Budapest University of Technology and Economics
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OPTIMIZATION OF COMPLEX INSULATION SYSTEMS

IN THE CASE OF POWER TRANSFORMER DESIGN

Ph.D. thesis booklet

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1 Introduction

1.1 Background of the research

Design of large power transformers is a complex, multidisciplinary task. The competitive market puts high pressure on the designers of the electrical machines. The minimization of the insulation distances has a pivotal role in the literature of the power transformer design optimization. During the design process, several electrical, thermal and mechanical properties have to be intended according to the requirements and requisitions. Moreover, from point of view of competitiveness, not only the technical but the economic aspects have to be considered during the design process [1]. Finding the parameters of the cost-optimal transformer construction in the given economic scenario is a complicated task, which belongs to the most general branch of the mathematical optimization problems [2, 3].

Therefore, in the engineering practice the transformer design process is divided into smaller, simplified sub-problems. The classical electric machine design approach splits transformer design process into the following three steps [4]:

- The preliminary or tender design stage, which is usually sufficient for a proposition, a design study, and the start of a requisition. The output of this step is called the key-design parameters.
- The final design, which is essentially the refinement of the preliminary design to the most minute and complete details. Its output is the final design engineering record and the drafting and manufacturing instructions.
- Checking of the final design, usually by another designer.

The scope of this research is those optimization problems, which are connected to the preliminary design stage. The main problem of the tender design stage is that the key-design parameters of a competitive transformer design have to be found in a very short time, while not only the technical but the economic aspects have to be considered simultaneously. To illustrate, how this optimization task is laborious, in a very simple case. See an idealized product, which is made from 10 standardized components with 10 discrete values [4].

The first analytic approach for transformer optimization is published at the beginning of the twentieth century [5]. Typically these early approaches where obtained using numerous simplifications yielding strong limitations in their scope and applicability. From the beginning of the computer era a lot of algorithm have been developed to calculate the key design parameters. These software utilize a wide range of numerical and mathematical programming methods to enhance the solution process to provide an accurate solution [6].

Numerous kind of objective functions can be defined for a preliminary design optimization task, where the following quantities are minimized [3]:

- minimize the manufacturing cost,
- minimize the total mass,
- minimize the outer dimensions,
- maximize the efficiency.

This research deals with the algorithms which optimize the transformer's total cost of ownership (TCO), which determine the direct and indirect costs of a product through it's lifetime. [3].

This idea is not new, first mentioned by Kapp [5], and at the beginning of the twentieth century the pioneer company in transformer manufacturing (GANZ) considered the lifetime costs. They produced transformers with different core loss and load loss ratios for water and steam power plants [7, 8]. Nowadays, more sophisticated methods are used considering much more economic parameters than the utilization factor of the equipment [9,10].

1.2 Motivation

The background of my research was a geometric programming [1] based transformer optimization program [2, 11], which continuously provided wrong results: higher windings and higher window height compared to what would have resulted from manual calculation. For quite some time it was widely accepted that the calculation errors were caused by the simplifications of the regulating windings, insulation distances and the cooling system. I realized that the difference is caused by the fact that in case of core-type transformers the short-circuit impedance cannot be formulated in posynomial form. The newly developed meta-heuristic algorithms described here not only correct this flaw but also allow to examine the design of the complex insulation system during the preliminary design process.

[1] Geometric programming is a branch of the nonlinear mathematical optimization problems. This optimization problem is formulated by special monomial equalities and posynomial inequalities. It is a rapidly evolving branch of mathematical programming tasks. Due to the newly developed interior point method based solvers even large scaled geometric tasks can be solved in efficiently and accurately in an average personal computer.

The determination of the cost-optimal parameters of a large power transformer is a general, nonlinear optimization task. The aim goal of the designer who follows the classical design rules is to minimize the amount of the insulation in a transformer design. I show some case studies in my thesis where the optimal design contains larger insulation distances than expected. Then my investigations concentrate on the impact of different neglections of the insulation system on the calculated key-design parameter values.

2 Theses

Thesis I

> I have developed a new metaheuristic transformer optimization method by combining geometric programming and the branch and bound algorithm. This new method can determine the cost optimal dimensions of an active part of an autotransformator in the case of different regulating winding arrangements. I have compared the performance of this method with other transformer optimization methods. I have validated the results by a finite element method based transformer design software.

Related publications: (J1) , (J4), (J8), (C1), (C2), (C3), (C4).

It can be proven (C1) that the short-circuit impedance cannot been formulated in monomial or posynomial form in the case of core-form large power transformers. However, (C1) hasn't contains a solution which can solve

This new metaheuristic method can take the into account Rogowski-factor correctly. Moreover, I have extended this method with other core types and the case of autotransformers.

The built-in power of an autotransformer is smaller than it's rated power. Therefore the cost optimal design is in contrast to the classical design rule – the minimalization of insulation volume does not lead to the cheaper transformer design. Combining the geometric programming with the branch and bound algorithms, I have developed a method which guarantees the optimal solution in these aforementioned layouts.

I have shown in a real transformer that the algorithm can found the global optimum of the problem efficiently. The performance of this new metaheuristic algorithm is compared with other heuristic and evolutionary strategy based algorithms.

The accuracy of the optimization results is verified by a finite element based transformer design software.

Thesis II

> I have examined the effect of the well-known simplification – which models the transformer with it's active part neglecting the costs of the oil and the cooling system – on the key-design parameters of a power transformer. I have improved the metaheuristic algorithm transformer optimisation model with new variables for

> taking the cost of the insulation oil and the external cooling system into consideration. I have shown, that in the case of small capitalization factors the cost of the cooling system and the insulation oil has an effect on the turn voltage, hence the core-copper ration of the cost optimal design.

Related publications: (J2) , (J5).

Determination of the cost optimal key-design parameters of a large power transformer is part of the most general branch of the non-linear optimization tasks. Due to the complexity and the importance of this topic several different, simplified transformer optimization model is published in the literature. The determination of the key-design parameters of a power transformer depends on the proper selection of the weight- and dimension ratio of the core and the windings. Therefore, these simplified transformer optimization models deal with the core and the windings (active part) of the transformer. These commonly used models neglect the cost of the outer cooling system and the insulating oil.

I have considered the influence of the insulation - and the cooling system on the key-design parameters of the transformer in a case of a natural oil-flow (ONAN/ONAF) cooled transformer. I have improved the metaheuristic optimization method to be applicable for this investigation.

I have examined the effect of the insulating oil and the outer cooling system on the optimal key-design parameters of a power transformer with the newly developed optimization method.

I have found that in the case of relatively high capitalization factors the cost of the outer cooling system is relatively small, according to the experience. Nonetheless, in the case of small capitalization factors, when the optimal power transformer design has relatively high load losses, the cost of the cooling system has a significant effect on the turn voltage, so the ratio of the core and copper masses.

Thesis III

> I have examined the influence of the tap-changing method selection on the cost optimal key-design parameters of a power transformer. I have improved the newly developed metaheuristic algorithm to take the coarse-fine regulated winding layouts into consideration. I have demonstrated that the coarse-fine regulated transformer can be cheaper than the reversing arrangement above

> a short circuit impedance value in a given economic environment even if this arrangement contains more windings.

Related publications: (J3), (J5), (C2).

The commonly used algorithms in the power transformer industry are using a simplified, two winding model for determination of the cost optimal key-design parameters in the preliminary design stage [6]. In the final design stage the designer complements this optimal two winding model with a regulating winding. This extension modifies the value of the short-circuit impedance, which is corrected by the manual change of the optimized geometry. [12]. These results corresponds to the practical needs but not ensures the optimal solution after this correction step. The different tap-changing methods – linear, reversing and coarse-fine – can be considered with this newly developed metaheuristic optimization method.

The reversing tap-changing method can be considered by the previous version of the metaheuristic optimization method which is shown in my first thesis. Nevertheless, in the case of nominal position ofthe tap changer the regulating winding is inactive. Hence it has just an indirect influence on the short-circuit impedance through the geometry. The new version of the metaheuristic optimization method can take into consideration the cases when the regulating winding is active.

The main advantage of the reversing tap-changing arrangement is its capability to cope with large number of turns without the need of extra regulating winding and insulation distance. Therefore, it can decrease the manufacturing costs compared to a coarse-fine or a linear arrangement. Aside from the further advantages of the coarse-fine regulation: smoother short-circuit impedance change in the full regulation range and cheaper cooling system [12]. I have demonstrated that the coarse-fine regulated transformer is cheaper than the reversing arrangement above a short circuit impedance value in the given economic environment.

Thesis IV

> The next step is the determination of the detailed winding layout after the calculation of the optimal key-design parameters. I have worked out a new, generalized geometric programming based optimization method to solve this design step. This optimization method can determine the optimal conductor dimensions and winding layout for disc type windings. This optimization method

takes the winding gradient and the aging of the insulation into consideration.

Related publications: (J6), (J7).

Modeling the transformer windings with their copper filling factors is a widely used estimation, which provides good practical results. The meta-heuristic optimization method is used this assumption. This simplification can be used not only in the preliminary but in the final design stage, as well. [2, 7, 13]. Nevertheless, many properties of the winding cannot be calculated without the exact knowledge of the winding layout.

This conception uses this widely known assumption [7] that these new design parameters do not have significant impact on the key-design parameters of the core and the cost optimal ration of the core and the copper masses.

The other methods, which can be found in the literature, solve this problem focusing on the minimal short circuit impedance. The suggested method takes the heating of windings into consideration therefore this approach enables to consider the ageing of the transformer insulation.

3 Utilization of the results

The utilization of the previously shown algorithms is continuous from their development. The metaheuristic optimization method, which is shown in my first thesis is used in the High Voltage Solutions kft and their partners. The software is used for decision making in the preliminary design stage, where the task is to find the cost optimal key-design parameters within a short time. This process is facilitated and accelerated by this optimization software resulting in an increase the rate of successful tenders.

Some methods which are discussed in my other publications are used in other software:

- I have compared transformer core temperature rise calculation methods in (J6). Some of these methods are utilized in a core designer software.
- The temperature rise calculation method which is shown in (J7) is used in a temperature gradient calculation tool.
- I have applied the solution of the problem (L1) as an extension of a BEM-FEM solver.

Publications

Publications related to the thesis

Articles in international journals

(J1) T. Orosz, Á. Sleisz and Z. Á., Tamus. "Metaheuristic optimization preliminary design process of core-form autotransformers," *IEEE Transaction on Magnetics*, vol. 52 no. 4, April, 2016. (IF: 1.243)

(J2) T. Orosz, B. Borbély, Z. Á. Tamus,"Performance Comparison of Multi Design Method and Meta-Heuristic Methods for Optimal Preliminary Design of Core-Form Power Transformers," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 61, no. 1, 2017.

(J3) T. Orosz and Z. Á. Tamus. "Impact of the Cooling Equipment on the Key Design Parameters of a Core-Form Power Transformer." *Journal of Electrical Engineering*, vol. 67 no. 6, pp. 399–406, 2016. (IF: 0.483)

(J4) T. Orosz, P. M. Sőrés, D. Raisz, Z. Á. Tamus, "Analysis of the Green Power Transition on Optimal Power Transformer Design," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 59 no. 3, pp. 125-131., 2015.

(J5) T. Orosz, Kleizer, Gábor, Iváncsy, Tamás, Z. Á. Tamus., "Comparison of Methods for Calculation of Core-Form Power Transformer's Core Temperature Rise," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 60, no. 2, pp. 88-95., 2016.

(J6) T. Orosz and Z. Á. Tamus, "Impact of the short circuit impedance and the tap-changing method selection on the key-design parameters of core-form power transformers," Electrical Engineering, Springer, 2017. (https://doi.org/10.1007/s00202-017-0642-z) (IF: 0.569)

(J7) T. Orosz, T. Nagy, Z. Á. Tamus, "A Generalized Geometric Programming Sub-problem of Transformer Design Optimization", Doctoral Conference on Computing, Electrical and Industrial Systems, Springer.

(J8) T. Orosz, I. Vajda, "Design Optimization with Geometric Programming for Core Type Large Power Transformers, " Electrical, Control and Communication Engineering, vol. 6, pp. 13-18, 2014.

Conference Proceedings

(C1) T. Orosz, Á. Sleisz, I. Vajda, "Core-Form Transformer Design Optimization with Branch and Bound Search and Geometric Programming", in *2014 55th*

International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Lettország, 2014.

(C2) P. Sőrés, T. Orosz, I. Vajda, "Lifetime Cost Sensitivity Assessment in Optimal Core-form Power Transformer Design", in: *9th International Conference on Deregulated Electrical Market Issues in South Eastern Europe*, Nicosia, Cyprus, 2014.

(C3) T. Orosz, I. Vajda, "Power Transformer Design Optimization with Geometric Programming," in *Topical Problems in the Field of Electrical and Power Engineering: Doctoral School of Energy and Geotechnology II.*, Parnu, Észtország, 2014.

(C4) T. Orosz, I. Vajda, "Költségoptimális nagytranszformátor tervezés Geometriai Programozás segítségével", in *29. Kandó Konferencia = 29th Kandó Conference*, Budapest, Magyarország, 2013.

Publications directly non-connected to the thesis

Articles in international journals

(J9) Z. Á. Tamus, T. Orosz, G. M. Kiss, "Modelling material dependent parameters of layer type straight coils for fast transient pulses", *Journal of Physics - Conference Series* vol. 646, 2015.

Articles in Hungarian journals

(L1) T. Orosz, Z. Á. Tamus, "Egyszerű módszer vasmagos transzformátortekercsek induktancia-mátrixának a nagyfrekvenciás meghatározására," Elektrotechnika, vol. 108, no. 6, pp. 13-16. 2015.

Conference Proceedings

(C5) T. Orosz, I. Vajda, Z. Á. Tamus, "Modeling the High Nemkonvencionális anyagból készített transzformátor optimalizálása geometriai programozás segítségével," in: *30. Kandó Konferencia [30th Kandó Conference]*, Budapest, Magyarország, 2014.

(C6) T. Orosz, Z. Á. Tamus, I. Vajda, "Modeling the High Frequency Behavior of the Rogowski-coil passive L/r Integrator Current Transducer with Analytical and Finite Element Method", in *Power Engineering Conference (UPEC), 2014 49th International Universities*, Cluj-Napoca, Románia, 2014.

(C7) T. Orosz, A. Szakállas, I. Vajda, "Transzformátor tekercselések helyettesítő kapacitásainak meghatározása koncentrált paraméterű modell számára analitikus és végeselem módszerrel", in *Fiatal Műszakiak Tudományos Ülésszaka XIX. Nemzetközi Tudományos Konferencia*, Kolozsvár, Románia, 2014.

(C8) A. Szakállas, T. Orosz, I. Vajda, "Investigation of Applicability of Direct and Indirect Measurement Methods in the Engineering Education", in *Topical Problems in the Field of Electrical and Power Engineering: Doctoral School of Energy and Geotechnology II.*, Parnu, Észtország, 2014.

(C9) W. R. Fernandes, T. Orosz, Z. Á. Tamus, "Characterization of Peltier Cell for the Use of Waste Heat of Spas", in *2014 55th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Riga, Lettország, 2014.

Other Publications

(O1) T. Orosz, Z. Á. Tamus, W. R. Fernandes, "Peltier-elem vizsgálata gyógyfürdők hulladékhőjének a hasznosítására", *Megtérülő Épületenergetika*, vol. 1, no. 5, pp. 23-27 2014.

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