Robustness Analysis of DC Distributed Power Systems by Means of Behavioral DC-DC Converter Models

J.A. Oliver, R. Prieto, L. Laguna and J.A. Cobos
Universidad Politécnica de Madrid (UPM) Spain
Centro de Electrónica Industrial (CEI)

Abstract

The aim of this paper is to determine the model requirements for dc-dc converters in order to analyze and evaluate the performance of different architectures of DC distributed power systems and to assure that all the specifications are met under all parameter variations. Based on these requirements a parametric model for the dc-dc converters is presented that can be identified as a function of the information given by the manufacturers in their datasheets. In this way, it is possible to make sensitivity and worst case analysis that can help the designer to evaluate the robustness of their architectures.

1 Introduction

Complexity of power distribution systems is continuously increasing due to the stronger requirements imposed by the loads (faster transient response, tightly regulated outputs), different levels of conversion, system protections, new energy storage elements and energy sources, etc.. This situation is common both for very low power systems such as those present in handheld devices and for large power systems such as data centers. Such increase in the complexity can be easily understood taking a look at the evolution of the number of CPU per rack shown in Fig. 1 [1].

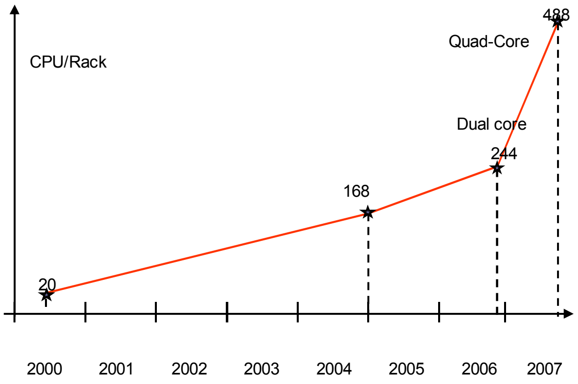


Fig. 1 ***Evolution of the number of CPU per Rack in data servers***

System designers have to address the design considering different architectures and alternatives assuring that all the requirements are met. Additionally, the selected architecture has to be tested not only under nominal conditions but also taking into account variations of the component parameter values and the temperature. Current circuit simulators provide powerful analysis tools (sensitivity analysis, Monte Carlo simulations, and worst case analysis) that allow verifying the robust performance of the whole system. Nevertheless, in order to apply these techniques, the parameters to be modified have to be all those provided by component manufacturers in their datasheets.

Traditionally, dc-dc converters have been designed ad-hoc for each particular application. Present day commercial dc-dc converters are replacing custom designs because of their significant advantages in terms of development time, they usually have lower area and smaller form factors, and they reduce the component count and also the cost.

In these cases, the internal structure of the dc-dc converter and their parameters are not known, since they are part of the intellectual property of the manufacturer, and the averaging techniques cannot be applied. So it is necessary to develop new modeling techniques that can capture the behavior of the converters preferably by means of the information provided by manufacturers in their datasheet. In this way, parameter analysis to determine the robustness of the system can be applied based on actual manufacturers' information.

This necessity has been recently identified. The modelling approach proposed by [3] is based on the small signal frequency identification of the converter. This approach is very accurate from the point of view of small-signal stability but it does not account for efficiency as a function of the input voltage and load, output voltage as a function of load or protections such as overvoltage, over-current, under-voltage and temperature. Additionally, it cannot be used for robustness analysis since the tolerances given by the manufacturers cannot be mapped to the model parameters.

The proposed model overcomes all those limitations. The trade-offs between simulation time and accuracy of dc-dc converters have been successfully addressed by the use of a hybrid model as shown in figure 1. All the protections and remote control features are managed by the logic system (event driven behavior) and the power stage and control is modeled by a Wiener-Hammerstein structure (see figure 1). The parameters of the proposed structure are based on the values given in the datasheets, allowing performing sensitivity analysis.

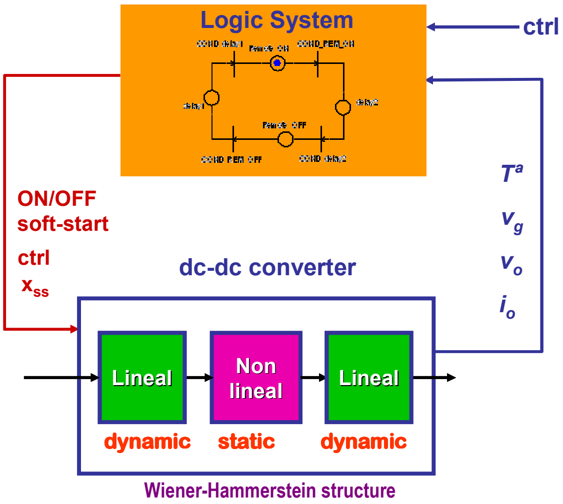


Fig. 2 Proposed dc-dc converter model structure

2 Model requirements

Present day trends toward the use of commercial components makes impossible to use well known modeling techniques such as averaging [2]. These commercial converters present significant advantages over custom made solutions since they can reduce significantly the development time, critical in fast changing markets, they usually have lower area and smaller form factors, reduce the component count and also the cost.

In these cases, the internal structure of the dc-dc converter and their parameters are not known, since they are part of the intellectual property of the manufacturer, and the averaging techniques cannot be applied. So it is necessary to develop new modelling techniques that can capture the behaviour of the converters preferably by means of the information provided by manufacturers in their datasheet or some additional measurements [2].

2.1 Static requirements

The efficiency of the power electronic converters depends on its operating conditions (input voltage and load), and this influence can have a significant effect on the performance of the power distribution system. Typically, at light load, the efficiency of the converter decreases considerably. Meanwhile this effect has been traditionally ignored because the tendency was to increase the power density, that is driven by the thermal limitations at maximum load, today there are more and more applications in which the light load efficiency has a critical impact on the whole system efficiency (especially in data servers or portable devices) [4]. As a consequence, it is very important from de designer point of view to have accurate models that account for the influence of the input voltage and load on the efficiency of the converter.

These static models can cover the first stages of the design in which very useful information can be obtained:

Power budget under all input voltage conditions and loads.

Thermal management. The power losses of all the components under different scenarios can be used as inputs to Finite Element Analysis tools

Wiring and protection pre-dimensioning. Based on the data provided by the simulation, the maximum steady-state currents under all working conditions can be estimated and used for the selection of the harnessing and protection pre-dimensioning.

2.2 Dynamic requirements

As it has been shown above, the static model of the converters provide a good information for the power distribution system designer that can help in the analysis of different architectures and the selection of the right components for those architectures. Nevertheless, there are some critical issues in the architecture that have to be addressed before making the final decision. All these factors are related to the stability of the system:

2.2.1 Small signal behavior

The models of all the components in a distributed power system have to account for their small signal behaviour. It means that they have to reflect the basic interactions among components that can yield to system instability. In the particular case of power converters, they have to correctly account for the input impedance, and the influence of the load in the input impedance and the output impedance.

The small signal models are of great interest in order to check for the robustness of a design applying well known techniques such as the Middlebrook's criterion.

2.2.2 Large signal behavior

The increasing complexity of the systems to be powered, not only due to the higher number of loads and sources but because of the higher requirements in terms of power management are driving the use of dedicated controllers and the development of communication buses, such as PMBUS, that are becoming an standard.

The added functionality of the power converters has to be taken into account, that is, the model has to include its event driven behaviour that includes functions such as:

Remote powering. System designers usually require the ability to power on and off some parts of the system in order to reduce the power consumption or to isolate them in case of faults. Thus it is necessary to take this functionality into account.

Programmable output voltage. Energy efficient techniques such as DVS require a programmable output voltage that will be modified as a function of the work load requirements of the microprocessor.

Programmable protections. Protections can play an important role on the stability of the system. Especially under-voltage protection that turn-off the converter when the input voltage drops below its minimum can yield to sustained oscillations due to the interactions of the converter and the input filter as will be shown in the validation section.

Soft-start. The start-up of the power system can be greatly improved by the adequate sequencing and selection of the soft-start characteristics of the power processing elements. To validate and design the power management system the models have to include the soft-start behaviour of the power converters.

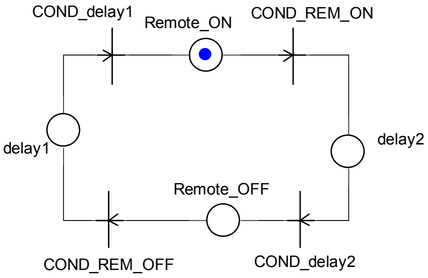
3 DC-DC modelling approach

The proposed model structure, shown in *Fig.* 2, captures the hybrid nature of the dc-dc converters:

The logic system, that can be represented by means of a state diagram, and can be implemented in a circuit simulator or VHDL-AMS.

The continuous system that represents the behaviour of the converter as a function of its state.

The logic system is in charge of defining the state of the converter, in this case three different states have been defined: ON, OFF and an intermediate state during SOFT-START. The transition conditions to move from one state to other state will be a function of the converter variables (output voltage, output current, input voltage and temperature).



Remote ON-OFF state diagram

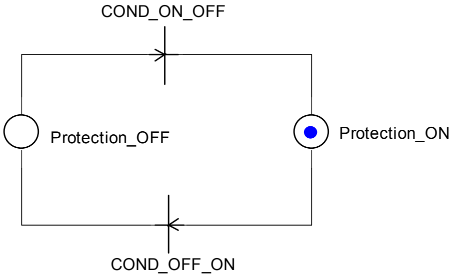


Fig. 3 State machines for the model of the logic system

For the continuous model of the converter a Wiener-Hammerstein structure has been selected, as shown in Fig. 4 This structure consists of three blocks: a static nonlinear block and two linear blocks for the input and output dynamics respectively.

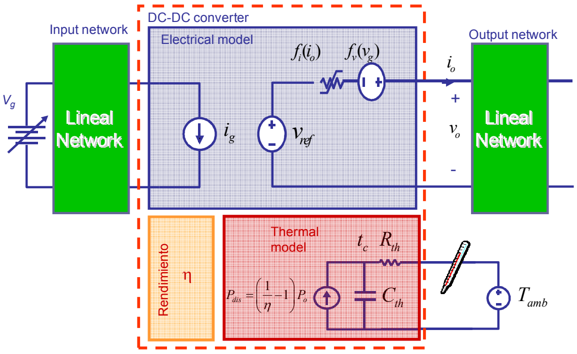


Fig. 4 Wiener-Hammerstein structure proposed for the converter

The static non-linear block. This element determines the steady-state behaviour of the converter, accounting for the variation of the output voltage with the input voltage and the load and also the influence of these variables on the efficiency of the converter:

$$v_{out} = V_0 + f_v(v_{in}) - f_z(i_{out}) \qquad (1)$$

$$i_{in} = \frac{1}{\eta(v_{in}, i_{out})} \frac{v_{out} \cdot i_{out}}{v_{in}} \qquad (2)$$

Both functions can be accurately implemented by means of look-up tables based on the graphical information given by manufacturers. A comparison of the simulated and measured results for a LAMBDA X1068S05 is shown in Fig. 5

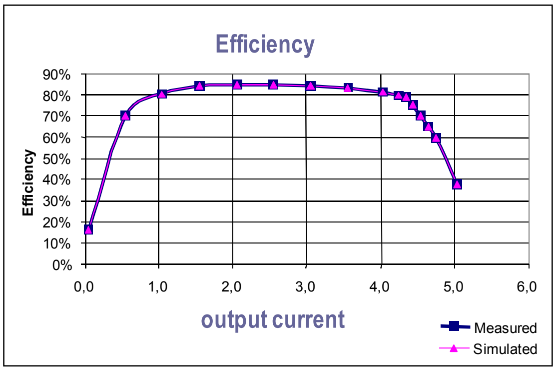


Fig. 5 Measurement vs simulated results of the efficiency as a function of load current

The linear dynamic input block. This block accounts for the high frequency behaviour of the input impedance, since the low frequency behaviour is given by the static block. It can be identified from the inrush current data of the converter [2]. A comparison of the measured and simulated inrush current for the LAMBDA X1068S05 is shown in Fig. 6.

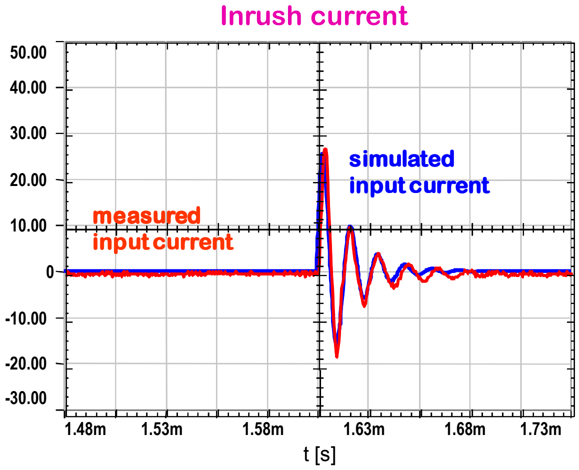


Fig. 6 Measurement vs simulated results of the inrush current

The linear dynamic output block. The dynamic response of the dc-dc converter to load changes is given by this network that is determined by the load step response provided by the manufacturer [2]. The comparison of the simulated and measured results for a load step from 0 to 100% is shown in Fig. 7

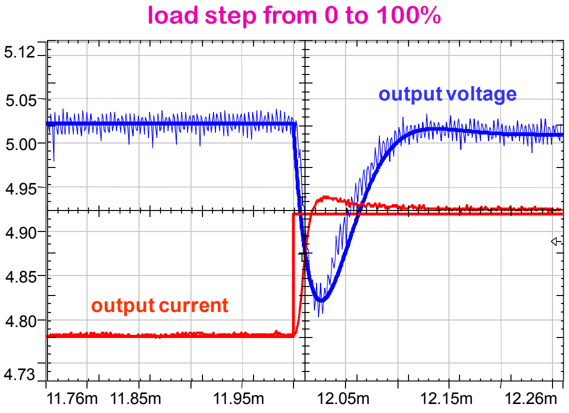


Fig. 7 Measurement vs simulated results under a load step from 0% to 100%

4 Robustness analysis

In order to highlight the usefulness of the presented parametric models for robustness analysis of DC distributed systems an example of an actual $28V_{DC}$ distributed power system for an aerospace application is represented in Fig. 8 that consists of eleven commercial dc-dc converters, twelve filters, protections, a hold-up circuit and six non-linear loads.

The power system, both the model and the actual system, have been analyzed under all test conditions specified by the manufacturer. One of those test, called power-up test, is used to identify the power-up capability of the system under worst case conditions, that is, under minimum input voltage.

In this case, the power-up capability for the minimum input voltage of 20 V was analyzed for two different busbar impedances: an smaller impedance that generates a voltage drop of 0,4V and the maximum specified busbar impedance that produce a voltage drop of 1,5V.

The simulation and measured results for the input current of the power system in the first case–smaller busbar impedance- are shown in Fig. 9. It can be noticed how, in spite of the spikes in the input current, produced by the charge of the hold-up capacitor, input filter capacitors and start-up of the non-linear loads, the input current stabilizes in 200 ms.

In the case of a busbar impedance that creates a voltage drop of 1,5V it can be seen in Fig. 10 that the input current becomes oscillating. This behaviour is also predicted by the simulation as shown Fig. 10.

The reason for these oscillations was identified thanks to the parametric properties of the proposed models. It was a consequence of the under-voltage protection of a dc-dc converter. Lowering this parameter, the oscillations were removed. The physical explanation of the oscillation was found on the following interaction: during start-up, when the input voltage of the dc-dc converter that caused the oscillations was higher than the minimum input voltage it became enabled and started to demand an input current with a high di/dt. This current generated a voltage drop in its input capacitor bellow the under-voltage protection condition. As a consequence, the converter turned off and again its input voltage started to increase. This process was the cause of the sustained oscillations.

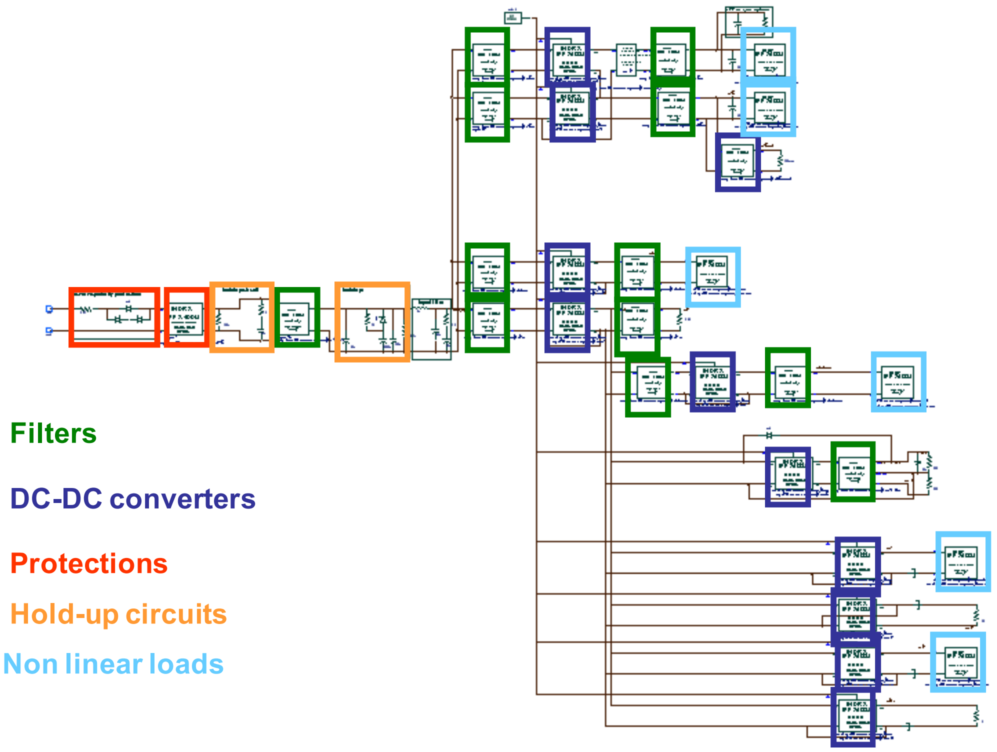


Fig. 8 Measurement vs simulated results of the inrush current

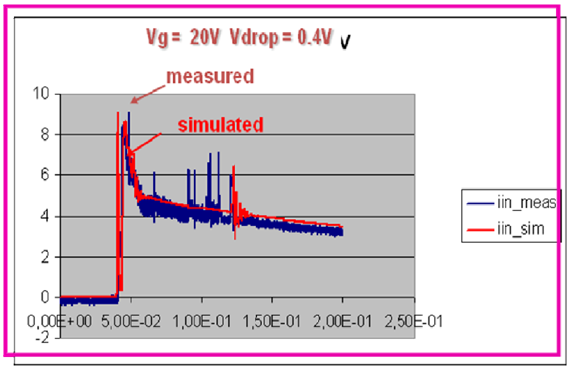


Fig. 9 Measurement vs simulated input current comparison for a power-up test with Vdrop=0,4V

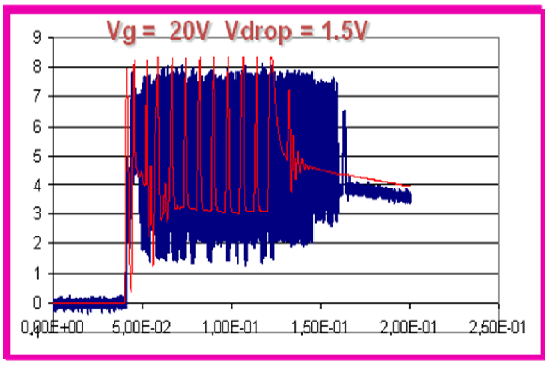


Fig. 10 Measurement vs simulated input current comparison for a power-up test with Vdrop=1,5V

5 Conclusions

This paper shows the requirements for the dc-dc converter models in order to analyze and evaluate DC power distributed architectures in terms of static and dynamic behaviour, and also to be useful for sensitivity and worst case analysis.

Under the light of these requirements, a parametric model for the dc-dc converters is presented based on the information provided by the manufacturers in their datasheets. In this way, it is possible to make sensitivity and worst case analysis that can help the designer to evaluate the robustness of their architectures.

The proposed model is used to establish the robustness of an actual DC distributed system for an aerospace application and to analyze its behaviour under all the test conditions specified for the system.

6 Literature

[1] W. Ott, "Challenges in digital power management," IEEE Applied Power Electronics Conference and Exposition, plenary sesion presentation, 2006.

[2] J. A. Oliver, R. Prieto, V. Romero, and J. A. Cobos, "Behavioral modeling of dc-dc converters for large-signal simulation of distributed power systems," IEEE Applied Power Electronics Conference and Exposition, APEC 2006.

[3] L. Amedo, R. Burgos, F. Wang, and D. Boroyevich, "Black-Box Terminal Characterization Modeling of DC-to-DC Converters," Applied Power Electronics Conference, APEC 2007.

[4] Milan M. Jovanovic, “Power Supply Technology – Past, Present and Future” Power Conversion and Intelligent Motion China, 2007, pp. 3-15