Pre-sizing of dc-dc converters by optimization under constraints; Influence of the control constraint on the optimization results

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***Abstract-* This paper presents an optimization approach to pre-size dc-dc converters by integration of the control constraint. This approach is carried out in two main steps. The first step consists on determining the most adapted architecture to answer the specifications and the appropriate technologies of the passive and the active components of the selected architecture representing the minimal of the major constraint (like volume or cost). In addition, the designer can have an evolution of this major constraint by technology considered for each component (active and passive) and used in the chosen architecture. The models used in these step are developed from manufacturer datasheets. The second step consists on optimizing the selected architecture by considering the appropriate technologies resulting from the first step under multi-physic constraints: thermal, losses (or efficiency), volume, electromagnetic compatibility and control constraints …. The proposed approach allows reducing significantly the computing time which is suitable in a pre-sizing phase where several parameters must be optimized and multi-physic constraints must be respected.**

I. INTRODUCTION

In recent years, more and more mechatronic applications (electric windows, electric clutch actuator, intelligent power closer systems, robotized gearbox…) including dc-dc converters are introduced in the automotive domain [1] [2] [3] [4].The operation of these converters depends on many physical domains strongly linked. Depending of the designer specifications and the real environment of the operation for these converters, several constraints (electrical, thermal, mechanical, volume, control and cost) must be taken into account in their pre-sizing. For this reason, a optimization approach under multi-physic constraints is developed with integration of a step for selecting the most adapted architecture in depending the criteria's required in the specifications and the appropriate technologies for the different components of this architecture representing the minimal of the major constraint (like volume or cost).

The works carried out in this paper are focused on the pre-sizing of the dc-dc converter often used in the mechatronic applications of the automotive domain. Recently, several research tasks are focused on the design of the power converters using different methods [5] [6] [7] [8] [9] [10] [11].The Most of these studies are focused on the dimensioning of an architecture defined before starting the design thanks to the designer experience by optimizing its volume, its efficiency or its cost separately or together under several constraints. However in a pre-sizing approach, the converter architecture and its component technologies are not well known in advance. In addition, in several works the control aspect of these converters is considered after the converter design and the controller parameters are dimensioned analytically while fixing a phase and gain margins or by optimization [12] [13] [14] [15].

In this context, this paper proposes an optimization approach for pre-sizing including a step to formalize the converter architecture and component technologies choices. In addition, the pre-sizing is carried out by optimization under multi-physics constraints which is very suitable for automotive applications where several constraints must be considered and standards are increasingly severe. Moreover, this optimization is carried out first without the control constraint [15] and then by integrating this constraint in the optimization process in order to evaluate its impact on the optimization results.

Firstly, the proposed approach will be presented. The two steps will be explained and motivated. Specific models will be presented for each step of the proposed pre-sizing method. Then, this approach will be applied to pre-size a DC-DC Buck converter for the automotive domain.

Finally, the pre-sizing results will be given and discussed in two cases without the control constraint and by considering this constraint.

II. THE PROPOSED PRE-SIZING APPROACH

The proposed approach can be carried out into two main steps (figure 1). The first one helps the designer to select easily architecture and appropriate component technologies for specifications and an operation well defined. Moreover, it allows to give an evolution of the major constraint (volume or cost) by technology of each component as a function of these parameters. In order to

978-1-4244-5697-0/10/$25.00 ©2010 IEEE

perform this step, analytical models are developed from manufacturer datasheet and databases are built for the passives and the actives component. It can be decomposed into different phases as shown in figure 1. The architecture choice (phase 1) is determined by an automated procedure according to the specifications (figure.2).

At the end of this first step an architecture and component technologies are proposed and a first estimation of the volume variations per component technology is given. This estimation helps the designer to carry out a quick analysis considering a major constraint (like volume) to refine the proposed choices or to modify the specifications.

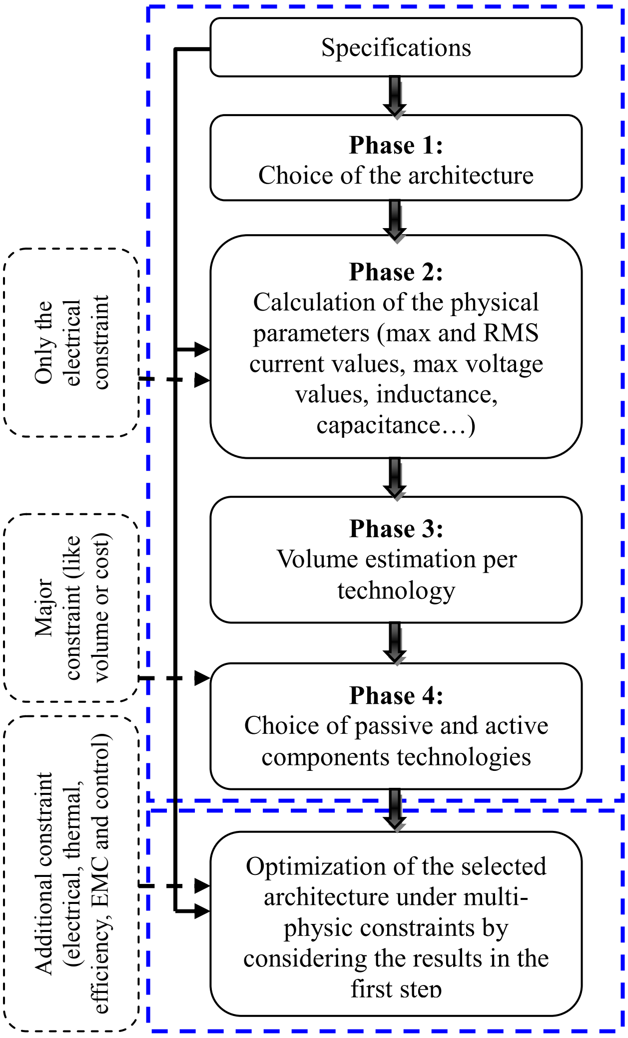

Fig. 1: Principle of the proposed pre-sizing approach

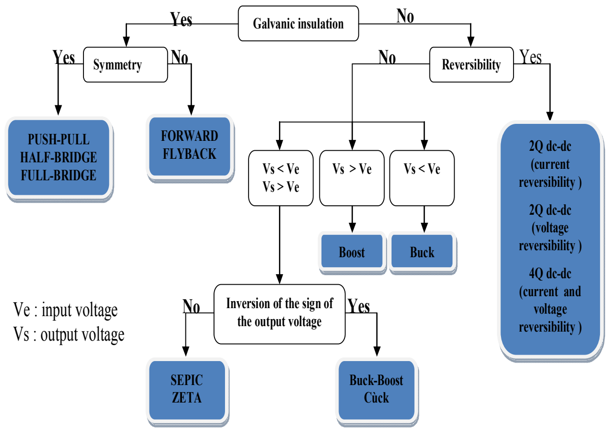

Fig. 2 : Architecture choice principle

The second step of the proposed pre-sizing approach allows optimizing the selected architecture under multi-physic constraints by considering the technologies proposed and refined in the first step. This optimization procedure is performed automatically by using analytical models to take into account different constraints (EMC, thermal, efficiency…) defined in the specifications. At the end of this step the optimized parameters allowing minimizing an objective function (volume) and respecting different constraints are determined.

III. THE FIRST STEP OF PRE-SIZING APPRAOCH

In order to quickly estimate the volume of the different components (actives and passives) by technologies, databases are built for every technology considered for each component and models are developed from manufacturer datasheet. The technology choices of passive and active components depend on physical parameters (switching frequency, capacitances, inductances, maximal voltage values, maximal and RMS current values, overall temperature…) and the major constraint (like volume or cost).

A. Capacitor technology choice by considering the volume as a major constraint

For the capacitor, three technologies are considered (film, tantalum and electrolytic aluminum). The voltage range is [10V, 100V]. Note that the voltage level is limited to 100V to consider low voltage in automotive applications.

The volume of a capacitor is given for the different technologies by checking the availability in the database of the needed capacitance value and the RMS current through the capacitor. For a given voltage, if the value of capacitance is not available in the database, it is carried out by the parallelization of an elementary capacitance available in the database.

The models used for performing this estimation are given by the following equations:

- Volume model:

$$Vol_C = k_1 \times C^3 + k_2 \times C^2 + k_3 \times C + k_4 \quad (1)$$

- Admissible RMS current model:

$$I_{eff} = k_5 \times C^{k_6} \quad (2)$$

k_i (with i = 1 to 6) are coefficients which depend on the capacitor technology and voltage level applied to the capacitor.

For a defined specifications (operation frequency, input and output voltage ripple, input and output current ripple…) and according to the availability of the capacitance in databases, the figure 3 shows an example of the volume evolution by technologies for the capacitor as function of the capacitance.

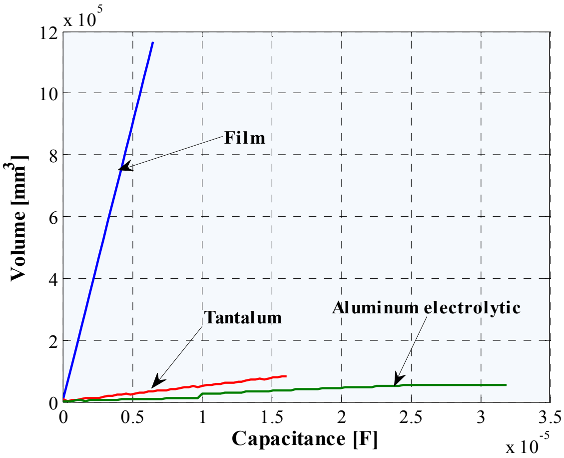

Fig. 3: volume variation by technologies of the capacitor

According to the figure 3, the designer can choose the best technology giving the minimum volume for the desired capacitance or he can choose the technology or technologies according to a range of capacitance variation for integration in an optimization process.

B. Inductor technology choice by considering the volume as a major constraint

For the inductor, four technologies are considered (Ferrite, Iron powder, MPP, High Flux). The volume estimation of the inductor is performed by using the following models:

- Volume model:

$$Vol_L = K_V \times (S_B . S_F)^{3/4} \quad (3)$$

K_v is a geometrical coefficient which characterizes the shape of the magnetic circuit. S_B is the necessary winding section for the realizable inductance. S_F is the effective section of the magnetic circuit.

- Peak flux density model :

$$\begin{cases} B = B_{max} \leq B_{sat} \ \ if \ \ F \leq F_C \\ B = K \times F^{\frac{1}{\gamma}} \ \ if \ \ F \leq F_C \end{cases} \quad (4)$$

Fc is the critical frequency where it is necessary to decrease the peak flux density to insure that the core losses are lower or equal to 500mW/cm^3.B_{sat} is the saturation flux density for each technology, k and γ are tow coefficients depending on the used technology and calculated from the core losses characteristics.

For example, for a given operating frequency, the volume of an inductor for the different technologies is given by computing the peak flux density (equation 4) allowing to compute the number of winding to realize the desired inductor. Then, the necessary winding section is determined depending on the physical parameters (RMS current, current density, skin thickness…) and the geometrical coefficient K_b. This section is compared to the total winding section of each existing magnetic circuit in databases. Finally, the volume is calculated by using the equation 3.

C. Switch technology choice by considering the volume as a major constraint

The technologies considered for the switches are Mosfets and Schottcky diodes. The choice of a switch technology depends on the switching frequency and the power density. Depending of the electrical parameter (maximum voltage and current, RMS and average current, switching frequency…) and using the electrical characteristic of each switch reference in the database, the losses are calculated and the volume is estimated according to the necessary heat sink resistance for dissipate these losses.

IV. THE SECOND STEP OF PRE-SIZING APPRAOCH

In this step, the designer can carry out an optimization under multi-physic constraints (electrical, thermal, efficiency, EMC and control). In order to perform this optimization, models representing the objective function defined by the total volume and the different constraints are developed.

A. Models for objective function

The model volume of the passive components (inductor and capacitor) is the same as that used in the first step. The volume of active components (switches) is given by the volume of the associated heat sink and it is estimated by the following model:

$$Vol_{hs} = \left(K_1 \times Rth_{ra}^{K_2}\right) \times h \times e \qquad (5)$$

K_1 and K_2 are coefficients depending on the heat sink profile. h and e are, respectively, the height and the thickness of the heat sink. Rth_{ra} is the thermal resistance of the heat sink.

Objective function:

$$Volume_{TOTAL} = \sum Vol_{\text{PASSIVE COMPONENTS}} + \sum Vol_{\text{ACTIVE COMPONENTS}} \qquad (6)$$

B. Models representing the constraints

Electrical constraint:

The electrical constraint models are given for the studies structure which is the dc-dc buck converter:

- Input and output voltage ripple :

$$\Delta U_{output} = \frac{U_{input} \times \alpha \times (1-\alpha)}{8 \times L_{output} \times C_{output} \times F_{sw}^2} \qquad (7)$$

$$\Delta U_{input} = \frac{I_{output} \times \alpha \times (1-\alpha)}{C_{input} \times F_{sw}} \qquad (8)$$

- Input and output current ripple :

$$\Delta I_{output} = \frac{U_{input} \times \alpha \times (1-\alpha)}{L_{output} \times F_{sw}} \qquad (9)$$

$$\Delta I_{input} = \frac{I_{output} \times \alpha \times (1-\alpha)}{8 \times L_{input} \times C_{input} \times F_{sw}^2} \qquad (10)$$

U_{input} and I_{output} are respectively the input voltage and the output current. α is the duty cycle and F_{sw} is the switching frequency. L_{ouput} and C_{output} are respectively the inductance and the capacitor for the output filter while L_{input} and C_{input} are those of the output filter.

Efficiency constraint:

$$efficiency = \frac{P_{output}}{P_{output} + \sum Losses_{COMPONENTS}} \qquad (11)$$

Thermal constraint:

This constraint is related to only the active components. It is represented by the semiconductors junction temperature Tjmax.

$$T_{jmax} = T_a + \sum Rth \times Losses_{Switch} \qquad (12)$$

T_a: is the overall temperature

EMC constraint:

The EMC model [7], [8], [9] is developed by supposing that the EMC disturbance can be decomposed into a differential mode (DM) and a common mode (CM). The DM disturbances use the same propagation ways as the current. However, the CM disturbances are propagated through power conductors and parasitic components. In order to evaluate the EMC disturbance, a line impedance stabilizer network (LISN) is considered. From the equivalent diagram in each EMC mode, the EMC disturbances can be analytically estimated (figure4). Figure 5 shows an example of the calculated and the simulated EMC disturbances in differential mode compared to an EMC standard.

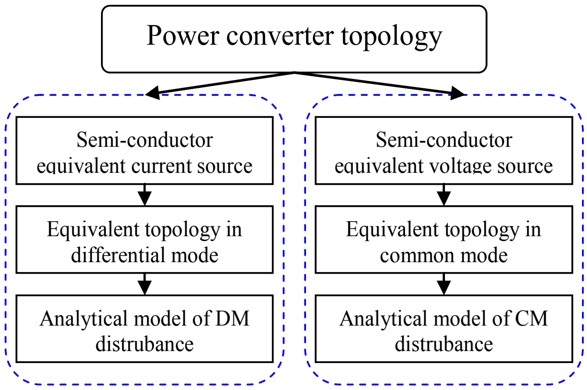

Fig 4 : Principle of the EMC model

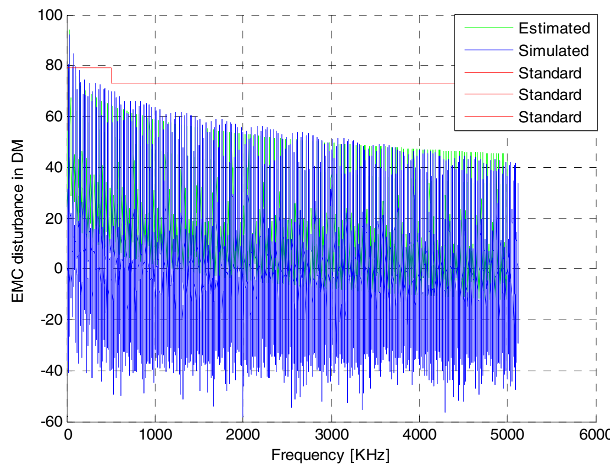

Fig 5 : EMC disturbances calculated and simulated in Differential mode

V. Application of the Proposed Approach

A. Specifications:

- Input network voltage (42V) and Output network voltage (14V)
- Output power: 1kW
- Switching frequency [20 … 200 KHz]
- Input and output voltage ripple ≤ 10% of the average value
- Electrical constraints : Input and output inductor current ripple ≤ 10% of the average value

- Thermal constraint: junction temperature ≤ 130°C
- Overall temperature 30°C
- Efficiency constraint: ≥ 80%
- EMC constraint: respect the standard ISM 55011
- Objective function to be minimized: the total volume
- Functional specifications: galvanic isolation is not needed

B. Results of the first step:

According to requirements from specifications, the adapted architecture is the dc-dc Buck converter:

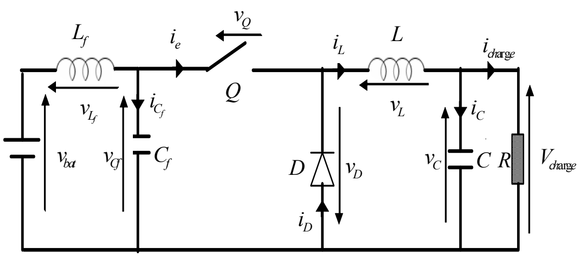

Fig. 6: Buck DC-DC converter

For a range of values for the passive components respecting the electrical constraints considered only in the first step, the technology giving the minimal volume of each component is given in the table 1 bellow:

TABLE 1: TECHNOLOGY CHOSEN FOR THE PASSIVE COMPONENTS.

Passive components	Technology
Capacitor	Ferrite
Inductor	Iron Powder

This technological choice can be changed if another major constraint is considered (like the cost or losses) instead of volume. For indication, the volume of the passive components corresponding to the minimal values of their components and respecting the required electrical constraints is "0.80 Liter".

C. Results of the second step:

The table 2 bellow gives the values of the different components obtained after optimization and respecting the considered constraints without the control constraint:

TABLE 2: THE MAIN PRE-SIZING RESULTS OBTAINED AT THE END OF THE SECOND STEP.

Input filter inductance (µH)	**362.5**
Elementary input filter capacitance (mF)	**2.24**
Number of the elementary input filter capacitance	**3**
Elementary output capacitance (mF)	**1.65**
Number of the elementary output capacitance	**1**
Output filter inductance L(µH)	**65.7**
Switching frequency Fs(kHz)	**20.4**
Heat sink thermal resistance for the Mosfet (°C/W)	**4.16**
Heat sink thermal resistance for the diode (°C/W)	**2.32**
Total volume (Liter)	**0.31**

The figure 7 bellow shows the EMC spectrum obtained after optimization and compared to the standard:

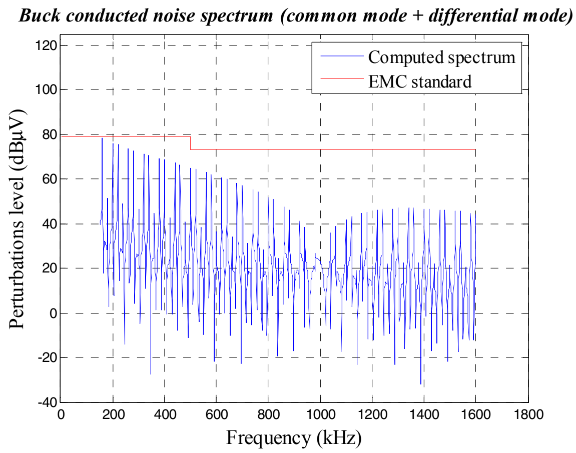

Fig. 7 : EMC spectrum

The optimization is performed using genetic algorithms to ensure that the objective function converges to value very close to the global optimum. The volume of the passive components representing 58.9% of the total volume which is "0.18 Liter", it is different from that obtained in the first step because the other constraints are more impressive as shown in figure 8 for the EMC constraint, hence the choice of the passive components values is different. Technologies are proposed for the passive components and a first estimation of their volume is given. The number of the elementary capacitor is limited to a maximum number of 30 elements to respect integration constraints.

D. Integration of the control constraint in the global optimization :

The closed control loop adopted for the studies structure is presented by the following figure:

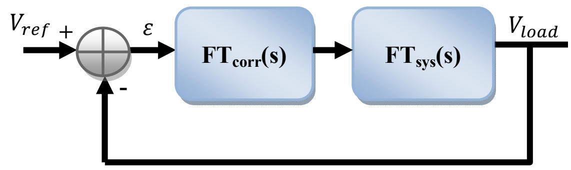

Fig. 8: closed control loop for the buck converter

$FT_{corr}(s)$: is the transfer function of the corrector PI defined by the following system, which is a basic choice of the corrector to perform the study control loop and to determine in a first approach the influence of the control constraint with a simple corrector:

$$FT_{corr}(s) = K_c \times \left(1 + \frac{1}{T_i.s}\right) \quad (13)$$

$FT_{sys}(s)$ is the transfer function of the buck converter which is determined by the ratio between the output load voltage and the duty cycle.

$$FT_{sys}(p)=\frac{V_{load}(p)}{\alpha(p)}=\frac{K_L}{a_0+a_1\cdot p+a_2\cdot p^2+a_3\cdot p^3+a_4\cdot p^4} \quad (14)$$

$$\begin{cases} K_L = \frac{V_{bat}}{[Lf \cdot Cf \cdot L \cdot C]} \\ a_0 = \frac{1}{[Lf \cdot Cf \cdot L \cdot C]} \\ a_1 = \frac{\frac{1}{R}\cdot[Lf \cdot \alpha_0^2 + L]}{[Lf \cdot Cf \cdot L \cdot C]} \\ a_2 = \frac{[Lf \cdot Cf + L \cdot C + Lf \cdot C \cdot \alpha_0^2]}{[Lf \cdot Cf \cdot L \cdot C]} \\ a_3 = \left[\frac{1}{R.\cdot C}\right] \\ a_4 = 1 \end{cases}$$

Integration of the control constraint:

In this work the control constraint is defined by ensuring the stability of the system in open loop. Otherwise, the all poles of this system must verify the following inequalities:

$$real(P_i) \leq 0 \quad with \ \ i = 1 \dots n \quad (15)$$

n is the system order.

The dynamical constraints (response time, overshoot…) are not considered in the optimization process to minimize the optimization time (minimum of iteration). The constraint of stability is only considered in the optimization process with the other constraints defined previously. The objective function of this optimization is the same as considered in the second step of the pre-sizing approach which is the total volume.

Optimization results with integration of the control constraint:

TABLE 3: THE OPTIMIZATION RESULTS OBTAINED AFTER INTEGRATION OF THE CONTROL CONSTRAINT.

Input filter inductance (µH)	**362.5**
Elementary input filter capacitance (mF)	**2.24**
Number of the elementary input filter capacitance	**3**
Elementary output capacitance (µF)	**1.65**
Number of the elementary output capacitance	**1**
Output filter inductance L(µH)	**65.7**
Switching frequency Fs(kHz)	**20.4**
Heat sink thermal resistance for the Mosfet (°C/W)	**4.16**
Heat sink thermal resistance for the diode (°C/W)	**2.32**
K_C	**3.76e-03**
T_i (s)	**5.22**
Total volume (Liter)	**0.31**

The volume obtained is the same that given in table 2. In this case, the optimized parameters of the various elements shown in table 2 represent a controllable structure, i.e. it exist values for the controller parameters ensuring system stability. The advantage of the optimization with the control constraint is to avoid the case where we have a structure not controllable. Otherwise, the input filter in the converter degrades the system stability and the design of the controller parameters becomes difficult. In fact, for a defined phase and gain margins and for an optimized structure (table 2), there are no values of the controller parameters ensuring stability. Thus, they are must be dimensioned in the global optimization process with the others parameters of the structure. In this case the minimum of the objective function (volume) is not necessarily the one obtained in the optimization without the control constraint.

VI. CONCLUSION

An optimization approach for pre-sizing of dc-dc converters is presented in this paper. In addition, an optimization by integration of the control constraint is done to show their impact in the global optimization. First, this approach proposes an adapted architecture to answer the specifications and appropriate technologies of the passive and the active components representing the minimal volume of the selected architecture. Only the electrical constraints are considered in this case. Moreover, the designer can obtain a quick evolution of the volume by technology for the different components to specify for a range of components variation the technology that represents the minimum volume. He can stop its design at the first step if the volume obtained satisfied the specifications. In case where others constraint must be considered an optimization must be performed. For this raison, the second step involves executing this optimization by considering the obtained results in the first step under multi-physic constraints: volume, thermal, efficiency, EMC and control. The designer has the choice to perform this optimization by considering only the technologies chosen in the first step or the all technologies and find the best combination of these technologies giving the minimum of the function objective. Models are developed from manufacturer datasheet and others one taking into account the multi-physic constraints are developed and validated by simulation and measurements. An optimization by integrating the control constraint is carried out and the obtained results shows that the pre-sizing of the controller must be considered in the global optimization and not separately to avoid a not controllable structure.

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