

Computer aided analysis and design of power transformers

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Abstract

In this paper, an integrated, three-dimensional, finite element package for the analysis and design of power transformers is developed, requiring no prior user experience in numerical methods and magnetic field simulation. The package consists of an automated pre-processor, magnetostatic solver and post-processor. High accuracy, low computational cost, minimization of user interaction and functional interface are the main advantages of the software, rendering it a powerful computational tool for characteristics prediction of single and dual voltage transformers, suitable for an automated design environment. For the development of the package, a particular scalar potential formulation was adopted. This method, in conjunction with the detailed representation of the real transformer geometry enables the achievement of high accuracy with the use of meshes of low density. The computational efficiency is also enhanced by the use of Morse technique for the storage of finite element matrices and Preconditioned Conjugate Gradient method for the solution of the finite element equations. The software has been incorporated in the design process of a transformer manufacturing industry for the evaluation of the leakage field and short-circuit impedance. The comparison of its results with measured values indicates the improvement of accuracy in comparison to the existing methodology, resulting in reduction of the design margin. Moreover, its employment has contributed to the decrease of the transformer industrial cycle and production cost.

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1. 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 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 [1].

The transformer users specify a desired level of load losses, no-load losses and short-circuit impedance (specified values). It is within the transformer designer responsibilities to implement the transformer design so as the transformer to meet the specified values at the lowest cost. The transformer is designed so that its losses and short-circuit impedance (designed values) are very close to the specified ones, while a design margin is used since, in practice, transformer measured losses and short-circuit impedance deviate from the designed ones due to constructional and measurement tolerances. The transformer manufacturer guarantees the values of losses and short-circuit impedance (guaranteed values), while the permissible deviations of the guaranteed values from the measured ones are specified by international standards and the transformer manufacturers are obliged to comply with them [2].

Accurate estimation of transformer losses and short-circuit impedance during the transformer design phase is crucial, since,

- it increases transformer reliability and manufacturer credibility;
- it secures the desired transformer efficiency;

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- it reduces the material cost, since smaller design margin is used;
- it decreases transformer delivery time, since there is no need for transformer prototype to confirm the accuracy of transformer design.

The decrease of delivery time is of primary importance for transformer market and can be achieved through reduction of the industrial cycle, i.e. the study-design-production time. For this purpose, suitable software systems employing appropriate tools for the automation of each phase of the industrial cycle are required, especially in cases of customer orders of small quantities and different transformer specifications. Therefore, the improvement of transformer characteristics prediction demands the development of new methods of leakage field evaluation, incorporable to an automated industrial environment and able to replace existing methodologies that include gross approximations and empirical factors in the transformer magnetic field simulation [3,4].

In this article, an integrated, three-dimensional, finite element package for the analysis and design of power transformers is developed, requiring no prior user experience in numerical methods and magnetic field simulation. The package consists of an automated pre-processor, magnetostatic solver and post-processor. High accuracy, low computational cost, minimization of user interaction and functional interface are the main advantages of the software, rendering it a powerful computational tool for characteristics prediction of single and dual voltage transformers, suitable for an automated design environment. The software has been incorporated in the design process of a transformer manufacturing industry for the evaluation of the leakage field and short-circuit impedance. It has also been used for the optimization of possible design modifications required for the improvement of transformer operating characteristics. The comparison of its results with measured values indicates the improvement of accuracy in comparison to the existing methodology, resulting in reduction of the design margin. Moreover, its employment has contributed to the decrease of the transformer industrial cycle and production cost.

2. Numerical field analysis techniques: past developments and current trends

The continuous research evolution of numerical techniques along with the increase of computational power of personal computers have established them as a widely used tool for the solution of a large scale of engineering problems. The finite element method (FEM) has prevailed in the electromagnetic field simulation and is often encountered in the analysis of electric machines and transformers. Two-dimensional (2D) and three-dimensional (3D) FEM have been applied for the prediction of transformer losses and leakage field by many researchers: for instance, eddy current losses due to high current leads are calculated in Ref. [5], while in Ref. [6] the method is used for the study of the circulating-current loss in transformer windings. The current distribution in transformer

windings is also analysed in Refs. [7] and [8]. A method for the computation of windings flux linkage with the use of the FEM model magnetic energy is developed in Ref. [9]. 3D FEM has also been used in high frequency transformers in Ref. [10]. The detailed modeling of the real transformer geometry, especially the windings area, has proven to be a factor with considerable impact on the accuracy of the FEM results and is therefore examined in several works like in Ref. [11], where the authors investigate the effect of simplifications of the winding geometry to the accuracy of forces calculation in a single-phase shell type transformer and in Ref. [12], where the issue of detailed representation of windings in 3D FEM models of electromagnetic converters is addressed.

The application of finite element analysis to an increasingly broad range of industrial and research problems has created the need for development of powerful software tools for its computer implementation. A great variety of commercial FEM packages are available with significant modeling and computational capabilities. However, their employment usually requires prior knowledge of electromagnetic field analysis and familiarity with the intricate details of numerical methods. In order to overcome these deficiencies, a lot of research effort has focused on the development of user friendly environments and program modules for specific applications. Several approaches concentrating on the facilitation of particular tasks involved in the FEM analysis appear in the technical literature: a computer animated post-processing package is implemented in Ref. [13] and a generalised, object-oriented post-processing tool is developed in Ref. [14]. The design of 2D and 3D pre-processing tools is realised in Refs. [15–17], while in Ref. [18], object-oriented programming is used for pre-processing and solving of coupled problems. As the solution of the FEM equations is one of the most time consuming tasks, especially in 3D applications, techniques of distributed programming are used in order to increase the applicability of the method in Refs. [19,20]. The parameterization of commercial FEM packages is also adopted as a method of their simplification for non-expert users in Refs. [21,22]. The design of non-commercial integrated packages is more infrequent and invokes 2D modeling: in Ref. [23], a 2D FEM package for the solution of magnetostatic and eddy current problems is developed, requiring user interaction in the geometry definition and in Ref. [24] a FEM based package, aimed for industrial use, able to solve coupled problems for solenoid actuators is presented.

The automation of the transformer design process demands a fast, reliable and rigorous finite element software. Programs that require high degree of commitment in application and understanding are not likely to be adopted by engineers in a transformer manufacturing industry. Moreover, the achievement of high accuracy usually requires the construction of large meshes, resulting to systems of equations with a lot of thousands of unknowns and their solution is restrictive in terms of memory and computing time [25]. The selection of a finite element formulation able to provide accurate results with the minimum possible computational effort, integrated in a user friendly environment, necessitating the less possible user interaction can provide an answer to the above shortcomings

and permit the transformer designers to benefit from the advantages of the method.

In the present paper, an integrated 3D finite element package for the transformer leakage field and short-circuit impedance evaluation, suitable for use in the manufacturing industry has been developed. The package consists of an automated pre-processor, magnetostatic solver and post-processor. The main emphasis throughout the package is given in the adoption of a 3D finite element formulation with high level of accuracy and low computational cost, the minimization of user interaction by automation of pre- and post-processing tasks and the convenience in the management of input and output data. The package has been incorporated in the design process of a manufacturing industry and its application has increased the accuracy in the short-circuit impedance prediction, resulting to reduction of the design margin and the production cost.

3. Special features of the transformer finite element model

Two main characteristics of the 3D FEM model adopted in the proposed computer-based environment contribute to its efficiency: the use of a particular reduced scalar potential formulation and the detailed representation of the transformer winding geometry, which is critical for the accuracy of the obtained results.

3.1. Adoption of a particular scalar potential formulation

The solution of a magnetostatic problem consists in finding the unknown magnetic scalar potential Φ_m (or the vector potential A) through solution of a partial differential equation. The equation describing the scalar magnetic potential is the Laplace equation:

$$\nabla^2 \Phi_m = 0 \quad (1)$$

The finite element analysis solves the above problem by discretizing the considered field space into finite elements (e.g. triangles, tetrahedra) and computing the unknown potential values in their vertices by resolution of a system of algebraic equations.

For the development of the transformer finite element analysis tool, a particular scalar formulation has been adopted, necessitating no prior source field calculation by Biot-Savart's law. According to this method, the magnetic field strength \mathbf{H} is conveniently partitioned to a rotational and an irrotational part as follows [26]:

$$\mathbf{H} = \mathbf{K} - \nabla \phi \quad (2)$$

where ϕ is a scalar potential extended all over the solution domain while \mathbf{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.

The representation of current sources through discretization of \mathbf{K} reduces the source field calculation computational

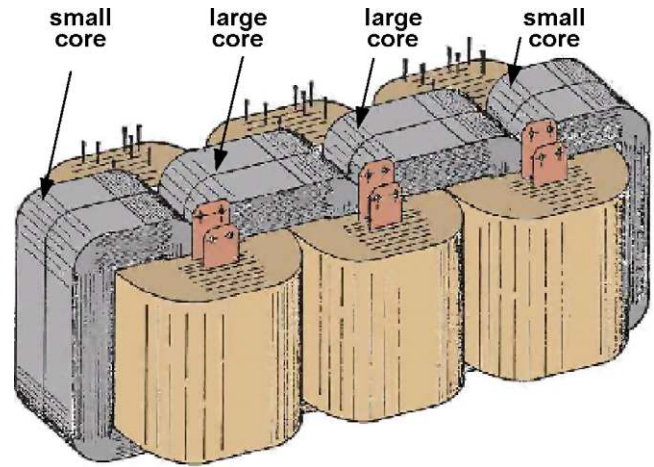


Fig. 1. Active part configuration of the three-phase wound core power transformer considered.

effort and does not suffer from cancellation errors, present in case of using Biot-Savart's law to determine source field distribution.

3.2. Detailed representation of the winding geometry

The active part of the considered three-phase, wound core, power transformers is shown in Fig. 1. The transformer magnetic circuit is of shell type and is assembled from two small and two large iron wound cores. The secondary winding division into sections that can be connected in parallel enables the production of a second high voltage level in case of dual voltage transformers.

For the representation of the transformer of Fig. 1, the one-phase part 3D model of Fig. 2 was used. It comprises the low voltage (LV) and high voltage (HV) windings of one-phase, as well as the small and large iron core that surround them. An air

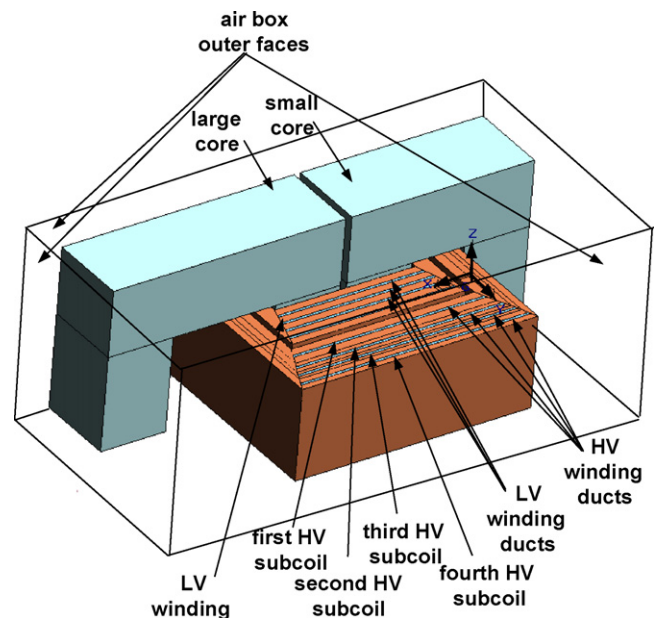


Fig. 2. Perspective view of the transformer one-phase part FEM model.

box, whose dimensions are equal to the transformer tank dimensions, surrounds the active part, therefore confining the field calculation to this domain. The xy -plane of the Cartesian coordinate system used is the transformer symmetry plane, and the z -axis crosses the cores symmetry plane. Due to the symmetries of the problem, the solution domain is reduced to one fourth of the device. These symmetries were taken into account by the imposition of Dirichlet boundary condition ($\Phi = 0$) along xy -plane and Neumann boundary condition ($\partial\Phi/\partial n = 0$) along yz -plane, xz -plane and the three outer faces of the air box.

During the construction of the model of Fig. 2, careful consideration was given to the detailed representation of the windings area, for two reasons:

- (1) the model should be able to represent any possible HV winding arrangement that produces the second primary voltage level. For this reason, the HV winding is divided into four subcoils, taking into account the possibility of parallel connection of its sections in case of dual voltage transformers;
- (2) the existence of cooling ducts in the windings area outside the cores windows affects the distribution of the magnetic field sources. The insertion of the ducts area into the model is a geometrical detail that must be taken into account during the construction of the model and the calculation of the fictitious field distribution described by Eq. (2).

4. Development of a dedicated software package

The 3D finite element package presented in this article consists of an automated pre-processor, magnetostatic solver and post-processor. The pre-processor is based on a parameterization process of initial meshes, eliminating the need for 3D model construction and meshing. The resolution of the FEM system of equations is conducted by the Preconditioned Conjugate Gradient algorithm, in order to increase the solver efficiency. A Windows based graphical user interface (GUI) is used in the data input and output. The main emphasis throughout the package is given in three points:

- adoption of a 3D finite element formulation with high level of accuracy and low computational cost;
- minimization of user interaction by automation of pre- and post-processing tasks;
- convenience in the management of input and output data.

The structure of the computer program is depicted in the flowchart of Fig. 3. Two programming languages were used during its development: the Fortran language, for the implementation of the finite element tasks (pre-processing, solution, post-processing) and the Visual Basic language, for the construction of the user-friendly, Windows based, input and output graphical user interface. Therefore, the Fortran part represents the FEM core of the software, while the Visual Basic part consists the User Interface.

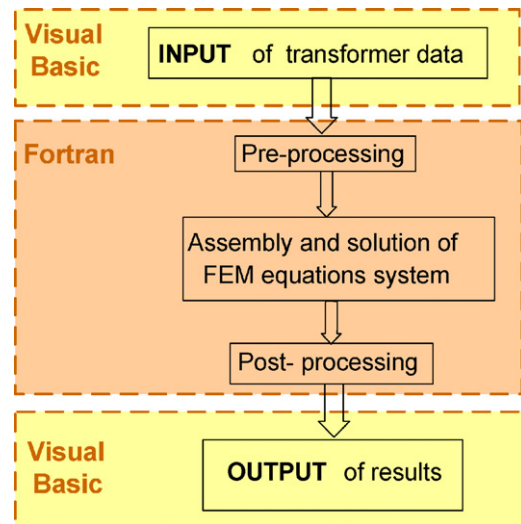


Fig. 3. Structure of the computer code for the analysis and design of power transformers.

5. Adaptation of the finite element core to the power transformer case

5.1. Pre-processing

A finite element software pre-processor must execute the following tasks:

- geometry definition;
- definition of material properties and boundary conditions;
- mesh generation.

The first task requires the construction of a 3D model with specification of coordinates of representative points of the considered geometry, taking advantage of possible existing symmetries. Once the model is constructed, material properties are assigned in each region and boundary conditions are imposed on its external surfaces. The pre-processing procedure concludes with discretization of the model space into finite elements.

The implementation of pre-processing tasks described above can become quite complex and requires specific computer aided design and field analysis knowledge. The application efficiency of mesh generation algorithms varies with the type of the considered problem and their implementation involves considerable programming effort. Furthermore, the adoption of an adaptive meshing technique demands higher level of interaction with the program user, increasing the amount of input data necessary for the model construction and meshing. On the other hand, as the developed software tool is dedicated to the analysis of three-phase wound core power transformers, a constant model configuration can be used. This way, the geometry definition and the specification of materials and boundary conditions must be done only once, as it is not affected by the change in the transformer dimensions. Therefore, instead of the development of an automated meshing program, a process of mesh parameterization was

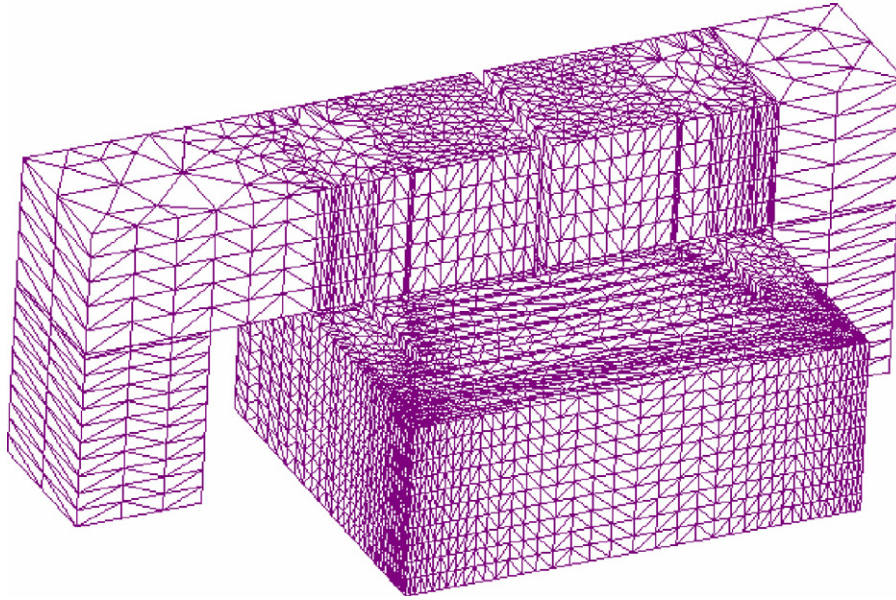


Fig. 4. Tetrahedral finite element mesh representing the transformer active part.

adopted, as it proved to be more efficient and versatile than a grid generation algorithm.

The main concept of the parameterization process relies on the modification of dimensions of existing meshes (constructed from an initial transformer model) according to the geometrical data of each considered transformer. This is realized by alteration of the mesh nodal coordinates with the use of equations deriving from the transformer geometry. As the construction of the initial mesh was crucial for the accuracy of the calculations conducted by the finite element method, careful consideration was given on its density and homogeneity. Meshes of various densities were constructed, providing the user the ability to choose the most suitable one (according to requirements in accuracy and computation time). Fig. 4 shows the active part of a constructed mesh of intermediate density. The mesh of Fig. 4 derived after refinement in areas of special interest: that is why the nodes density is considerably greater in the windings area, in order to obtain greater accuracy in the magnetic field sources region.

For the simplification of the parameterization process, the initial meshes were divided into multiple regions. The division was based on the dimensions affecting the nodes of each region: thus, an effort was made to group neighboring nodes whose coordinates depend on the variation of the same transformer geometrical parameters into simply connected regions. This procedure resulted to 84 regions, whose perspective view is shown in Fig. 5, [27].

The initial meshes are integrated to the program input data in the form of ASCII files. An identification number (ID) is assigned to each node and element of the mesh, while the material property of each element is represented by a number. This method allows the program to identify the region where each element belongs and the coordinates of its vertices with the use of the ID values stored in the nodes and elements arrays

during the reading of input data. The vertices nodes of the elements are stored in the $Nelem \times 4$ array *NUME*, where *Nelem* is the total number of mesh elements. The material of each element is stored in the $Nelem \times 1$ array *MATERIAL*. The material of each mesh region is represented by an integer $k \in [1 \dots 84]$.

The parameterization process is illustrated in the diagram of Fig. 6. It is invoked after the input of the transformer geometrical data. No user interaction is necessary, other than the specification of the desired mesh density. A database of initial meshes of various densities is available and the program selects the one corresponding to the density defined by the user. The parameterised mesh derives from modification of the mesh nodal coordinates, described in the followings.

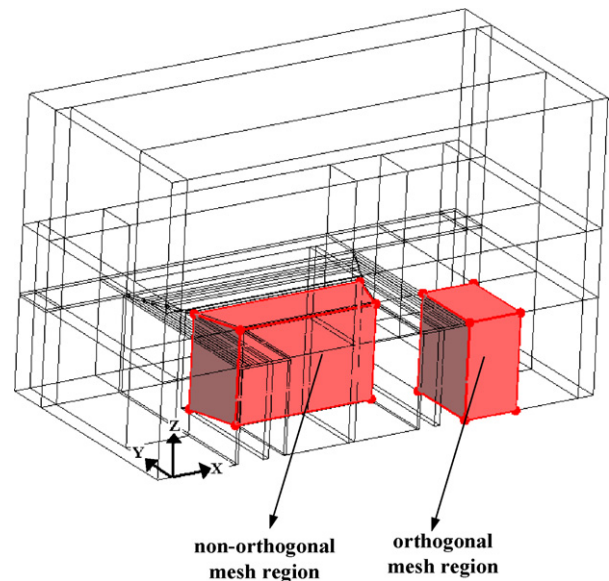


Fig. 5. Perspective view of model division to regions [27].

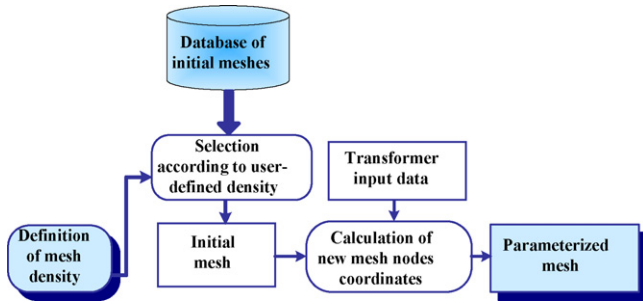


Fig. 6. Diagram of mesh parameterization process.

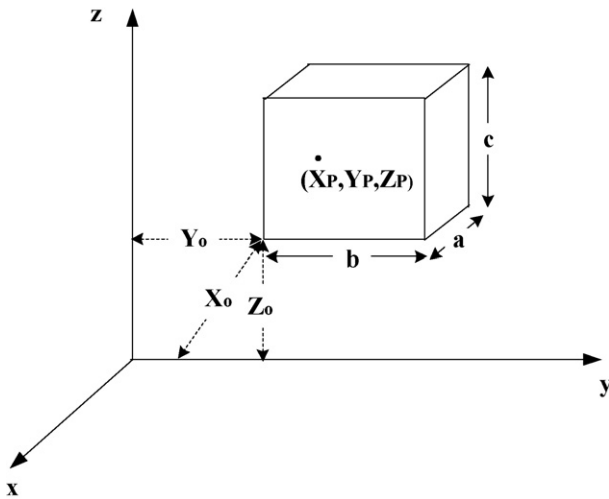


Fig. 7. Orthogonal mesh region [27].

Let us consider an orthogonal mesh region, shown in Fig. 7, [27], where (X_P, Y_P, Z_P) are the coordinates of a random point inside the region (a, b, c) are the dimensions of the region along x, y and z -axis while (X_o, Y_o, Z_o) are the distances of the region origin from the Cartesian coordinate system origin. A change in the model dimensions will affect the dimensions (a, b, c) as well as the distances (X_o, Y_o, Z_o) . The new coordinates of point P will derive from (3). In this equation, the superscripts “old” refer to the old (initial) coordinates, while the superscripts “new” refer to the new coordinates (after the change of the transformer dimensions).

$$\begin{cases} X_P^{new} = \frac{a^{new}}{a^{old}}(X_P^{old} - X_o^{old}) + X_o^{new} \\ Y_P^{new} = \frac{b^{new}}{b^{old}}(Y_P^{old} - Y_o^{old}) + Y_o^{new} \\ Z_P^{new} = \frac{c^{new}}{c^{old}}(Z_P^{old} - Z_o^{old}) + Z_o^{new} \end{cases} \quad (3)$$

The procedure is similar for a non-orthogonal mesh region and the only difference relies on the fact that dimensions (a, b, c) and (X_o, Y_o, Z_o) are not constant and depend on the coordinates of the examined point P. For example, in the region of Fig. 8, [27], the distance X_o is function of the y -coordinate of point P. In this case, X_o can be easily calculated with the use of the line equation of the region edge, which derives from the region boundaries.

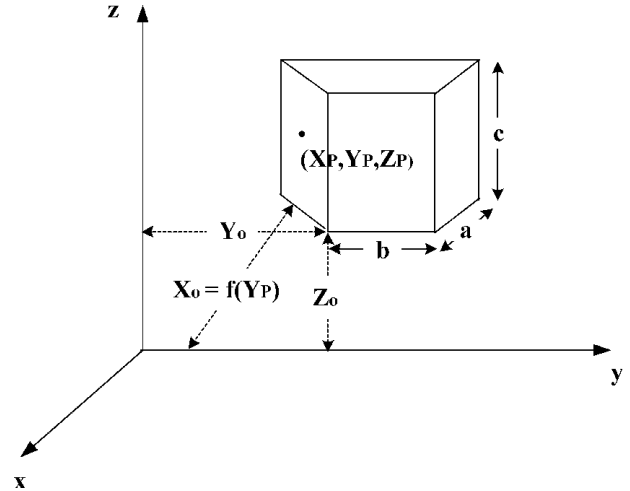


Fig. 8. Non-orthogonal mesh region [27].

The following Fortran pseudocode describes the parameterization subroutine. Each element of the mesh is examined, according to its material property. Given the region where it belongs, the coordinates of its vertices are recalculated by the transformation Eq. (3). For the nodes of elements that belong to common faces of neighboring regions, the possibility of applying the transformation more than once is eliminated by controlling whether the examined node has already been processed (with the use of the $N \times 1$ array of logical variables *RECALC*, where N is the total number of mesh nodes).

```

DO I=1, Nelem
  IF MATERIAL(I).EQ.k THEN
    DO J=1,4
      IF RECALC(NUME(I,J)).EQ.FALSE THEN
        Calculate X(NUME(I,J))
        Y(NUME(I,J))
        Z(NUME(I,J))
      } with the use of (3)
      RECALC(NUME(I,J))=.TRUE.
    ENDIF
  ENDDO
ENDIF
ENDDO

```

5.2. Assembly and solution

The step following the completion of pre-processing tasks is the assembly and solution of the FEM equations. This part

requires little user interaction but is the most time and computer resources intensive. This presents a unique challenge in the choice of solution methods and underscores the need for efficient solution algorithms.

The magnetic scalar potential at each mesh node is calculated by solution of the discretised form of the differential equation governing the magnetostatic problem. The matrix form of this equation is of the form of (4)

$$[S][\Phi] = [F] \tag{4}$$

where $[S]$ is the stiffness matrix and $[F]$ is the magnetic field source vector. The general form of their elements is:

$$S_{ij} = \int_{S_{\text{element}}} \nabla a_i a_j dS \tag{5}$$

$$F_i = \int_{S_{\text{element}}} a_i \mathbf{K}_i dS \tag{6}$$

A mesh comprising N nodes, results to a $N \times N$ stiffness matrix, and a $N \times 1$ source vector. The stiffness matrix is assembled from elementary 4×4 matrices, constructed individually for each element of the mesh. It has the form of Fig. 9.

As shown in Fig. 9, the matrix S is quite sparse, comprising a large number of non-diagonal zero elements. The use of this matrix results to significant abuse of system storage space, especially in cases of mesh densities of a few thousand nodes. For this reason, the search for an alternative storage technique was essential, in order to reduce the required memory and disk space. A Morse storage technique was adopted, generating a system matrix with only the non-zero terms of the initial stiffness matrix. The flowchart of Fig. 10 explains the operations that build up this system matrix.

Typical methods for solving system of linear algebraic equations are either direct or iterative. Gaussian elimination and all its variants fall under the category of direct methods. A

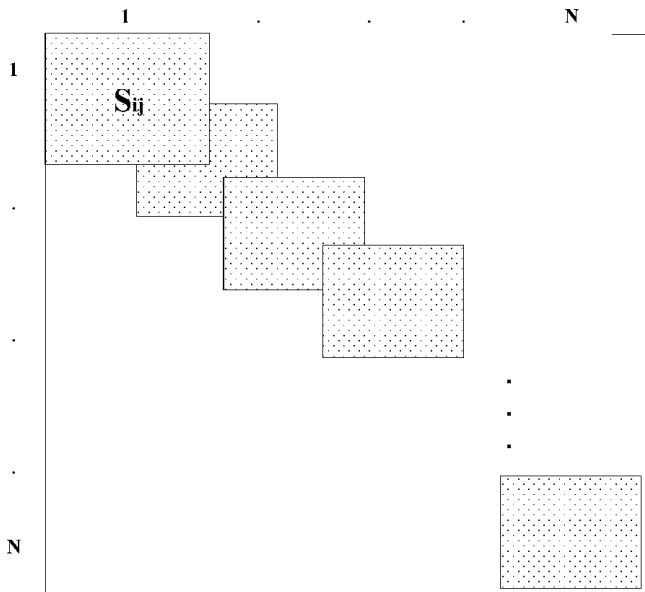


Fig. 9. Stiffness matrix.

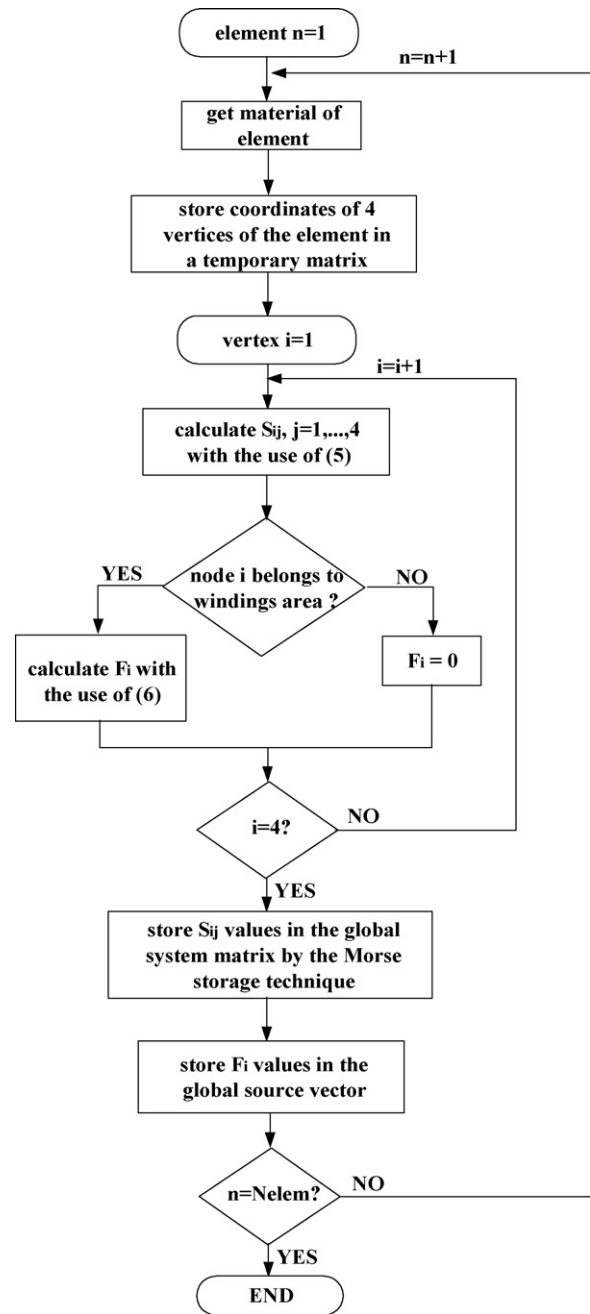


Fig. 10. Flowchart for the assembly of FEM matrices.

direct method computes the solution to a finite precision in a finite number of operations. Operation counts for Gaussian elimination vary from $O(N^3)$ to $O(N^2 \log N)$ for N unknowns depending upon the properties of the coefficient matrix and how the sparsity structure of the matrix is exploited. The minimum operation count that can be achieved, $O(N^2)$, is for the minimum degree algorithm, which is nearly optimal. Iterative methods, of which Jacobi, Gauss Seidel, and its variants, the conjugate gradient and the preconditioned conjugate gradient are typical examples, begin with an initial guess of the solution. These methods then proceed to improve the current approximations by successive updating steps or iterations. The operation count of iterative methods is dependent on the convergence properties

of the algorithm [28]. The faster one of these algorithms, the Preconditioned Conjugate Gradient (PCG) computes solutions to N unknowns in $O(N^{3/2})$ operations, which is better than the best direct method based solution. For the above reasons, the PCG was implemented in the developed FEM software solver, as it is more efficient in the aspect of less memory requirement, less computational amount and less round off error. Moreover, by limiting the number of PCG iterations or by reducing the given accuracy, computational time can be saved and acceleration of its convergence can be achieved.

5.3. Post-processing

The post-processor provides the indispensable interface between the user and the finite element solution for a field problem [29]. The solution of the FEM equations results to computation of the magnetic scalar potential at each node of the mesh. From this data, other quantities need to be extracted, in a way that the software user can exploit the results of the FEM analysis. The handling of large amount of data generated by the finite element solver and their efficient visualization according to the user requirements constitute the final step to the accomplishment of a functional and powerful FEM software.

In the case of the transformer short-circuit impedance evaluation, global quantities like the windings leakage inductance and the inductive voltage drop are the results to which the user must have direct access after the execution of calculations.

Besides the computation of global quantities, the distribution of field variables like magnetic induction or field strength may be quite helpful to the software user, especially in areas of particular interest. For example, the magnetic induction variation or the force distribution in the space of the windings provide crucial information to the designer regarding the transformer performance characteristics during short-circuit test. For this purpose, the possibility of field quantities visualization along pre-selected surfaces of the transformer model was embedded in the software as a post-processing task. Two visualization surfaces were chosen:

- (1) transformer symmetry plane: this surface crosses the transformer symmetry plane, including the windings gap and the cores window. The flux and force distribution in this plane enables the user to estimate the magnitude of the exerted forces in the transformer frame during short-circuit.
- (2) a surface vertical to symmetry plane, crossing the center of the windings: the magnetic induction and forces are maximized along this surface, thus providing a representative image of the expected variations during short-circuit.

Fig. 11 illustrates the magnetic magnitude density plot during short-circuit, along the transformer active part and the pre-selected surfaces mentioned above.

6. Graphical user interface

The Visual Basic (VB) programming language was chosen for the implementation of the FEM software GUI, as the

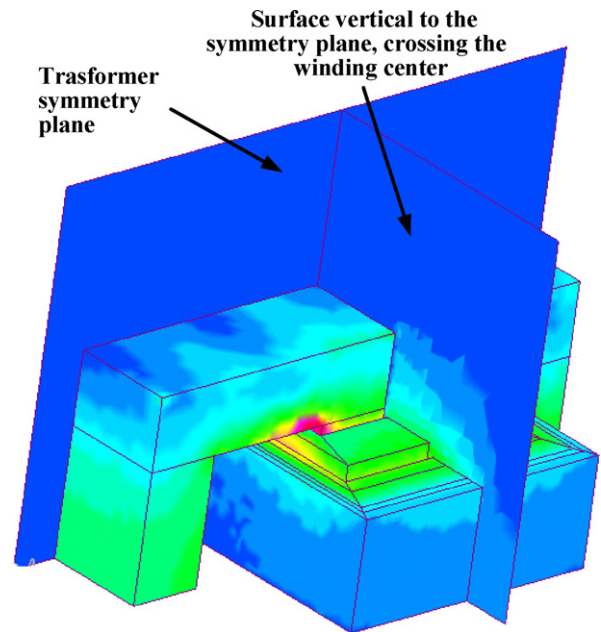


Fig. 11. Density plot of transformer magnetic induction under short-circuit test.

ActiveX components and the event-oriented approaches that it provides contribute to the development of a Windows interface that integrates the finite element analysis and enhances the user's ability to incorporate it in the transformer design process.

6.1. Input data configuration

During the design of the GUI, careful consideration was given to the convenience in the management of input and output data and the ability of importing data of existing design files database. This way, the transformer designer should be able to employ the software without dealing with internal operating details (model construction, solution of equations, post-processing) and with the minimum possible effort. Such an interface is suitable for engineers in the transformer manufacturing industry, where the design process must be fast, rigorous and effective. Moreover, it does not require prior experience and electromagnetic field analysis knowledge, the lack of which can deprive the achievement of optimal results from commercial finite element software packages.

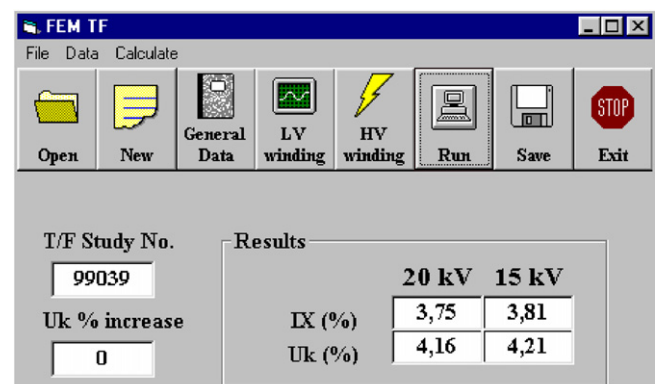


Fig. 12. FEM software main screen.

Fig. 12 illustrates the main FEM software form for the management of input data and the visualization of output results. Graphic features including command buttons and menu schemes provide full control over the data management (opening of existing data files, creation of new ones, modification of existing data and saving).

The input data are grouped in three forms, which can be invoked through command buttons or menus:

- the first one refers to the general transformer data (core dimensions, rated power, frequency and resistive voltage drop). In this form, the user must also specify the desired density of the mesh that will be used for the FEM calculations;
- the second form contains the low voltage winding data, consisting of the rated voltage, connection, thickness, number of ducts, leads thickness, winding height and number of turns;
- in the third form, the high voltage winding data are specified: rated voltage, connection, conductor dimension, insulation dimension, winding height, number of layers and ducts. Apart from this data, information necessary for the production of the second high voltage level (if existent) must be given. This information regards the topology of the winding sections that will be connected in parallel.

The input data forms are organized in a way that eliminates the amount of data to be entered: a minimum set of parameters must be specified and the software undertakes the calculation of the rest of values appearing in the transformer data sheets.

6.2. Visualization of output data

The global quantities mentioned above (inductive voltage drop, short-circuit impedance) are displayed in the FEM software main screen and can be saved in an output data file. An additional graphics file, containing density plot similar to the one of Fig. 11 is also derived after the completion of the software calculations, and the user can access it independently.

7. FEM software application to the transformer manufacturing process

7.1. Evaluation of the software accuracy

The results obtained by the developed FEM software were juxtaposed to the results of the existing design methodology, indicating the contribution of the proposed model to the accuracy of the short-circuit impedance evaluation.

The existing design methodology has been developed by transformer manufacturing industry using an optimal solution searching algorithm [30]. The design engineer introduces the data in the computer program and the program calculates whether acceptable solutions can derive from the specified data. 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

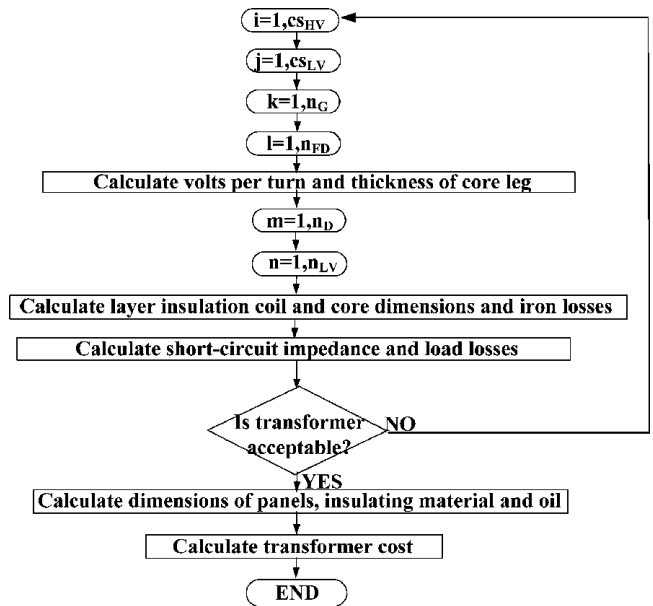


Fig. 13. Block diagram of the transformer design methodology used in the manufacturing plant.

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 [31].

The solution algorithm of this methodology is presented in the block diagram of Fig. 13, where n_{LV} are the different values for the turns of the low voltage coil, n_D the values for the core's dimension D (width of core leg), n_{FD} the tries for the magnetic flux density, n_G the different values for the core's dimension G (height of core window), cs_{LV} the different values for the calculation of the cross-section area of the low voltage coil and cs_{HV} the different values for the calculation of the cross-section of the high voltage coil.

Fig. 14 shows the measured short-circuit impedance distribution of 15 transformers of the same design, 20–6.6 kV/400 V, 630 kVA, along with the guaranteed value and the values calculated by the existing design methodology and

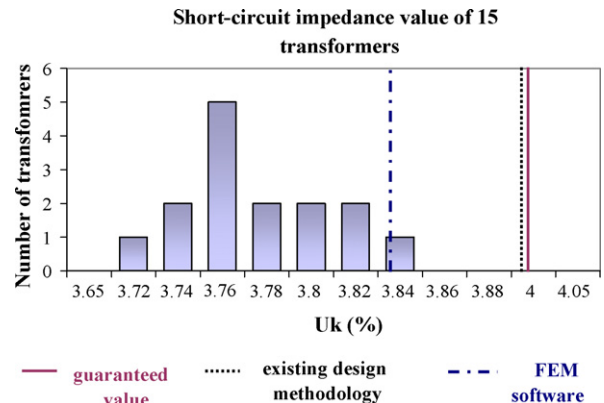


Fig. 14. Distribution of short-circuit impedance measured values of 15 transformers, 630 kVA, 20–6.6 kV/400 V.

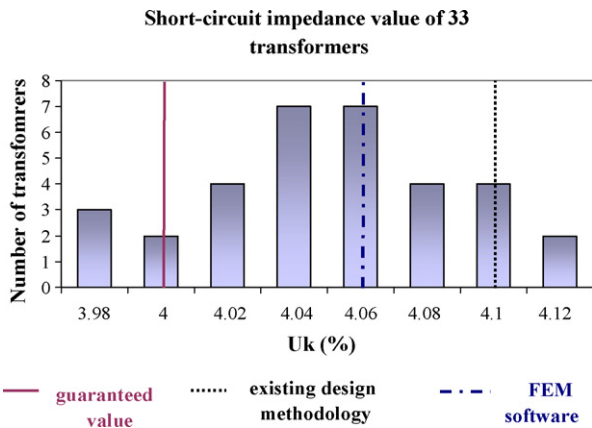


Fig. 15. Distribution of short-circuit impedance measured values of 33 transformers, 100 kVA, 20 kV/400 V.

the developed FEM software. It is clear that the use of the FEM software reduces the deviation in the transformer short-circuit impedance evaluation from 6.1% (with the use of the existing design methodology) to 1.57% (result of developed FEM software). The respective distribution for a batch of 33 transformers, 20 kV/400 V, 100 kVA is illustrated in Fig. 15. In this case, the deviation in the short-circuit impedance evaluation is reduced from 1.23 to 0.39%. The short-circuit impedance value corresponding to the FEM software in Fig. 14 was calculated with the use of sparse mesh (below 3000 nodes).

7.2. Cost-efficiency of the developed software

The cost-efficiency of the developed software relies on its two main advantages: the low computational time required for the production of accurate results and the significant reduction of user interaction compared to commercial FEM packages.

As the accuracy provided by a sparse mesh is equivalent to the one of a mesh of several thousands of nodes, it can be used systematically in the short-circuit impedance evaluation. Table 1 compares the solution times required for different mesh densities in the case of an average and high performance personal computer. The use of a coarse mesh density reduces the solution time to a few minutes, enabling the employment of the method in an automated transformer design process.

On the other hand, although the meshes appearing in the first rows of Table 1 are quite sparse, the execution time corresponding to densities above 50,000 nodes is also satisfactory, due to the employment of the solver and matrix

Table 1
FEM solution times for different mesh densities

Number of mesh nodes	Pentium, 225 MHz, 64 MB RAM (min)	Pentium 4, 2.4 GHz, 512 MB RAM (min)
3,260	5	1.5
23,696	60	20
32,555	90	35
55,473	270	140
89,603	420	190

storage scheme described in Section 5.2. As the number of unknowns increases with the mesh size, high densities are bound to increase significantly the solution time of the system of equations, unless an iterative solver is employed: the use of the PCG algorithm was therefore essential for two basic reasons:

- it does not confine the user to small or medium mesh densities, by eliminating the possibility to result to enormously high execution times, if he decides to use a very dense mesh (perhaps to validate the accuracy of a design that has specific requirements),
- it enables the fluent use of the software in systems of average computational capability, not requiring operating systems of high performance, and further enhancing the flexibility of the software.

Besides the considerable reduction in the solution time of the FEM equations system, the automation of pre- and post-processing tasks implemented by the developed software contributes to the overall efficiency of the software. Table 2 lists the main pre- and post-processing tasks requiring user interaction during the application of commercial FEM packages to the transformer short-circuit impedance evaluation. Next to them appears a column with the equivalent tasks where the user of the developed FEM software must interfere. A percentage of user interaction is assigned to each task, estimated for users of average experience on electromagnetic field analysis techniques. As shown in Table 2, the calculation of the transformer model dimensions and the mesh generation tasks are replaced by the input of geometrical data and the selection of mesh density. The model construction and post-processing of magnetic field results are fully automated and need no user intervention. Therefore, a total reduction of user interaction by 85% is achieved, increasing the software’s applicability to an automated design environment. The results of Table 2 are illustrated in the histogram of Fig. 16, where the required percentages of user interaction for each pre- and post-processing task are drawn in the case of commercial FEM packages and the developed FEM software.

Table 2
Pre- and post-processing tasks automated by the developed FEM software package

	Commercial FEM packages (%)	Developed FEM software (%)
Pre		
a	Calculation of model dimensions 20	Input of transformer data 10
b	Construction of model 45	–
c	Mesh generation 15	Selection of mesh density 5
Post		
d	Calculation of global parameters 5	–
e	Visualization of results 15	–
	Total user interaction 100	Total User Interaction 15

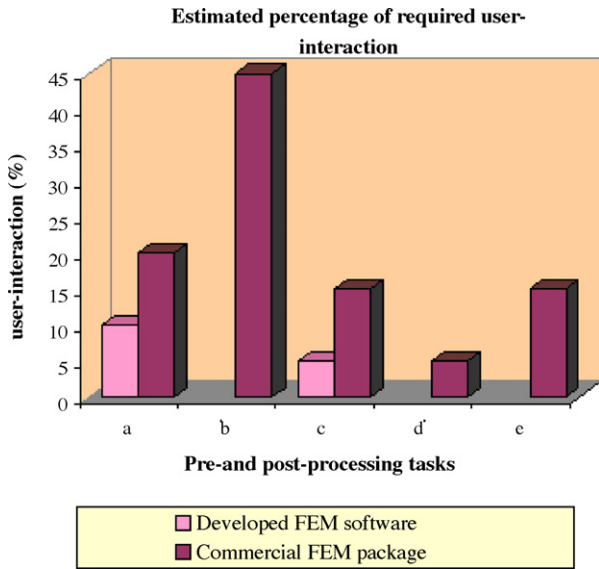


Fig. 16. Estimated percentage of user interaction required by pre- and post-processing tasks in commercial and developed FEM software (tasks a, b, c, d and e are defined in Table 2).

7.3. Creation of an integrated computational environment

The developed FEM software was incorporated to the design process of a transformer manufacturing industry. More specifically, it was linked to the existing transformer study software of the industrial plant, as a tool for the prediction of the short-circuit impedance. Fig. 17 gives an overview of the transformer industrial cycle of the manufacturing industry, underlying the part where the developed software interferes.

With respect to Fig. 16 and the software performance characteristics presented above, the incorporation of the developed tool affects many aspects of the industrial cycle, resulting to reduction of the production cost and delivery time:

- the accuracy in the short-circuit impedance prediction reduces the transformer design margin. This ability offers significant savings of the material of the transformer frame, which is sized according to the predicted short-circuit impedance value. Moreover, reduction of the design margin affects the transformer techno-economical optimization, which relies on the definition of the design with performance characteristics close to the specified values at the lowest cost;

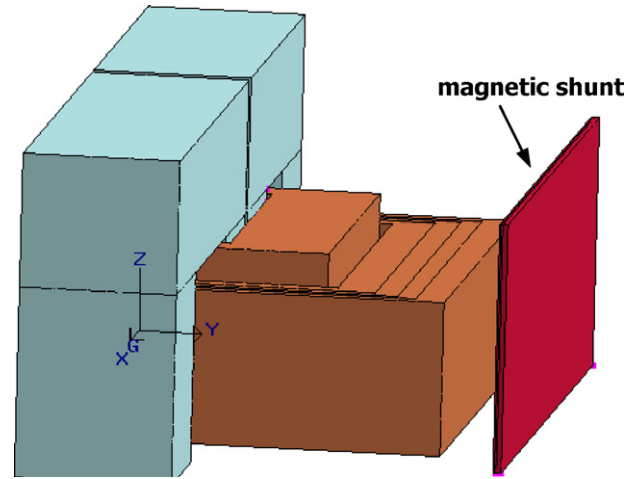


Fig. 18. Placement of magnetic shunt outside the transformer windings for the correction of the short-circuit impedance value.

- the need for transformer prototype construction, used to confirm the accuracy of the design is eliminated. The delivery time is therefore considerably reduced, since the construction of a batch of transformers can proceed only after the completion of the construction and quality control procedure of the prototype. Moreover, in the case of prototype failure during the transformer tests, the design phase must be repeated and the industrial cycle is significantly prolonged.

7.4. Transformer geometry optimization

Apart from the transformer characteristics prediction during the preliminary design stages, the developed software was employed as a tool for the choice of the optimal transformer configuration in the final stages of the industrial cycle. In cases where the difference between the actual (measured after the transformer production) and specified transformer short-circuit impedance value overruns the upper or lower limit of the deviation imposed by international standards, design modifications should be implemented in order to meet the specifications. For instance, reduction of the short-circuit impedance value can be achieved through electric shielding, which attenuates the stray flux from the transformer windings. On the other hand, magnetic shielding increases the magnetic stray field and the winding leakage inductance.

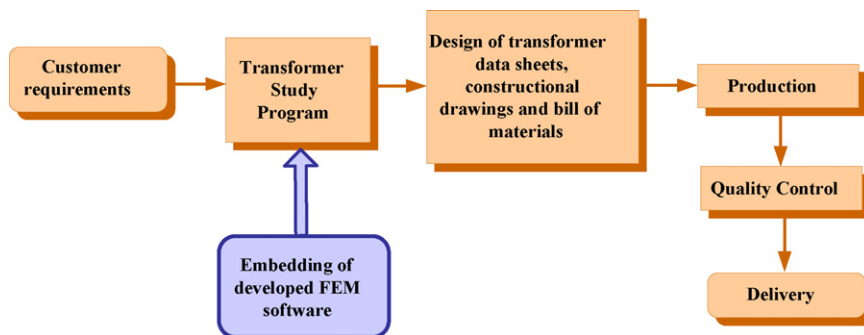


Fig. 17. Incorporation of the developed software in the transformer industrial cycle.

The finite element method was used in conjunction with proper optimization methods for the evaluation of the corrective actions mentioned above: e.g., the optimal dimensions of magnetic shielding (Fig. 18) can be calculated with respect to its impact to the transformer leakage field and losses, calculated by FEM, and its construction cost [32]. The general mathematic form of the magnetic shunt geometry optimization consists in the minimization or maximization of an objective function $F(\mathbf{X}_i)$, where \mathbf{X}_i is the vector of the design variables of the problem. In case of the magnetic shunt, the design variables comprise the geometrical parameters of the shunt, while the objective function is governed by the desired change in the transformer leakage field. The vector \mathbf{X}_i is subject to constraints imposed by the transformer geometry (active part and tank dimensions). Various deterministic algorithms can be employed for this purpose, like the Steepest Descent method, Conjugate Gradient Fletcher-Reeves (CG-FR) method Davidon-Fletcher-Powell (DFP) method, the Broydon-Fletcher-Goldfarb-Shanno (BFGS) method or the Pattern Search method [33,34].

8. Conclusion

The development of an efficient, integrated software tool for the application of 3D FEM in various stages of the transformer industrial cycle has been presented. In this package, an automated pre-processor, magnetostatic solver and post-processor, implemented in Fortran programming language, are combined with a Visual Basic interface that enhances and simplifies the application of FEM by users that are not knowledgeable in the details of field analysis. Furthermore, the accomplishment of high accuracy at low computational cost, offered by the adopted FEM formulation and the detailed geometry representation render this tool suitable for power transformer design office use. Application of the developed software to the design process of a transformer manufacturing industry has verified the accuracy in the prediction of short-circuit impedance. These results provide significant economic gains to the transformer manufacturer through reduction of the industrial cycle and the production cost. Furthermore, in cases where the design does not meet the specifications, the software tool can be applied in order to minimize the increase in the transformer cost due to the necessary design modifications, by optimization of the intervention required to improve the transformer operating characteristics.

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