# Modelling and design approaches for the preliminary design of power electronic converters

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# MODELLING AND DESIGN APPROACHES FOR THE PRELIMINARY DESIGN OF POWER ELECTRONIC CONVERTERS

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**Abstract –** This paper presents different modelling approaches and design tools initially developed for the preliminary design of mechatronic system and applied here to power electronic converters. Different type of models, components level and system level, are needed and exemplify with a DC/DC converter. A dedicated framework is used to manipulate and associate the models. An optimization of the converter is finally realized.

**Keywords** – Power converters, system engineering, surrogate models, model based design, multidisciplinary optimization.

## 1. INTRODUCTION ON DESIGN TOOLS

The increase of computation capabilities of computers and the development of numerical tools boosted modelling & simulation (M&S) usage during product design process [1]. Similarities exist between mechatronic system design and power converter design, especially in early design stages [2][3]. Two levels of knowledge are necessary in order to achieve a mechatronic or power electronics system design [4]. First, a component level knowledge which includes sizing laws, design drivers and technological limits of a component. Secondly, a system level knowledge which concerns sizing scenarios and requirements of the system and how to link them with component sizing. This paper illustrates how methodologies and models developed initially for the design of mechatronic systems can also be applied to the power electronic domain. In addition, different levels of knowledge and their uses are introduced in order to create an optimal sizing procedure. A DC/DC converter with filtering and dissipation components is used to illustrate the concepts introduced.

## 2. THE PRELIMINARY DESIGN OF POWER CONVERTERS

### 2.1. SIZING PROBLEM OF POWER CONVERTER

A lot of new applications require the use of power converters to manage power sources, such as battery, supercapacitor, for embedded systems. The objectives of this case study are:

- The definition of the sizing procedure and the optimization problem of a DC/DC converter for an ultra-capacitor.
- The sizing of the main components and the determination of optimal design variables such as the Pulse Wide Modulation (PWM) frequency.

### 2.2. ARCHITECTURE, COMPONENTS

The studied DC/DC converter (Fig. 1 and Fig. 2) is composed by one film capacitor, two IGBT transistors, and one inductance. A heatsink is used to cool the IGBT modules.

Fig. 1: Power converter prototype (ARCEL)

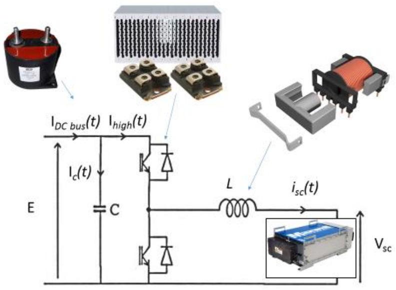


Fig. 2 : Architecture of a DC/DC converter for power management of an ultracapacitor

### 2.3. DESİGN DRİVERS, REQUİREMENTS AND OPTİMİZATİON

**Components design drivers**

*Inductance*

The inductance have to store magnetic energy for the maximum current. This will have an influence on the section of iron and the value of the airgap. For thermal aspects Joules and iron losses have to be evaulated and the winding hot spot temperature have to be estimated through a thermal model. Moreover, we will check that the size of the winding remains acceptable. Generally during the sizing the value of airgap is limited to ensure good precision for the magnetic analytical model. In this study, it is proposed to build a model which allows the estimation of the influences of airgap for widest range of variation [5].

*Capacitor*

The capacitor has to limit the amplitude of the voltage ripple. For the thermal aspects, it is assumed that the losses are dissipated from the RMS current in the electrodes and the dielectric losses in the dielectric. A thermal model of the capacitor will be used here to estimate the hot spot temperature.

*IGBT*

In order to select the IGBT modules, the junction temperature will be estimated. This criteria requires to choose the size of the heatsink and to make compromise for the value of the switching frequency (filter / loss compromise).

**Requirements**

The DC/DC converter specifications used for numerical applications are the followings:

- DC bus voltage: E = 300 V
- Ripple voltage max. of the DC bus: 1%
- DC current of the load (supercapacitor): 140 A
- Current ripple max. of the load: 35 %
- DC voltage of the load: 125 V

## 3. SYSTEM LEVEL AND COMPONENTS LEVEL MODELS

Models support Systems Engineering processes. Models also facilitate capitalization especially if their built or used are generic. Different types of models can be used such as distributed parameters (3D FEM, 3D CFD [6]) for local level, lumped parameters (1D/OD, ODE/ADE) [7] and state machine for global level. In order to capture and structure knowledge, Knowledge-Based Engineering [8] can be used. This tends to use component database and model libraries [8].

### 3.1. SYSTEM LEVEL MODELS

Knowledge at system level enables the evaluation of sizing variables for system' components for several sizing scenario. The simple layout of the considered converter allows to express these models with algebraic equations. Table I represents the current and voltage filtering equations. Table II shows the variables required for the thermal evaluation of the components. For more complex architectures, these models can be obtained using regression process on PWM circuit simulations [9] or using directly system models [10].

I Current and voltage filtering equations

| Component | RMS current |
|---|---|
| Inductor | $\Delta I_L = \dfrac{E(1-\alpha).\alpha}{L\,f}$ |
| Capacitor | $\Delta V = \dfrac{I_{max}(1-\propto)\propto}{C\,f}$ |

IIa : Current equations

| Component | Mean current | RMS current |
|---|---|---|

| | | |
|---|---|---|
| Inductor | $I_L$ | $I_L\sqrt{1+\frac{1}{12}\left(\frac{\Delta I_L}{I_L}\right)^2}$ |
| IGBT | $\alpha I_L$ | $\sqrt{\alpha}.I_L\sqrt{1+\frac{1}{12}\left(\frac{\Delta I_L}{I_L}\right)^2}$ |
| Diode | $(1-\alpha)I_L$ | $\sqrt{1-\alpha}I_L\sqrt{1+\frac{1}{12}\left(\frac{\Delta I_L}{I_L}\right)^2}$ |
| DC Capacitor | 0 | $\sqrt{\alpha(1-\alpha)} \times I_L\sqrt{1+\frac{1}{12(1-\alpha)}\left(\frac{\Delta I_L}{I_L}\right)^2}$ |

IIb : Mains losses evaluations

| Component | Conduction losses | Commutation losses |
|---|---|---|
| Inductance | $R_L I_{RMS}^2$ | - |
| IGBT | $V_0 I_{mean} + R_0 I_{RMS}^2$ | $f(E_{on}+E_{off})$ |
| Diode | $V_0 I_{mean} + R_0 I_{RMS}^2$ | $f\frac{1}{8}I_{RM}E.t_{rr}$ |
| DC Capacitor | $R_S I_{RMS}^2$ | - |

### 3.2. COMPENENT LEVEL MODELS WİTH SCALİNG LAWS

In the design of mechatronic systems scaling laws allow estimation models [11] to be obtained from a single reference component by using three main modeling assumptions:

a. Material similarity: all material and physical properties are assumed to be identical to those of the component as the reference;
b. Geometric similarity: the ratio of all the lengths of the component under consideration to all the lengths of the reference component is constant;
c. Uniqueness of the design driver: only one main dominant physical phenomenon drives the evolution of the secondary characteristic $y$.

The mathematical form of scaling laws is a power law:

$$y = kX^a \quad \textbf{(1)}$$

With $y$ is the secondary characteristic to be estimated, $X$ is a definition parameter of the component, and $k$ and $a$ are numerical constants calculated from a reference component.

Their simple form makes them easy to manipulate and customize as they require only one reference to determine the coefficients $k$ and $a$. They have a monotonous progression valid over a wide range of sizes (several orders of magnitude) which avoids the risk of possible mathematical aberrations of metamodels used outside their construction bounds [12].

#### 3.2.1 Scaling laws for ferrite cores

Geometrical similarities, i.e. conservation of geometrical ratio during scale changes, enable to obtain interesting characteristics by reducing considerably the number of inputs [13]. Ferrites pot cores follow geometrical similarities and all the geometrical parameters can be expressed from the external diameter of the inductance.

III : Scaling laws for ferrite cores

| Characteristics | Scaling ratio |
|---|---|
| Length | $D^*$ |
| Surface | $D^{*2}$ |
| Volume/Mass | $D^{*3}$ |

With the notation proposed by M. Jufer [14] where $x^* = x/x_{ref}$ is the scaling ratio of a given parameter.

#### 3.2.2 Scaling laws for IGBT modules

The table IV introduces the different scaling laws used to estimate the IGBT characteristics where I express the current rating of the module.

IV : Scaling laws established for the IGBT modules

|  | Scaling laws | Reference |
|---|---|---|
| Definition parameter : Current | I | 80 A |
| Maximum voltage | $V_{max}^* = 1$ | 900 V |
| Voltage drop | $V_0^*=1$ | 1 V |
| Dynamic resistance | $R_0^*=I^{*-1}$ | 20 mΩ |
| Commutation losses | $(E_{on}+E_{off})^*=I^*E^*$ | 8.2 mJ for E=450 V |
| Thermal resistance | $R_{th\_JC}^*=I^{*-1}$ | 0.30 °C/W |

### 3.3. COMPONENTS MODELS WITH SURROGATE MODELS

Scaling laws have assets that make them attractive for the design of mechatronic systems. However they have some limitations. Although the similarity of the materials can be easily verified for a given technology of electronic components, the geometric similarity is not necessarily verified or sought. Surrogate modelling technique can be used to overcome these limitations [15]. Surrogate modelling technique consists in replacing high detail models (FEM, CAD models) by analytical models which are explicit and easily handle-able. It is proposed here to use a specific surrogate modelling technique, the VPLM methodology [16], to build the magnetic and thermal models of inductance. Similar thermal models of capacitor and heatsink can be found in another Electrimacs contribution submitted to the special session: *Thermal Management of power electronics and electrical machines*.

#### 3.3.1 Surrogate thermal model for inductance

The thermal resistance of inductance component is required to estimate the hot spot temperature of its winding. Inductance using ferrites pot cores is considered for this study. Fig. 3 introduces the simplified model of the inductance considering the following assumptions:

- Geometrical simplification: axi-symmetry hypothesis.
- Ferrites cores follow geometrical similarities except for the airgap.
- Material simplification: the winding is composed by copper wires and potting resin. The winding coefficient drives the thermal conductivity of the equivalent material. The equivalent thermal conductivity is calculated using the formula given in [17].
- Natural convection cooling, conductive and radiative heat transfers are considered.

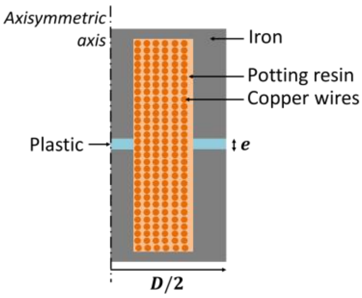


Fig. 3 : Simplified model of inductance

Two types of losses are considered for the thermal modelling: Joules losses dissipated in the equivalent material for the winding and cores losses dissipated in ferrite cores.

According to the VPLM methodology [16], the thermal resistance of the inductance is given by (2) and has a maximum relative error less than 8% with the FEM simulations (Fig. 4).

$$R_{th\_ind} = \frac{5.283}{\lambda D} Gr^{-0.107} \pi_{cd}^{-0.0197} \pi_{rad}^{-0.151} \quad \textbf{(2)}$$

Where: $Gr = \frac{\rho^2 g \beta \varphi D^4}{\mu^2 \lambda}$ is the modified Grashof number (expressed in term of heat flux) which defined the natural convection phenomena; $\pi_{cd} = \frac{\lambda_{winding}}{\lambda}$ is the thermal conductivities ratio which defined the conduction; $\pi_6 = \frac{\rho^2 D^3 \varepsilon \sigma T_a^4}{\mu^3}$ is the radiative dimensionless number.

#### 3.3.2 Surrogate magnetic model for inductance

The objective is to represent the magnetic circuit of an inductance. The model has to take in account the magnetic field in the airgap for small and big values, and using finite elements simulations the proportion of the magnetic field outside the magnetic circuit is also considered. These effects are not well modelled by classical analytic models.

The inductance is represented by the reluctance of the magnetic circuit $R_L$:

$$L = n^2 / R_L \quad \textbf{(3)}$$

Where $L$ is the inductance, $n$ the number of turns.

Two assumptions are considered for the study:

- The reluctance of the ferrite magnetic circuit is considered during the FEM simulation but neglected for the final expression.
- The saturation effects are not considered.

According to the VPLM methodology [16], the reluctance is given by (4) and the model has a maximum relative error less than 1% with the FEM model (Fig. 4).

$$R_L = \frac{3.86}{\mu_0 D} \pi_e^{0.344 - 0.226 \log(\pi_e) - 0.0355 \log(\pi_e)} \quad \textbf{(4)}$$

Where $\pi_e = e/D$.

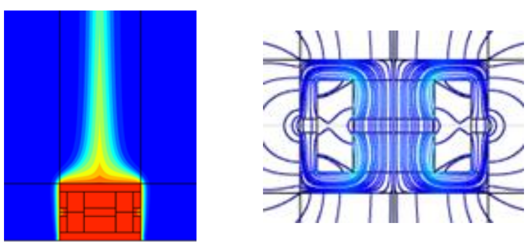

Fig. 4 : COMSOL simulation results for inductance models (right: thermal, left: magnetic)

## 4. MODELS MANİPULATİON AND DESİGN PROCESSUS

### 4.1. ASSOCİATİON OF ACAUSAL MODELS

In order to facilitate capitalization in models libraries [18] and reuse of the models for different applications, acausal models are generally preferred [2], [19].

### 4.2. FROM ACAUSAL TO CAUSAL MODELS

Moving from acausal non-oriented model and unusable for sizing or optimization tasks to causal model which has inputs and outputs, requires to solve several problems to be sure to obtain an explicit and ''balanced'' code (no complex numerical solving and equality between number of inputs and number of outputs).

Three types of problem must be solved:

1. Set of equations underconstrained

The set of equations introduces too much variables to be determined. It is required assuming ones of them known. During optimization procedures, it will be possible to includes them into the set of optimization variables. For the DC/DC converter, the explicit evaluation of diode and IGBT losses and inductance and capacitance value require assuming the switching frequency known.

2. Set of equations overcontrained

A set of equations is over-constraint if the number of equations is greater than the number of variable to be determined. This sizing problem appears for the selection of a component which has to fulfill two constraints. For example, the capacitor has to ensure a filtering function (limitation of voltage ripple) without overheating. During optimization procedure, it is possible to adapt the set of equations with an oversizing coefficient used for one equation and the other equation is added to the constraints of the optimization problem.

3. Algebraic loop

This problem is classical for coupling equations like: $x = f(y)$ and $y = g(x)$. Solving these equations requires the use of numerical solver inside the optimization procedure.

This problem occurs when a criterion used to select a component depends on the internal characteristics of this component. For example, the selection of IGBT module with thermal criterion: the silicon temperature of the transistor depends on its thermal resistance junction to case. It is possible to transform the problem in an explicit way by breaking the algebraic loop with the use of an oversizing coefficient. It is used on a simplified selection criterion independent of internal characteristics of the IGBT. The silicon temperature will be verified by the optimization algorithm trough the problem constraints.

### 4.3. CAUSAL MODELLİNG OF THE SİZİNG PROCEDURE

Acausal models presented before can generate causal models for the problem introduced before thanks to ordering and matching algorithms [20]. Causal model were generated component by component and they are associated in a causal modelling [21] environment win order to represent system level sizing procedure. Their connections uses $N^2$ diagram [22] topology. This way, a sizing procedure and the related optimization problem architecture can easily be implemented. In addition to component level knowledge, the choices made during sizing must be validated by operational scenarios. These sizing scenarios can be represented by different model types such as algebraic equations, time response simulations [23] harmonic response simulations [24] or surrogate models [25] like response surfaces for instance. Usually, these kinds of model have imposed inputs and outputs. Therefore, information flows are causal at system level design and causal model must be used.

## 5. OPTİMİZATİON AND RESULTS

### 5.1. OPENMDAO FRAMEWORK

In order to optimize the system design, it is possible to associate optimization algorithms to the sizing procedure [25]. Multidisciplinary Design Optimization (MDO) is relevant for mechatronic systems design [26] and by the way for converters design. MDO frameworks such as openMDAO [27] enable building global system models by associating elementary models and offer optimization algorithms libraries. Due to the number of requirements and design drivers, MDO of power converters could require constrained (linear or non-linear) optimization.

The preliminary design framework used in this paper aims to satisfy in the best manner the needs and problems while designing a system by using the interesting concepts introduced earlier. More details about this framework are described in [10].

### 5.2. OPTİMİZATİON

The optimization procedure conducts on the problem defined in 2 gives a minimum mass of 9.78 kg. The final PWM frequency, around 10 kHz, is a compromise between cooling mass (heat sink) and filtering mass (inductor and capacitor). The airgap inductor, 7.2 mm, find thanks to FEM surrogate models, is bigger than that would be find with an over simple analytical model.

## 6. CONCLUSİON

In this paper several design approaches to generate models dedicated to the preliminary design of power electronic converters were introduced. The framework presented enables to make connections between all these models and to conduct optimization tasks.

The preliminary sizing of a DC/DC converter has been done using optimization and different types of models such as scaling laws and surrogate models. These models permit to evaluate components characteristics such as hot spot temperature, air gap and mass. Optimization enable to realize the compromise between cooling mass and filtering mass.

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