On the Multiobjective Optimal Choice of Isolated dc-dc Converter Topology and Design Using Genetic Algorithms

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Abstract

This paper presents a computer-aided design (CAD) tool dedicated to the multiobjective optimal design of isolated dc-dc power converters. This tool, developed in Matlab environment, is based on multiobjective optimization (MO) using Genetic Algorithms (GAs). The design problem requires minimizing the power loss, weight and cost of the converter while ensuring the satisfaction of several constraints. The optimization variables are, as for them, the operating frequency, the current density, the maximum flux density, the transformer dimensions, the wire diameter, the core and conductor materials, the converter topology (among flyback, forward, push-pull, half-bridge (HB) and full-bridge (FB)), the semiconductor devices (among diodes, IGBTs and MOSFETs), the number of these devices associated in parallel, the number of cells associated in series or parallel and the kinds of input and output connections of these cells. Finally, a design example is presented and discussed.

1. Introduction

The trend in switch mode power supplies (SMPS) is towards the reduction of its overall dimension. Indeed, a small size and a lightweight are often the main requirements in many applications.

The design of such converters involves a large number of design variables as well as the application of knowledge from several engineering fields. The classical procedures fix a subset of these design variables and introduce a number of simplifications based on the engineer's know-how. Therefore, an initial design can be obtained in a small time but further iterations through hardware testing are usually required [1]. Moreover, the obtained solutions, although good, are rarely the optimal ones.

In order to allow the designers to use more design variables and fewer simplifications in a reasonable amount of time, mathematical optimization techniques offer an organized and methodical way of approaching the design variables. So, these techniques permit to reduce the duration and complexity of the hardware prototypes testing and can, even, lead to trade-offs not imagined *a priori*. It should be noticed that the use of optimization techniques to the design of power electronics systems can be integrated into the broader field of the CAD methods.

In this paper, a CAD tool based on MO using GAs for the design of isolated dc-dc power converters is presented. This tool offers a support for the selection of the optimal topology. The choice of the optimal topology has already been discussed elsewhere (see, e.g., [2]-[3]) but, at our knowledge, no MO procedure taking several topologies into account has been suggested so far.

The design problem requires minimizing the weight, losses and cost of the converter while ensuring the satisfaction of a number of constraints. These constraints include, e.g., appropriate limits on the temperature rise in the transformer. The optimization variables are, as for them, the operating frequency, the current density, the maximum flux density, the transformer dimensions, the wire diameter, the core material, the conductor material, the converter topology (among Flyback, Forward, Push-Pull, HB and FB converters), the semiconductor devices (among IGBT or MOSFET), the number of semiconductor devices associated in parallel, the number of cells associated in serial or parallel as well as the kinds of input and output connections (series or parallel) of these cells.

Several mathematical optimization techniques are available in the literature. In this paper, a multiobjective and constrained optimization procedure based on Evolutionary Algorithms (EAs) is used. Among the several approaches to evolutionary optimization, GAs have been chosen and the so-called Elitist Nondominated Sorting Genetic Algorithm (also known as NSGA-II) [4] is chosen to perform the search and optimization procedure.

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The remainder of this paper is organized as follows. First, the modeling of the isolated dc-dc converters is discussed in Section 2. Then, in Section 3, the CAD tool is presented. Finally, a design example is presented and discussed in Section 4.

2. Modeling of isolated dc-dc converters

In order to carry out a trade-off between the computation time and the accuracy in the design procedure, analytical models are adopted. These models permit to design the isolation transformer and filter inductor, to select the semiconductor devices and capacitors from manufacturers' datasheets and to evaluate the objective functions, viz. the losses, the weight and the cost of the power converter, as well as the constraints. The dc-dc power converters considered in this paper are the Flyback, Forward, Push-Pull, HB and FB converters. For conciseness, the description of each of them as well as their design rules are not presented in this paper but can be easily found in literature (see, e.g., [5]).

2.1. Transformer and inductor modeling

The inductor or transformer size and weight modeling is based on the area product A_p which is the product of the core cross-section A_c and the winding area A_w (see Fig. 1) [6]. Note that, since the winding area is orthogonal to the core cross-section, the volume and weight of the magnetic component are uniquely determined once the area product is known.

Considering, on the one hand, the core dimensions, defined in Fig. 1, the area product can be computed as a function of the following dimensionless coefficients [7]:

$$k_1 = A/E \quad ; \quad k_2 = B/E \quad ; \quad k_3 = C/E \tag{1}$$

and only one of the core dimensions. For instance, the dimension E of the lateral leg of the magnetic component core is chosen in this paper. The area product can therefore be expressed as follows:

$$A_p = \left(k_1 \cdot k_2 \cdot k_3 - 2 \cdot k_1 \cdot k_3 - 2 \cdot k_2 \cdot k_3 + 4 \cdot k_3\right) \cdot E^4 \tag{2}$$

At this stage, it is important to emphasize that these coefficients k_i will be considered as design variables in the optimal design procedure.

On the other hand, the area product can also be computed as follows [7]:

$$A_p = A_c \cdot A_w = \frac{\sum VA}{K_f \cdot K_u \cdot f_s \cdot J_w \cdot B_m} \tag{3}$$

where ΣVA is the sum of the volts-amperes products for each of the windings of the magnetic component, f_s is the switching frequency, J_w is the current density (assumed equal in each winding) and B_m is the maximum flux density. K_u is the window utilization factor by copper, i.e. the ratio of the total copper area with respect to the total window area. Practical values of this factor range from 0.3 to 0.5 – 0.6 for round wires [5]. Finally, K_f is the waveform factor which is 4.44 for a sinusoidal waveform and 4 for a square waveform.

Equation (3) links the dimensions of the magnetic component to its electrical and magnetic characteristics. In this relation, the term ΣVA is defined by the specifications of the converter, the factors K_f and K_u are constant values imposed by the waveforms and the windings. Finally, the switching frequency f_s, the maximum flux density B_m and the current density J_w are three of the optimization variables.

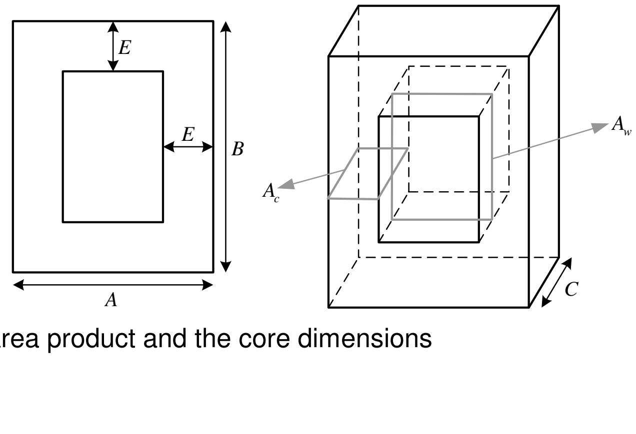

Fig. 1. Definition of the area product and the core dimensions

Once all of these quantities as well as the coefficients k_i are known, the area product is uniquely defined. Therefore, all the dimensions of the magnetic component (mean path length, mean length turn, volume, etc.) can easily be computed.

The choice of the core material is made through a discrete optimization variable. Four kinds of materials are considered in this paper: alloys of iron and silicon (Fe-Si alloys), ferrites, amorphous materials and nanocrystalline materials. Typical specifications of these kinds of materials are listed in Table 1 where B_{sat} is the saturation flux density, and K_c, α and β are constants necessary to estimate the core loss (see below). Finally, the cost coefficient is the relative cost of each core material with respect to the cost of the FeSi alloys.

As for the core material, the choice of the conductor material is made through a discrete optimization variable. Two kinds of conductor materials are considered here: aluminum and copper. Typical specifications of these kinds of materials are listed in Table 2 where ρ is the resistivity and the cost coefficient is now the relative cost of each conductor material with respect to the cost of copper.

The total loss of the magnetic component consists of two parts: the core loss P_{core} and the copper loss P_{copper}. Note that, due to the trend for higher operating frequencies in SMPS, the characterization of the magnetic components losses plays an important role in converters design and optimization.

Usually, the core loss is given in W/kg [5] and can be computed as follows:

$$P_{core} = K_c \cdot f_s^{\alpha} \cdot B_m^{\beta} \tag{4}$$

where the constants K_c, α and β can be established from the manufacturers datasheets by using curve fitting methods.

When the frequency grows, eddy current losses in windings, i.e. the losses due to skin and proximity effects, cannot be ignored. In this paper, the model developed by Dowell for a winding made of copper foil [8] is used to estimate the ac resistance. This model is chosen because it is in a closed form, hence very convenient to use in an optimal design procedure, and well accepted among the researchers community. Moreover, it is easily extensible to different windings structures.

According to [8], the copper loss can be expressed as:

$$P_{copper} = F_R \cdot R_{dc} \cdot I^2 = R_{ac} \cdot I^2 \tag{5}$$

where F_R is the eddy current loss factor, R_{dc} is the dc resistance and I is the rms current value.

Finally, it should be noticed that the cost C_{magn} of the magnetic component is considered to be proportional to its weight. So, it can be computed as follows:

$$C_{magn} = k_c \cdot W_c + k_w \cdot W_w \tag{6}$$

where k_c and k_w are the cost per unit of weight expressed in €/kg of the core and winding materials, respectively, and W_c and W_w are the weight of the core and windings of the magnetic component, respectively. Note that quantifying the cost of the magnetic components is not straightforward because prices change with volume, manufacturer, time and negotiation [9]. It is the reason why such as simple relation as (6) is used in this paper.

Core material	B_{sat} [T]	K_c	α	β	Specific weight [kg/m^3]	Cost coefficient
Fe-Si alloys	2	$5\cdot10^{-4}$	1.70	1.95	6000	1
Ferrite	0.38	$1.9\cdot10^{-7}$	1.64	2.67	4800	1.5
Amorphous material	1.5	$7.3\cdot10^{-3}$	1.95	1.95	7180	2
Nanocrystalline material	1.2	$1.2\cdot10^{-6}$	1.79	2.10	7330	2

Table 1. Typical core material data

Conductor material	ρ [Ω·m]	Specific weight [kg/m^3]	Cost coefficient
Aluminum (Al)	$2.7\cdot10^{-8}$	2700	0.33
Copper (Cu)	$1.7\cdot10^{-8}$	8920	1

Table 2. Typical conductor material data

2.2. Semiconductor devices modeling

The semiconductor devices (diodes, IGBTs and MOSFETs) are selected from a database according to their current and voltage ratings. To do so, the maximum voltage and current stresses across the devices, under worst case operating conditions, are first calculated. Then, the devices which have suitable ratings are selected. As the database also provides the datasheets of the selected devices, their cost and weight are known. The choice between IGBT or MOSFET devices is performed using a discrete optimization variable. Note that if IGBTs are used and that two or more of these semiconductor devices are associated in parallel, the current capability of the devices is derated.

The total loss of the semiconductor devices consists of two parts: the on-state losses and the switching losses. Note that their computation is profusely described in literature (see, e.g., [10]) and, so, it is not recalled in this paper for conciseness purpose.

2.3. Thermal and heatsink modeling

An estimation of the magnetic component temperature is needed during the optimization procedure to verify that temperature specifications are not exceeded. In magnetic components with natural air cooling, as considered in this paper, the dominant heat-transfer mechanism is by convection [11]. The Newton's equation of convection is so used to determine this temperature rise (ΔT):

$$\Delta T = R_{th} \cdot \left(P_{core} + P_{copper} \right) \tag{7}$$

where R_{th} is the thermal resistance.

Based on the total loss of the semiconductor devices, the heatsink can be designed in order to limit the junction temperature. This temperature is estimated from the ambient temperature T_a, the thermal resistances (junction-case: $R_{th,ja}$, case-heatsink: $R_{th,ch}$ and heatsink-ambient: $R_{th,ha}$) and the total loss P_{sc} of all the semiconductor devices by [5]:

$$T_j = T_a + \left(R_{th,jc} + R_{th,ch} + R_{th,ha} \right) \cdot P_{sc} \tag{8}$$

From (8), the thermal resistance of the heatsink $R_{th,ha}$ needed to limit the junction temperature to a predefined value (typically 125 °C) can be computed and, then, the heatsink can be selected from the manufacturers datasheets.

Finally, it should be noticed that more details about the above-described models can be found in [12].

3. Computer-aided design tool

As mentioned previously, in this paper, a MO technique based on GAs is used. Those are stochastic search techniques that mimic natural evolutionary principles to perform the search and optimization procedures. GAs have been chosen because they overcome the traditional search and optimization methods (such as gradient-based methods) in solving engineering design optimization problems [13]. Indeed, there are, at least, two difficulties in using traditional optimization algorithms to solve such problems. Firstly, each traditional optimization algorithm is specialized to solve a particular type of problems and may not be applicable to a different type of problems. Secondly, most of the traditional methods are designed to work only on continuous variables. However, in engineering designs, some problem variables are restricted to take discrete value only. In this paper, this requirement arises, e.g., for the choice of the core and conductor materials. In solving problems having discrete search space (in the case of zero-one or discrete variables), traditional methods assume the search space to be continuous and introduce artificial constraints to favour permissible discrete values. So, the algorithm spends a considerable amount of time in evaluating non feasible solutions.

Among the several MO techniques using GAs, the so-called NSGA-II [4] is used to perform the isolated dc-dc converter optimal design. It should be noticed that the presence of several conflicting objectives in a problem gives rise to a set of optimal solutions (known as Pareto-optimal solutions) instead of a single optimal solution. This set of Pareto-optimal solutions constitutes the Pareto front.

The structure of the CAD tool, developed by the authors in Matlab environment, is presented in Fig. 2. The aim of this tool is to design converters optimized with respect to the power loss, weight and cost and ensuring the satisfaction of a number of constraints, including, e.g., appropriate limits on transformer temperature rise. A detailed description of this CAD tool can be found in [14].

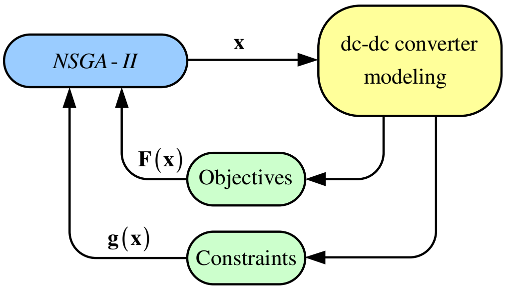

Fig. 2. CAD tool

Finally, it should be emphasized that each optimization variable (denoted **x** in Fig. 2) is restricted to vary between lower and upper bounds defined by the designer.

4. Design example

The design example which follows is based of the following specifications: 750 V input voltage, 600 V output voltage and 50 kW output power. The Pareto front, i.e. the results, is presented in Fig. 3. Each point of this Pareto front corresponds to an optimal power converter which respects all the constraints.

From Fig.3, one can conclude that two topologies, viz. the HB and FB topologies, dominate the three others for the considered specifications. Moreover, the solution closest to the ideal point (which is an utopian solution) corresponds to the FB topology.

A detailed analysis of these results, and particularly of the optimization variables, permits to draw some conclusions about the design of the power converter.

First, for the considered specifications and optimization variables, each solution of the Pareto front corresponds to the association of two cells. Moreover, the optimal input connection kind of these two cells is parallel. Indeed, this kind of input connection permits to reduce the current rating of the semiconductor devices (IGBTs or MOSFETs depending on the considered solution) and, so, their on-state and switching losses.

Second, the transformer dimensions (defined by the dimensionless coefficients) as well as the conductor diameter (d_s) have converged to optimal values (k_1^{opt} = 2.37, k_2^{opt} = 2.70, k_3^{opt}= 1.17 and d_s^{opt} = 0.34 mm).

Third, the combination of a core in nanocrystalline material and windings in copper is better to minimize the power loss whereas the combination of a core in ferrite and windings in aluminium is better to minimize the weight and cost of the converter.

Finally, it should be pointed out that only the switching frequency, the maximum flux density and the current density have not converged to an optimal value.

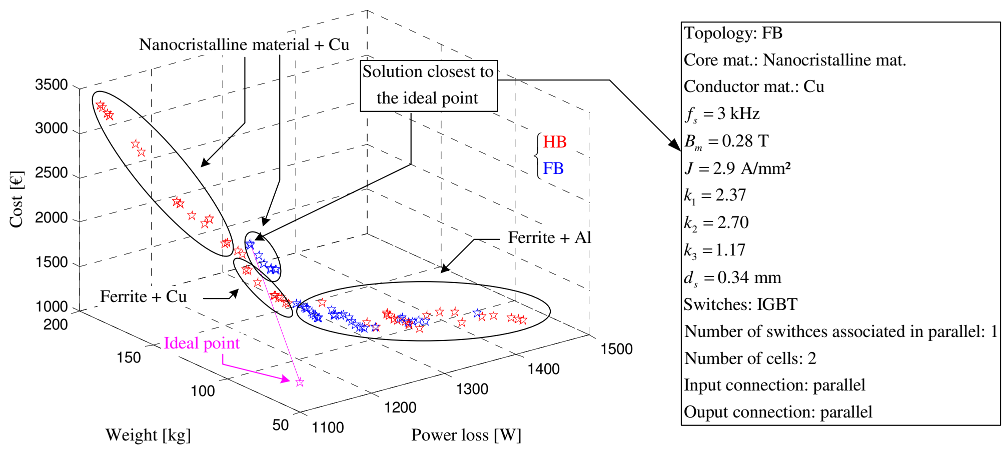

Fig. 3. Pareto front

5. Conclusion

In this paper, a CAD tool based on MO optimization using GAs for the design of isolated dc-dc converters has been presented. The design problem requires minimizing the weight, losses and cost of the converter while ensuring the satisfaction of a number of constraints. A design example has also been considered.

A first advantage of the proposed CAD tool is that it is multiobjective. So, several conflicting objectives, often present in engineering design problems, can be optimized simultaneously. A second advantage is the number of solutions considered in a small time. Indeed, the tool compares a large number of solutions (in the order of several thousands to several tenths of thousands) to retain only the best in a time less than one minute. A third advantage of this tool is its flexibility. Only the databases and the specifications of the converters must be modified to use it in a new design problem. At last, a fourth advantage is that it proposes to the designer a set of optimal solutions – instead of a single one – so that the designer can choose *a posteriori* which solution best fits the under consideration application or which objective function to promote. Moreover, in industrial framework, this set of solutions can be confronted with additional criteria or engineer know-how not included in models.

The main limitation of the proposed CAD tool is that it can only be used in the first stages of the design procedure. In order to use it in the next phases, more accurate models of the converters should be considered. To extend the tool to other topologies of power converters is another issue to investigate in future work.

6. Literature

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