Multi-objective Optimization Based Design of High Efficiency DC-DC Switching Converters

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ABSTRACT

In this paper we explore the feasibility of applying multi objective stochastic optimization algorithms to the optimal design of switching DC-DC converters, in this way allowing the direct determination of the Pareto optimal front of the problem. This approach provides the designer, at affordable computational cost, a complete optimal set of choices, and a more general insight in the objectives and parameters space, as compared to other design procedures. As simple but significant study case we consider a low power DC-DC hybrid control buck converter. Its optimal design is fully analyzed basing on a Matlab public domain implementations for the considered algorithms, the GODLIKE package implementing Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA). In this way, in a unique optimization environment, three different optimization approaches are easily implemented and compared. Basic assumptions for the Matlab model of the converter are briefly discussed, and the optimal design choice is validated "a-posteriori" with SPICE simulations.

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1. INTRODUCTION

Switching converters are of paramount importance in several applications, ranging from power delivery, consumer electronics, automotive application etc. There is a well established body of knowledge (see for example [1],[2]) where "pseudo optimal" design rules are set up, mainly basing on simplified analytical models, single components optimization, topologies and control strategies choices. This approach, although simplistic, leads to set the design parameters in an easy but robust way. Nevertheless a more detailed design requires that several goals have to be met simultaneously within prescribed constraints, and quite a significant number of design parameters have to be set [3]. This can become a strong need as long as high efficiency, low dimensions and weight are pursued. A significant example arises in ubiquitous DC-DC converters in battery operated devices, since the problem of energy efficiency and the reduction of weight and volume are of primary importance. Some studies for improving the design in those terms are available in literature [4]-[8], most of which focus their attention on the accurate modeling of some specific effects, in such a way as to provide the designer with new insight for taking decisions on topology, control strategy and parameters. In this context some effort has been given to consider the design as a multi-objective optimization problem [9][10], but still with a Monte Carlo approach. Some examples of application of multi-objective optimization techniques to converters in different contexts can be found in [11],[12].

In this paper we demonstrate how, also for this application field, an appropriate formulation of the optimization problem together with the state-of-art algorithms and simulation environments can directly be applied, giving a full satisfactory answer to the design problem and providing the designer with more accurate and sophisticated tools at an affordable computational burden.

We apply multi-objective optimization (MOO) formulation to the design of a hybrid control low power buck converter, using a public domain MOO package [10],[13], to obtain a Pareto front in the design parameters space [14],[15]. This will be done by adopting a simplified model of the design goals as presented in [5]-[7], with the a-posteriori validation of the designed device by a SPICE simulation. The availability of a detailed Pareto optimal set, along with giving to the designer more insight and flexibility in the choices, is greatly helpful when the calculated optimal parameters have to be translated into the discrete values of commercial components. The possibility of a more accurate modeling approach, by including SPICE simulations for the evaluation of the design goals will be also discussed, giving an estimation of the required additional computational effort.

2. STOCHASTIC OPTIMIZATION ALGORITHMS AND PARETO OPTIMAL FRONT TRACING

Most of the real-world optimization problems involve multiple conflicting objectives that must be mutually reconciled. These problems are called multi objective optimization problems (MOO), or vector optimization problems, in contrast to single objective optimization (SOO), or scalar optimization problems [16]. If we define as $f_k\left(x_1, x_2, ...x_M\right)$ the fit function associated to the *k*-th goal in a proper parameters space, the optimization problem is often expressed as:

$$\begin{aligned} &\min\left(f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots f_N(\mathbf{x})\right) \\ &\mathbf{x} \in \mathbf{X} \subseteq \mathbb{R}^M \end{aligned} \qquad (1)$$

where **X** is the feasible set of the decision variables vector **x**. In multi-objective optimization, usually it does not exist a feasible solution that minimizes all objective functions simultaneously. Therefore, either the problem is reduced to a scalar one by means of a weighted sum [17] of individual objectives, or a different notion of optimal has to be defined, that is the well known Pareto optimal. A (feasible) solution is “Pareto optimal” if it cannot be improved in any of the objectives without degrading at least one of the other objectives. In such terms, different Pareto optimal solutions can be found, and a their set is defined as “Pareto optimal front”.

In the last years, Multi-Objective Evolutionary Algorithms (MOEA) have demonstrated to be extraordinary facilities for solving optimization problems in different areas. Evolutionary algorithms such as the Genetic Algorithm [18] has become a standard approach, and schemes based on Simulated Annealing [19] and Particle Swarm Optimization [20],[21] are now familiar. Currently, most evolutionary multi-objective optimization (EMO) algorithms apply Pareto-based ranking schemes.

Such powerful, systematic and nowadays well assessed approach to optimal design, is still not so commonly adopted in the electronic circuit design area. Main goal of this paper is show the possibility of extending the use of MOEA optimization tools to the switching converters design. As simulation environment we adopted a public domain MATLAB tool, known as the GODLIKE package [22] which allows, in a unique environment, to use different algorithms and to compare directly their performances by producing optimal ranking schemes. The test case proposed in this paper confirm the viability and the effectiveness of this package in the definition of the Pareto optimal front for a typical electronic design problem. In this way we suggest how, at present, it’s quite realistic to introduce the EMO algorithms in the standard optimal design of electronic devices.

3. OPTIMAL DESIGN OF AN HYBRID CONVERTER

The effectiveness of the proposed approach is shown by pursuing the optimal design of hybrid control low power buck DC-DC converter. We already mentioned how some basic important requirements in their optimal design are to achieve high power efficiency, for best exploitation of batteries, and at the same time high power density, to reduce volume and weight of the device. The choice of the circuit parameters and control strategy to fulfill both requirements is not trivial.

In the standard design of fixed frequency converters, it is well known how high switching frequency is required in order to achieve high power density, since the higher is the frequency, the smaller is the inductance and capacitance [5]. At the same time there is a trade off problem in the frequency choice, since losses increase significantly at high frequencies. Converters operating at fixed frequency has the advantage of simple design, but their efficiency rapidly decays at low loads since the switching losses are constant over the whole load range (figure 1a); on the other hand, as shown in [6], converters operating at variable frequency exhibit lower losses at low loads (figure 1b), but the design became more difficult because the range of the switching frequency can be relatively wide. In Fig. 1.is sketched a qualitative comparison between the efficiency in the two control schemes based on the current literature

A more sophisticated strategy is the so called hybrid control, based on the idea of operating at variable frequency in Discontinuous Current Mode (DCM) and at fixed frequency (the maximum one allowed for the converter) in Continuous Current Mode (CCM).The control system select the frequency according to the load (as it happens in the variable frequency converter) for low loads. As the load increases and the converter switches to CCM, the control system select a fixed (maximum) frequency, which is independent from the load.

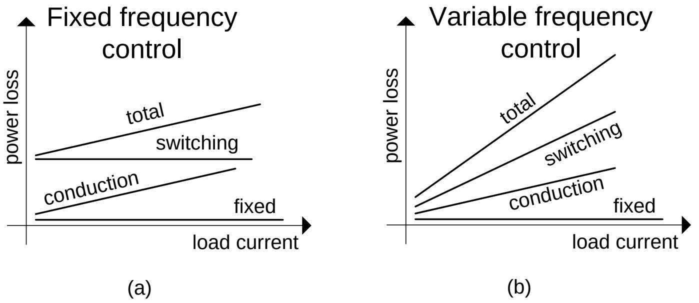


Figure 1. Power losses as function of load for fixed frequency control (a) and variable frequency control (b) converters

The advantages of the hybrid control are revealed from the (qualitative) diagram reported in Fig. 2 [7], where the continuous line (a) indicates the efficiency of a hybrid converter, while dotted line (b) and dashed (c) the efficiency of converters with variable and fixed frequency. It appears clearly as in the hybrid control system the efficiency shows an optimal trend, since it is quite independent from the load.

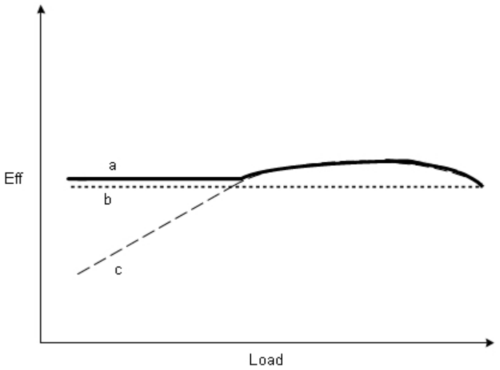


Figure 2. Comparative diagram of hybrid (a), variable (b) and fixed frequency control (c) as reported in [7]

Moreover the frequency range has been reduced since the frequency now has to vary only in DCM and remains fixed in CCM. This reduction of the frequency range allows a simpler choice of the passive components. Then it is clear how an hybrid control strategy can strongly improve the converter’s efficiency helping at the same time the designer to make easier choices.

Once the topology and the control strategy have been fixed, the optimal design of the converter is reduced to the problem of minimizing the size and maximizing the efficiency for variable loads. It can be explored with reference to the following case, where we consider a synchronous low power buck converter with hybrid control and design constraints defined as follows:

- input voltage = 5 V;
- output voltage = 3.3 V;
- maximum current load = 500 mA;
- maximum ripple =2.5%.

The circuit topology is sketched in Fig. 3

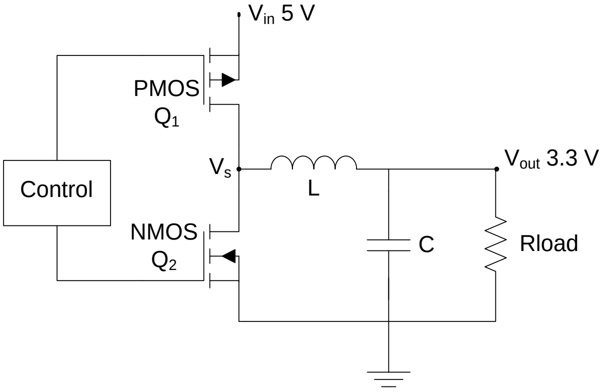


Figure 3. Schematics of the considered synchronous rectifier low power buck converter

For the optimal design we use the optimization criteria defined in [7] for hybrid converters, by formulating a multi objective optimization problem. In particular we assume the inductance *L* and the maximum switching frequency f_s as decision variables, whereas the considered objectives to minimize are:

1. *Power loss ratio* $(1-E)$, where $E = P_{loss}/(P_{loss}+P_{load})$ is the converter efficiency;
2. *Capacitance* $C=[V_{out}(1-\delta)]/(8L\cdot f_s^2\cdot\Delta V_c)$, ΔV_c is the maximum output ripple and δ is the duty-cycle;
3. *Inductor diameter* D (with other geometrical parameters kept fixed).

Note that objective 2 and 3 are directly related with size and weight of the converter, as well as to the handiness in choosing or realizing the passive components. For the inductance *L* a simplified model of a cylindrical air inductor with 0.30 mm copper wire diameter has been considered. Allowed ranges for decision variables are 1-50 µH for *L* and 0.1-20 MHz for f_s.

The model for the circuit operation and for losses is the same as described in [6],[7]. Solving the optimization problem (1), we get a set of optimal results (not dominated in the Pareto sense), each of them representing the best reachable goal for a selected direction of search. In our case, as said, this has been achieved within the MATLAB® environment and GODLIKE package, by using and comparing Genetic Algorithm, Simulated Annealing and Particle Swarm Optimization algorithms. Among the possible settings for those algorithms, few parameters are most significant, namely initial population, number of generations and Pareto fraction (which is the number of points on the final front as compared to the initial population). High values of the initial population makes anyway the Pareto front more detailed, as well as an high value of the number of generations improve the accuracy of the results. These values have to be considered in a trade off with a reasonable computational cost once the interest problem is specified. Moreover some limitation to the population size arise intrinsically in the algorithm implementations, as it will be evidenced hereinafter.

With reference to the considered (simplified) model for the direct multi-objective optimization problem, we have set the initial population parameter to range from 210 to 2400 points (higher values lead to non convergence problems of the code when compared with different algorithms). After some trials we estimated that 20 is good choice for the number of generations. Finally, for each simulation we assumed an unitary value for the Pareto fraction. In Table 1, we compared the performances of the different algorithms, by using a single-core Intel i5-5200U at 2.2 GHz for the computations.

The results in term of Pareto front evaluation are reported in Fig. 4, for the case of GA, 2400 points. The availability of the complete Pareto optimal front, allows to make an easier choice of the final design. Furthermore, a reduction of the possible choices is easily obtained by restricting a-posteriori some design variable intervals, that correspond to select a subset of the entire Pareto Front to offer to the designer. For example, if we ask a maximum power efficiency of at least 88%, using a capacitance value less than 1 µF, we get the subset of points reported in Table II (with reference to the SA algorithm results). Among them, the possible final design choice is evidenced in Fig.4, being characterized by closest commercial values for inductance and capacitance, respectively of 2.2 µH and 560 nF.

Table 1 Computation times for different algorithms

algorithm	initial population	Pareto points	time [s]
GA	210	210	4.15
SA	210	210	4.10
PSO	210	210	4.37
GA	600	600	7.21
SA	600	600	7.16
PSO	600	600	8.02
GA	2400	2400	33.7
SA	2400	2400	32.8
PSO	2400	2400	37.4

With the proposed choice we get a maximum efficiency of 90% in CCM with maximum load (500 mA) at a maximum switching frequency $f_s = 1.16$ MHz. As the load decreases, the efficiency also becomes lower, reaching the value of 85% at 218 mA of current load (this is the boundary between the CCM mode and the DCM mode). For the adopted control scheme the efficiency remains almost constant for lower loads.

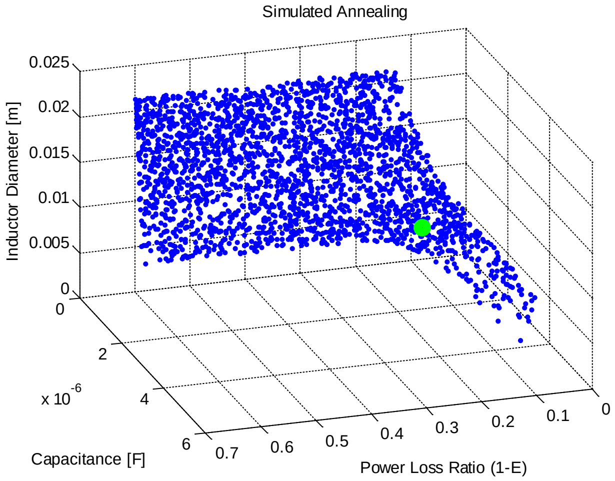


Figure 4. Pareto front of the problem (2400 points) as obtained by SA in GODLIKE. The final design choice is evidenced by a large dot

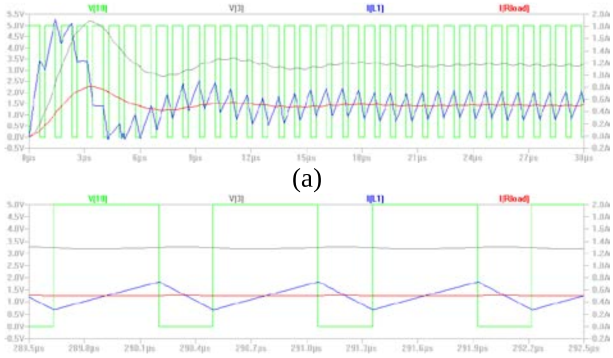
Table 2. A subset of optimal design choices (Pareto front with 2400 points)

L [μH]	**f [MHz]**	**LOSS %**	**C [nF]**	**D [mm]**
14,8	0,41	7,68	681	11,6
4,55	0,70	7,86	772	6,44
6,38	0,74	8,42	482	7,63
6,56	0,80	8,76	406	7,73
5,91	0,86	9,02	386	7,34
28,5	0,57	9,97	187	16,1
22,4	0,68	10,0	165	14,2
2,19	1,16	10,1	558	4,96
12,5	0,93	10,4	156	10,7
16,7	0,91	10,7	122	12,3
10,3	1,06	10,8	147	9,71
7,98	1,21	11,3	145	8,53
31,6	0,76	11,3	092	17,0
36,3	0,78	11,7	077	18,2
39,4	0,78	11,9	071	18,9

4. SPICE VALIDATION OF THE OPTIMAL DESIGN

A validation of the described design procedure can be straightforwardly obtained by using a full SPICE simulation of the designed circuit with the parameters value returned by the MATLAB optimized design and realistic models for the PMOS and NMOS. Fig. 5a,b show the results of a test case of this validation step.

In these diagrams, V(10) is the control voltage: when this signal is high, the upper MOS (PMOS) is on; I(L1) shows the classical trend of the inductor current; V(3) and I(Rload) are the load voltage and current. The values fully agrees with the results of the MATLAB optimized design, and the simplifying assumptions used for the optimization problem are validated.



(a)

(b)

Figure 5. SPICE validation: (a) transient; (b) regime

Although in the considered test case the simplified model shows to be fully satisfactory, an important extension to the proposed scheme could be the inclusion of the full SPICE simulation in the optimization loop. This can be in principle easily realized by using a SPICE model for the forward problem, including in the MATLAB optimization loop a proper call to SPICE and using the evaluations of SPICE for the computation of the objective functions. This scheme is in principle quite interesting since avoids any simplifying assumptions in the device model, in such a way to enlarge the scope of the optimal design to those circuits where getting reliable simplified models is more difficult. On the other hand in such implementation, the evaluation of the direct problem (a SPICE call) easily became dominating in the computational burden, resulting in the total simulation time roughly proportional to the number of SPICE calls multiplied by the single SPICE simulation time.

5. CONCLUSION

We have shown how the application of multi-objective optimization gives nowadays useful and realistic opportunities for the optimal design of switching converters. The possibility of calculating a complete Pareto optimal front, as well the corresponding decision parameter set, gives to the designer a more complete picture of the problem parameters space at affordable computational time and burden. Moreover, the complete knowledge of not dominated optimal set allows more easily the choice of commercial discrete values for components, keeping the achieved optimal goals.

The relative easiness of using public domain standard optimization environments make us confident of the straightforward possibility in extending such tools to a broader class of converters, and more generally design problems in electronic circuits.

More accurate modeling of the device, as for example with a full SPICE numerical model, can be in principle integrated in the optimization environment via Matlab, at the price of increasing significantly the computational burden.

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