Integrative Scheme/Tool for Automated Development of Switched Mode Power Supplies based on SIMPLORER

N. Froehleke, H. D. Njiende, D. Hahm
Institute of Power Electronics and Electrical Drives
University of Paderborn
Pohlweg 47-49
33098 Paderborn, Germany
froehleke@lea.upb.de
http://lea.upb.de

P. Wallmeier

Ascom Energy Systems
Coesterweg 45
59494 Soest, Germany

peter.wallmeier@ascom.de
http://www.ascom.com

Acknowledgement

The authors acknowledge gratefully the financial support granted by the European Commission under project BRST- CT98 5310, the co-operation with University of Leuven and the support by the industrial partners of the consortium.

Keywords

High frequency power converters, Switched-mode power supplies, magnetic devices, design , software.

Abstract

A survey about a CAE-tool for the optimized development of SMPS is presented incl. its underlying methodology, supporting the selection of power and control topologies by an expert system, the magnetic component and thermal design by an enhanced modeling base for transformers and inductors, embedded into the multi domain simulator SIMPLORER. Additionally, off-line tools for analysis of the ever increasing multitude of new power electronic topologies and controllers based on MATHEMATICA supplement the tool to facilitate an efficient evaluation and comparison[1]. A design optimizer for magnetic components with solenoidal or planar windings is accessible through the SIMPLORER simulation sheet, which proved its capability on various applications by considerable power loss or volume reductions

1. Introduction

Switched mode power supply (SMPS) producers are facing fast technological developments in the fields of power semiconductors, circuit and control topologies. Contrary to these positive factors for innovation is the limited availability of computer tools capable of shortening the innovation cycle and which assist the design personnel during the entire development process of high quality products.

Available simulators used in the power electronic field neither offer a support for selection of switched mode power supply (SMPS) topology and controller assigned to customer specifications nor a means to perform the physical design and automated optimization of magnetic components. Since the capability to adapt development schemes to new requirements and regulations decides about the future competitiveness of SMPS-producing industries, the objective of the underlying project CAE-WPS [1] for this contribution intends to reduce costs, time to market, required design expertise and to increase the quality of virtual prototyping. This contribution describes a new design methodology for a computer aided design tool for SMPS supporting the following functions:

---

[1] Funded by the European Community, Contract N° BRST-CT98-5310 (DG 12 - HIAS), Integrative CAE-tools for optimised development of welding power supplies with high power density“, For information search for „CAE-WPS“ in "*dbs.cordis.lu/EN_GLOBALsearch.html*"

- A *computer aided selection* (CAS) of the best matching power supply topologies using a knowledge base.
- A *computer aided DC and AC analysis* (CAA) of power circuitry developed with a computer algebra program generating input for improved model libraries [1].
- *Design* of power electronic, control circuitry and magnetic components, taking care of high-frequency effects, using a computer aided design program (CAD) supported by the CAA-model libraries, libraries for the selection of components, materials, and circuit and system simulation using multi domain simulator SIMPLORER [2].
- *Thermal design* through SIMPLORER using compact models for power semiconductors and magnetic components, while total assemblies are simulated using macro models for airflow, screens, heatsinks etc. parameterized by thermal simulations and measurements [3] or by coefficients taken from literature.
- *Computer aided optimization* (CAO) of magnetic components with respect to selected cost functions which might be efficiency, weight etc. by applying state-of-the-art numerical optimization algorithms [4], [5], [6].

Improved models for magnetic components with respect to electrical and thermal behavior upgrade the SIMPLORER and simulation results and lead subsequently to more efficient designs.

Figure 1 illustrates the structure of the tool. The left side contains the modules of tool CAE-WPS, which

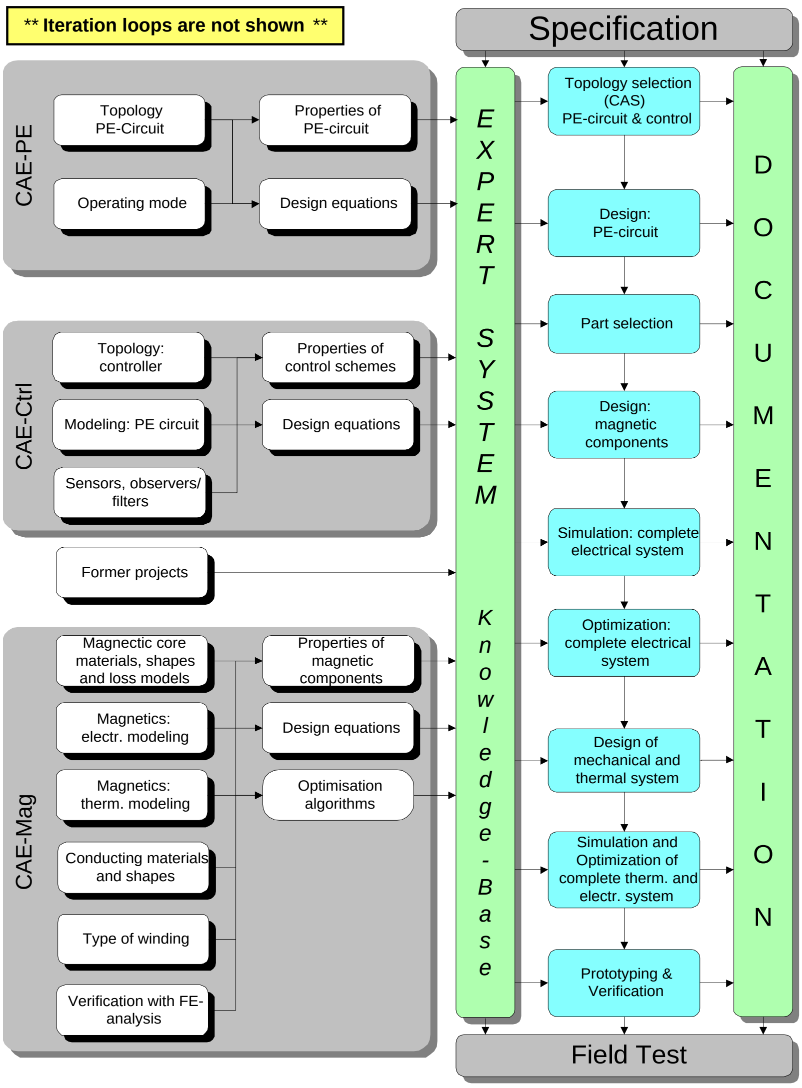
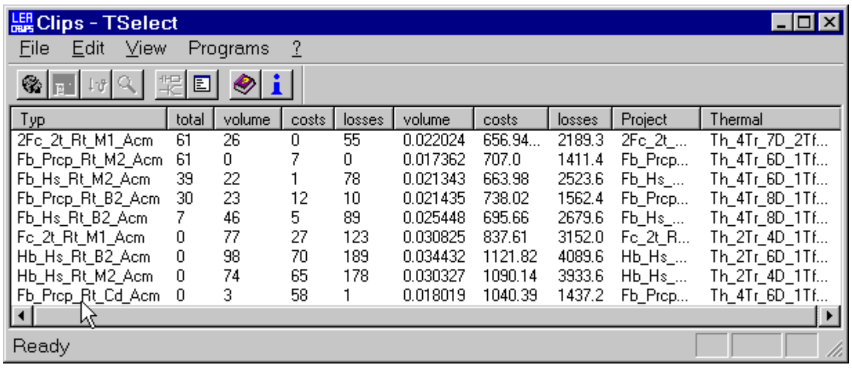


Fig. 1 : Structure of CAE-WPS. Blocks on the left side represent blocks that generate data for the knowledge base, which is used during the design stages shown on the right.

are linked via the expert system to the design process on the right side. Note, that the expert system comprises both the knowledge base and the expert system shell, which was implemented using CLIPS [7].

2. Selection and Parameterization of a Power Circuit

Until *today* the *development of WPSs*, or in general SMPS, follows the time consuming and costly procedure: The developer selects the circuit topology according to specifications predominantly using already known and qualified concepts, which are not necessarily the optimal ones. After design of components and calculation of stress quantities the selection of off-the-shelf components is performed, while the magnetic components are specifically designed. It is not common practice, yet, that the total circuit comprising power and control part, is simulated before building it, in order to reduce the time consuming and costly experimental phase. Reasons are lack of adequate models for power components and wiring/parasitics. Thus, the *design duration* and the *results* are heavily *relying* on *experience, qualification* and *motivation* of the designer, which is a non satisfying, intolerable situation.


Clips - TSelect

File Edit View Programs ?

Typ	total	volume	costs	losses	volume	costs	losses	Project	Thermal
2Fc_2t_Rt_M1_Acm	61	26	0	55	0.022024	656.94...	2189.3	2Fc_2t_...	Th_4Tr_7D_2Tf...
Fb_Prcp_Rt_M2_Acm	61	0	7	0	0.017362	707.0	1411.4	Fb_Prcp...	Th_4Tr_6D_1Tf...
Fb_Hs_Rt_M2_Acm	39	22	1	78	0.021343	663.98	2523.6	Fb_Hs_...	Th_4Tr_6D_1Tf...
Fb_Prcp_Rt_B2_Acm	30	23	12	10	0.021435	738.02	1562.4	Fb_Prcp...	Th_4Tr_8D_1Tf...
Fb_Hs_Rt_B2_Acm	7	46	5	89	0.025448	695.66	2679.6	Fb_Hs_...	Th_4Tr_8D_1Tf...
Fc_2t_Rt_M1_Acm	0	77	27	123	0.030825	837.61	3152.0	Fc_2t_R...	Th_2Tr_4D_1Tf...
Hb_Hs_Rt_B2_Acm	0	98	70	189	0.034432	1121.82	4089.6	Hb_Hs_...	Th_2Tr_6D_1Tf...
Hb_Hs_Rt_M2_Acm	0	74	65	178	0.030327	1090.14	3933.6	Hb_Hs_...	Th_2Tr_4D_1Tf...
Fb_Prcp_Rt_Cd_Acm	0	3	58	1	0.018019	1040.39	1437.2	Fb_Prcp...	Th_4Tr_6D_1Tf...

Ready

Fig. 2: Typical output of the assessment of topologies by TSelect

The software system CAE-WPS is *structured modular* (see Fig. 1) and shows three different levels: at the *lowest level* software modules are generated, supporting/accelerating the *analysis* and *design stage* by computers. Although the various modules are coupled an interactive operation is supported and the comparison of design variants. *Optimising strategies* are forming the base for the *intermediate* level,

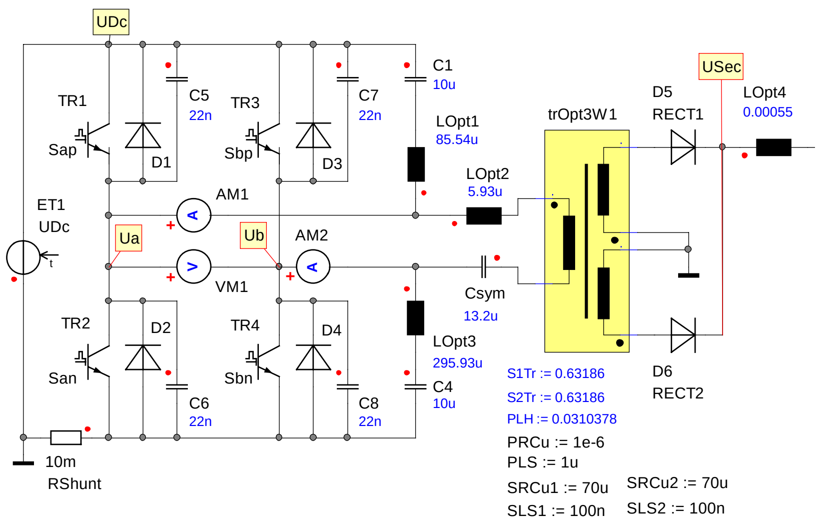


Fig. 3: Typical model of the power circuitry (excerpt) used for SIMPLORER simulations

supporting the design of magnetic components but not the total power electronic circuit, yet. The *highest level* is devoted to the *expert system* which supports the user by selecting the right circuit and controller topology, type of magnetic assembly and makes use of former projects.

Contrary to above mentioned hand governed design process – supported in maximum by decoupled computer tools – nearly the entire design is computer assisted within CAE-WPS. More specifically, aspects of power electronic circuitry are treated within module CAE-PE (see Fig. 1), which comprises a topology library, a component library, and selection rules. Using computer aided analysis of converter topologies based on Mathematica [1], [8] symbolic expressions for design rules and stress quantities are calculated and fed into the knowledge base. Before calculating evaluation criteria for each converter pre-selection rules are applied, which provide criteria for exclusion of topologies not suitable for the given specification in order to raise the efficiency of the tool. For qualifying topologies, however, part values and stress quantities are computed yielding a means to compare them in respect to user defined design goals. The software module TSelect generates a choice table (incl. estimated values for volume, cost, and losses, see Fig. 2) serving to select a topology, for which a ready-to-use SIMPLORER simulation model is created automatically and initial values are calculated, as depicted in Fig. 3. After a training on the tool the industrial partners of the project used the tool to develop welding power supplies based on state-of-the-art topologies, such as [15] and [16].

3. Controller Selection and Design

The controller selection and design tool (CAE-Ctrl) (see Fig. 1) used to compare different control schemes is also based on results obtained by a Mathematica based software package. Knowledge gained by the use of this module is fed into the knowledge base to assist the designer selecting the appropriate control scheme. For enhancement of the user interface control schemes are included in the simulation templates available for each topology. Like the part values, the controllers are automatically parameterized by TSelect when generating the electrical simulation model. So far, basic control schemes like peak-, average- [11], [13], and constant-on-time-current-mode control were implemented and tested. A typical implementation is shown in Fig. 4, which employs both block diagram and state graph to model the controller and modulator.

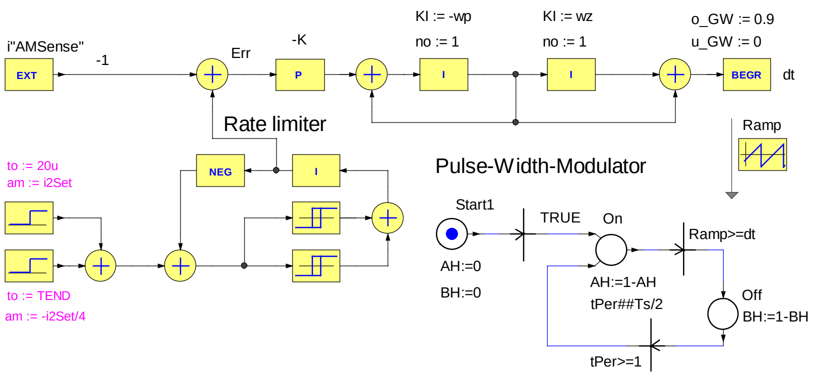


Fig. 4: Model of average current mode control (block diagram) and modulator (state-graph) (excerpt)

4. Thermal Model

The tool CAE-WPS in conjunction with SIMPLORER allows generation of temperature predictions based on compact modeling of components and of the WPS-assembly. The use of ordinary differential equations allows the description by equivalent resistance-capacitance networks, which became only recently a viable tool for system design and are of course simple to integrate in a multi domain simulator. Primarily used in electronic equipment cooling the networks are derived either numerically or experimentally, see [14]. However, no other reference is known on parameterization of such models in order to generate an optimum electro-thermal system design. Using TSelect, for each power electronic component the average power dissipation is calculated, either by direct symbolic formulae or via simulations. The dissipated power is input to a thermal model of the magnetic components and the

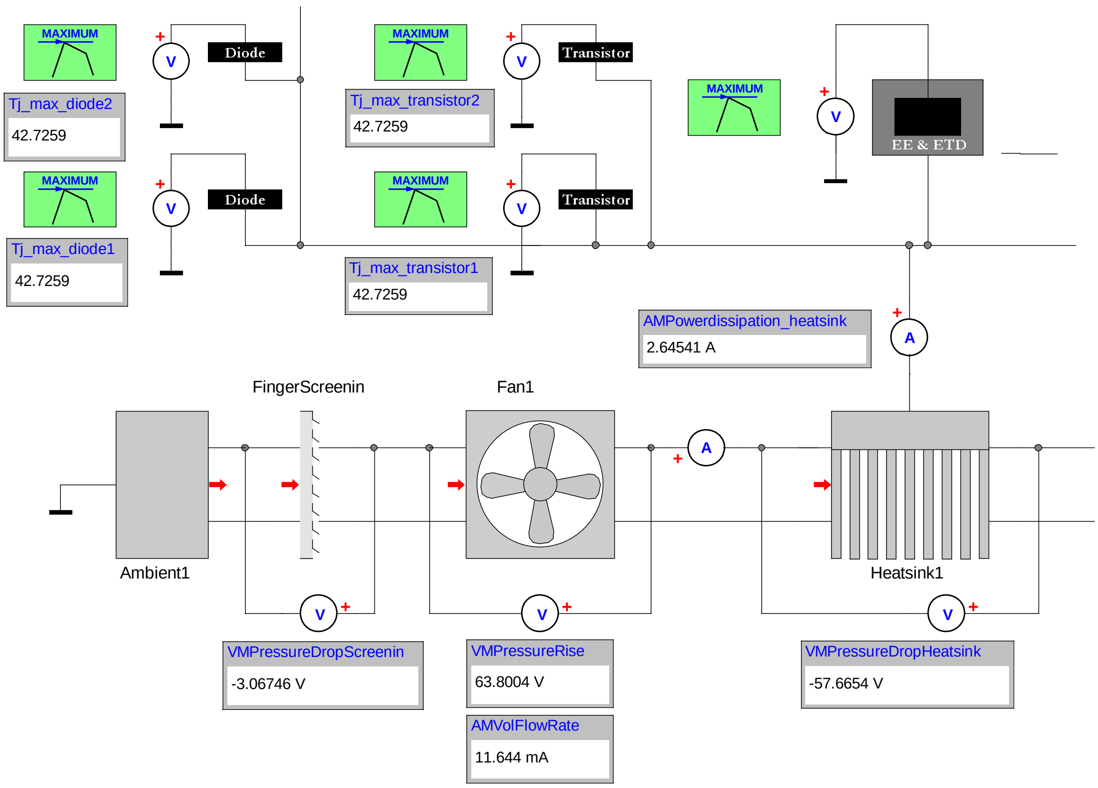


Fig. 5: Example of a thermal model used by CAE-WPS (excerpt)

power supply assembly, which comprises power electronic parts as well as heat sinks, fans, screens, wind tunnels, etc. Thus, it is possible to locate hot spots within magnetic devices and the assembly before the prototyping stage. An excerpt of a typical model is depicted in Fig. 5.

5. Magnetic Component Design and Optimization

The design of magnetic components (CAEOMAG) is performed within two steps, see [4] and Fig. 6 for data flow between CAEOMAG and SIMPLORER. A rough pre-design/optimization, included in the expert system, is implemented, based on the area product approach using simulated stress quantities, wherefrom crest factor, volt-second etc. derive. This pre-optimization algorithm provides data about the expected volume, losses and temperature rise of a fixed core and winding set-up of inductors and transformers, inputted via a graphical user interface, see Fig. 7 a). Thus, initial values for a subsequent optional parameter optimization of these components are derived. The core and winding dimensions, like e.g. the air gap width, the layer thickness in gapped inductors and in transformers are optimized with respect to design objectives such as minimum temperature rise, minimum power losses, etc., summarized in objective function F, see [4], and which is shown in Fig. 7 b).

The underlying electrical winding model, briefed in [4] and elaborated in [5], supports planar and solenoidal wound gapped inductors and transformers using foil, litz or round wires and considers all relevant parasitic effects like eddy current losses, leakage, gap effects and core losses including rate dependencies and capacitive effects. Skin and proximity effects, caused respectively by inner current density displacement and by eddy currents, are considered in a way that considerable accuracy improvements result [6], [12]. Edge effects are considered by manipulating the skin effect factor after FEA analysis of foil windings in solenoidal structures and multi-turn windings in planar structures were evaluated. To account for gap effects caused by the fringing field in air gaps, a method utilizing the current sheet technique and a separate field solution for induced fields was implemented for linear gapped solenoidal inductors in [6] and [12]. The core is divided into straight and curved segments whose respective losses are summarized to the total core losses. The reluctances of the segments are calculated using mean cross section and path length formulations. The influence of air gap fringing is considered by applying conformal mapping techniques. The capacitance model uses a plate capacitor approximation assuming a radial electric field for solenoidal and an axial field for planar structures.

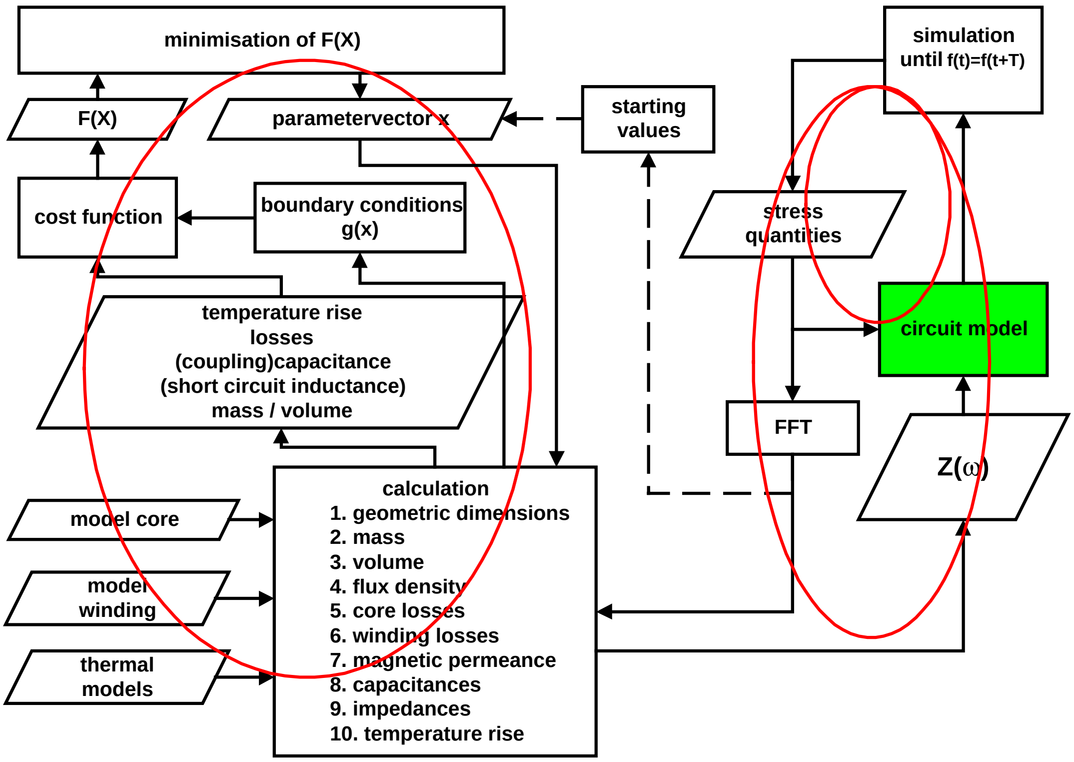


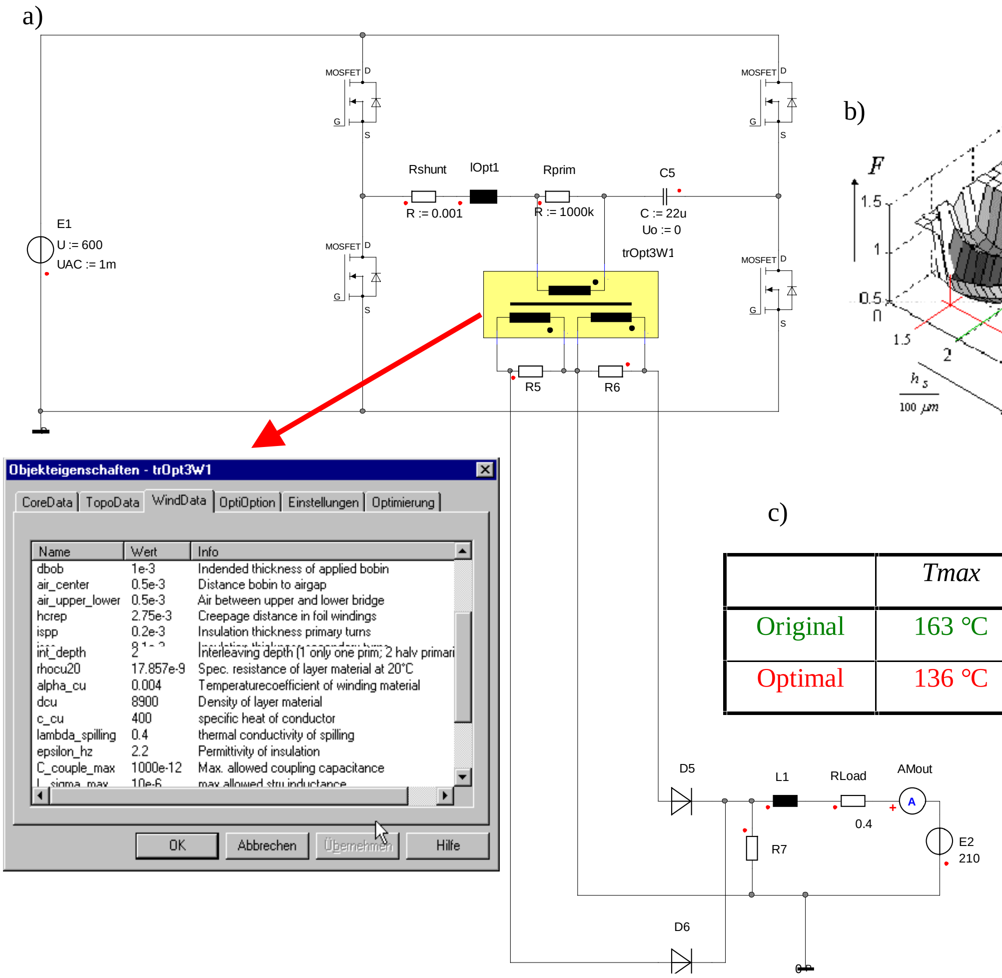
Fig. 6: Design and Optimization tool CAOMAG – setup and iteration loops

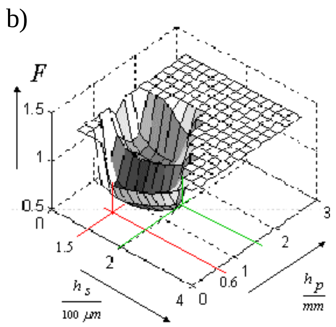
6. Experimental Results

Fig. 7 a) shows an excerpt of a schematic of a power stage of a 5 kW (10 kW peak) welding power supply and the user interface of the transformer design and optimization together with the objective function (see Fig. 7 b)) using a constant core but variable primary and secondary conductor thickness. Note, the two major subminima caused by the discontinuous change in parallel connected wires to fill the window as good as possible. Losses of the original design are reduced by at least 24 %, which leads to a temperature decrease of 27 °C. The model accuracy compared to measurements of the original transformer is depicted in Fig. 8 using the short circuit impedance as model quality indicator. The model reveals good agreement with the measured values as well for the resistance as for the inductance. Please note, that the winding consists of two different winding types, complicating the modeling tremendously. The matrices Cs and Cp code the series and parallel connection scheme of the layers. Entries of 1 in the i-th and j-th column of a row in Cs indicate a series connection of these layers. Analogous is true for the parallel connection.

Fig. 10 shows the connection editor. Layers are numbered starting from inside. Type of conductor (foil, litz or round wire), thickness of layers and number of turns are set.

As shown in Fig. 9 a) for a 5 kW welding power supply an inductor was optimized and designed. The air gap length and the conductor thickness are optimized while other dimensions are kept constant. Fig. 9 b) shows a parameter optimization of the air gap width and conductor thickness with the objective function *F* being minimized.

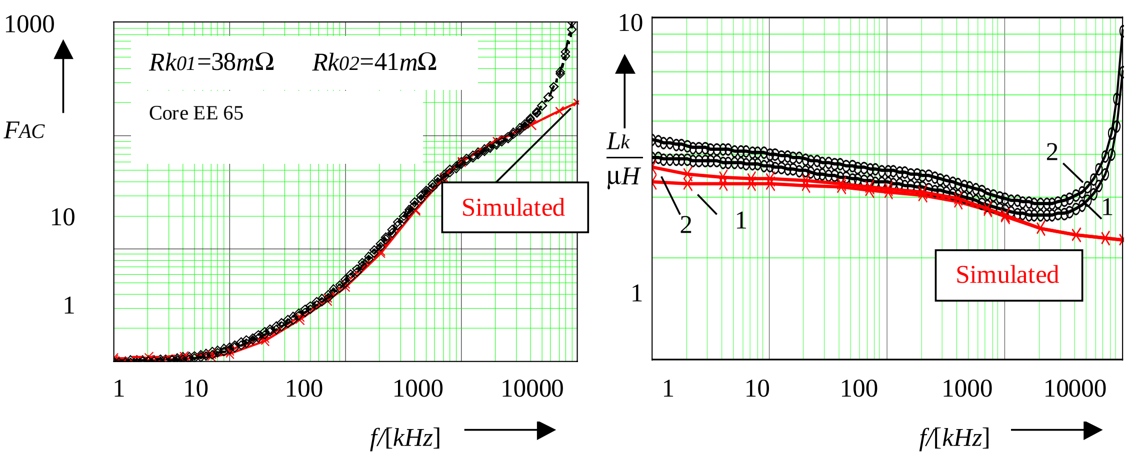




c)

	Tmax	*Pv*
Original	163 °C	112 W
Optimal	136 °C	85 W

Fig. 7: a) A part of a SIMPLORER-worksheet of the 5 kW-welder (10 kW peak) and the Wizards for a transformer b) Result of a parameter study and c) comparison of optimum and current design.



Connection Data Cs: 1000000000000000000000 0000000000000000000001 0111111111100000000000 0000000000011111111110	Cp: 1100 0010 0001	Layers: Primary: 1.4 mm round wire, Secondary: 0.2 x 36 mm Cu-foil	Ni: 20,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,20 leg_info: 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Fig. 8 : Measured and simulated resistance ratio of 5 kW - transformer design example and its winding data

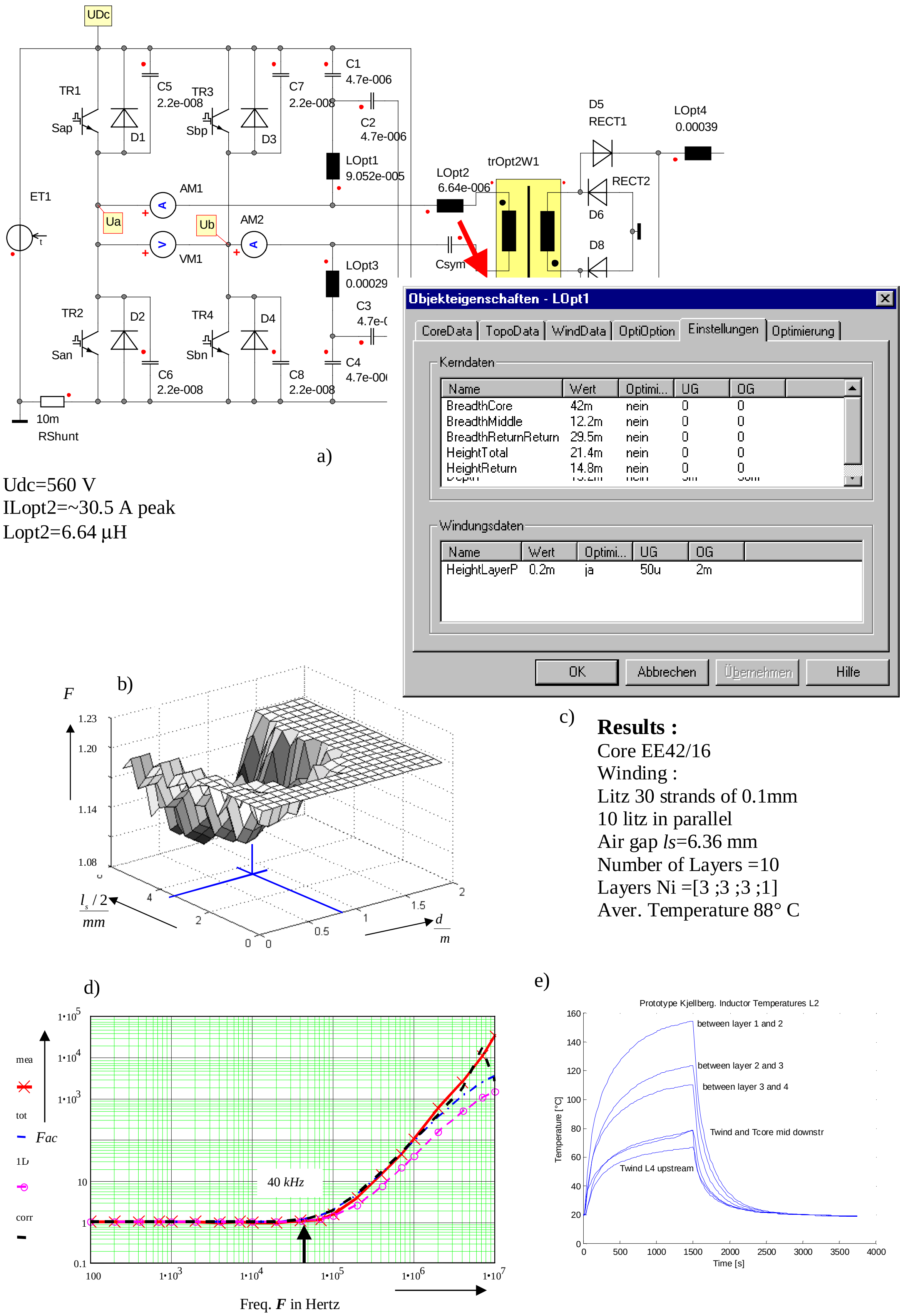


Fig. 9: a) A part of a SIMPLORER-worksheet of the power supply and the wizard for the inductor Lopt2, b) Results of a parameter study, c) optimization results , d) Measured and simulated resistance ratio of the inductor and e) Temperature measurement of winding and core of the inductor.

After optimization a configuration of 10 litz of 30 strands in parallel and 10 windings is found. The optimized air gap width is set to be 6.36 *mm*. The results are outlined in Fig. 9 c). The model accuracy is illustrated in Fig. 9 d) with resistance factor F_{AC} as quality factor. Depicted are measurement results (mea), and F_{AC} considering only 1D-effect (1D), F_{AC} considering 1D and 2D (air gap) effects (tot) and correction of the last taking the resonance into account (corr).The accuracy error between measurement (mea) and simulation (corr) is less than 5%at a switching frequency of 40 kHz. Temperature measurements are illustrated in Fig. 9 e). The difference between measurement after 1500s (~80°) and simulation (88°) is about 10%. Considering that the measured temperature value at steady state is a little higher this error is even smaller.

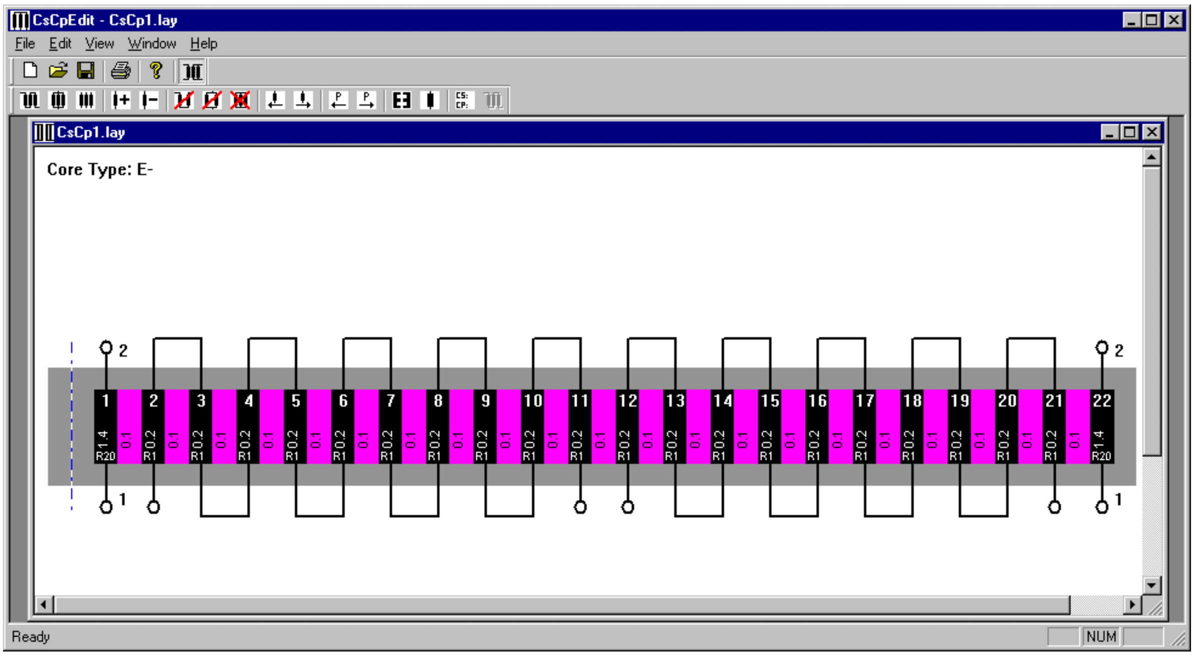


Fig.10: Series and parallel connection editor

Summary and outlook

In this contribution a CAE-tool for the optimized development of SMPS is presented incl. its underlying methodology, supporting the selection of power and control topologies by an expert system. The methodology and results of simulator-coupled magnetic component design and optimization tool are outlined. Optimization and modelling of welding power supply transformers and inductors are presented. The optimization shows a power loss reduction of a selected transformer of at least 24%. All parasitic effects are considered in the modelling so that design results and measurements are quite accurate.

Further research and implementation work e.g. in fields of low power topologies, filter design, upgrade of electro-thermal modelling of magnetic components and assemblies is planned towards maturing the CAE-WPS tool. A web-based tool which is under development, will be available at the beginning of the next year, while the whole development facilities will be available as add-on to SIMPLORER in 2002.

References

[1]. J. Sun, H. Grotstollen. *A Symbolic Computation Package for Averaged Analysis of Power Electronic Systems*, Proceed. Of 15th Ann. IEEE Applied Power Electronics Conf. (APEC) 1996, pp. 96-102.

[2]. SIMEC GmbH. *Reference Manual to the simulator system SIMPLORER*, Chemnitz, Feb. 1999.

[3]. K. VAN DAMME, M. BAELMANS. *Thermal Modelling of Welding Power Supplies with High Power Density in a CAE-Environment,* presentation at the 6th Int. Workshop on Thermal Investigations of IC´s and Systems (Thermonic), in Budapest, Sept. 24th – 27th , 2000.

[4]. P. WALLMEIER; N. FRÖHLEKE; D. HAHM; H. MUNDINGER. *Integrating magnetic component design and optimization into circuit simulator SIMPLORER,* Power Conversion and Intellig. Motion (PCIM) 2000, June 2000, pp. 533-538.

[5]. P. WALLMEIER. *Automatisierte Optimierung von induktiven Bauelementen für Stromrichteranwendungen,* Ph.D-Thesis, University of Paderborn, 2000.

[6]. P. WALLMEIER, H. GROTSTOLLEN. *Automated optimization of high frequency inductors,* Proceed. Of Ann. Conf. of IEEE Ind. Electronics Society (IECON), Aachen, 1998, pp. 342-347.

[7]. STB LYNDON B. JOHNSON SPACE CENTER. *CLIPS "User Manual,*" Aug. 98, www.ghgcorp.com/clips/CLIPS.html

[8]. N. FRÖHLEKE, R. PIEPER, H. MUNDINGER, H. GROTSTOLLEN. *Computer Aided Investigation of the Auxiliary Resonant Commutated Pole Converter for Wide Range Applications such as Welding Power Supplies*, 25th Ann. Conf. of the IEEE Ind. Electronics Society (IECON 99), San Francisco , November 29th – Dec. 3rd , 1999, pp. 891 – 896.

[9]. F. CANALES, P. M. BARBOSA, F. C. LEE. *A Zero Voltage and Zero Current Switching Three Level DC/DC Converter,* APEC 2000, pp. 314-320.

[10]. R. AYYANAR, N. MOHAN. *A Novel Full-Bridge DC-DC Converter for Battery Charging Using Secondary side Control Combines Soft-Switching over the Full Load Range and Low Magnetics Requirement,* APEC 2000, pp. 340-346.

[11]. P. COOKE. *Modeling Average Current Mode Control,* APEC 2000, pp. 256-262.

[12]. P. WALLMEIER., H. GROTSTOLLEN. *Improved modeling of inductive losses in gapped HF-inductors,* Proc. of IEEE Ind. Appl. Soc. Annual Meeting (IAS) 1998, pp. 913 – 920.

[13]. J. SUN, R. M. BASS. *Modeling and Practical Design Issues for Average Current Control,* APEC 1999, pp. 980-986.

[14]. F. CHRISTIAENS. *Thermal Modelling and Characterization of Electronic Components: Steady-State and Transient Analysis,* Ph-D Thesis, Kath. Univ. of Leuven, Belgium, 1998.

[15]. H. MUNDINGER, N. FRÖHLEKE, M. SCHNIEDERMANN. *Enhanced Analysis and Design of a 3-level DC/DC converter with zero voltage and zero current switching,* to be reviewed for EPE 2001.

[16]. N. FRÖHLEKE, H. MUNDINGER, A.O.: *Resonant Transition Switching Welding Power Supply*, Int. Conf. on Ind. Electr. Contr. & Instr., IECON 97, pp. 615-620.