Modeling, Analysis and Simulation of a DC Distributed Power Architecture for an Airborne Application

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***Abstract*—This paper describes a design and analysis method for a DC distributed power architecture design in Airborne Application, utilizing simulation. Typically the used system components are commercial off-the-shelf components (COTS) thus complicating the system level analysis and simulation. Within this paper, it is shown how these systems can be designed utilizing simulation results, based on behavioural models of dc/dc converters. Additionally, models for commercial EMI filters are developed. This enables system level simulations and important information from efficiency, transient response, failures and stability is obtained assisting the designer to reach an optimum power system solution with minimum time and effort. Complex systems in avionics require high reliability. Therefore, the system level simulation is an essential tool for reaching the feasible solution complying with all the requirements[1].**

I. INTRODUCTION

Distributed power systems comprise various different components and can be very complex in nature. As stability is a major concern of the power systems it is desirable to detect any potential stability problems at an early design stage. Power system stability can be analysed as small signal stability, interactions between input filter and dc/dc converter as shown in [1] and [2], or large signal stability due to converter turn-on/off delays, start-up and protections. Proper system simulation assists avoiding any problems concerning the above mentioned stabilities. Additionally, accurate simulations improve the distributed power system design considerably.

In order to minimize time to market, the utilized power modules are typically commercial off-the-shelf (COTS) components. Therefore, rarely any detailed information of the converter structure is obtainable. Thus concerning the system level simulation it is desirable to develop models for the commercial components. Plenty of research concerning the dc/dc converter modeling techniques has been provided. General averaged model for the converter has been developed in [3] and been applied to distributed power system simulations in [4]. Additionally, in [5] and [6] is described how to obtain hybrid parameter models which are limited to analyse small signal stability. Neither of the above mentioned models is adequate to analyse large signal stability. Therefore, improved dc/dc converter models are required. In [7] and [8] behavioral model for dc-dc converter is developed based on the Wiener-Hammerstein structure. Thus enabling adequate dc distributed power system simulations as presented in [9]. In [9] a parameterization software tool is used to generate behavioral models for power converters, easing the capture and generation of fast and accurate models based on the information provided by the manufacturer or measurements. Additional EMI filters increase the system complexity but they are required in order to successfully comply with the tight EMC requirements. The designed distributed power system is presented in Figure 1.

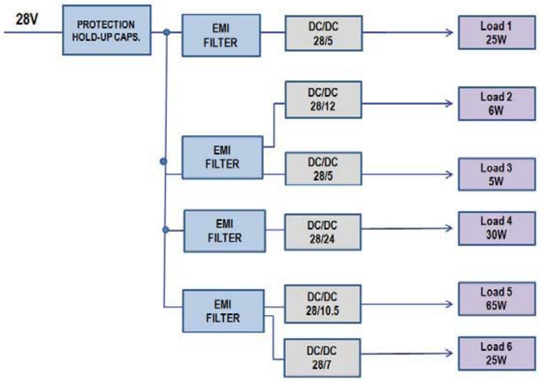

Fig. 1. Distributed power system block diagram.

The power system dc/dc converters presented in this paper are modeled as described in [7] and [8]. The system level analysis is completed as recommended in [9] and [10]. In

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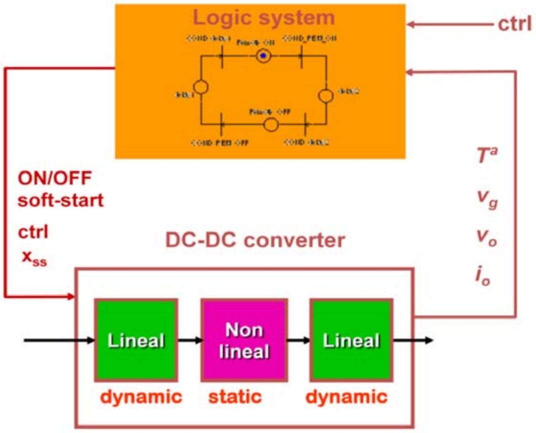

Fig. 2. Dc-dc converter behavior model structure.

addition, EMI filter models are developed based on typical input filter structure [11] and impedance measurements. The system small signal stability is analyzed, assessing the interactions between EMI filter and dc/dc converter. Thereafter, the whole system is simulated and the obtained results are used to facilitate the final design.

II. SYSTEM COMPONENT MODELING

A. *Dc-dc converter models*

As the objective is to model commercial converters, the utilized model is required to be identified based on available information. The power stage of the dc-dc converter is modeled based on Wiener-Hammerstein structure whereas events driven behavior is managed by the logic system [10] as shown in Figure 2.

This behavior model can be generated from the parameters obtained from the converter datasheet. Thereafter, it can be implemented to a circuit simulator [12] utilizing hardware description language. The following information is required in order to obtain simulation models for the dc-dc converters:

- Static behavior: Output voltage dependence on the load current and input voltage, as well as efficiency dependence on the load current and input voltage.
- Dynamic behavior: Inrush current and output voltage transient response.
- Events driven behavior: Protections, soft start and remote control.

The static parameters describe the basic power processing behavior whereas the dynamic information includes high frequency dynamics and large signal behavior to the converter model. The events driven behavior can have a significant influence on the system level stability and is important to take it into consideration in the converter model. All of these parameters are typically obtainable from the datasheets.

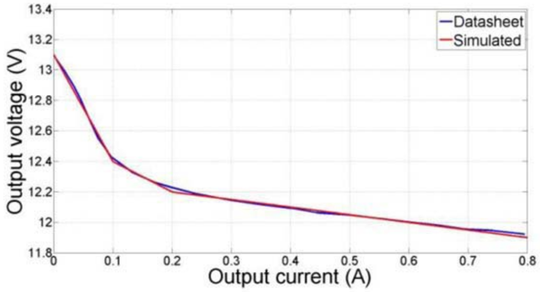

Fig. 3. The simulated converter static behavior compared to the datasheet value.

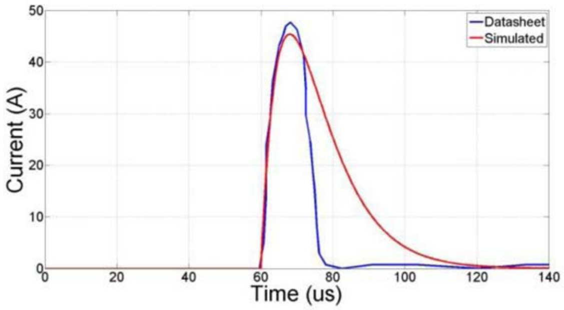

Fig. 4. The simulated inrush current vs. datasheet value.

The utilized dc/dc converters were modeled based on the information provided within the datasheets and obtained from the measurements. The model validation was done by comparing simulation results to the datasheet curves provided by the manufacturer. Utilizing the created static converter model, simulated load regulation is compared to the datasheet value as presented in Figure 3.

As Figure 3 presents, this simulation model provides accurate results concerning the static behavior. The dynamic and events driven behavior of the converter can be validated by comparing inrush current simulation and the corresponding datasheet value as shown in Figure 4.

From Figure 4 it can be observed that the simulation model predicts the peak value of the current. With this simple model it is not possible to predict exact dynamic behavior. However, it is adequate enough for the required system level simulations. The model validation, as presented in the previous Figures was carried out for every dc-dc converter utilized within the system.

B. *EMI Filter Models*

The proposed models for the commercial EMI filters are based on the general topological structure of an input filter [11]. In order to estimate these component values, the frequency response of each filter was measured. The

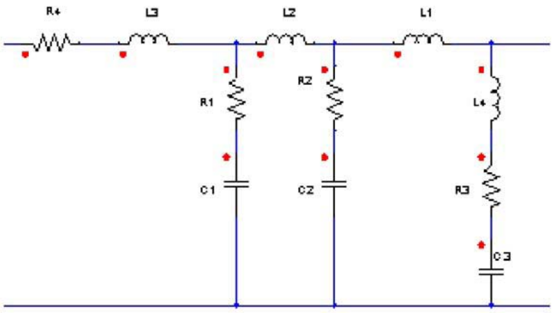

Fig. 5. Equivalent EMI filter model structure.

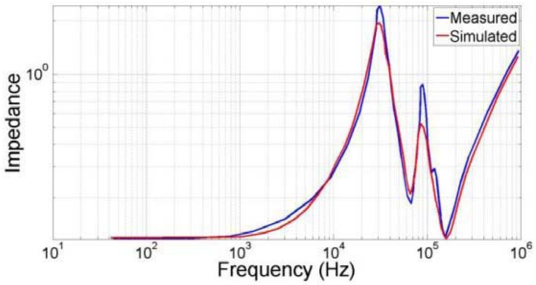

Fig. 6. Simulated and measured output impedances.

following measurements were carried out:

- Short circuit input impedance
- Open circuit input impedance
- Output impedance

The best suitable model for each EMI filter was obtained by fitting simulated ac responses to the measured ones. In addition to the basic filter components, the parasitic values are needed to take into consideration due to their affect on the ac response at high frequencies. Utilizing this principle, EMI filter models for each commercial filter were obtained. One of the used equivalent input filter circuits is presented in Figure 5.

The designed system utilizes distributed EMI filter design in order to guarantee stable operation of the system. Therefore, various EMI filters from different manufacturers are used and each filter has its own equivalent circuit. Figure 6 presents the comparison of simulated output impedance value compared to measured value of one equivalent circuit.

Based on the results presented in Figure 6, the simulation models of the input filters can be assumed to provide adequate models for the utilized EMI filters in order to obtain necessary system level simulations.

III. SIMULATION AND SYSTEM DESIGN

Two types of instability problems, small signal and large signal, can occur within distributed power systems. Small signal instability is due to the interactions between the input filter and dc/dc converter as described in [1] and [2]. Whereas, large signal instability can occur at system level due to the converter start-up, turn-on/off signals or protections.

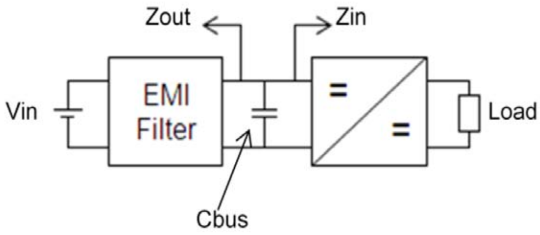

Fig. 7. Impedance interactions between input EMI filter and a dc/dc converter.

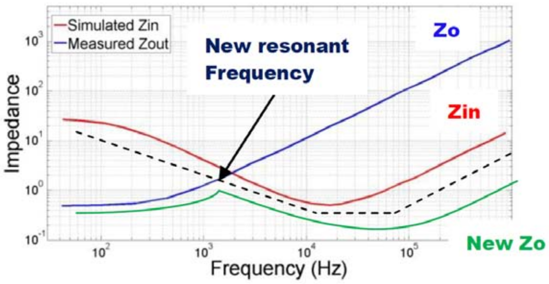

Fig. 8. Measured EMI filter Zout compared to the simulated converter Zin and suggested bus capacitor.

A. Stability Analysis

While additional commercial EMI input filters are utilized within the system, the small signal stability is of interest. The impedance interactions between the converter and its input filter are to be analysed in order to guarantee stability. Equation 1 shows the Middlebrook criterion [2] for impedance inequalities:

$$Z_o << Z_{in} \tag{1}$$

where Z_o is the filter output impedance and Z_{in} is the converter input impedance as shown in Figure 7.

Utilizing the developed behavioral models, the dc/dc converter input impedance can be simulated without greater hindrances. Thus the simulated input impedance can be compared to the measured filter output impedance. Each converter input impedance as well as EMI filter output impedances were analysed. Based on the analysis, one possible instability problem was discovered, as demonstrated in Figure 8.

Figure 8 shows that the Middlebrook criterion $Z_o << Z_{in}$ is not met, thus resulting potential system level instability problems. This small signal instability problem can eliminated by adding sufficient capacitance at the filter output as the

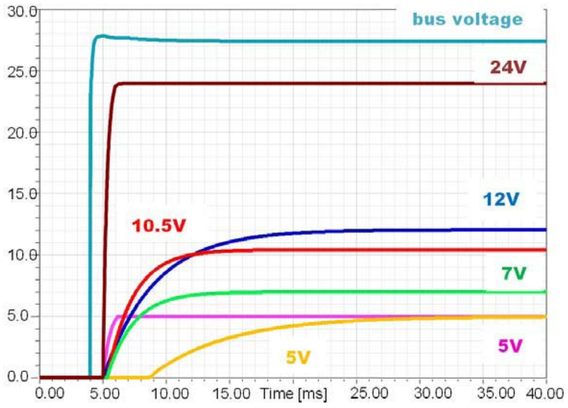

Fig. 9. The converter output voltages at the system start-up.

dashed line presents in Figure 8. The selected capacitor is required to have low ESR and ESL values due to their impact on the capacitor impedance at high frequencies. The capacitor solution utilized within this design was to parallel four 22uF, 50V AVX multilayer capacitors with low ESR and ESL values.

Even though the individual input filter and dc-dc converter complies with the small signal stability criterion, the system level stability is not guaranteed. Large signal instability problems may occur due to pulsating loads or converter protection. Therefore, the ability for system level simulations is a necessary tool in order to confirm proper operation of the whole system under various operating conditions. The whole system start-up was simulated and the results are shown in Figure 9.

From Figure 9, can be observed stable start-up behavior. The utilized converters within the system are from various manufacturers and they all have different start-up behavior.

B. System Simulations

The power architecture in this application is required to operate within the input voltage range according to [13] in steady state. Therefore, the system level simulations enable the estimation of the system power consumption by determining the steady-state current absorbed by the system for various input voltages.

The system behavior can be analyzed by making a load step. A load step from zero to full load was simulated in the 10.5V output voltage converter. This power module and the 7V converter share an EMI filter and therefore it is of interest to analyze the effects of the load step on both module output voltages as well as on the bus voltage. Figure 10 presents the simulation results.

From Figure 10, it can be observed that the load step from no load to full load in 10.5V module does not have affect on the 7V output voltage. However, the load step causes voltage deviations in the 10.5 module output voltage as well as in the bus voltage.

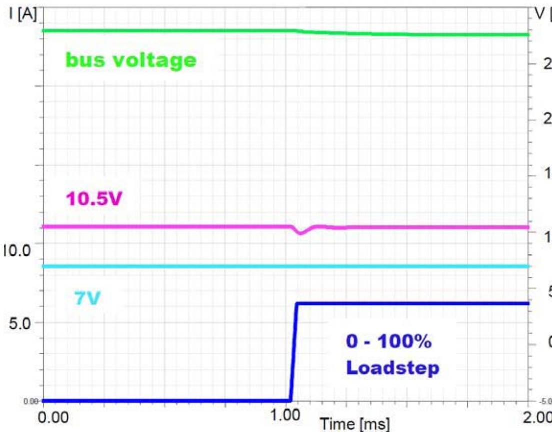

Fig. 10. The converter output voltages at the system start-up.

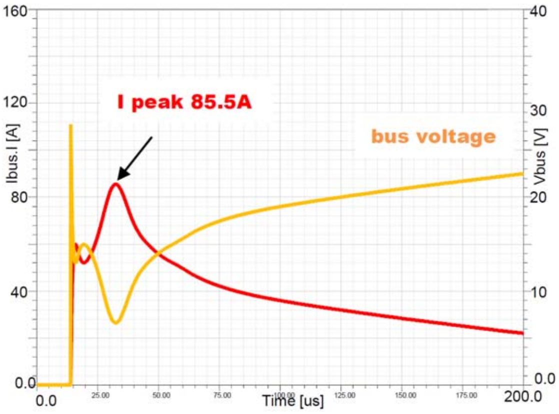

Fig. 11. The simulated input current and bus voltage during the start-up.

The system inrush current can be simulated in order to determine whether protection is necessary within the designed system. This is especially useful in applications, where large capacitors are required at the system input in order to provide hold-up time for the system. While simulating the inrush current, line impedance as well as parasitic component values of the circuit components should be taken into consideration, due to their affect on the inrush current. Inrush current protection was designed for this system based on the system inrush current simulations. The simulations show a high inrush current peak during the start-up, as presented in Figure 11.

The following section presents the comparison between the simulated and measured values.

IV. EXPERIMENTAL RESULTS

The accuracy of the simulations is validated through experimental results. Figure 12 presents the startup of the whole system and the system bus voltage.

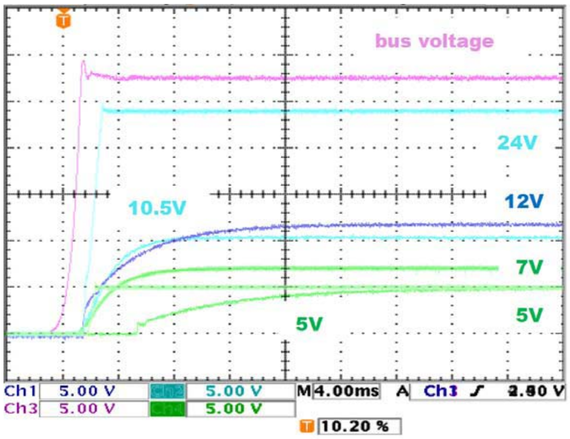

Fig. 12. The measured system start-up.

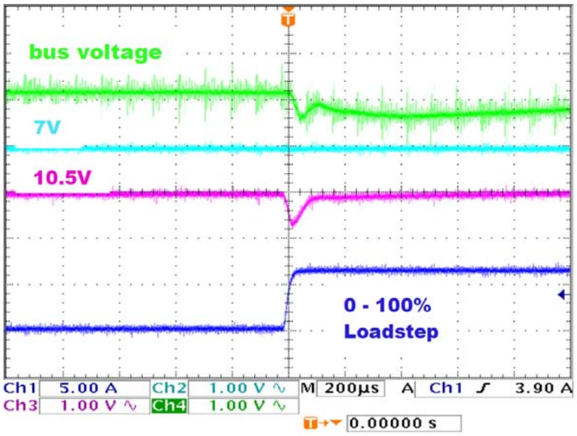

Fig. 13. Load step in 10.5V power module.

The system startup behaves as predicted by the simulation results. A load step from no load to full load was introduced at the 10.5V power module output. The output voltages of 10.5V and 7V modules as well as the bus voltage were measured. The results are presented in Figure 13.

In order to capture the voltage deviation, ac measurement was used. It can be observed that the 7V output is not affected by the load step as predicted by the simulations. The measured voltage deviation in 10.5V module is compared to the simulated value as shown in Figure 14. The dashed line shows the simulation result and subsequent to the comparison between measured values, it can be observed that the modeled dc-dc converter predicts well the behavior of the actual converter in a load change situations.

The inrush current was measured with and without the protection. As predicted by the simulation, a high peak current exists that corresponds to the simulated peak current value. Subsequent to the inrush current protection implementation, the measurements were compared to the simulations as presented in Figure 15.

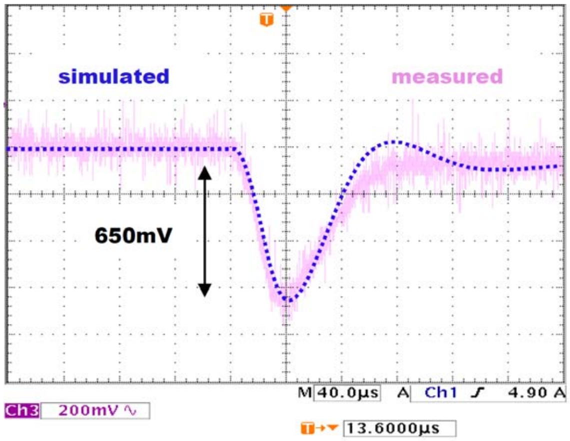

Fig. 14. Detailed comparison between measured and simulated voltage deviation in 10.5V module during the load step.

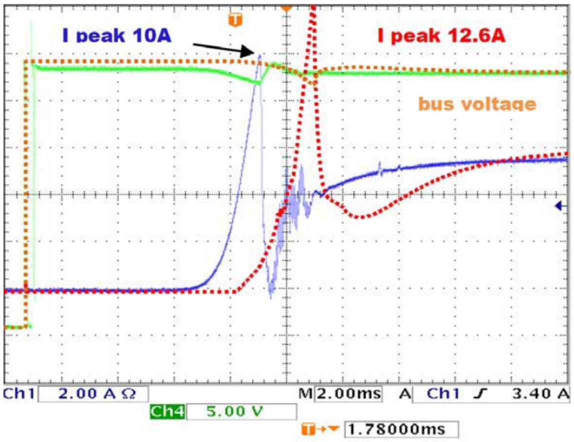

Fig. 15. Measured and simulated inrush current with the protection.

The simulated peak current value will not predict the exact behavior of the actual system. This is due to the implementation method of the inrush current protection model in the simulated system. Accurate protection circuit component models were not available and therefore, simplified component models were utilized. However, the results are adequate enough to verify the functionality of the designed inrush current protection.

V. CONCLUSION

Due to the utilized COTS components within the system, traditional modeling techniques are not applicable. In this paper, the dc/dc converters are modelled based on the Wiener-Hammerstein structure and the behavioural models are obtained applying the information provided in the datasheets and measurements. The commercial EMI filters are modeled based on typical input filter structure and the filter ac response. Both small and large signal stability are analysed as well as the overall efficiency, power consumption and transient response. The experimental results show that the simulations predict the system behavior accurately. Utilizing simulations within distributed power system design, is an important tool in order to reduce the design time and avoid system instability as well as design errors.

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