The Numerical Optimization of an Inductor for Traction Drive Systems - A Parametric Optimization Environment -

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Abstract — **Optimum design is defined as a design that is feasible and the best solution possible. All design variables are determined simultaneously so as to satisfy a set of constraints and optimize a set of objectives. Here, a parametric pre-processor and a general purpose optimization environment are presented. Both are implemented in MATLAB, providing the graphical interface and controlling external processes. Due to the open architecture of the package, finite element as well as analytical models can be implemented. An optimization task is discussed to outline the general application range of the tools. The optimum design of an inductor used in a traction drive system is described in detail. Special attention is paid to the formulation of the quality function.**

I. INTRODUCTION

The development and design of electromagnetic devices reflects a complex process. Originating from an initial idea, the construction runs through different phases. This procedure is terminated when a final concept is selected and considered to be optimized, subject to various targets and constraints. As a whole, the task of the design engineer is to find solutions for technical problems. On the way to the physical and technical product, certain aspects have to be considered. Technological and material depending questions, cost effectiveness and ecological constraints have to be taken into consideration. A cut-set of the mentioned boundary conditions controls the feasibility of the final design. The design process strongly depends on the experience of the engineer and reflects an optimization procedure with often contradicting targets. Therefore, the necessity of a systematic design with engineering tools is obvious. In this paper, solution strategies using modern numerical methods to accelerate and ensure a high standard technical product in an overall design process are discussed.

Simulation and the numerical optimization of electro-magnetic devices is one key to enhance product quality and manufacturing efficiency. Each device has different specifications and thus the goal of the optimization is strongly device dependent. To obtain an optimization procedure which is of general applicability and allows a high number of independent design parameters as well as a simple implementation of a wide range of constraints and the formulation of multiple objectives in a single quality function, heuristic optimization methods are used. Stochastic optimization algorithms as Evolution Strategy, Simulated Annealing and Genetic Algorithms offer all these specifications. The disadvantage of a larger number of quality function evaluations compared with optimization algorithms based on derivatives is largely compensated by the simplicity of the implementation of constraints and multiple goal quality functions [1]-[5]. This disadvantage will vanish with the further development of computer hardware and by applying massive parallel computers.

To predict the system behavior of an electromagnetic device and thus to evaluate the quality of the device under investigation field analysis tools are in common use. Semi analytical [2] and numerical methods can be used. The correct choice of an field analysis tool is problem dependent [1]. To simulate electromagnetic fields the finite element analysis (FEA) of electromagnetic devices has proven to be a reliable tool for the evaluation of new designs. Combining stochastic optimization algorithms and field simulation techniques into an optimization environment allows the creation of an easy to use design tool [1]. Here, a parametric optimization environment is developed to automate the design of electrotechnical devices. The optimum design of an inductor used in a traction drive system is described in detail to demonstrate the methodology and practical implemen-tation of the methods used.

II. PARAMETRIC PRE-PROCESSOR

A key requirement for the combination of numerical field analysis tools and optimization algorithms is a pre-processor providing the possibility to parametrize the 2D or 3D models. This includes, apart from the parametrization of the geometry, the parametric definition of material properties, problem defining data and post-processing algorithms. *MATLAB* has been chosen as the environment to implement an interactive graphical pre-processor. Starting from a sketch of the device geometry, the entire analysis procedure for the model can be

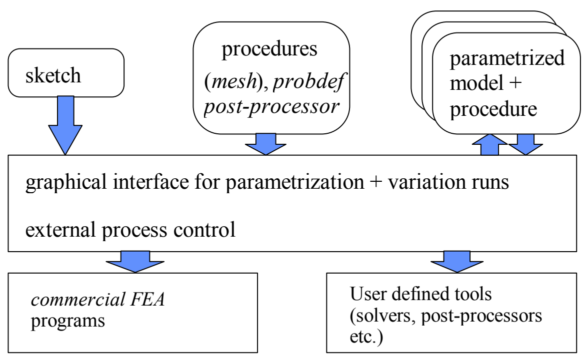

Fig. 1. Structure of the parametric pre-processor implemented in *MATLAB*.

defined. The resulting parametrized sketch file contains all data to describe the steps of the field analysis, constraints checking and the post-processing algorithms (evaluation of the quality function). Once the analysis procedure of the field model is defined, simple parameter variation runs can be performed. Out of *MATLAB* the pre-processor controls the full procedure by calling external programs, such as the mesh generator, equation system solver and post-processor routines. Fig. 1 shows the structure of the parametric pre-processor. The open structure allows the combination of different analysis tools.

III. OPTIMIZATION ENVIRONMENT

The developed optimization environment provides the following features:

1. Different optimization algorithms.
2. Monitoring of the optimization process at run-time.
3. Defined stop and restart procedures in case of problems during execution.
4. Handling parametrized procedures provided by the parametric pre-processor optimizing finite element models.
5. Open architecture supporting the optimization of non-FEA models.
6. Implementation of additional optimization algorithms without changing the whole structure of the environment.

Four optimization algorithms have been implemented into the optimization environment: Evolution Strategy, Simulated Annealing, a combination of both and Adaptive Simulated Annealing. Details can be found in [2]. In case of an optimization of a finite element model, the parametrized sketch file includes all information required to start the optimization. The environment controls the external process calls for the FEA. Whereas the parametric pre-processor is an interactive graphical tool, the optimization process is entirely automatic and can be run as a background process. The optimization can be stopped at any time and restarted from the previous position. This feature has been found very useful in a network environment, when a long lasting optimization should be stopped to allow for the maintenance of the network. The progress of the optimization can be monitored graphically. Depending on the optimization algorithm, key data may be visualized together with the variation of all parameters. Due to the open architecture of the optimization environment, non-FEA models can be processed as well. The user has to provide the constraints checking algorithm and the quality function, that may be external programs or *MATLAB*-macros (Fig. 2).

IV. OPTIMIZATION OF AN INDUCTOR - AN ANALYTICAL APPROACH

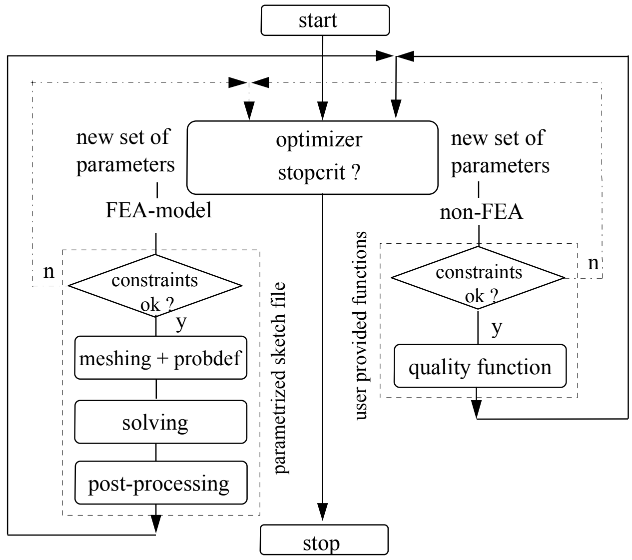

Fig. 2. Structure of the optimization environment.

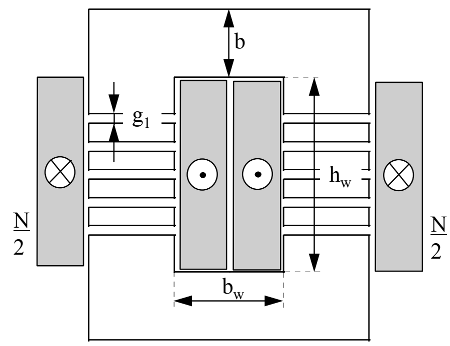

Fig. 3. Geometry and design parameter of the inductor example.

TABLE I
SET OF DESIGN PARAMETER AND CONSTRAINTS

set of design parameters:		constraints:		
b	yoke width	$d+b_w$	<	500 *mm* (depth)
d	yoke thickness	$2*(b+b_w)$	<	750 *mm* (width)
b_w	window width	$2*b+h_w$	<	660 *mm* (height)
h_w	window height	g_0	<	$h_w/2$
g_0	total air gap	J	<	10 A/mm^2
N	number of turns	B_{max}	<	1.5 *T* (no saturation)

As an example the optimization of the design of an inductor used in a traction drive system is chosen (Fig. 3). Apart from the required electrically and magnetically characteristics a minimum of weight is demanded. Here, the inductor must have an inductance L of 3 mH up to a maximum current of 1350 A. The current density J in the copper windings must not exceed 10 A/mm^2. The maximum dimensions for the inductor are given values constraining the geometry (Table I). The total air gap is subdivided into multiple gaps with a length less than 1/6 of b and d respectively to minimize the leakage flux. An (4/4, 20)-Evolution Strategy was chosen to tune the design parameters

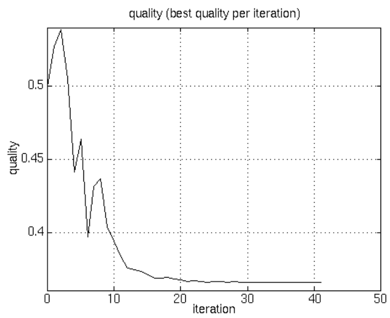

Fig. 4. Quality versus iteration count during optimization.

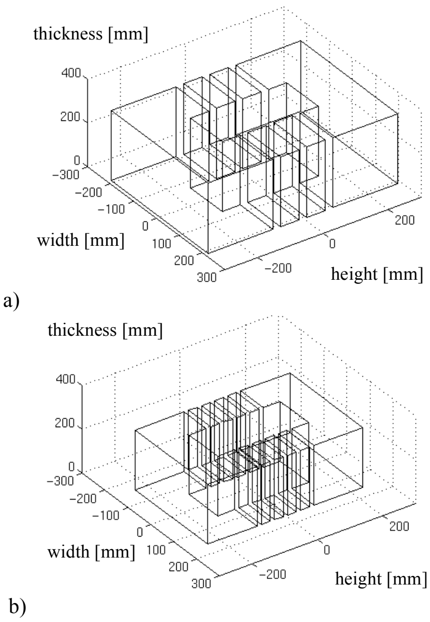

Fig 5. a) Initial and b) optimized geometry of the inductor.

during the optimization [2]. Particular attention must be paid to the formulation of the quality function q.

$$q = \frac{m_i}{1000} + \frac{\left| L_{given} - L_i \right|}{L_{given}} + penalty$$

with (1)

$$penalty = \begin{cases} 0 & : \; if \quad B_i \le B_{max} \\ \dfrac{\left| \mathrm{B}_{max} - B_i \right|}{B_{max}} & : \; if \quad B_i > B_{max} \end{cases}$$

Here m_i is the weight of the inductor, L_{given} is the specified inductance of 3 *mH* and B_{max} is the maximum flux density inside the iron parts. Index i indicates the quantities calculated from the actual set of design parameter. The set of parameter is rejected in the case constraints are violated and new sets of design variables are generated until they meet the constraints [2].

The optimization run is started with an initial set of parameters not matching the constraints. Fig. 4 shows the rate of convergence of the numerical optimization for the inductor. One of the first accepted parameter sets describes an inductor with a total weight of 650 *kg* (Fig. 5a). Using the Evolution Strategy, the step length of the parameter variation is used as stop criterion. After the optimization, the inductance is maintained at 3.001 *mH* and the flux density and the current density do not exceed the maximum values. The final weight is 349 *kg* (Fig. 5b).

CONCLUSION

A parametrized environment for the optimization of electromagnetic devices has been developed. The emphasis was put on the development of a tool that is easy to use and applicable to both, FEA and non-FEA field simulations. The example demonstrates the open architecture of the environment and will be extended in future, incorporating more optimization algorithms. Another central point in the further research and already started activities is the automatic selection of the parameters defining the optimization strategy and the massive parallelization of the procedures.

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