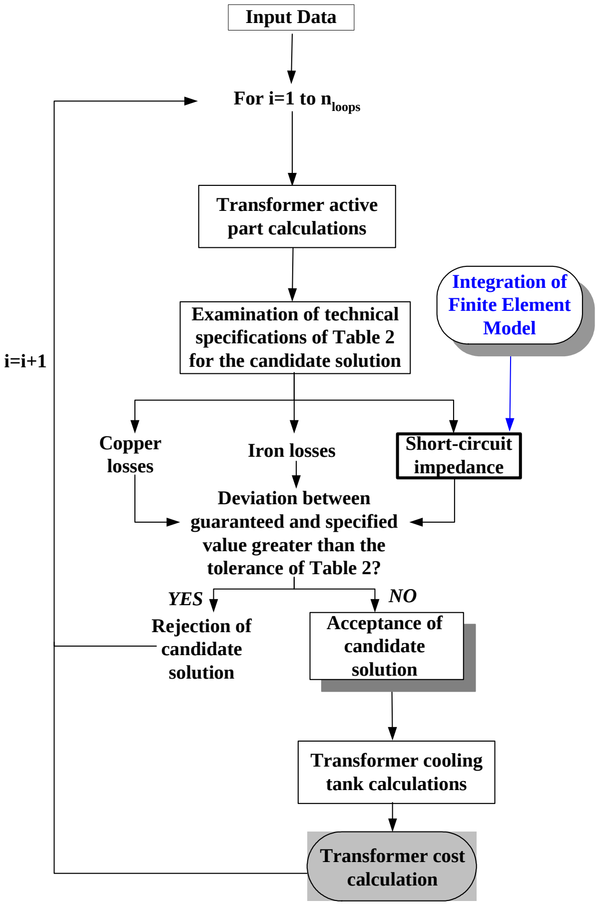

Fig. 4. Integration of finite element model to the existing transformer study software.

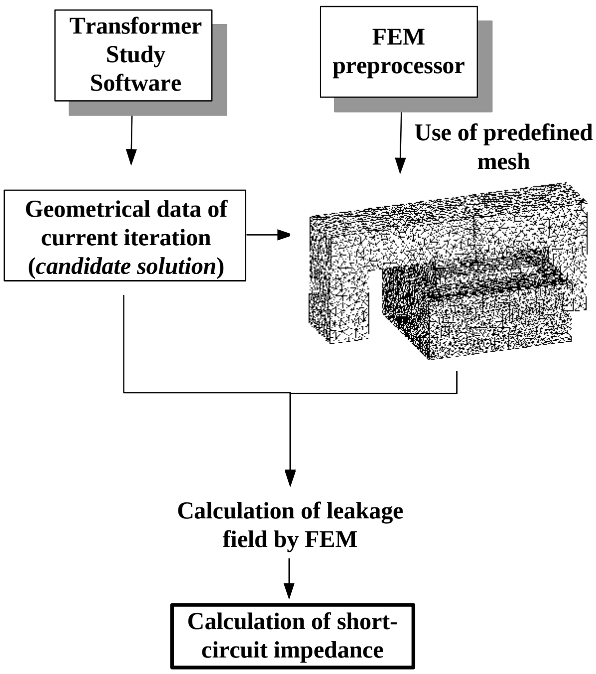

Fig. 5. Interaction between transformer study software and finite element model.

4. BENEFITS FROM THE INCORPORATION OF FEM TO THE TRANSFORMER DESIGN PROCESS

The benefits from the incorporation of the finite element model to the existing manufacturer design process affect many aspects of the manufacturing cycle:

1. Increase in the accuracy of the leakage field and short-circuit impedance calculation, especially in cases of transformers that do not fit into large scale standardized constructions. In these cases, experiential ways of predicting the transformer leakage field (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, 3D FEM enables the detailed representation of the transformer geometry, which is crucial for the acquisition of reliable results.
2. Reduction of the transformer industrial cycle, as the accurate prediction of the operational characteristics eliminates the need for construction of transformer prototype (to confirm the accuracy of transformer design) as well as for short-circuit tests under nominal voltage (which are very laborious and expensive).
3. Reduction of the transformer construction cost, by overcoming the need to oversize the transformer in order to remain within the design margins.
4. 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.

5. CONCLUSIONS

The present paper presented the development of a cost-effective 3D FEM model for the computation of the leakage field and short-circuit impedance of three-phase, wound core, distribution transformers. The method has been embedded to the automated design process of a transformer manufacturing industry, enabling the accurate prediction of the performance characteristics. This numerical model, along with the optimal solution search algorithm of the study software, enable the techno-economical optimization of the transformer design, resulting to significant benefits for the manufacturing industry.

6. REFERENCES

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