Development of power transformer design and simulation methodology integrated in a software platform

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Abstract — **In the present paper, a Transformer Design Optimization (TDO) software platform is developed providing an integrated design, simulation and visualization environment. The software is based on advanced computational methods (optimization techniques as well as coupled field formulations), enabling computation of the optimal transformer active and mechanical part configuration, analysis and optimization of cooling system, mechanical design of tanks, optimal selection between different core types and winding materials, losses and short-circuit impedance analysis as well as economic evaluation in transformer management.**

Keywords — **Power transformers, design optimization, numerical methods, economic analysis, software platform**

I. INTRODUCTION

The main motivation to use a software package in the transformer manufacturing process is to provide design engineers with an additional tool helping increase profits. 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 [1]. In order to compete successfully in a global economy, transformer manufacturers need design software capable of producing manufacturable and optimal designs in a very short time. The first transformer design was made on computer in 1955 [2]. Several design procedures for low-frequency and high-frequency transformers have appeared in the literature after the 70's. Judd and Kressler [3] presented a technique for designing transformers with given size and type of structure to have maximum volt-ampere (VA) output while at the same time insuring the satisfaction of a number of design constraints. Poloujadoff et al. [4] show the variation in the price of the transformer depending on the primary turns, which is an approximately hyperbolic function. Jeweel [5] does a functional proposal with students in electrical engineering, in which the student designs, builds and tests a 10 VA transformer. Grady et al. [6] deal with the teaching of design of dry type transformers, based on a computer program, where the user optimizes its design based on trial and error. Furthermore, Rubaai [7] describes a computer program yielding an optimal design of a distribution transformer based on user input data. Andersen [8] presented an optimizing routine, Monica, based on Monte Carlo simulation. Basically, his routine uses random numbers to generate feasible designs from which the lowest cost design is chosen. Hernandez and Arjona [9] develop an object-oriented knowledge-based distribution transformer design system, in conjunction with FEM, which is used as a tool for design performance validation. Deterministic methods provide robust solutions to the transformer design optimization problem. In this context, the deterministic method of geometric programming has been proposed in [10] in order to deal with the design optimization problem of both low frequency and high frequency transformers.

The present paper presents the development of an integrated transformer design and simulation software platform, conveniently integrating design optimization as well as economic, electromagnetic and thermal analysis capabilities.

II. STRUCTURE OF THE DEVELOPED SOFTWARE SUITE

The structure of the developed software platform is depicted in the flowchart of Fig. 1. It includes two design methods: i) traditional design, implementing computation of the transformer design and operational characteristics by a classical design model, based on analytical equations, and ii) optimal design, yielding the optimum value of the main design parameters based on non-linear mixed-integer programming, in order to achieve minimum transformer cost and the desired technical specifications. The software is designed to be as interactive as possible, providing access to all design parameters so that its users have the ability to customize the design to meet their own inventory needs.

Direct (traditional) transformer design produces transformer design and operational characteristics calculated by an algebraic design model, based on analytical equations, for a set of input design parameters provided by the user. These parameters are depicted in the upper part of the graphical user interface of Fig. 3 (Transformer Input Parameters), while a significant number of other parameters and design constants used for the calculations are also calculated by the software, based on the main transformer input parameters.

Optimal design is based on mixed integer non-linear methodology (MINLP), developed in [11]-[13], resulting to the optimum values of four design variables, namely the number of secondary winding turns, the magnetic induction magnitude (B), the width of core leg (D) and the core window height (G) (Fig. 2), while the rest of the transformer design and operational characteristics are calculated by the algebraic design model mentioned above. Upon user selection, the windings current density values can be added to the design vector or their value can be either prescribed or defined by the thermal short-circuit test method. The ranges and initial values of the design variables are provided in the lower part of the graphical user interface of Fig. 3 (Variables for Optimization). The characteristics of the optimum design can be validated by the use of three dimensional (3D) finite element method (FEM) and visualized as plots, while mechanical drawings of the active part and tank can also be illustrated. Furthermore, economic analysis tools, based on the Total Owning Cost method [14] can be employed for the economic evaluation of the optimum design and provide the possibility to compare it with other sub-optimal solutions. A large database of optimum designs of various ratings is also available to the user, which can be used as guidelines in order to render the optimization procedure deskilled and easy to implement. All the aforementioned tools are included in a carefully designed graphical user interface (Fig. 3), accompanied by proper data management tools.

After the design stage, three types of analysis are available to the user, namely economic, electromagnetic and thermal, each one of them offering the opportunity to simulate the designed transformer under varying operating conditions and observe how the transformer would behave under those conditions. Thus, information very close to the actual measurements on a prototype in the laboratory can be obtained, and the performance of the designs can be verified in a more efficient and less expensive way. Results of the above analyses can be exploited in order to optimize specific parts of the design (e.g. transformer tank structure). Moreover, long-term economic analysis of the life cycle costs provides an insight to the energy efficiency of the design, both from the point of view of manufacturers or utilities.

The software integrates a large database of optimum designs that can be used as guidelines in order to render the optimization procedure deskilled and easy to implement. All the aforementioned tools are included in a carefully designed graphical user interface, accompanied by proper data management tools. The output results of each module integrated in the developed software are properly organized and stored, so that the user can get the most of each capability offered in the platform.

III. ADVANCED ANALYSIS CAPABILITIES

A. Economic Analysis Tools

The total owing cost technique provides transformer manufacturers and users with a robust tool for the economic evaluation of different transformer designs. It is incorporated in TDO software in order to enable its user to compare the optimum design with other designs (either sub-optimal designs or different designs defined by the user) and evaluate its energy efficiency. For the proper TOC calculations the loss cost coefficients, namely factors A and B, used for the calculation of no-load and load loss cost, respectively, must be defined. The proposed software enables the definition of constant factors by the user or their calculation according to IEEE Standard C57.120 [15]. The considered transformer designs are then classified according to their TOC ranking.

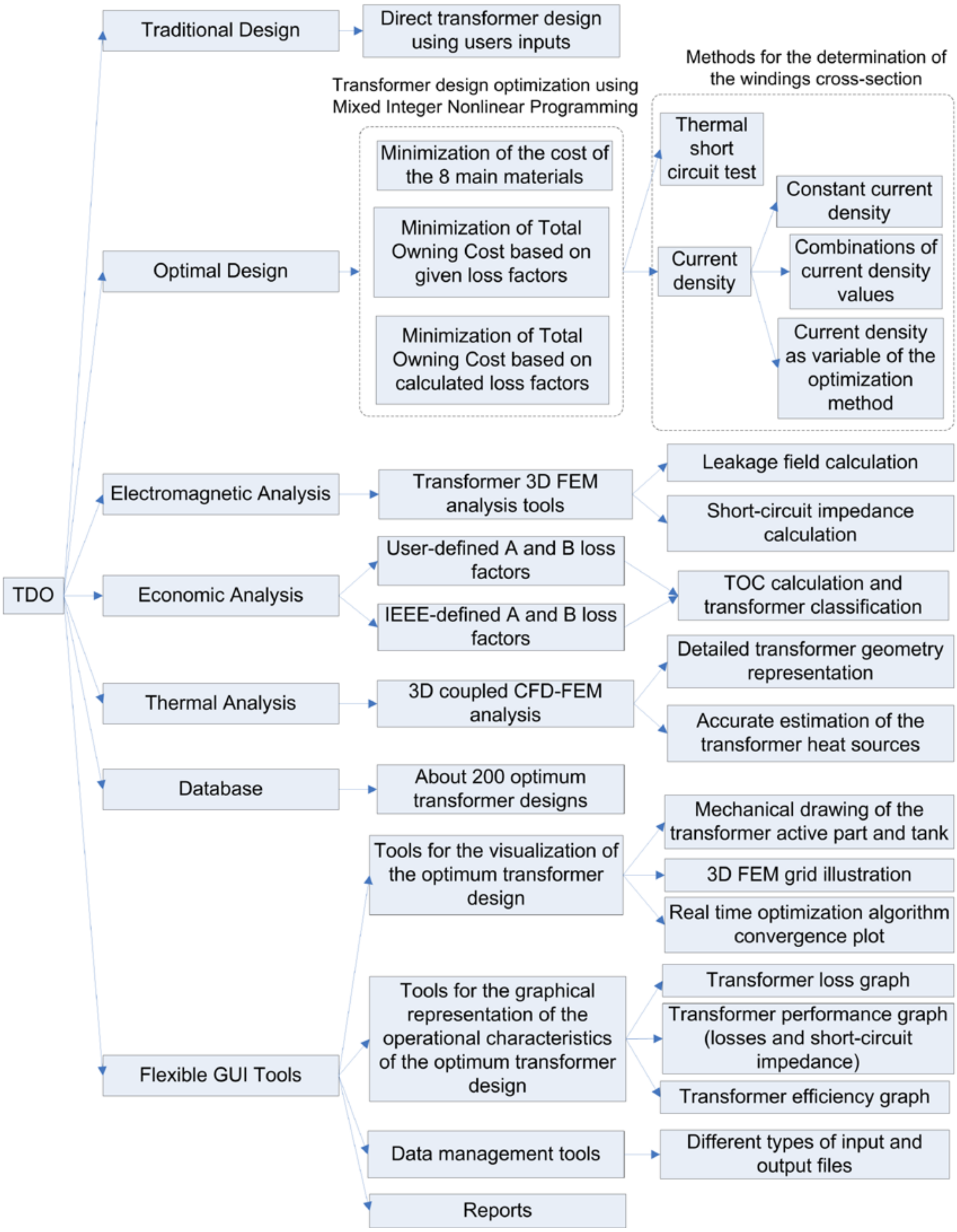


Figure 1. Flowchart of the methodologies integrated in the developed software platform

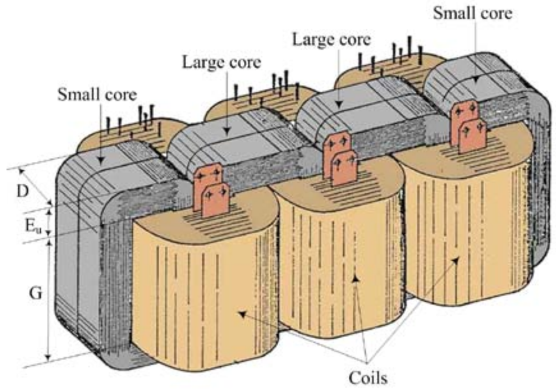


Figure 2. Active part configuration of the three-phase wound core power transformer considered **Error! Reference source not found.**.

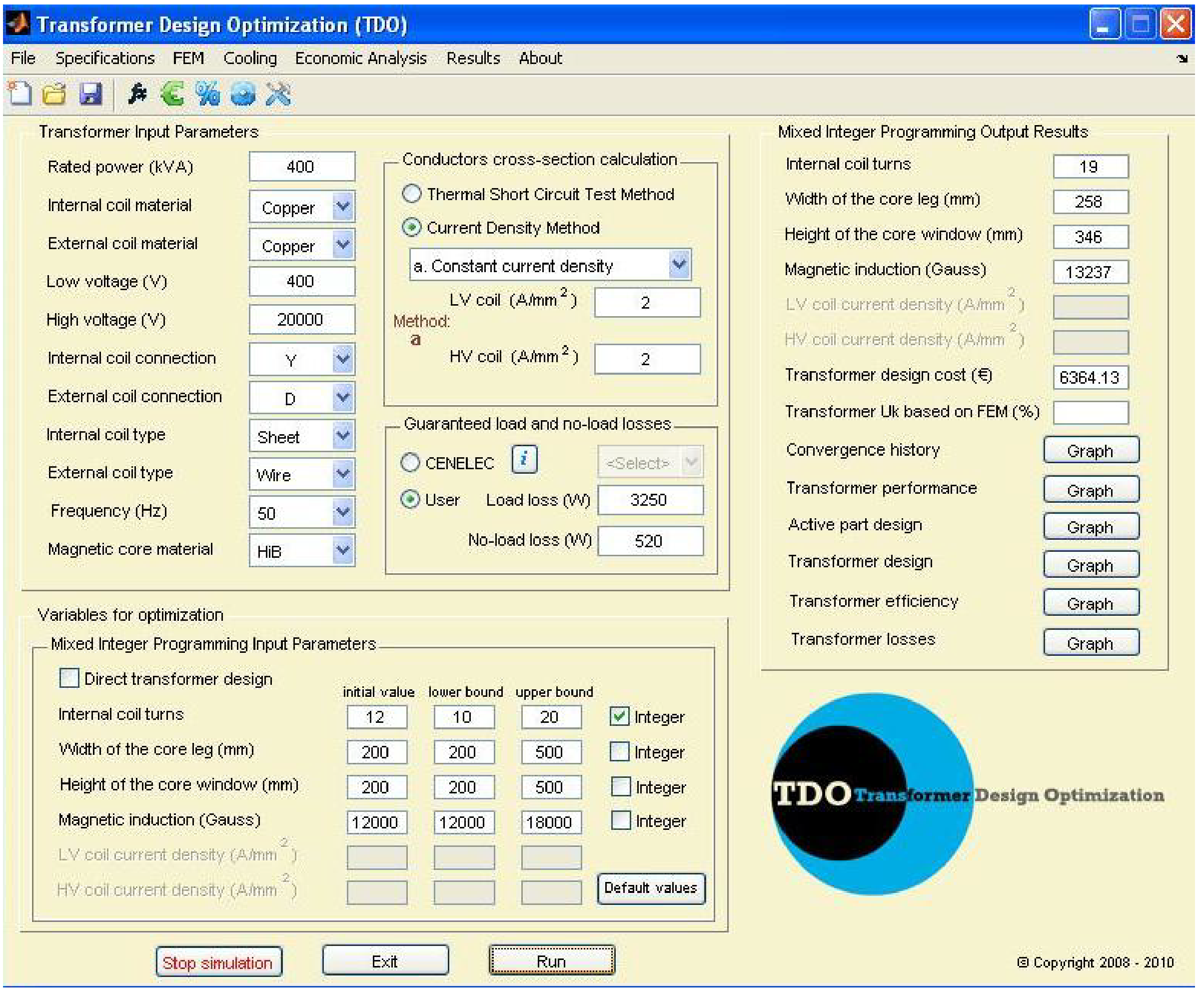


Figure 3. Graphical user interface of the proposed software package.

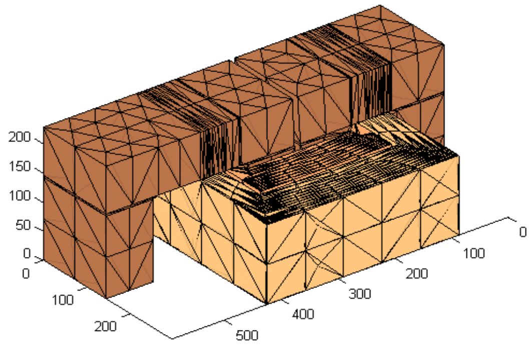
B. Electromagnetic Analysis Tools

After the execution of the MINLP algorithm and the derivation of the optimum design (or the direct design yielded by the user inputs), a set of numerical analysis tools incorporated to the software provide the user the ability to verify its performance characteristics. More specifically a 3D FEM magnetostatic model incorporated in TDO software, developed in [16], is built automatically, using the geometrical data of the optimum solution and computes the transformer magnetostatic field under short-circuit test, according to its main electrical data (Figure 4). This analysis yields the transformer leakage field and short-circuit impedance, which are crucial operational parameters and provide a criterion for the verification that the optimum designs meets the imposed specifications.

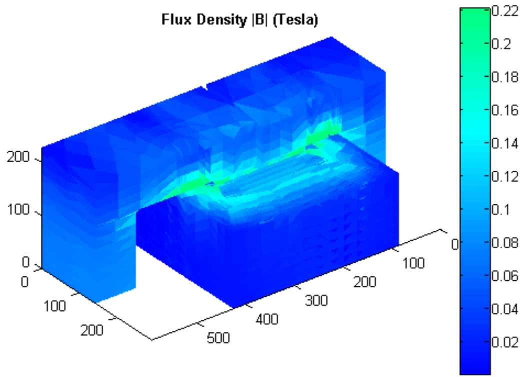
C. Thermal Analysis Tools

TDO incorporates the possibility of thermal analysis by the development of special routines enabling the interaction of different software packages and their parameterization for the examined transformer problem. More specifically, a detailed 3D geometry model of the transformer active and mechanical part according to the design specifications is produced by TDO. Next, a separate software package is employed to create and optimize the 3D FEM mesh needed for the solution of FEM equations [17]. Finally, a finite element software is used for the solution of the coupled problem [18]. Special post-processing routines of the temperature distributions yielded by [18] are implemented in TDO, in order to derive results at specific parts of the active part, as well as the hot spot location. This procedure is necessary in order to specialize and adapt the FEM and

CFD calculations to the specific transformer characteristics [19], while it provides the possibility to repeat and automate the analysis involving a reduced effort.
The proposed methodology combines 3D thermal and fluid flow FEM analysis, for the derivation of the transformer temperature distribution under different loading conditions.

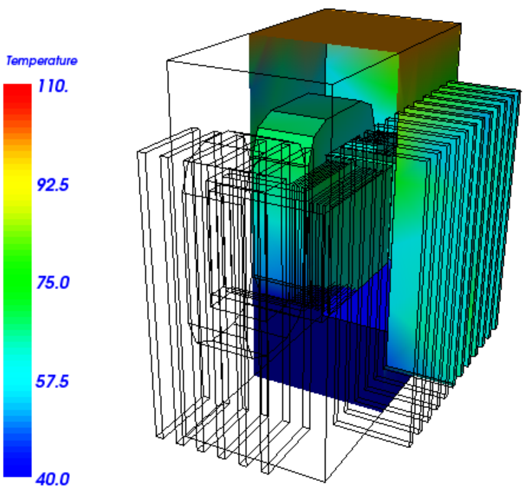


(a)

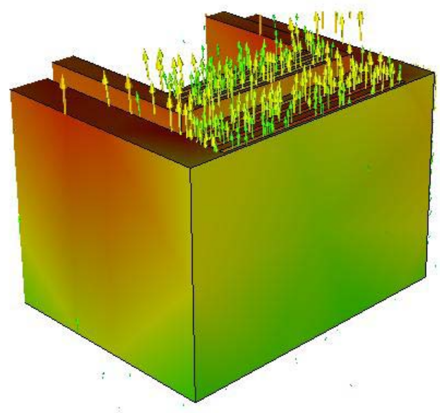


(b)

Figure 4. 3D FEM electromagnetic analysis tools incorporated to TDO: (a) 3D FEM mesh and (b) leakage field distribution.



(a)



(b)

Figure 5. Results of the thermal analysis incorporated in the TDO software: (a) Temperature distribution at the transformer active part and tank walls (operation under nominal load), (b) Vector plot of the oil velocity at the upper parts of the LV and HV windings ducts and gap (the color scale corresponds to the velocity magnitude along the transformer height).

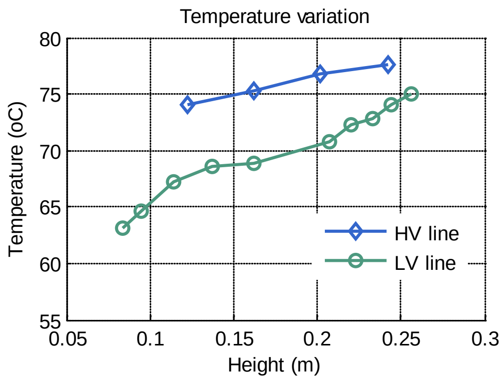


Figure 6. Post-processing of results of the thermal analysis incorporated in TDO software (temperature variation along the inner corner of HV and LV winding).

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