OPTIMIZATION OF INDUCTORS IN POWER CONVERTERS FEEDING HIGH POWER PIEZOELECTRIC MOTORS

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Abstract

Magnetic components are key components in power converters. In order not only to reduce the losses but also to reduce the expenses and the production time, the behavior of magnetic components has to be accurately predicted and some geometrical parameters be optimized. The design and optimization tool (CAEOMAG) is integrated in a circuit simulator SIMPLORER. This tool is succinctly presented in this paper. The optimization parameters are the core geometry, the air gap length or the layer thicknesses. Using a new approach of optimization: the distance between the air gap and the inner layer is optimized for reducing the losses caused by the air gap fringing and for decreasing hot spot temperatures. The inductors designed for a LLCC-resonant converter were optimized using CAEOMAG. Results are presented and realization problems depicted.

1. INTRODUCTION

High current high frequency inductors are one of the most significant loss contributors in resonant converters. In order not only to reduce the losses but also to reduce the expenses and the production time, the behavior of these magnetic components has to be accurately predicted and some geometrical parameters be optimized.

Within project PAMELA (Piezo Active Motor for more ELectrical Aircraft) power converters have been developed for feeding high piezoelectric motors (HPM) aimed at company SAGEM SA, [1]. The magnetic components used for this converter are optimized and designed using magnetic component design and optimization Tool (CAEOMAG) integrated in the circuit simulator SIMPLORER [2].

Mostly the core geometry (thickness, height and air gaps), winding geometry (type of conductor, layer thickness) and winding structure are the optimization parameters. Because of the air gap fringing and its losses effects it is recommendable that the distance between the air gap and the inner winding be optimized for field shaping. This leads to a reduction of losses and particularly to a decrease of hot spot temperature, which is known to be in front of air gap on the adjacent winding. The high current inductors in the resonant converter are optimized considering this effect.

The magnetic component design and optimization tool (CAEOMAG) is presented in section 2. In section 3 the optimization process of high current inductors is described and experimental results are outlined in section 4.

2. MAGNETIC COMPONENT DESIGN AND OPTIMIZATION TOOL

The structure and data flow of CAEOMAG is described in [3], [4]. The design of magnetic components is performed within two steps. Fig. 1 shows the set up of CAEOMAG including iterations loops. Starting from the circuit model a simulation is performed at steady state, generating approximate stress quantities. The 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 and are inputted via a graphical user interface. Thus initial values for a subsequent optional parameter optimization of these components are derived. The core and winding dimensions, like e.g. air gap width, the layer thickness in gapped inductors and in transformers are optimized with respect to design objectives such as minimum size, minimum temperature rise, costs, etc., which are summarized in an objective function F, see [3], [4]. This main optimization is represented in the left loop.

The non iterative pre-optimization is based on parameters such as weighted procurement, assembly, modification, cooling and shielding expenses and are expressed in a heuristic objective function

$$F_i = \sum_C w_{C_i} K_{C_i} . \tag{1}$$

It is supplemented by volume aspects in the total objective function

$$F_{tot_i} = \frac{1}{2} \cdot \left(\frac{F_i}{max(F_i)} + \frac{V_{h,i}}{max(V_{h,i})} \right) . \tag{2}$$

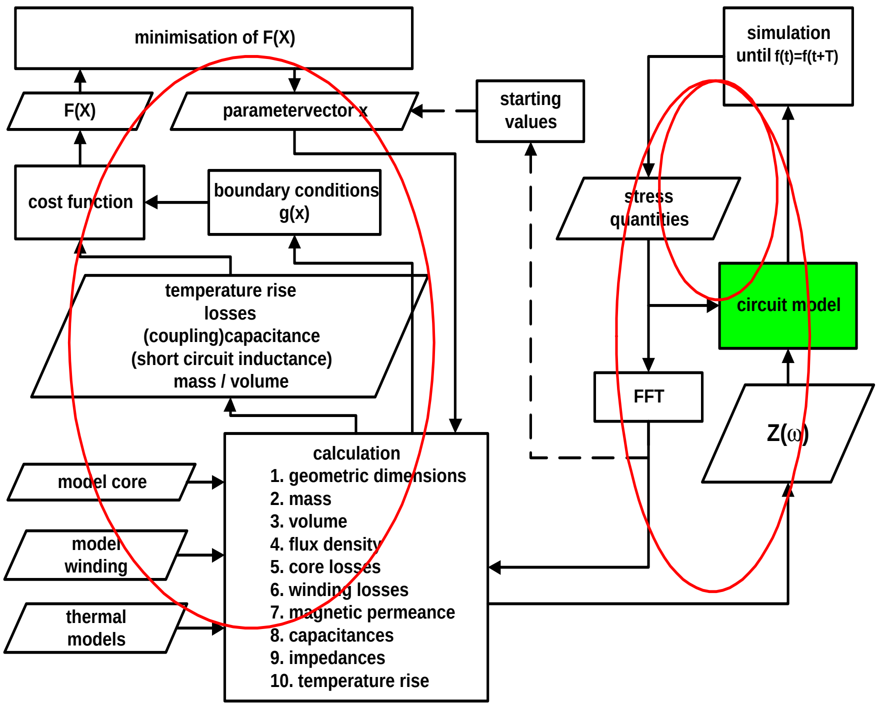

Fig. 1: Design and optimization tool CAEOMAG - Setup and iteration loops

K_C summarizes costs for procurement, assembly, modification, cooling and shielding and w_C for their respective weightings. i represents the different core types (E, EC, ETD, U, UR, RM, PM, P, PQ) and $V_{h,i}$ the enveloping volume of the respective core.
It is the target to find the minimal total objective function $F_{ges,i}$. Thus the optimal core type is found. The area product approach is then used to find the optimal core size of the available inductor. The area product is the product of effective cross section of core and of winding window see Fig. 2.
The model used in the pre-optimization stage is a simplified model in which eddy currents losses are not considered. Winding volume, core cross section, core volume and thermal resistances (thus losses) are functions of the area product A_P, [4].

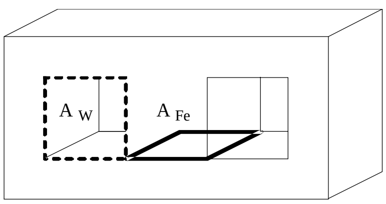

Fig. 2: Area product

For the optimization, data from the model are summarized into cost function $F(x)$

$$F(x) = \frac{1}{\sum_1^K w_i} \sum_1^K \left(w_i \cdot \frac{Y_i(x)}{Y_i(x_0)} \right) + P(g(x)) \qquad (3)$$

where w_i are weighting factors, $Y_i(x)$ total power losses, total mass of components, self capacitance and (or) overtemperature. $P(g(x))$ represent the penalty functions which symbolize saturation flux density, maximal temperature difference and core geometry. The parameter vector x contains core geometry, thickness of a conductor and the air gap length.
A combination of a deterministic optimizer (Nelder-Mead Method) with a non deterministic optimizer (Evolution strategy) leads to rapid search of minimal objective function $F(x)$.
For the model used in the tool essential parasitic effects are considered. DC-pre-magnetization of the core and curve form of flux density are taken into account for calculating the core losses. Path length and cross section of the magnetic circuit are calculated by considering form of corner segments and airgap fringing.
Eddy current effects (Skin, proximity, edge as well as airgap fringing effects) are considered by calculating power losses in the winding . Fig. 3 illustrates the modelling approach for litz and round wires: airgap and conductor layers are replaced by current sheets. The

total potential is considered a superposition of the airgap between two ideal permeable infinite long plates A_G, of the single conductor layers $A_{L,\,i}$ and of a disturbing potential A_S.

$$A_T(x, y) = A_G(x, y) + A_S(x, y) + \sum A_{L,\,i}(x, y) \quad (4)$$

For foil conductors all layers are reduced to one single layer in order to simplify the complex 2D-Field problem.

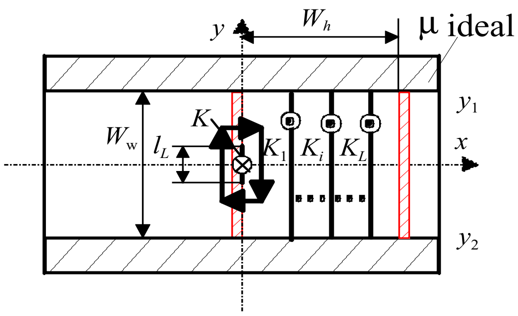

Fig. 3: Approach for solution of 2D Fieldproblem

An equivalent circuit is then set up reflecting eddy currents, leakage and capacitive effect.

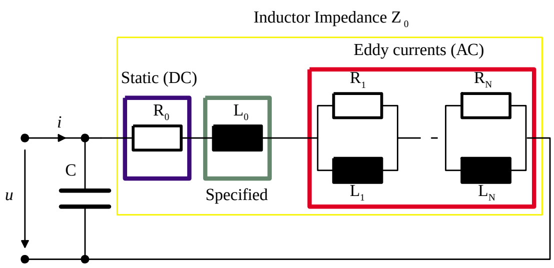

Fig. 4: Quasi-stationary Model of an inductor

Since the losses lead to a temperature increase in the components the thermal modelling is very important. A two-node thermal model is considered with losses (core and winding) as sources of heat and three thermal resistances, Fig. 5. In this model convection, thermal conduction and heat radiation are taken in account.

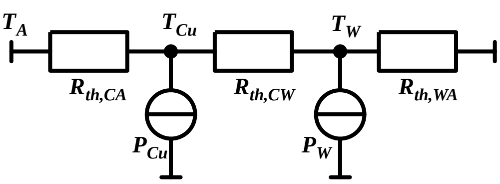

Fig. 5: Thermal Model

The design and optimization tool CAEOMAG is integrated in the circuit simulator SIMPLORER. CAEOMAG is accessed through a Graphical User Interface implemented as SIMPLORER wizard. The wizard currently either represents an inductor (Lopt), a two-winding (Topt2W) or three-winding transformer (Topt3W) each symbolizing a circuit model see Fig. 4. Stress quantities are provided to CAEOMAG via simulator SIMPLORER [3], [4].

3. OPTIMIZATION OF HIGH CURRENT INDUCTORS

For minimizing power losses and weight an optimization of the magnetic component is necessary.

There are several field shaping techniques [5], [6]. Mostly winding losses within high current high frequency inductors are minimized by optimizing the winding thicknesses. However, at high frequencies 2D-airgap effects are significant and are to be dealt with. Both the winding thickness and the airgap length have to be optimized simultaneously, see Fig. 6.

High current inductors of power converter for high power piezoelectric motors are objects of the optimization study in [1]. While the optimization of inductors of the "auxiliary mode" is relatively simple, that of the "main mode" causes tremendous difficulties. The frequency of both modes is around 20 kHz while the currents are 148 A peak in the parallel coil and 112 A peak in the serial connected coil.

For the inductor optimization and design a worst case is considered with higher currents than at the normal operation point.

Initially, previous to the main (winding) optimization, an adequate core is selected. The EE core is found to be optimal regarding criteria: costs and the enveloping volume. Using the area product approach, the following core geometry values are obtained:

	Optimized	4*EE 70	4*EE 80
Eff. core cross section (mm2)	1360.1	2732	1560
Eff. Volume (mm3)	316509	408000	287200
Area product (mm4)	1849880	1555600	1684400

Table 1: Results of pre-optimization

From Table 1, it is retained that 4 EE80 cores staked in parallel build an optimal core configuration. On the one hand their area product as well as effective cross section and volume are next to the optimized values on the other hand their winding window is larger that of 4 EE70, which offers more potential for further winding optimization.

In order to restrict the field of search, and thus encircle an optimal area, a parameter optimization is carried out where the weight factors of power losses, total mass and overtemperature is at maximum and that of self capacitance at minimum. F is the objective function, l_L the air gap length and d_{cu} the conductor thickness.

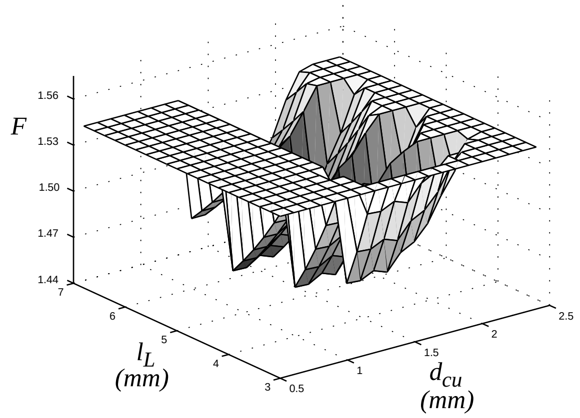

Fig. 6: Parameter optimization of conductor thickness and air gap length

It is then proceeded to a precise parameter optimization which yields the results in Table 2. The layer configuration, the conductor thickness as well as the air gap length are automatically optimized for suitable total losses, mass and overtemperature.

Air gap length	6.6mm
Material	litz wire; 124 strands of 0.1mm; 7 in parallel
Turns per Layer	4;4;4;1 (13 turns in total)
Total Losses	202.26 W
Hot spot	390.47°C

Table 2: Results of inductor optimization

The temperature (hot spot) of the layer adjacent to the airgap is still too high. Fig. 7 shows the temperature distribution in an inductor (winding and core).
The distance between air gap and adjacent layer is then optimized. Fig. 8 illustrates the decrease of hot spot temperature ratio (temperature with divides by temperature without underlay) with increasing isolation layer thickness added on top of the bobbin (defined as underlay)

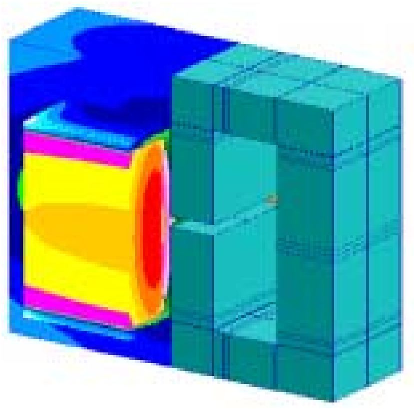

Fig. 7: Temperature distribution in an inductor, [7]

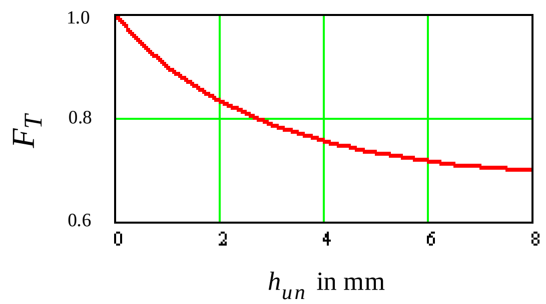

Fig. 8: Hot spot temperature ratio of inductor

Distancing the layers from the airgap is one way to minimize this temperature thus reducing the field strength in the conductors and therefore decreasing the 2D-losses (caused by air gap) [5]. Doing so, the DC-copper losses increase, since the mean turn length of windings becomes higher. After a further optimization, using an underlay, the following results are obtained:

Air gap length	4.7mm
Material	litz wire; 102 strands of 0.1mm; 10 in parallel
Turns per Layer	3;3;3;2 (11 turns in total)
Total Losses	181.86 W
Hot spot	273.86°C
h_{un}	~5mm

Table 3: Results of inductor optimization with underlay

Table 3 depicts the enhancement of the inductor with adequate winding configuration and thickness. The

underlay clearly leads to a decrease of hot spot temperature. Note, that due to the optimization procedure the layer configuration of inductors in Table 2 and 3 differ though inductance and current is equal.
Fig. 9 shows the frequency response of the AC/DC resistance ratio at small signal excitation. (2D), (2Du) and (1D) respectively represent the total losses without underlay, with underlay and 1D losses without air gap effects. The latter however; are equal for both without and with underlay. Minor differences in Fig. 9 concerning calculations without and with underlays result in large variations of the hot spot temperature. It is to be noted, that the total resistance ((2D) or (2Du) resistance) is the (1D) resistance augmented by resistance caused by airgap effects.
The worst case (with higher currents) is considered in this optimization process.

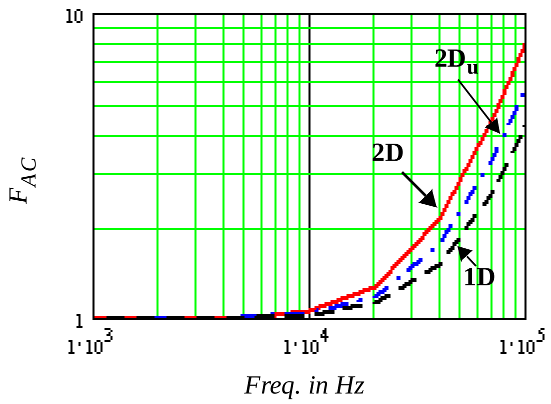

Fig. 9: Calculated AC/DC resistance ratio of inductor

4. EXPERIMENTAL RESULTS

Measurement are performed on designed inductor L_p (~38.8µH) of LLCC-resonant converter in [1]. For the technical implementation of the inductors some practical aspects are to be taken into consideration:
a) The 10 parallel litz wires, longitudinally wound on the core center leg, should not be intermeshed, otherwise it will lead to additional power losses due to heightened skin and proximity effects.
b) Conductor layers should be accurately isolated from each other.
c) For appropriate cooling, an air channel is built.
Impedance measurement of the inductors are carried out using HP4192. Fig. 10 depicts the AC/DC resistance ratio. Until 25 kHz measured and simulated resistance ratio match very well. After that point there is a divergence which can partly be explained by the difficult winding of the 10 parallel litz wires for exact reproduction of the model. The larger difference between physical set-up and model derives from an extra half-turn physically in order to reach the connecting pins.
Note, that small signal measurements results do not yield a representative comparison with calculated results, derived by large signal excitation. But since appliance for the latter is usually not at one's disposal small signal measurements are only of compromising nature.
Temperature measurements are undertaken using J-thermocouples. While the hot spot temperature of about 199°C is measured, a value of 174°C is calculated by the design and optimization tool.

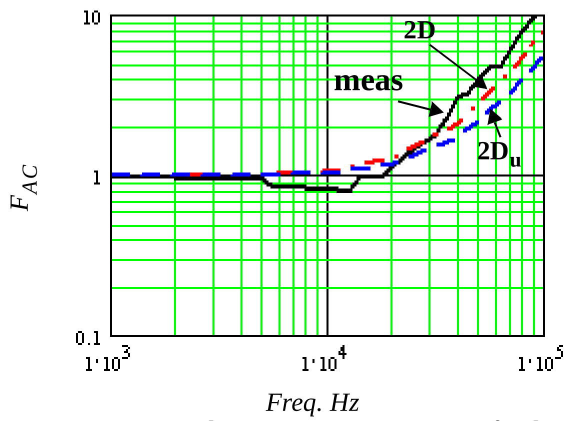

Fig. 10: Measured AC/DC resistance ratio of inductor

5. CONCLUSION

In this paper a design and optimization tool (CAEO-MAG) integrated in circuit simulator SIMPLORER is presented. Costs, weight, power losses and temperature of inductive components are optimized. A complementary field shaping technique, the optimization of distance between air gap and winding, for improving the temperature distribution of the inductor, is outlined. A high frequency high current inductor is designed using the described optimization strategy. Simulation and experimental results are depicted.

6. ACKNOWLEDGEMENT

The development of the high power LLCC-resonant converter is a project in cooperation between SAGEM SA (France) and the Institute of power electronics and electrical drives (University of Paderborn, Germany). It is founded under the scope of the EUREKA-project PAMELA, which is an European project with partners from industries and universities.

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