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MÁSTER EN ELECTRÓNICA INDUSTRIAL

Analysis and Simulation Of DC Distributed Power Systems Based on Behavioral Models: Analysis Guidelines

Sanna Vesti

División de Ingeniería Electrónica
Departamento de Automática, Ingeniería Electrónica e Informática Industrial

POLITÉCNICA

Proyecto Fin de Máster

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Sanna Kaarina Vesti

Máster en Electrónica Industrial

Universidad Politécnica de Madrid

Centro de Electrónica Industrial

Escuela Técnica Superior de Ingenieros Industriales

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Octubre, 2010

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ANALYSIS AND SIMULATION OF DC DISTRIBUTED POWER SYSTEMS BASED ON BEHAVIORAL MODELS: ANALYSIS GUIDELINES

Autor: Sanna Kaarina Vesti

Directores: Pedro Alou Cervera

Jesús Á. Oliver Ramírez

Octubre, 2010

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Chapter 1

Introduction

At present, distributed power systems are utilized within various applications ranging from hundred watts to hundreds of kilowatts. They are popular especially in complex, advanced electronic systems demanding lightweight or multiple power and voltage levels. Common system applications are industrial control, automotive and telecommunications as well as airborne applications [Luo, 2005], [Interpoint, 2010]. Distributed power systems employ multiple advantageous aspects compared to a traditional architecture. One of the most attractive features is their significantly faster time-to-market, due to the utilized COTS (commercial-off-the-shelf) components. These components are possible to be configured into various applications complying with the relevant authority requirements [Mammano, 1993].

Different architectures for distributed power systems exist and a typical application is presented in Figure 1.1 [Luo, 2005].

These systems consist of multiple commercial components, which increase the system complexity as well as potential stability problems, especially in applications with paralleled dc-dc converters, which is a potential source for dynamic interactions [Luo, 2005]. In addition, various authority requirements need to be complied while performing reliable and stable operation. Due to these constraints, the design of these systems is challenging. Moreover, traditional modeling methods are not applicable for the commercial components, further complicating the system analysis.

The purpose of this thesis is to provide simulation and analysis guidelines for a given architecture. However, the selection of an optimum design architecture lies outside the scope of this work. The provided recommendations are based on a designed distributed power system for avionic application, focusing on the relevant

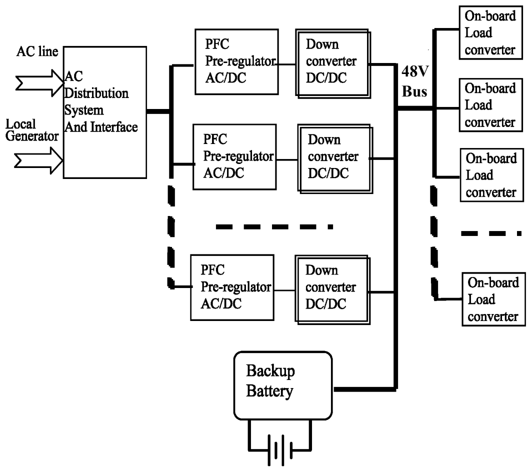

Figure 1.1: A typical structure of a distributed power system.

requirements and constraints of this application. Within this study, the designed system is simulated based on behavioral component models. Utilizing the system level simulation results, the performance characteristics as well as local and global stability are analyzed. This introduces a fundamental design advantage since proper system operation can be validated under every operating condition prior to implementing the actual system.

This thesis is dived into six chapters including introduction and conclusion. Chapter 2 describes the modeling methods for the most fundamental system components, dc-dc converters and EMI filters. The commercial dc-dc converters are modeled based on the behavioral modeling method provided in the literature. Whereas for the EMI filters, an equivalent circuit models are developed. A detailed modeling procedure and practical implementation of both models are provided in this chapter. The next chapter focuses on presenting the utilized distributed EMI filter solution as well as describes methods on designing a concentrated EMI filter. Comparisons between these two solutions are also provided. Chapter 4 introduces the system component selection based on the relevant system requirements. In addition, a detailed system analysis procedure is explained. Moreover, an implemented prototype is designed based on the simulations and the system design verification through the experimental measurements are showed. In Chapter 5, detailed analysis guidelines of the distributed power systems for a given architecture are provided. Finally, Chapter 6 concludes the thesis and recommendations for future work is introduced.

The following sections within this introduction present a distributed power system for avionic applications and its special requirements. In addition, detailed description and the specification of the designed power system provided.

1.1 Distributed power system for avionic application

First extensive usage of distributed power systems were in avionics industry providing small size and lightweight. In addition, the ability of a dc-dc converter to provide close output voltage regulation in spite of fluctuations at the input or load is an attractive feature for many sensitive subsystems [Interpoint, 2010]. Within any distributed power systems, a bus voltage that supplies the dc-dc converters is an important design parameter. In aerospace applications, it is standardized for 28Vdc whereas many industrial controls use 24Vdc or in case the battery backup provides the supply voltage, its voltage level defines the bus voltage [Luo, 2005].

Special requirements

Power systems for avionic applications have many restrictions and requirements, which commercial applications do not have. These special features are presented in Figure 1.2.

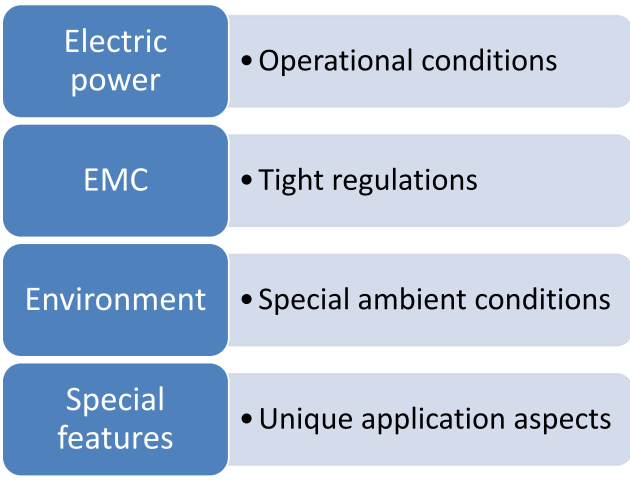

Figure 1.2: Special requirements concerning avionic applications.

The electric power and the input voltage operating conditions depend on the available power generating systems on-board. These sources can be either AC or DC and their requirements are governed by multiple standards describing various input voltage conditions. However, the most frequently used standard for electric power characteristic is military standard, MIL-STD-704 [Gaia, 2010], also applied within the designed system.

EMC is a significant issue in the design of any power system. However, within avionic applications, the EMI limitations regarding conducted noise levels are the tightest. The classification of the avionic standard for EMC is:

- Conducted emission (CE)
- Conducted susceptibility (CS)
- Radiated emission (RE)
- Radiated susceptibility (RS)

The difference between emission and susceptibility is that emissions concern the noise generated by the power system whereas the susceptibility defines the noise environment where normal operation without degradations needs to be guaranteed. As for electric power also for EMI, various standards exist but the most commonly the military standard, MIL-STD-461 is applied. The EMI limits and measurement practices are provided within this authority regulation.

Avionic electronics has an intensive and unique environment. Above all, the huge temperature variations within the system require large temperature range from the system components. In addition, specific criteria concerning issues such as humidity, dust, salt, explosive decompression and shocks need to be considered. These requirements however mainly concern the enclosure of the power system and are outside the scope of this thesis. In addition to the above-mentioned requirements, avionic applications often employ special features. They include for instance specific output voltage levels for particular loads as well as certain protection features.

Commercial- off- the- shelf (COTS) components

Strict authority regulations as well as high reliability demand addresses significant design challenges for avionic application. Therefore, the available COTS converters are typically utilized within the power systems. These standard and ready to use components are suitable for various applications. Their attractive features are among other things:

- Cost-effectiveness
- Versatility
- Applicability

These COTS parts can be configured for various power system architectures as well as used in different applications [Gaia, 2010]. The COTS converters for avionic applications incorporate specific features due to the unique requirements for these applications. Commonly these provided features are:

- Overcurrent and overvoltage limits
- Unique output voltage levels
- Enable pin

In addition to the above-mentioned requirements, every COTS component is required to comply with the relevant authority regulations. Overcurrent protection limits the amount of current a power supply will provide, whereas overvoltage protection prevents the power supply from providing too high of an output voltage [Gaia, 2010]. In addition to these protections, an input undervoltage protection might be required depending on the application. The output voltage trimming function is due to the special applications demanding unique voltage levels, such as radars [Gaia, 2010]. In case the required output voltage is outside the standard range, manufacturers provide a possibility to adjust the voltage level with an external resistor network. In addition, within some applications remote control of the converter is required.

Despite the integrated input filter within every COTS converter, they are not able to comply with the strict requirements for EMC. Therefore, supplementary filter is required to achieve those specifications. Due to that, the power systems typically consist of additional commercial EMI filters.

Design challenges

Various design challenges exist due to the plethora of avionic system requirements presented in this chapter. Figure 1.3 presents the challenges faced within complex power system design. Great concern are the commercial components. Due to the limited available information concerning their structure, traditional modeling methods are not applicable. Therefore, advanced modeling methods need to be adapted in order to create simulation models for these components. Within this thesis the modeling method of the commercial dc-dc converters and EMI filters are covered in Chapter 2.

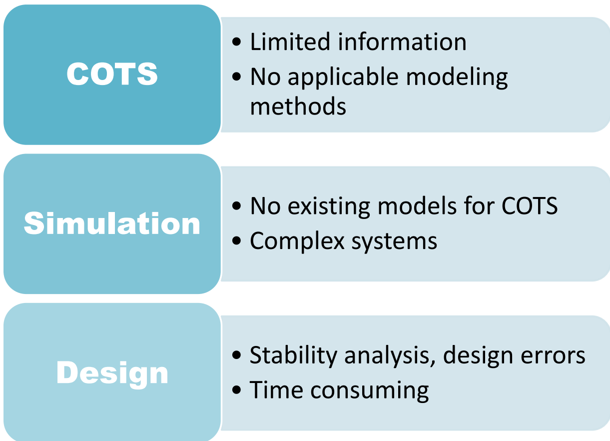

Figure 1.3: Design challenges of complex distributed power systems.

The lack of proper simulation models for the commercial components as well as general system complexity complicates the system analysis and simulations. These systems comprise of various components and therefore one of the primary concerns is the system integration and interactions between the power system components, which should be taken into consideration at the development stage [Luo, 2005]. Considerable amount of difficulties are due to the additional EMI filters, necessary within every distributed power system application. This increases system complexity and potential stability problems due to the component interactions. Due to the presented challenges, design time of these types of systems is large and regarding the systems complying with the military standards, it is the longest [Brush, 2004].

1.2 Designed system

Within this work, a distributed power system for avionic application is designed according to [MIL, 2004b] concerning the aircraft electric power characteristics and [MIL, 2004a] regarding the electromagnetic interference as well as [RTCA, 2004] concerning lightning induced susceptibility. The operating conditions for avionic systems are specified as:

- Normal operation
- Abnormal operation
- Emergency operation

Normal operating conditions for the bus voltage are presented in Figure 1.4. The normal operation limits apply while the power system is being supplied as intended. Abnormal operation refers to an operation when malfunction or failure has occurred and the bus voltage limits are as shown in Figure 1.5 for abnormal operation.

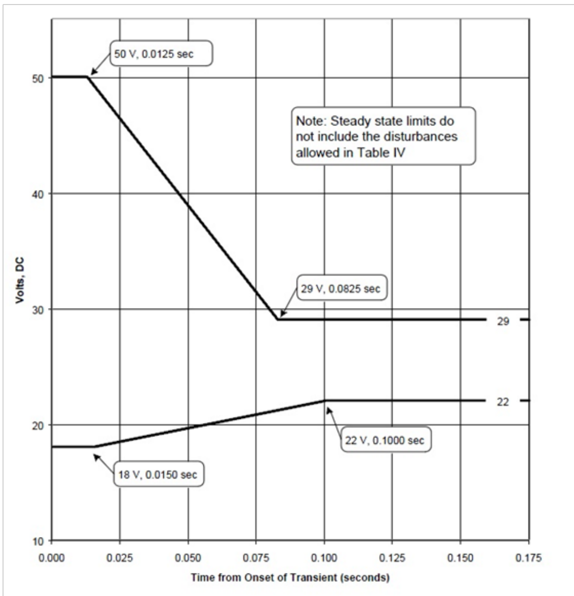

Figure 1.4: Normal voltage transients for the bus voltage within the 28Vdc system.

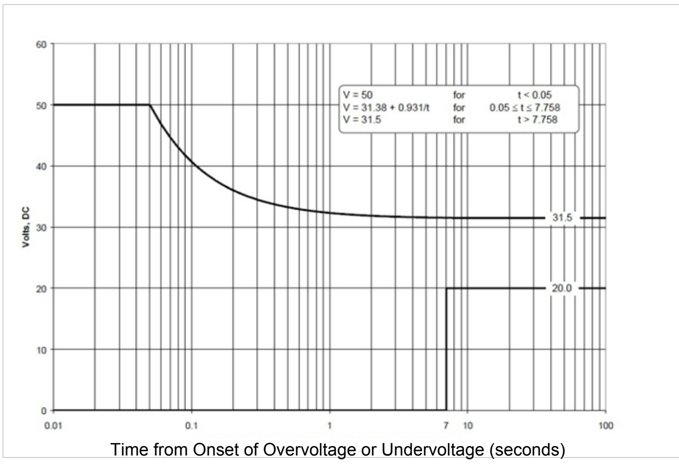

Figure 1.5: Abnormal voltage limits for the bus voltage within 28Vdc system.

Correspondingly, the emergency operation occurs in case of loss of the main generating equipment and the power system is being supplied according to the emergency limits, while the bus voltage is between 16 and 29 volts [MIL, 2004b]. A summary of the electric power requirements for 28Vdc bus voltage are shown in Table 1.1.

Table 1.1: Operation conditions for 28Vdc power system for avionic application.

Operation condition	**Bus voltage limits (Vdc)**
Normal	22 - 29
Abnormal	20 - 31.5
Emergency	16 - 29

The designed power system consists of six dc-dc converters each supplying a load according to its demands. Table 1.2 shows the load requirements from few watts until 65W with the output voltages from 5V to 24V. A block diagram of the designed distributed power system is presented in Figure 1.6. This system consists of the following components:

- Six Commercial dc-dc converters
- Four Commercial EMI filters
- Four Holdup capacitors

- Transient suppressor
- Additional electronics

Table 1.2: Load requirements for the designed system.

Load	Output voltage (Vdc)	Power (W)
Load 1	5V	25W
Load 2	12V	6W
Load 3	5V	5W
Load 4	24V	30W
Load 5	10.5V	65W
Load 6	7V	25W

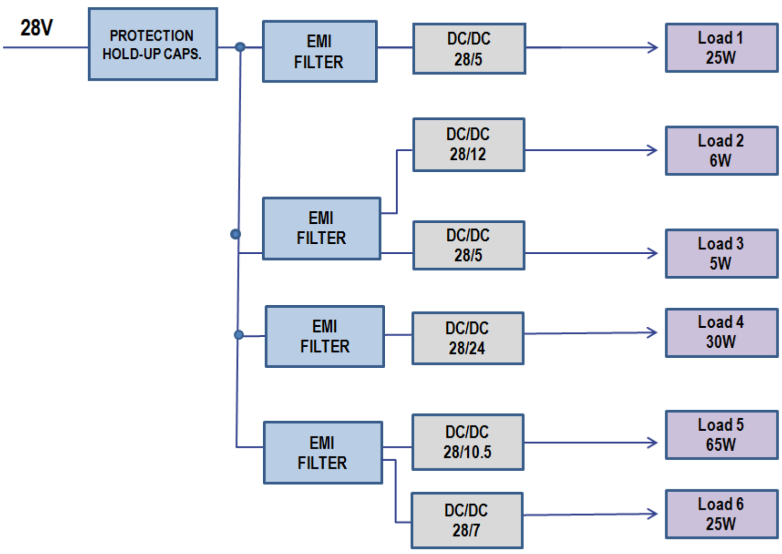

Figure 1.6: A block diagram of the designed distributed power system for avionic application.

As one important objective in avionic applications is the minimization of the system size and weight, the optimum design solution is to select converters from various manufacturers. A detailed description of the selected dc-dc converters is provided in Chapter 4. Due to the tight EMC requirements stated in [MIL, 2004a], additional EMI filters are utilized within the system. In the current system due to the critical design time, a conventional distributed EMI filter solution based on manufacturer recommendations is selected. This solution, as well as a design of a concentrated EMI solution is presented in Chapter 3.

Furthermore, power systems are generally obliged to maintain a certain voltage level for a specified period, subsequent to the removal of the bus voltage. Therefore, characteristically holdup capacitors are utilized within the system design to provide energy storage. Transient protection is necessary within avionic applications due to the lightning strikes and the suppression device is selected based on the requirements stated in [RTCA, 2004].

The selection of each component is based on the relevant system requirements. A specific description of the component design methods and procedures is provided in Chapter 4.

Chapter 2

System Modeling

In this chapter the modeling method for the most fundamental system components, dc-dc converters and EMI filters, is described in detail. As mentioned in Chapter 1, the modeling of COTS components is a demanding task due to the lack of existing models for these components. Therefore, advanced modeling approaches are required. This chapter describes a behavioral modeling method for commercial dc-dc converters found in the literature. Based on this method, simulation models that include event driven behavior, are created. Thus, the global system stability analysis is feasible. Simulation models for commercial EMI filters concerning the differential mode noise are developed based on measurements.

The first section describes the behavioral modeling structure for a converter and thereafter the practical implementation is presented as well as the model validation and evaluation. Furthermore, the modeling method for commercial EMI filters is explained in detail in the second section. These models are based on a general input filter topology and frequency response measurements.

2.1 Dc-dc converter models

Typically, the current models for dc-dc converters are based on the knowledge of the converter topology, control and component values. Concerning the commercial components, this information is not available. In this section a modeling principle and structure, for COTS converters is explained. However, since this behavioral model structure is widely available in the literature and this chapter provides a general overview to this model structure. More emphasis is focused on the practical model implementation and validation. This described behavioral model structure is applicable to any standard dc-dc converter from any manufacturer.

2.1.1 Model structure

Plenty of research concerning the dc-dc converter modeling techniques exists. General averaged model for the converter has been developed in [Sanders et al., 1991] and been applied to distributed power system simulations in [Emadi, 2004]. Additionally, in [Cho and Lee, 1985] and [Cho and Lee, 1988] is described how to obtain hybrid parameter models, which are limited to analyze small signal stability. However, neither of the above-mentioned models is adequate to analyze large signal stability. Thus, an improved dc/dc converter model is required. In [Oliver et al., 2009] and [Oliver et al., 2006] behavioral model for dc-dc converter is developed based on the Wiener-Hammerstein structure.

As the objective is to model commercial converters, the utilized model for these dc-dc converters is required to be identified based on available information. In addition, this model needs to be general for every dc-dc converter, regardless of the used topology or implemented control method. The utilized model for the converters consists of two parts, logic stage and power stage of the dc-dc converter, based on Wiener-Hammerstein structure [Oliver et al., 2006] as presented in Figure 2.1. The Wiener-Hammerstein structure describes static and dynamic converter behavior as well as its control whereas the event driven behavior is modeled as a logic system.

Static behavior

The static parameters describe the basic power processing behavior of a dc-dc converter. This converter behavior is modeled as an equivalent circuit shown in Figure 2.2, where the converter output is modeled as a constant voltage source, v_{ref} which is the regulated converter output voltage. It is dependent on the load current according to Equation 2.1. The input side can be modeled as a constant current source that is the absorbed input current of the converter. In the utilized model, this current value depends on the output power as well as the efficiency as shown in Equation 2.2. This utilized model does not take into consideration the influence of the input voltage.

$$v_{out} = v_{ref} - f(i_{out}) \tag{2.1}$$

$$i_{in} = \frac{1}{\eta(i_{out})} \cdot \frac{v_{out} \cdot (i_{out})}{v_{in}} \tag{2.2}$$

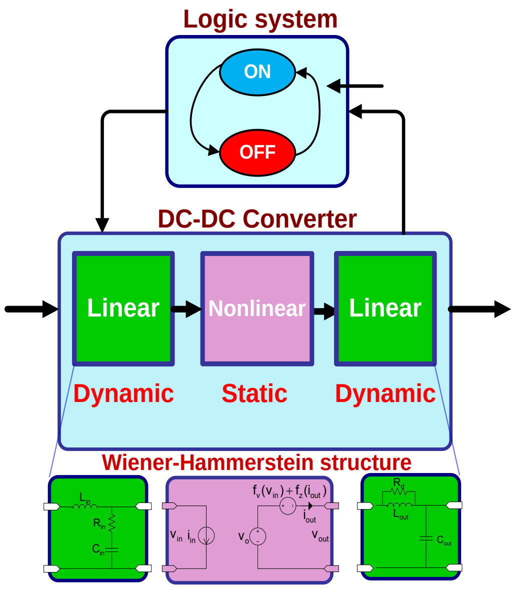

Figure 2.1: Dc-dc converter behavioral model structure

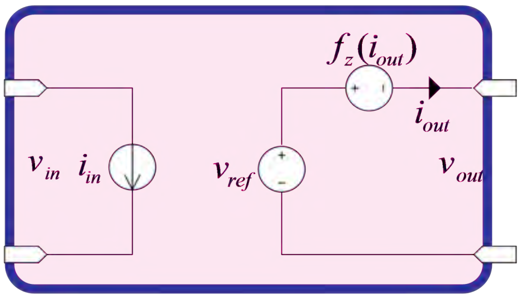

Figure 2.2: Static non-linear model structure of a dc-dc converter.

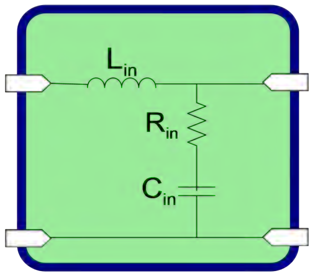

Figure 2.3: Input dynamics network of the behavioral dc-dc converter model.

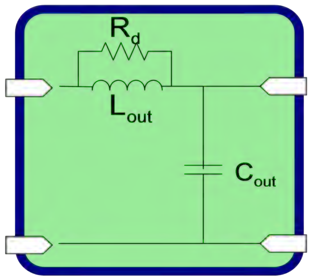

Figure 2.4: Output dynamics network of the behavioral dc-dc converter model.

Dynamic behavior

The dynamic information includes high frequency dynamics and large signal behavior to the converter model. The input dynamics can be modeled as a simple RLC-equivalent circuit as shown in Figure 2.3. The component values are obtained based on the following parameters of the inrush current curve:

- Input voltage
- Peak current value
- Peak time

The output dynamical structure is modeled as an equivalent circuit presented in Figure 2.4.

Correspondingly, these component values are obtainable from the transient response behavior of the converter. The following information from the transient waveform is required:

- Current step
- Voltage peak value
- Peak time
- Settling time

The manufacturer typically provides the information regarding the inrush current as well as the transient behavior on the datasheets.

Logic system

Logic system includes the event driven behavior to the converter model structure. The converter behavior depends on its state and the logic structure modifies the converter state in the case an event occurs. These events consist of converter protection features, remote control and soft start. Therefore, considering the actual model, this behavior is managed by a state machine changing the model structure. Since these features are included as a part of the dc-dc converter model, the system large signal stability simulations are possible.

2.1.2 Practical model implementation

The modeling structure described in previous subsection enables adequate DC distributed power system simulations as presented in [Prieto et al., 2008].The procedure to implement the behavioral model begins with the information gathering regarding the relevant behavior and inserting the data to a software parameterization tool which creates the component model as illustrated in Figure 2.5.

Gathering information

Starting point for the model creation is the available information, which in the case of COTS component is limited to a datasheet. Furthermore, measurements provide additional and more specific data concerning the converter characteristic behavior. The required data concerns the static, dynamic and event driven behavior of the

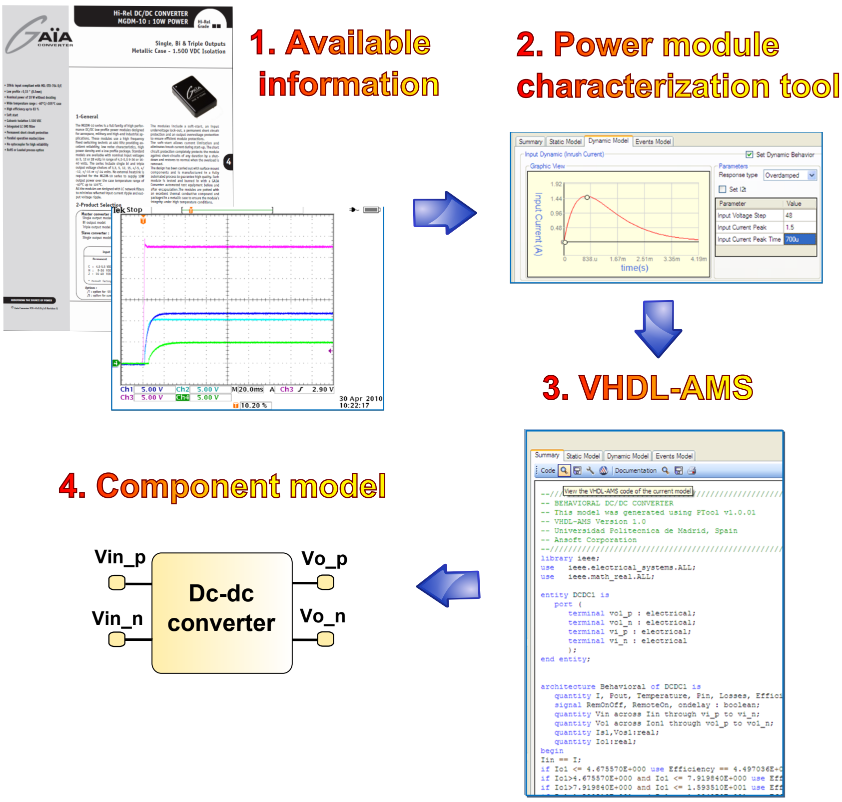

Figure 2.5: Practical implementation of a behavioral dc-dc converter model

converter. An example of the information gathering from the datasheet is illustrated in Figure 2.6.

Thus in order to obtain the linear output dynamic structure for the model, the required information is obtained from this curve as:

- Current step, manufacturers provide typically load step from 50% to 100%
- Voltage peak value, 420mV
- Peak time, 30μs
- Settling time, 270μs

The model assumes the settling time to be the instant of time, when the output voltage reaches 5% of the nominal value.

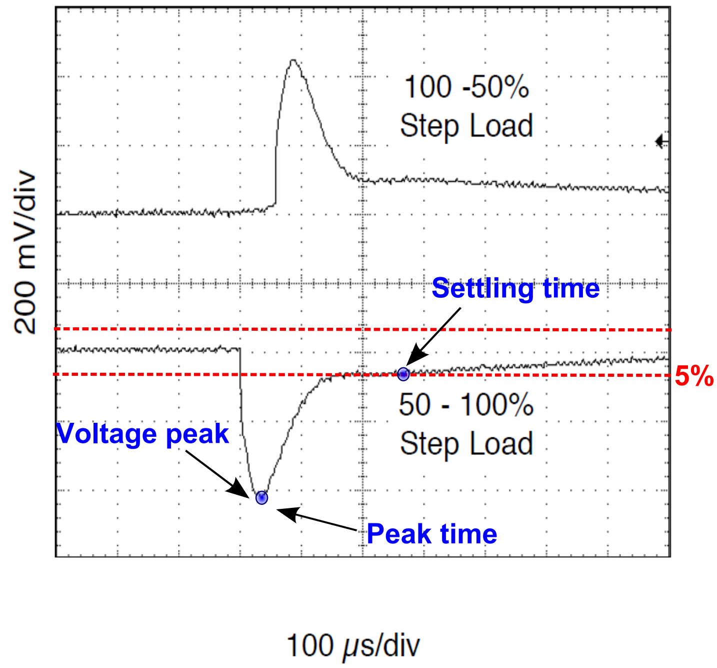

Figure 2.6: Necessary transient response parameters from the datasheet for the output dynamic network model.

Power module characterization- tool

In [Prieto et al., 2008] a parameterization software tool is developed to generate the behavioral models in a convenient and simple way. Table 2.1 summarizes the software requirements concerning the parameters of each structure. Additionally, the utilized implementation methods of model structures are described.

Hardware description language and component simulation model

As the model parameters are set, the power module characterization- tool creates a VHDL-AMS code of the modeled converter. Thereafter, this generated model is imported to a circuit simulator [Prieto et al., 2009] utilizing hardware description language. The specific requirements for the utilized circuit simulator are described

Table 2.1: Parameters for behavioral dc-dc converter model

Model structure	**Parameters**	**Implementation**
Static	Efficiency as a function of load current. Output voltage as a function of load current.	Lookup table
Dynamic	Inrush current Transient response	Parameter fitting
Event Driven	Protections Remote control Soft start	State machine

in [Oliver et al., 2008]. Subsequent to the model generation, the parameters are easily modified in case deemed necessary. For instance, additional measurements might provide more accurate information on the specific converter behavior.

Every dc/dc converter utilized within the system, are modeled based on the gathered information provided by the manufacturers on their datasheets or obtained from the measurements. The behavior of each created simulation model is evaluated by comparing simulation results to the datasheet curves or measurements. At first, the static behavior is validated as shown in Figure 2.7 regarding the efficiency dependence on the converter output power. The efficiency curve of the created simulation model is compared to the corresponding datasheet value at the nominal input voltage of 28V. The dashed line shows that the simulation model provides accurate results concerning the static behavior of a converter.

Correspondingly, the dynamic behavior was assessed in Figure 2.8 regarding the inrush current.

It can be observed that the simulation model provides accurate results concerning the peak value and the peak time. These inrush current parameters are the most relevant while regarding the converter behavior. Finally, the whole behavioral model including the event driven behavior is validated. Since converters from various manufacturers are utilized within the designed system, each of them needs an individual model to describe its characteristic behavior and special features.

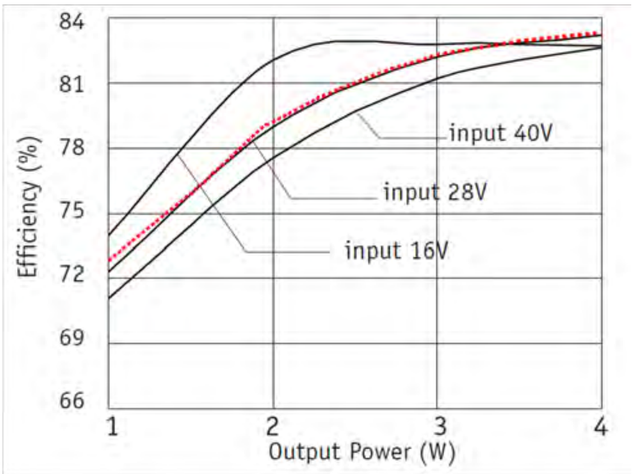

Figure 2.7: The simulated efficiency as a function of output power compared to the datasheet value.

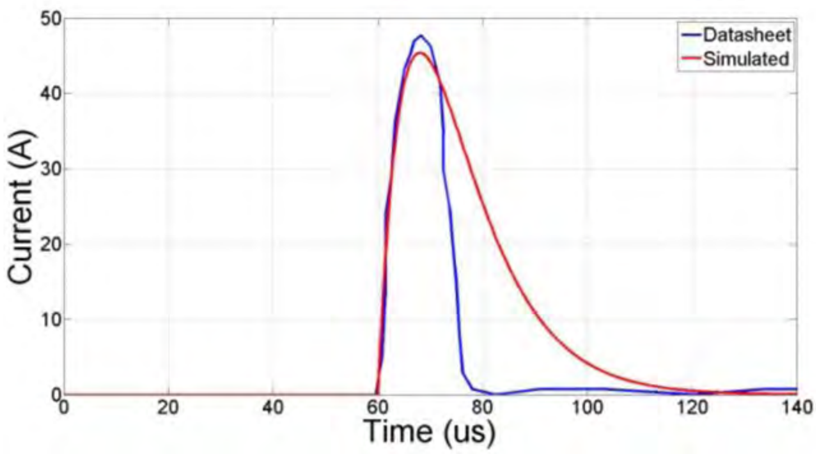

Figure 2.8: Simulated inrush current compared to the datasheet value.

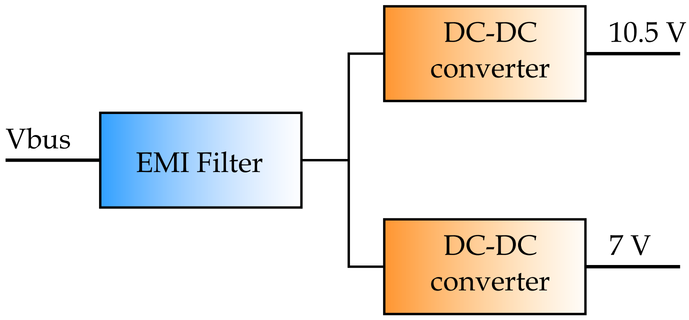

Figure 2.9: Two dc-dc converters sharing an EMI filter.

2.1.3 Improved models

The datasheets typically provide limited amount of information concerning specific converter behavior. Therefore, the dc-dc converter models can be further improved by performing measurements to the converters. The models can be modified in order to better describe the converter behavior. Depending on the application some relevant and more detailed information might be required in order to perform accurate system level simulations.

The existing dc-dc converter model does not take into consideration the affect of the input voltage variations to the output voltage e.g. audiosusceptibility. This means that depending on the converter topology and implemented control method, sudden input voltage drop might cause deviation at the converter steady state output voltage. Thus regarding the designed system this might occur when a load step is introduced to a converter sharing an EMI filter with another converter as shown in Figure 2.9.

As the two converters have a common input voltage, it is of interest to verify audiosusceptibility through measurement. Thus, it can be estimated whether the input voltage has an effect on the output voltage and is necessary to be included within the converter model. The measurement was carried out by introducing a load step from no load to full load on the output of 10.5V power module while the output voltage of the 7V module was observed. The measurement results show, Figure 2.10, that in this particular case the audiosusceptibility is not necessary to be taken into consideration regarding the analyzed converter since the effect is negligible.

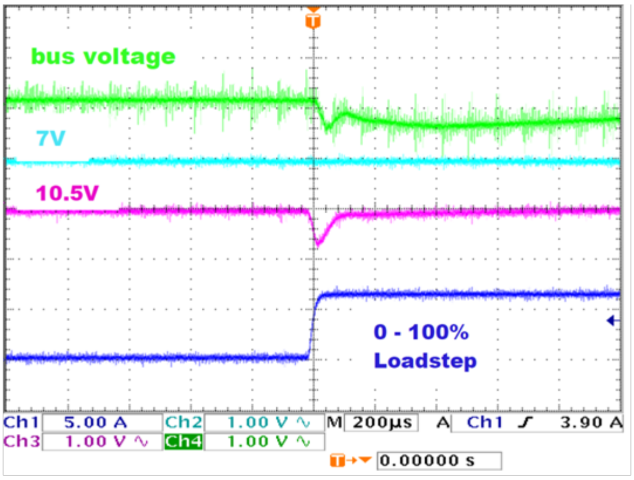

Figure 2.10: Transient measurement while a load step is introduced at the output of 10.5V power module.

2.2 EMI filter models

Due to the tight EMC requirements for avionic power systems, additional commercial EMI filters are required. The proposed models for these components are based on the general topological structure [Erickson and Maksimovic, 2000] of a typical input filter as shown in Figure 2.11. This structure consists of LC-low pass filter as well as the parallel RC- damping network. Typically, due to the filter size optimization a two-stage filter structure is utilized. Sometimes, manufacturer provides the utilized filter topology however without the component values.

Based on the general topological structure or provided filter topology, a simulation model is created. In order to estimate the component values of the equivalent filter circuit, the following frequency response measurements are to be carried out:

- Input impedance while output is short-circuited.
- Input impedance while output is open circuit
- Output impedance while input is short-circuited

The component values are attained manually by defining the resonance frequency values of the measured impedances. The best suitable model for each EMI

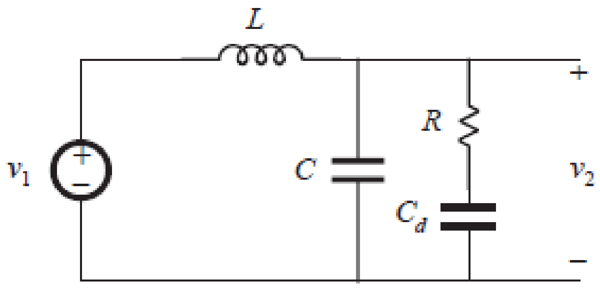

Figure 2.11: typical input filter structure concerning differential mode noise.

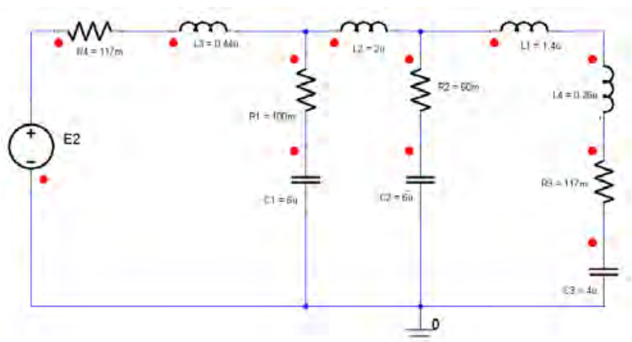

Figure 2.12: Equivalent circuit for the commercial EMI filter concerning differential mode noise.

filter is obtained by fitting the simulated frequency responses to the measured ones. In addition to the basic filter components, the parasitic values are taken into consideration due to their affect at high frequencies. Thus utilizing this principle, models for each commercial EMI filter were accomplished. Figure 2.12 presents an obtained equivalent circuit for one EMI filter.

Model validation

As the component values are fitted, the simulated frequency responses can be compared to the measured curves. Figure 2.13 presents the comparison between the simulated short circuit input impedance and measured impedance for the obtained

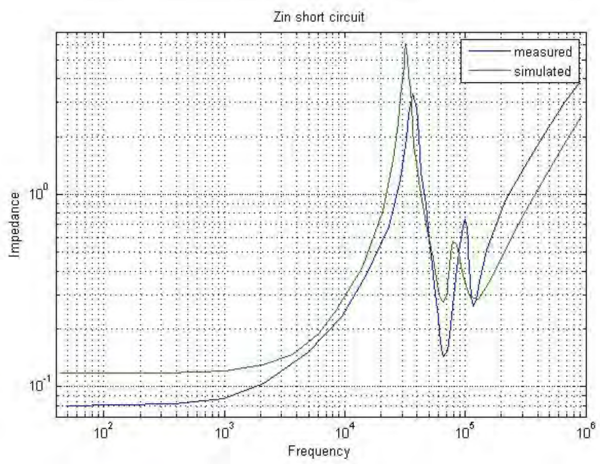

Figure 2.13: Simulated short circuit input impedance compared to the measurements.

equivalent circuit.

Correspondingly, Figure 2.14 shows the measured open circuit input impedance compared to simulation results. A detailed comparison of the simulated output impedance to the measurements is illustrated in Figure 2.15. Based on these presented results these filter models can be assumed to provide adequate models for the utilized EMI filters in order to execute system level simulations. As the system design is based on distributed EMI filter solution, various filters from different manufacturers are used and each filter has its own equivalent circuit.

By utilizing the modeling methods described in this chapter, every system component is modeled. Thus, a simulation model for the distributed power system is obtained enabling the whole system simulation and analysis, presented in detail in Chapter 4.

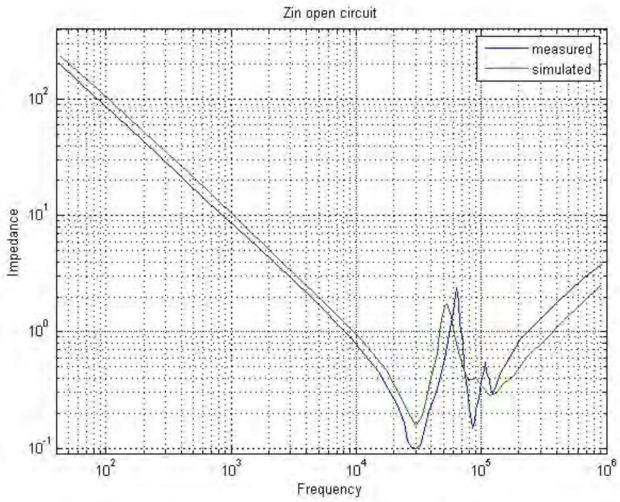

Figure 2.14: Simulated open circuit input impedance compared to the measured impedance.

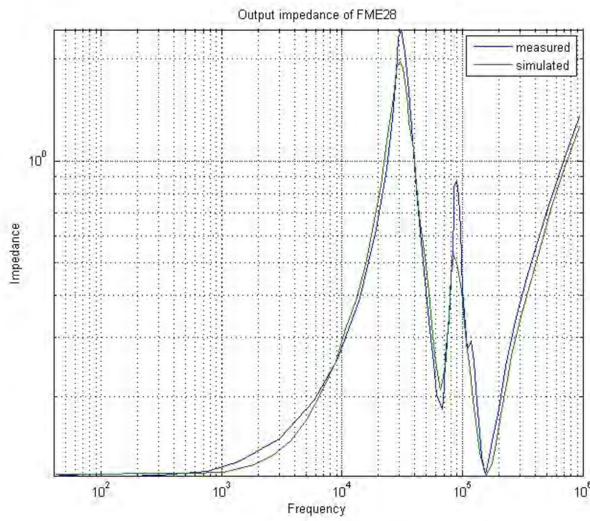

Figure 2.15: Measured output impedance compared to the simulated output impedance of the equivalent circuit.

Chapter 3

EMI Filter Solution

Within distributed power systems, multiple solutions for locating the EMI filters exist. Challenging aspect is to optimize the input filter design guaranteeing stability and proper system operation as well as required noise attenuation. Due to the limited design time, a conventional distributed EMI filter solution was selected for the system. This solution is based on COTS components according to the manufacturer recommendations.

Due to the various possibilities for input filter placement, an interesting aspect is to evaluate the design optimization. As a starting point for this analysis, a single EMI filter providing similar filtering performance is designed for the system. This concentrated filter is designed subsequent implementing the prototype. Therefore, in order to provide similar performance than the distributed solution, required attenuation level as well as the system input impedance need to be obtained.

This chapter provides a comprehensive description of the utilized EMI filter solution. In addition, the design of a centralized single filter solution based on the same restrictions is presented. Thereafter, comparisons are made between these solutions.

3.1 Distributed solution

Since design time is a critical parameter, all of the utilized EMI filters are commercial components. By selecting an EMI filter according to the recommendations for each particular dc-dc converter, the compliance with the tight EMC constraints is guaranteed by the manufacturer. As the optimum design solution concerning size, was to select the utilized power supplies from various manufacturers, the conventional EMI solution comprises of commercial filters from corresponding manufacturers. This distributed EMI filter placement is demonstrated in Figure 3.1.

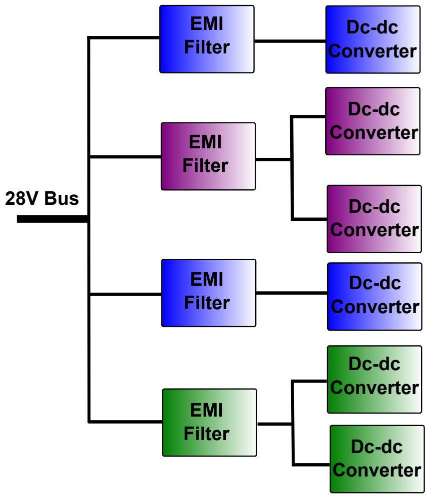

Figure 3.1: Distributed EMI filter solution.

The solution consists of:

- Two converters with an individual EMI filter
- 2 x Two converters from the same manufacturer sharing an EMI filter

In the figure, colors illustrate different manufacturers. Depending on the filter structure, some have larger maximum current capability hence two converters can share the same filter. The main advantage of the distributed solution is compliance with the relevant EMC requirements. Customized EMI filter is challenging and time consuming to design. Therefore, the conventional solution assures rapid development time.

To further improve the system EMI performance, a common mode noise capacitor is added between an input and output ground of a dc-dc converter as demonstrated in Figure 3.2 thus contributing on reducing the conducted common mode noise. Considering the designed system, this capacitor is implemented within every converter. A fundamental aspect while selecting the capacitors is to maintain the required isolation between primary and the secondary. Therefore, they need to be high voltage components and within the designed system 500V capacitors we utilized.

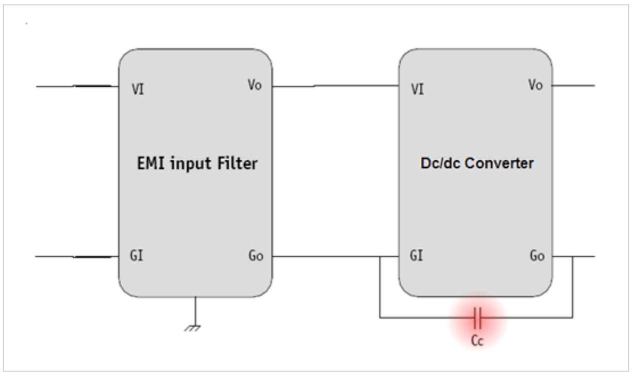

Figure 3.2: Common mode capacitors to improve EMI performance.

Initial conducted noise measurements for the system are compared to the limits of the relevant EMC standard, MIL-STD-461, as shown in Figure 3.3. It can be observed that the system complies relatively well with the relevant standard. However, it should be emphasized that the noise measurements were carried out with the available measurement setup thus the environment was not optimized for the sensitive noise measurement.

3.2 Design of the concentrated differential EMI filter

The design of the concentrated EMI filter is a starting point for a comprehensive EMI filter optimization analysis within distributed power systems. This solution comprises of a single input filter instead of utilizing individual filters for each dc-dc converter. This filter is designed based on the same constraints as the distributed solution. Furthermore, only the differential mode noise is taken into consideration.

Most fundamental requirements for the design of centralized EMI filter are:

- Filter structure
- Required attenuation
- System input impedance

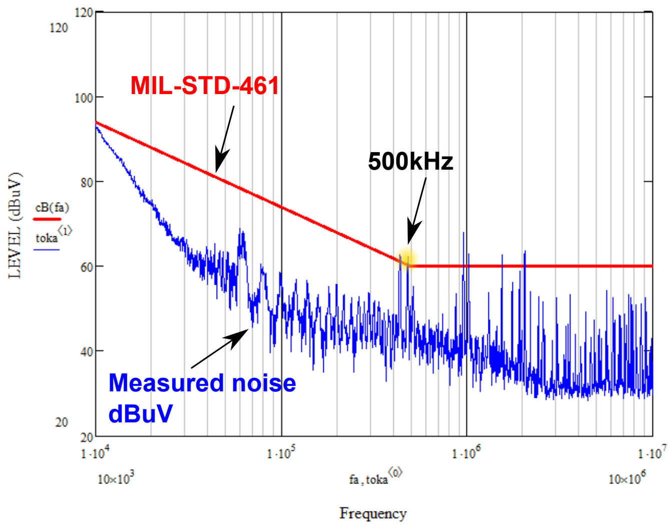

Figure 3.3: Measured common mode noise compared to the military standard MIL-STD-461.

All of these aspects impact on the filter design and provide essential design guidelines. Hence, they need to be covered in detail prior to the actual filter design.

3.2.1 Filter structure

In order to comply with the avionic constraints concerning small size, a two-sectioned EMI filter structure is selected. This provides the same attenuation as the single section filter but with a reduced size and weight of the filter components. Figure 3.4 presents a two stage input filter with RL- parallel damping network.

The objective of the damping network is to guarantee stability by damping the output impedance of the filter. It can be implemented in various ways however the most utilized network is parallel RC- damping as presented in Figure 3.5. This solution has the simplest implementation thus applied within the designed concentrated EMI filter as well.

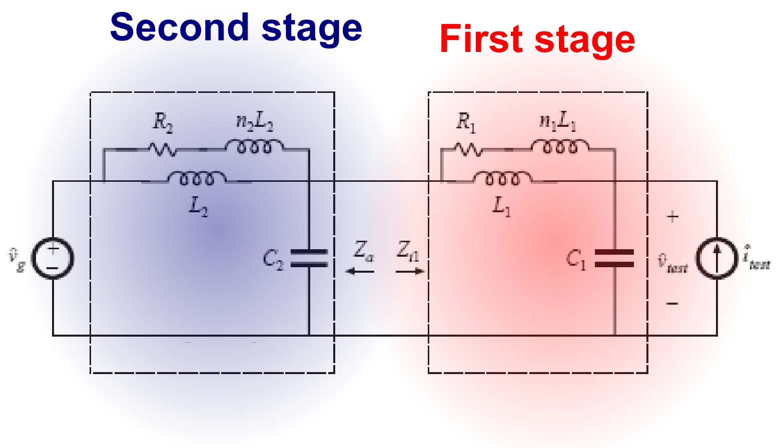

Figure 3.4: Two staged EMI filter with parallel RL parallel damping.

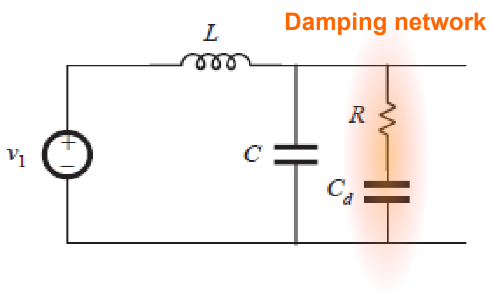

Figure 3.5: Typical input filter structure with RC parallel damping.

3.2.2 Required attenuation

The required attenuation at a specific frequency is essential design parameter within any filter. Typically, it is demanded at the converter switching frequency or depending on the application and relevant EMC standard. In order to provide similar filtering performance, the attenuation of the distributed solution needs to be obtained. This is feasible by simulating the system harmonic current spectrum without filtering as well as with the noise attenuation.

For this purpose, each dc-dc converter is modeled as a noise current source. This noise current waveform is typically provided in the datasheets as a input current ripple of each converter as illustrated in Figure 3.6.

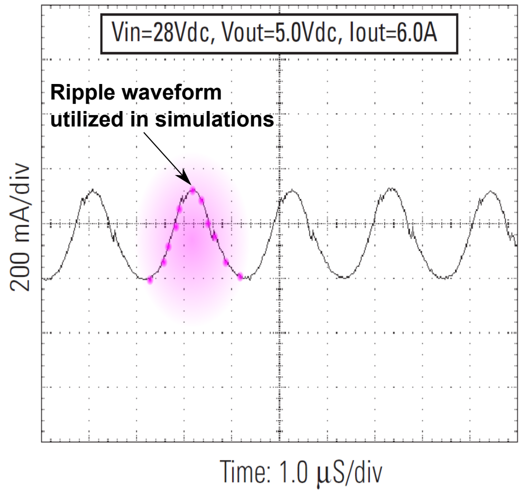

Figure 3.6: Input ripple current provided in the datasheet

This current waveform is inserted to the simulator through 2D Lookup table feature. Subsequent to noise current modeling, the harmonic current spectrum of the system can be simulated. Thereby, the desired attenuation can be estimated by comparing these simulations as shown in Figure 3.7.

Due to the modeling method of the noise current and the performance features of the utilized simulator, the results are not well applicable at lower frequencies. However, the interesting frequency at the proximity of 500kHz, which is the switching frequency of each dc-dc converter, according to the datasheet information. Therefore, the required attenuation should be evaluated at 500 kHz hence the obtained attenuation from the figure is 80dB. Thus, the concentrated EMI filter is required to provide similar attenuation performance. In order to confirm this result, simulated harmonic spectrum is compared to measurements as shown in Figure 3.8. It can be observed that at 500kHz, simulations and measurements provide similar attenuation.

3.2.3 System input impedance

An essential design issue is that the filter will not cause instabilities within the system as described in [Middlebrook, 1976]. Applying the Middlebrook's stability

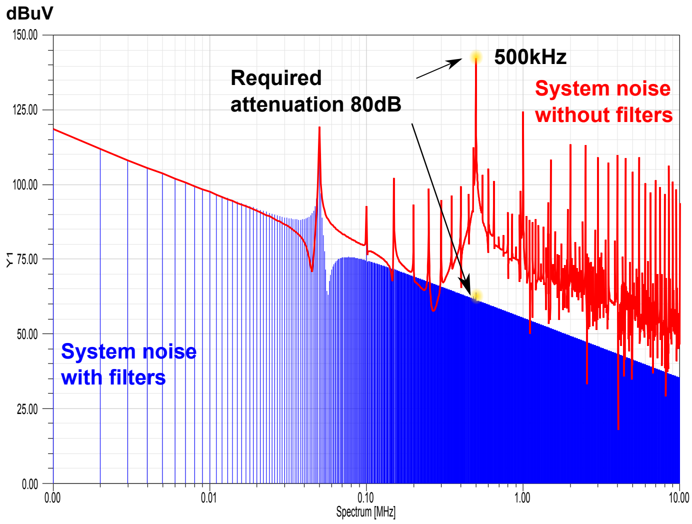

Figure 3.7: Simulated system noise spectrum without attenuation compared to the harmonic spectrum with the utilized filters.

criterion to the filter design according to Equation 3.1 stability is guaranteed.

$$Z_{out} << Z_{in} \tag{3.1}$$

Therefore, the input impedance has a significant importance within the EMI filter design. Most fundamental design guideline for an input filter is the Middlebrook's stability criterion concerning the impedance interactions. Therefore, in order to design input filter that provides stable system operation, the whole system input impedance is required.

Input impedances of each dc-dc converters contribute on the system input impedance. Individual input impedance for the converter is obtainable through the created behavioral model. As described in Chapter 2, the converter input dynamics is modeled as RLC network shown in Figure 3.9. Hence, the input impedance of each converter is as presented in Equation 3.2.

$$Z_{in} = R + sL + \frac{1}{Cs} \tag{3.2}$$

These component values for the input dynamics are obtainable from the inrush current waveform as described in detail in [Oliver et al., 2006]. As the model for a

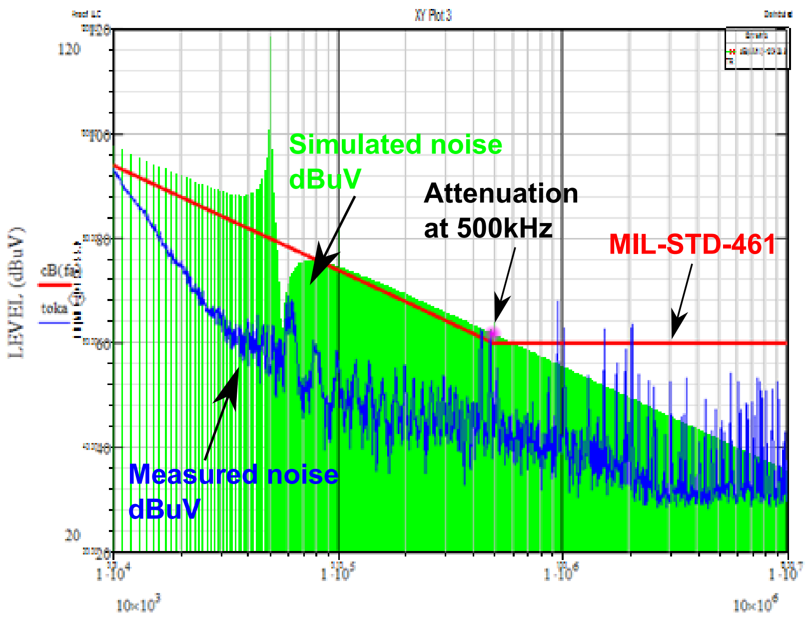

Figure 3.8: Simulated system noise compared to the noise measurements.

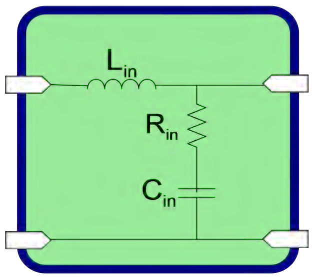

Figure 3.9: Equivalent input circuit of the modeled dc-dc converter.

dc-dc converter is constructed utilizing the software parameterization tool, the component values are obtainable directly from the created VHDL-AMS code for each converter. The system input impedance is a parallel connection of the impedances of each dc-dc converters.

At first the individual input impedance of each converter is discovered by inserting the obtained component values to the impedance equation. Thereafter, the whole system input impedance is obtained paralleling the converter input impedances. The transfer function of this impedance is described in Equation 3.3 and the corresponding parameters are as presented in Table 3.1.

$$Z_{in,system} = \frac{a_0 + a_1 \cdot s^6 + a_2 \cdot s^5 + a_3 \cdot s^4 + a_4 \cdot s^3 + a_5 \cdot s^2 + a_6 \cdot s}{b_0 \cdot s^5 + b_1 \cdot s^4 + b_2 \cdot s^3 + b_3 \cdot s^2 + b_4 \cdot (s)} \tag{3.3}$$

Table 3.1: Coefficient values for the input impedance transfer function.

Coefficient	**Value**
a_0	267794879800000.0
a_1	0.000000004264641764
a_2	0.001349293873
a_3	274.4699454
a_4	1349951.727
a_5	2215952180.0
a_6	1340302486000.0
b_0	0.007075198698
b_1	35.89084032
b_2	164057.5841
b_3	144191096.8
b_4	37751079020.0

This input impedance is illustrated in Figure 3.10. Consequently, the concentrated EMI filter is required to be designed so that its output impedance is much smaller than obtained system input impedance in order to guarantee stable operation.

3.2.4 Design procedure

The selected structure for the concentrated differential EMI filter is two-stage filter with RC- parallel damping network within both sections. The component values for this single filter need to be selected in order to provide the similar attenuation features than the conventional solution at 500kHz. In addition, the maximum output impedance of the filter is limited to be lower than the obtained input impedance of the system resulting in stable system operation.

The values are selected according to [Erickson and Maksimovic, 2000] where guidelines are provided for two stage input filter. Within this section, the design

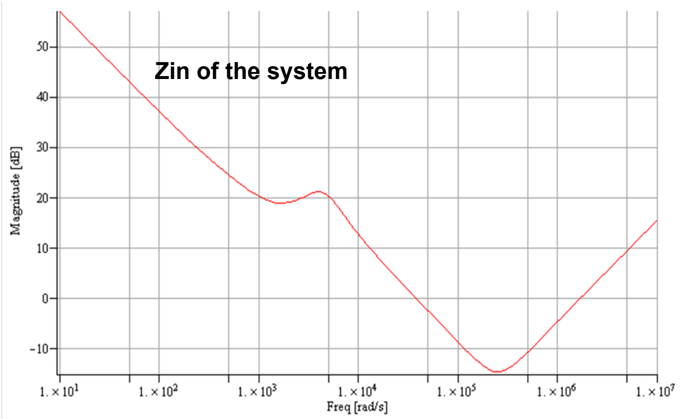

Figure 3.10: Simulated input impedance of the whole system.

procedure is briefly described. Thereafter comparisons between the utilized filters and the concentrated design are carried out. Table 3.2 presents design principles and corresponding equations to facilitate the selection of the filter component values.

Table 3.2: Design principles for the concentrated EMI filter.

Description	**Parameter**
Interactions prevention	$f_2 = k_f \cdot f_1$
Characteristic impedance	$R_{0f} = \sqrt{\frac{L_f}{C_f}}$
Optimized capacitor sizes	$n = \frac{Cb}{C_f}$
Optimum peak Z_{out}	$R_{0f} \cdot \frac{\sqrt{2 \cdot (2+n)}}{n}$
Optimized damping resistor	$R_f = R_{0f} \cdot \sqrt{\frac{(2+n) \cdot (4+3n)}{2 \cdot n^2 \cdot (4+n)}}$

The equations are based on the restrictions and recommendations for an optimum input filter design. For two-stage structure, an essential issue is to prevent interactions between the sections. Hence parameter k_f is used to separate the resonance frequencies of the two sections. Recommended is to select the resonance frequency f_1 of the first section to be smaller than the resonant frequency $f_2$of the second section. Thus, since the attenuation is divided between the sections, the first stage provides larger part of the attenuation.

Parameter R_{0f} is the characteristic impedance of one section, whereasL_f and

C_f are the corresponding LC- filtering components. Parameter n is used to optimize the capacitor sizes of one section. The choice of damping capacitor C_b will not affect on the filter's high frequency attenuation however the size is required to maintain optimized. In addition, within optimum design, the peak output impedance as well as the damping resistor value should be as defined in the table.

The concentrated filter is designed selecting the best suitable component values by varying the design parameters. The two stages are designed separately according to the provided principles. The process initiates from the first section by choosing the filtering component values. Figure 3.11 presents the output impedance of the first stage without damping thus illustrating the importance of the damping network. Compliance with the stability criterion is not obtainable without damping network.

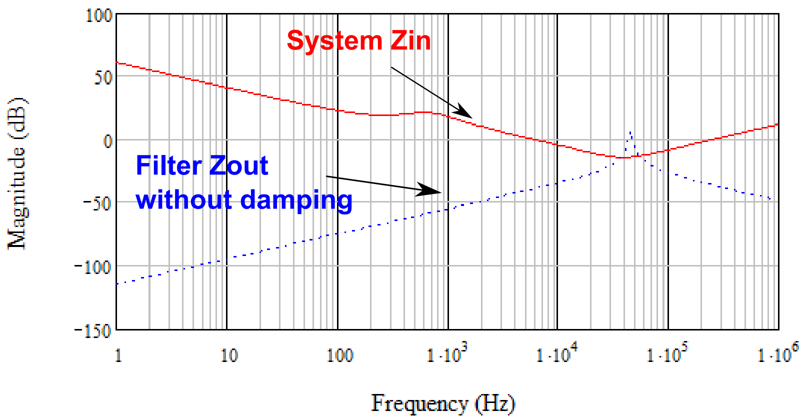

Figure 3.11: Filter output impedance of the first stage without damping network.

Thereafter, the optimum damping network is designed based on the described equations. In a similar manner, the components for the second section are obtained utilizing the provided equations and following the design steps according to [Erickson and Maksimovic, 2000]. A two stage concentrated input filter for differential mode noise is designed and the obtained component values are presented in Figure 3.12.

In order to validate the design, the performance characteristics are verified through simulations. Concerning stability, Figure 3.13 compares the simulated system input impedance to the theoretical output impedance of the obtained EMI

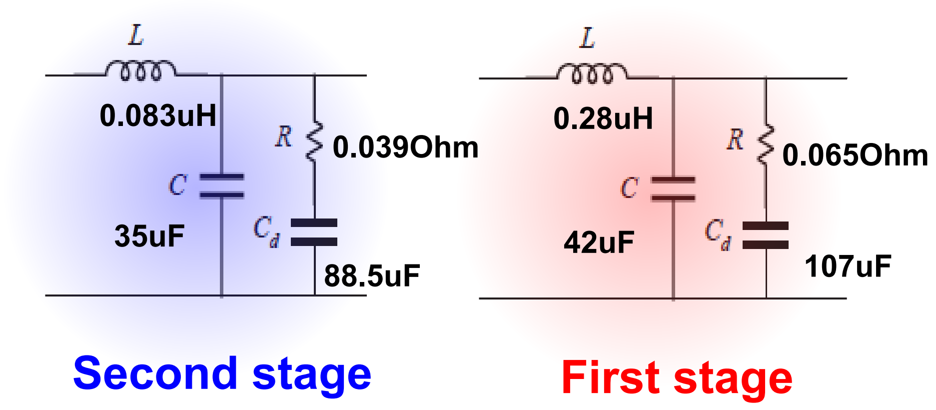

Figure 3.12: Designed two stage EMI filter with the component values.

filter. From the figure, it can be observed that the concentrated filter complies with the stability criterion regarding the impedance inequalities.

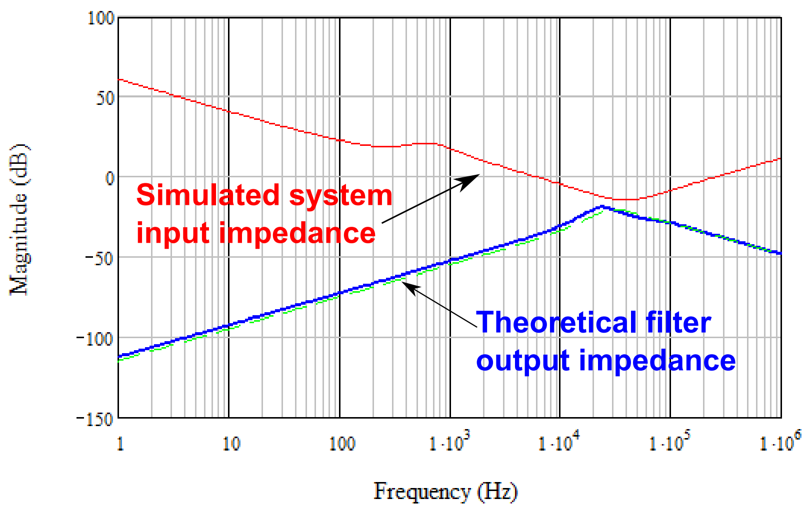

Figure 3.13: System input impedance compared to the filter output impedance.

A fundamental design constraint, the required attenuation can be confirmed by comparing the simulated harmonic spectrums of the two EMI solutions. This is

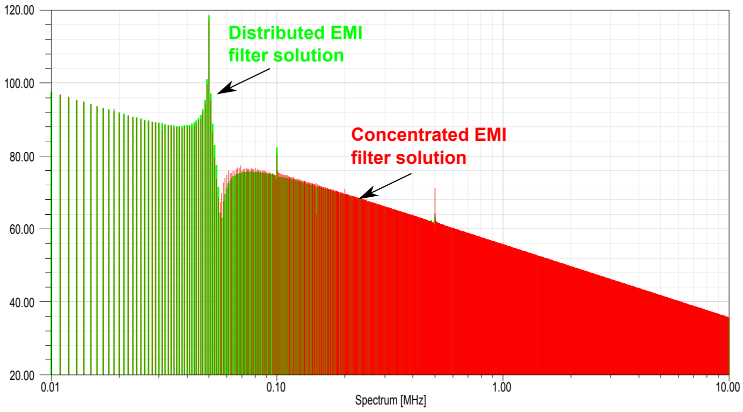

Figure 3.14: Simulated noise spectrum of the distributed EMI filter compared to the concentrated solution.

demonstrated in Figure 3.14. It can be observed that the designed concentrated filter provides similar attenuation features as the utilized distributed filter solution.

As the two stage concentrated EMI filter is obtained, comparisons between these two filter options are done. Concerning the distributed solution, the obtained equivalent circuits for the filter models are utilized for the comparisons. Table 3.3 provides a comparison regarding the combined values of the capacitors and inductors as well as the energy storage within the filter components.

Table 3.3: Comparison of the EMI filter solutions

Parameter	**Concentrated**	**Distributed**
Capacitance	273uF	190uF
Inductance	0.36uH	39.3uH
Inductor energy	6.5uJ	31.2uJ
Capacitor energy	107mJ	75mJ

The results of the two designed solutions for this particular system show that the energy stored within the capacitors is larger thus contributing to a larger filter size. Correspondingly, the energy stored within the inductor it is smaller in the concentrated filter solution. These results provide an interesting starting point for further EMI filter solution analysis. In addition, the concentrated filter design could be further optimized by adjusting the presented design parameters. Future work is to continue with the optimization analysis and provide detailed comparisons between various solutions concerning interesting system parameters such as stability and overall filter size.

Chapter 4

Power System Analysis

Power system analysis is the most fundamental aspect while designing distributed power systems. As the components are selected according to the relevant requirements and the commercial components are modeled as described in chapter 2, simulations regarding the whole system can be executed. These simulations enable comprehensive system analysis at various operation conditions. Thus, design errors or stability problems can be discovered prior to implementing the system. Based on the obtained simulation results a prototype is implemented.

This chapter describes in detail the methods for recognizing the relevant constraints influencing on the component selection. In addition, the utilized components within the system are described in detail. A comprehensive analysis procedure for the designed system is presented including local and global stability assessments as well as the main operation. Finally, the system design is validated comparing the measurements to the simulation results.

4.1 System design

System design consists of component selection, comprehensive stability analysis as well as system performance simulations. Within this section, the main system components, dc-dc converters, EMI filters, holdup capacitors and transient suppressors are chosen selected based on the relevant requirements regarding the authority regulations as well as the specific system features and functionalities. System small and large signal stability analysis is executed as well as comprehensive system evaluation based on simulations is provided. Moreover, it is shown how these system simulations enable the design of specific system features, such as protections.

4.1.1 Selected components

The system component selection aims to an optimize design solution which is especially important within avionic applications. Therefore, concerning the dc-dc converters, small size and weight as well as the load demands are the most essential selection principle. The utilized EMI filter is conventional and it is based on the manufacturer recommendations. Transient protection device is selected based on special requirements for avionic applications provided in [RTCA, 2004]. Furthermore, holdup time capacitors are required to provide energy for the system according to the relevant constraints.

The bus voltage influences on the voltage stress of the system components connected to the bus. Figure 4.1 provides the normal voltage transients for a 28Vdc power system [MIL, 2004b]. As it can be observed from the figure, the maximum bus voltage value is 50V. Therefore, this value is the maximum voltage for the selected components.

Dc-dc converters and EMI filters

The chosen dc-dc converters are presented in Table 4.1. These converters provide the optimized design solution regarding size and weight as well as the load demands. Each manufacturer provides different additional features and protections within their COTS converters. Since the converters are selected based on the most critical requirements, the additional features depend on the manufacturer and not every converter fulfills all the required features. Thus regarding the application some additional electronics can be implement in order to comply with the system functionality requirements.

The utilized distributed EMI filter solution selection is described in detail within Chapter 3. The selected conventional EMI design is based on the selected commercial filters modules as provided in Table 4.2 according to the manufacturers recommendations.

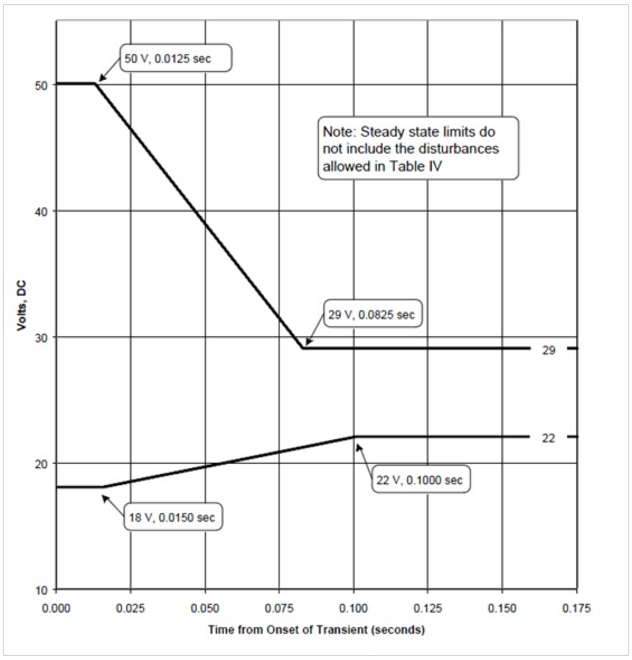

Figure 4.1: Normal operating conditions for 28Vdc bus voltage.

Table 4.1: Selected commercial dc-dc converters for the designed system.

Requirement	Module	Manufacturer
Load 1, 5V and 25W	CB30SI-5-B	Martek
Load 2, 12V and 6W	MGDS-10-J-E	Gaia
Load 3, 5V and 5W	MGDS-10-J-C	Gaia
Load 4, 4V and 30W	CB30SI-24-B	Martek
Load 5, 10.5V and 65W	MOR2812SV	Interpoint
Load 6, 7V and 25W	MOR289R5SV	Interpoint

Transient protection

Lightning strikes are relatively common in airplanes [Mel Clark,] and thus the sensitive electronics within the power system need to be effectively protected with transient voltage suppressors. The lightning-caused transient voltages are defined in the Aircraft standard RTCA/DO-160E Section 22 [RTCA, 2004].This document defines both, voltage and current threat levels and their waveforms types. In order

Table 4.2: Selected commercial EMI filters for the designed system.

Power module	Filter module	Manufacturer
CB30SI-5-B	CBF30	Martek
CB30SI-24-B	CBF30	Martek
MGDS10-J-E and MGDS-10-J-C	FGDS-2A-50V	Gaia
MOR2812SV and MOR289R5SV	FME28-461	Interpoint

to select the transient suppressor, the waveform and threat level need to be known. The lightning exposure threat levels are presented in Table 4.3 [RTCA, 2004].

Table 4.3: Threat levels based on the transient waveform.

Level	Waveform	Waveform	Waveform
	3	4	5A
	Voc/Isc	Voc/Isc	Voc/Isc
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	300/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600

Where the Voc is the peak open circuit voltage (Volts) and Isc is the peak short circuit current in (Amps). Typically while selecting a transient voltage suppressor, the datasheet parameters are provided as 10/1000 μs waveforms whereas for aircraft applications the waveforms are given as shown in Figure 4.2 according to [RTCA, 2004]. Thus for avionic applications the transient suppressor parameters need to be converted to correspond to the presented waveforms. A detailed method for the parameter conversion is described in [Mel Clark,].

Regarding the designed system, the transient requirements are threat level 4, meaning that the device is installed in severe electromagnetic environment and the applicable waveform is 3 [RTCA, 2004]. According to the recommendations in [Mel Clark,] for 28V dc aircraft power distribution lines a Microsemi transient voltage suppressor RT65KP48A is selected. This device suppresses transients up to 65kW at 6.4/69μs.

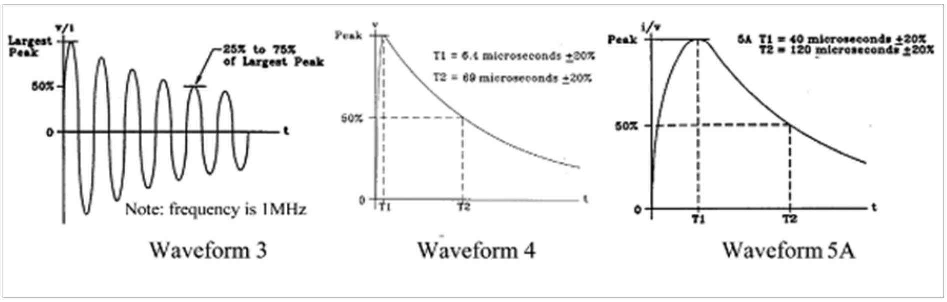

Figure 4.2: The surge waveforms according to the RTCA/DO-160E Section 22.

Holdup capacitors

Holdup capacitors are typically required in avionics systems in order to provide enough time for the system to store data and control the shutdown. The power system undervoltage limits are provided in [MIL, 2004b] as illustrated in Figure 4.3.

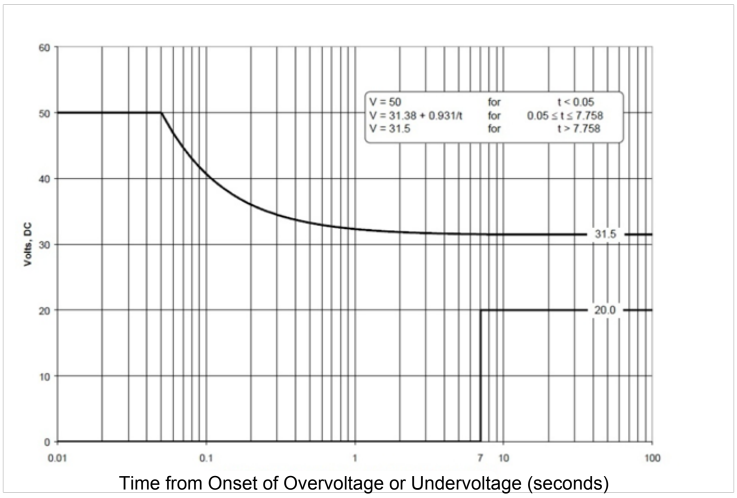

Figure 4.3: Abnormal and undervoltage operating conditions for 28Vdc bus voltage.

From this figure it can be observed that the worst case undervoltage duration is 7s. However, utilizing only capacitors it is not possible to comply with this requirement and typically an external power backup is utilized to comply with this requirement. Therefore, the demand for the holdup capacitors concerns mainly a power interrupt defined in [MIL, 2004b] and the requirement is to provide energy during a power interrupt of 50ms.

To maintain the system operation during the power interrupt, the selection of the capacitor depends on the system specifications according to Equation 4.1.

$$C_{holdup} = \frac{2 \cdot (P_{system}) \cdot (t_{holdup})}{\eta \cdot ((V_{nom}^2) - (V_{drop}^2))} \tag{4.1}$$

Regarding the designed system these parameters are: $P_{system} = 170W$, $t_{holdup} = 50ms$ and $\eta = 0.8$, which is the estimated efficiency based on the converter efficiencies as well as $V_{nom} = 22V$ and $V_{drop} = 16V$ according to the operating condition [MIL, 2004b]. Thus, the calculated holdup capacitance value for the system is approximately 93mF. The most critical criterion regarding the capacitor selection in avionic system is the height and weight. Due to the enclosure requirements, the maximum height for the utilized components on the bottom side of the PCB is 12mm and 18mm on the top side. Two possible holdup capacitor solutions were considered as presented in Table 4.4. As it can be observed, compromises within the preferred features are required in order to select the best suitable capacitor solution for each design.

Table 4.4: The system holdup capacitor- solutions.

Component	**Electrical specs**	**Area**	**Height**
Cubisic LP	50V and 15mF	3375mm	12mm
THQ3	50V and 24mF	1000mm	15.8mm

In addition to the above-mentioned parameters, concerning capacitors, reliability and the ESR value are always important and must be taken into consideration. Finally, subsequent to the evaluation of these solutions, the most critical design parameter was the employed area. The final holdup time capacitor- solution was based on the smallest area. Thus the chosen capacitor solution is to parallel four 24mF THQ3 capacitors in order to provide the required holdup time for the system.

4.1.2 System stability analysis

As stability is major concern within any power system, it is desirable to detect any potential instability problems at an early design stage. The system stability can be analyzed from two different perspectives as shown in Figure 4.4. Small signal stability is analyzed as the interactions between an EMI filter and a dc-dc converter whereas large signal stability is a system level issue.

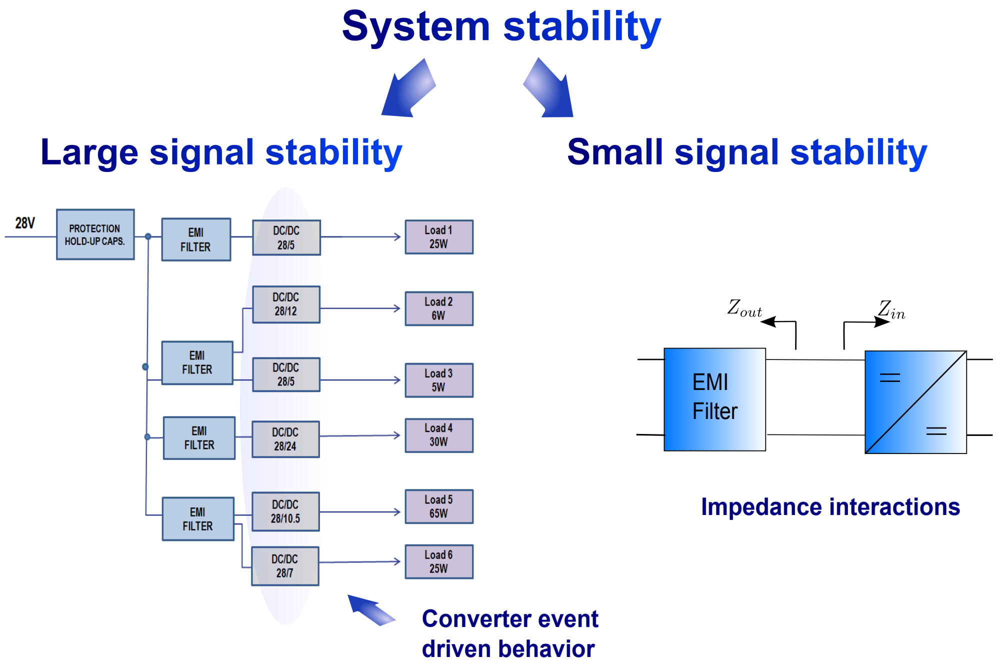

Figure 4.4: Power system stability analysis as small signal and large signal.

Small signal stability

Small signal stability is a local system issue and concerns the impedance interactions between an EMI filter and a dc- dc converter. Middlebrook presented in [Middlebrook, 1976] a method to determine whether these impedance interactions would cause instability. This stability criterion is described in Equation 4.2.

$$Z_{out} << Z_{in} \tag{4.2}$$

where Z_{out} is the filter output impedance and Z_{in} is the converter input impedance as shown in Figure 4.5.

Utilizing the developed behavioral dc-dc converter model, the input impedance is easily obtained through simulations. Additionally, output impedance- measure-

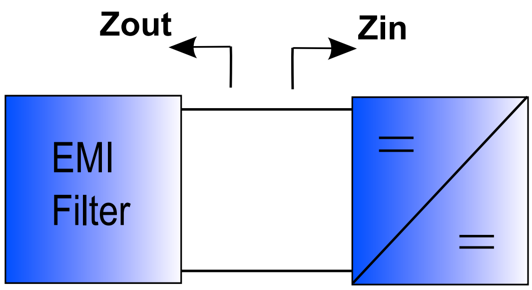

Figure 4.5: Small signal stability as impedance interactions between an input filter and a dc-dc converter.

ments were performed for the filter models and the simulated input impedance can be compared to the measured filter output impedance as shown in Figure 4.6.

Within this figure, the simulated input impedances of two dc-dc converters sharing an EMI filter are compared to the measured filter output impedance. It can be observed that the output impedance is clearly smaller than the input impedance of the converter. As this analysis is carried out for each converter Z_{in} and the corresponding filter Z_{out} one possible instability problem was discovered as demonstrated in Figure 4.7.

It can be observed that the Middlebrook stability criterion $Z_{out} << Z_{in}$ is not met. This small signal instability problem can be eliminated by altering the filter output impedance. It can be achieved by adding sufficiently capacitance at the filter output. Thus shifting the resonant frequency of the output impedance the stability criterion is met as demonstrated in Figure 4.8, where the dashed line presents bus capacitor impedance.

Regarding the actual system design, this instability problem was solved utilized paralleling four 22uF and 50V AVX multilayer capacitors. It should be emphasized that the selected bus capacitors are required to have low ESR and ESL values due to their impact on the capacitor impedance at high frequencies.

Large signal stability

Within the distributed power systems, the event driven behavior of the dc-dc converters has a significant influence on the overall system stability. Even though the individual input filter and dc-dc converter complies with the small signal stability

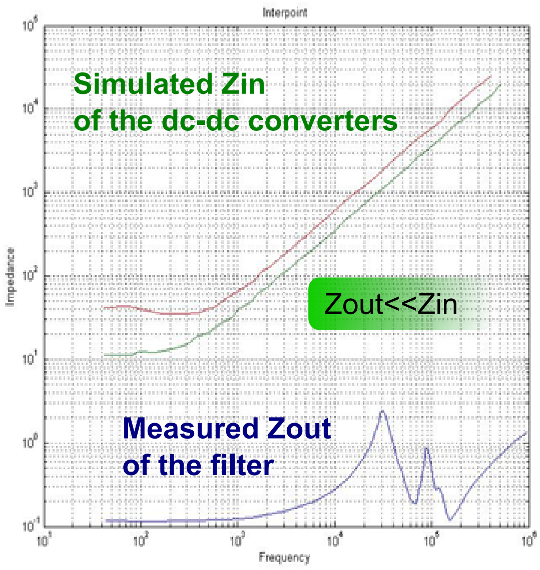

Figure 4.6: Simulated input impedances of two dc-dc converters sharing an EMI filter compared to the measured filter output impedance for small signal stability analysis.

criterion, the system level stability is not guaranteed. Large signal instability can occur at the system level due to various reasons:

- Pulsating loads
- System startup and turn-on delays
- Remote control
- Protections

These events modify the converter behavior thus possibly introducing global stability problems. The utilized model structure of the dc-dc converters, takes into consideration the event driven behavior. Thus, large signal stability analysis through simulations is possible. The analysis is accomplished considering the above-mentioned features that might lead to instability.

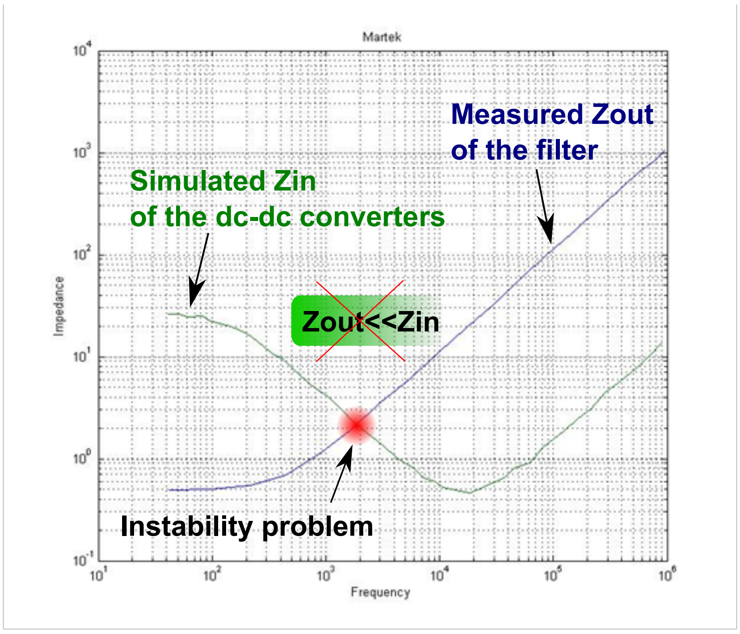

Figure 4.7: Possible discovered instability problem while analyzing the impedance interactions.

Pulsating loads

Within avionic applications, some of the supplied loads can be pulsating i.e. they require power for a certain time according to a specific cycle. Thus, the load is demanding a pulsating power between full and no load. Therefore, it is essential to validate the transient behavior of the converter providing power to the load. The output voltage should reach the steady state condition fast enough in order to supply the load according to its demands. If this condition is not met, some oscillation might occur and the system level stability might be jeopardized. Figure 4.9 shows the simulated output voltage while load step from zero to full load is introduced.

Based on the simulations, it can be estimated whether the converter responds to the transients fast enough. In case the transient behavior is not as desired, some additional capacitance can be added at the converter output to provide energy for the load. Detailed comparisons between the simulated and measured transients are provided in the next section.

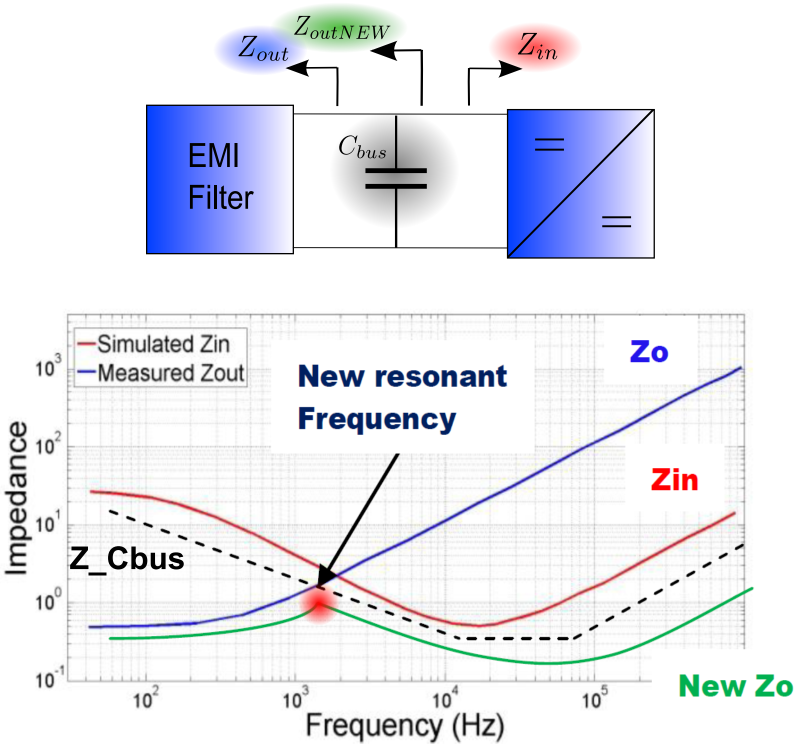

Figure 4.8: Dc-dc converter behavioral model structure

Startup behavior

Stable and controlled system startup at every operating condition is essential within the global system stability. Every dc-dc converter has a specific startup behavior depending on its implemented topological structure. This behavior is provided on the converter datasheets and the created simulation model considers this. Therefore, utilizing the simulations, the whole system startup can be estimated under every operating condition. The system power up is demonstrated in Figure 4.10 at the nominal input voltage of 28Vdc.

The aim of the startup simulations is to validate that the power up occurs properly when the system is supplied within various operating conditions provided in[MIL, 2004b]. In addition to the startup estimation with various input voltages, the power up with no load and full load conditions can be assessed. Figure 4.11

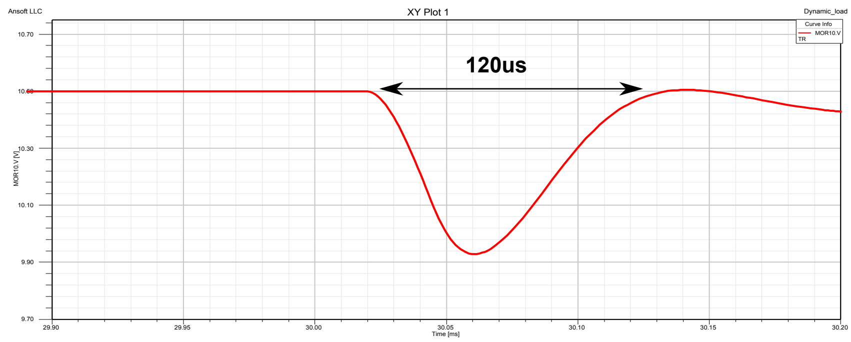

Figure 4.9: Simulated output voltage during a load step from zero to full load.

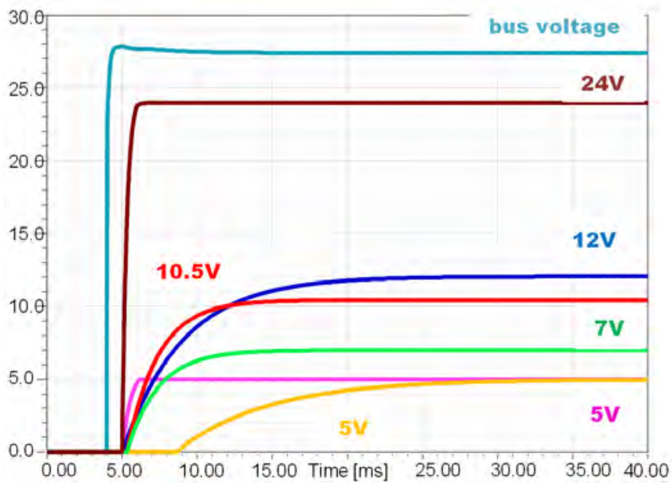

Figure 4.10: System startup with nominal operation condition.

presents the startup at 20Vdc which is the steady state value in abnormal conditions.

In order to make the simulations correspond the actual implemented system, an estimated voltage drop on the cables is taken into consideration within the startup simulations. In this simulation, a voltage drop of 1.5V is utilized and the stability of the startup is estimated. If the voltage drop is too large, a stable system startup is not guaranteed.

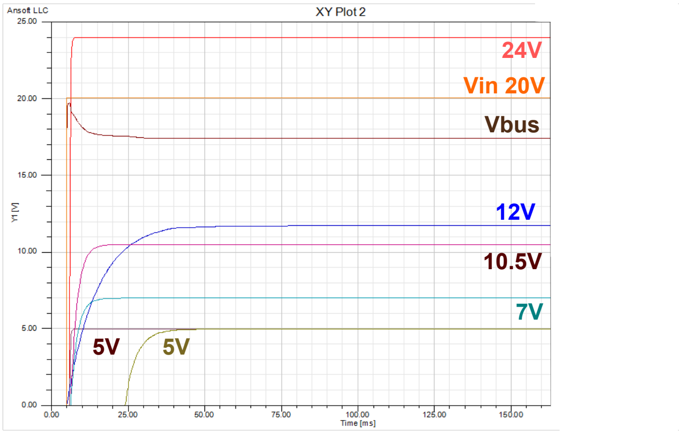

Figure 4.11: System startup with abnormal operation condition.

Remote control and protection

Depending on the system application, commercial power supplies are required to have certain additional features. For instance, a particular converter might be required to stop delivering power to a specific load. This feature can be implemented as remote control that controls the converter operation mode. An external signal is applied to a dc-dc converter to turn it on or off and thus alter its behavior within the system which might be a potential source of stability problems.

The COTS power supplies typically employ certain protection features such as input overvoltage and undervoltage as well as output overvoltage. These protections are implemented within the dc-dc converter simulation model. Especially, the input undervoltage protection might cause instability problems in case the bus voltage is reduced below the undervoltage protection limit.

4.1.3 System simulations

The system level simulations assist in the detailed analysis of special features within the system. Furthermore, they enable the system performance evaluation under various operating conditions and thus provide valuable information of the overall system behavior. Additional features and specific functionalities of the system can be designed based on the information provided by the simulations.

Inrush current

Each dc-dc converter has its own specified inrush current absorption depending on the converter structure, which the simulation model takes into account. In addition, if the system is required to provide holdup time, the influence of large holdup capacitors to the system inrush current is significant. Therefore, current absorbed by the entire system during the startup can be estimated through the simulations.

While simulating the inrush current, the line impedance should be taken into consideration depending on the application as shown in Equation 4.3, due to its effect on the actual inrush current.

$$R_{inrush} = \frac{V_{drop}}{I_{max}} \tag{4.3}$$

In the simulations, the voltage drop of 0.1V was utilized. The simulated inrush current peak during the start-up is presented in Figure 4.12. This simulation was completed without taking into consideration the holdup capacitors.

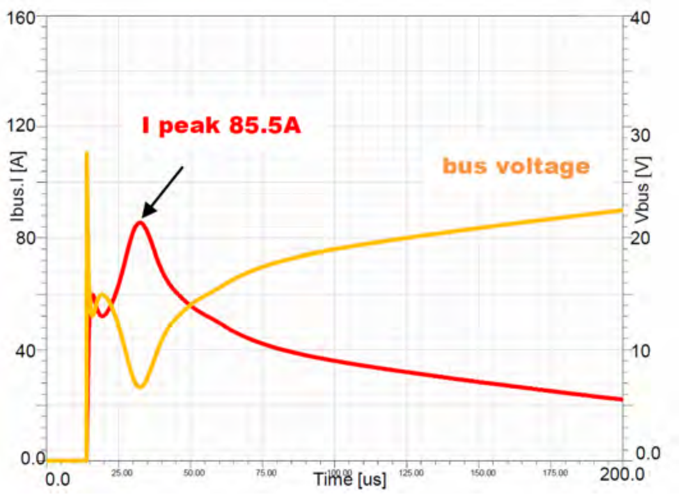

Figure 4.12: Simulated inrush current of the system.

As the system inrush current is simulated, the necessity for inrush protection can be estimated. Within the actual system, inrush current peak absorbed by the system was desired to be limited and protection was designed. In Section 4.2 considering the experimental results, detailed design verifications are provided and the inrush current simulations are compared to the measurement values.

Startup sequence

Startup sequencing refers to a configured system turn-on according to specific requirements within the application. A certain dc-dc converter is turned on subsequent, the whole system or one particular converter has reached the steady state or at a certain instant of time. Depending on the load type it might have constraints when it can be supplied i.e. it is being supplied exclusively if a certain converter is providing energy to other load within the system. Regarding the designed system a specific startup sequence was required as illustrated with the simulations in Figure 4.13.

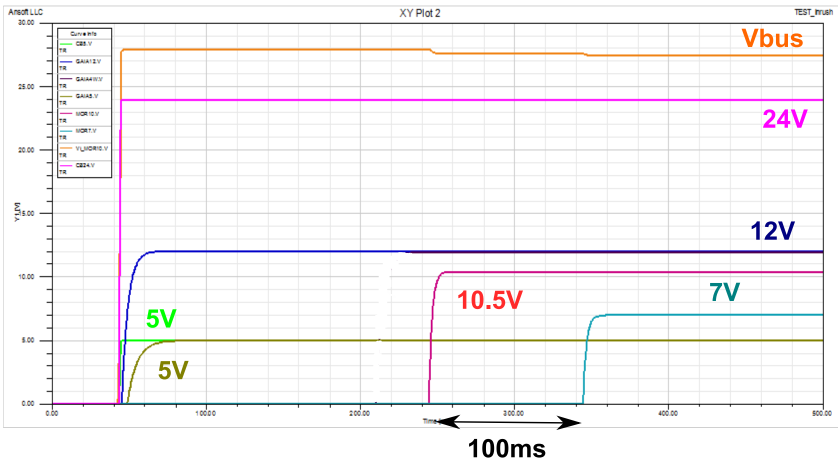

Figure 4.13: Special startup sequence of the designed system at nominal operating conditions.

The main objective within the sequencing is that power module of 7V needs to be generated 100ms subsequent to the 10.5V converter. In addition, prior to generating the either one of these voltages, the rest of the system is required to reach the steady state. From the simulations, it can be observed that a proper startup behavior is obtained regardless of the configured sequencing.

General operation

Significant design advantage while utilizing the simulations is the possibility to evaluate the system performance at every operation condition without practical implementation. Therefore, estimating the system power consumption at various input voltage levels, valuable information concerning the optimized PCB design is obtained. The power consumption within the designed system is estimated by simulating the system input current at steady state. Table 4.5 presents the power consumption estimations based on the absorbed current at various input voltage levels. Within the performed simulations, the source impedance of approximately 0.25Ω was considered in order to correspond the real environment.

Table 4.5: The system power consumption estimations at various operating conditions based on simulations.

Source voltage	Bus voltage	Input current	Power
32.0V	30.6V	5.6A	171.4W
28.0V	26.4V	6.5A	171.4W
25.0V	23.1V	7.5A	173W
20.0V	17.5V	10.2A	178W

4.2 Implemented system

As the optimum component selection is obtained and essential simulations have validated proper system operation, a prototype is implemented. A block diagram of the constructed system is presented in Figure 4.14 and the load requirements are recapitulated in Table 4.6. In addition, The system specifications are summarized in Table 4.7.

A detailed layout design of the implemented system lies outside the scope of this thesis. The PCB design solution is summarized within this section. The top side of the designed prototype is shown in Figure**??** where the commercial dc-dc converters are located as emphasized in the figure. Figure 4.15 correspondingly presents the bottom side where EMI filters and control electronics are situated.**??**

The dc-dc converter have the largest power consumption and due to thermal design of the power system, they are located on the top side of the PCB where more

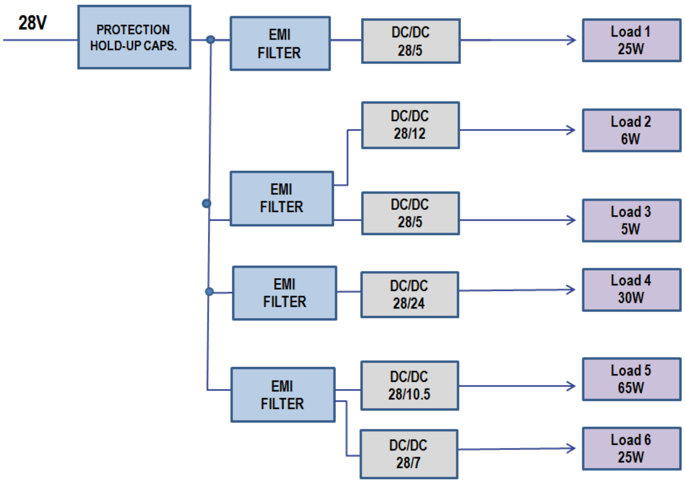

Figure 4.14: A block diagram of the implemented system.

Table 4.6: Load requirements for the implemented system.

Load	**Output voltage (Vdc)**	**Power (W)**
Load 1	5V	25W
Load 2	12V	6W
Load 3	5V	5W
Load 4	24V	30W
Load 5	10.5V	65W
Load 6	7V	25W

Table 4.7: Power system specifications.

Power	170W
Nominal input voltage	28V
Applicable standards	MIL-STD-704, MIL-STD-461, RTCA-DO-160

cooling is provided. Due to the lack of area on the top side, the EMI filters are located on the bottom. However, they should always be located to a close proximity of thecorresponding dc-dc converter.

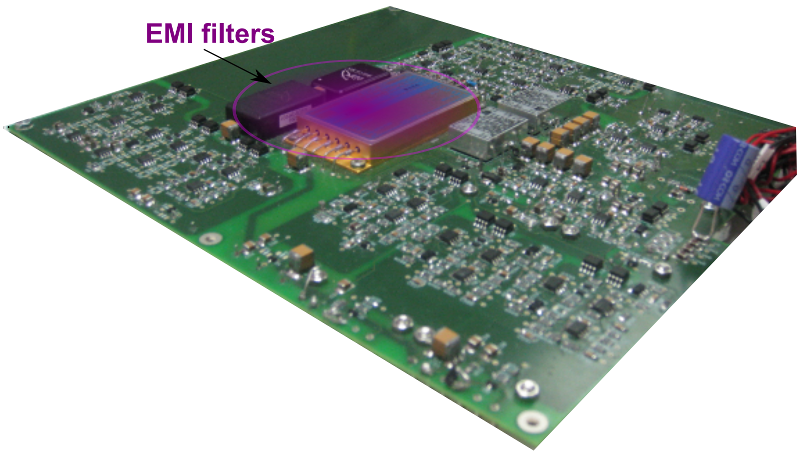

Figure 4.15: Designed prototype with the dc-dc converters.

4.3 Design validation

The final success within the design of distributed power system is discovered subsequent implementing the actual prototype. The prototype measurements are used to comprehensively validate the essential system simulation results concerning proper system operation according to the requirements and specifications.

Turn-on behavior

A stable system start-up under various operating conditions is an essential operational feature that needs to be guaranteed. Since the utilized converters are from various manufacturers, they all employ different start-up behaviors. The simulated startup at the nominal operating conditions is compared to the corresponding measurements as shown in Figure 4.17. It can be observed that the simulations predict the system behavior accurately.

During the startup, the system absorbs substantial amount of current. Based

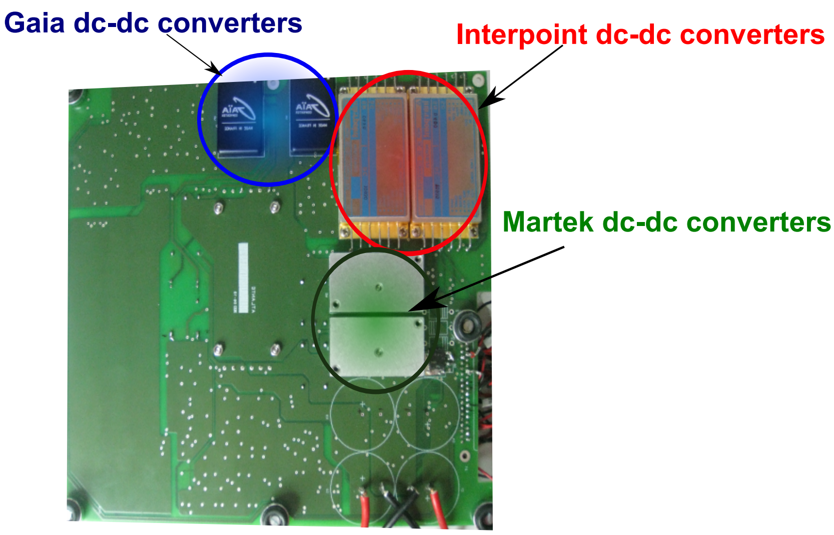

Figure 4.16: Design prototype with the EMI filter as required control electronics.

on the system inrush current simulations, current limiter is decided to implement. Subsequent to the design of inrush current protection, system start-up was simulated. Based on the obtained results, the protection was implemented within the system. Inrush current measurements are compared to the simulation results as provided in Figure 4.18.

The simulated peak current value will not predict the exact behavior of the actual protection circuit. This is due to the implementation method of the simulated current limiter components within the simulated system. Accurate component models were not available for the utilized simulator and therefore, simplified models for the protection components were utilized. However, the results are adequate to verify the functionality of the designed inrush current protection. The inrush current of each converter depends on the topology and the implemented design.

Transient behavior

The system behavior under load transients is analyzed through simulation in Subsection 4.1.3. Power module 10.5V is supplying a pulsating load and it is essential to evaluate its behavior under load transient condition. A load step from no load to full load is introduced at the output of the power module 10.5V output and its

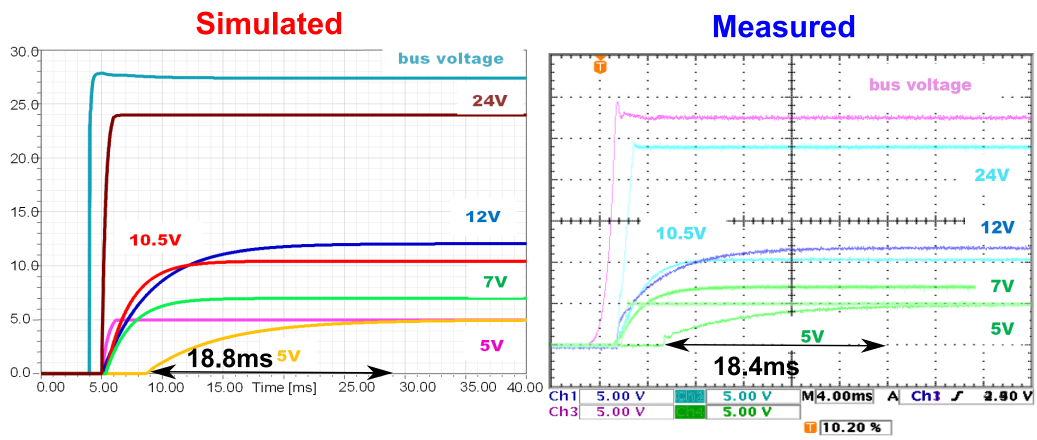

Figure 4.17: Simulated and measured system startup at the nominal operating conditions.

influence within the system is observed as shown in Figure 4.19. The corresponding measurements were executed for the system as shown in Figure 4.20.

A detailed and scaled comparison between the simulated and measured output voltage within the same scaling is presented in Figure 4.21.

The dashed line shows the simulation result and subsequent to the comparison of measured value, it can be observed that the modeled dc-dc converter predicts accurately the transient behavior of the actual converter. However, based on these simulations, it was deemed necessary to add capacitance at the converter output in order to provide more energy for the load during a transient. Since additional capacitance is added at the output of the converter, the maximum capacitive load needs to be verified from the datasheet. It is of significant importance, that this specified value is not exceeded, otherwise a stable converter operation is not guaranteed.

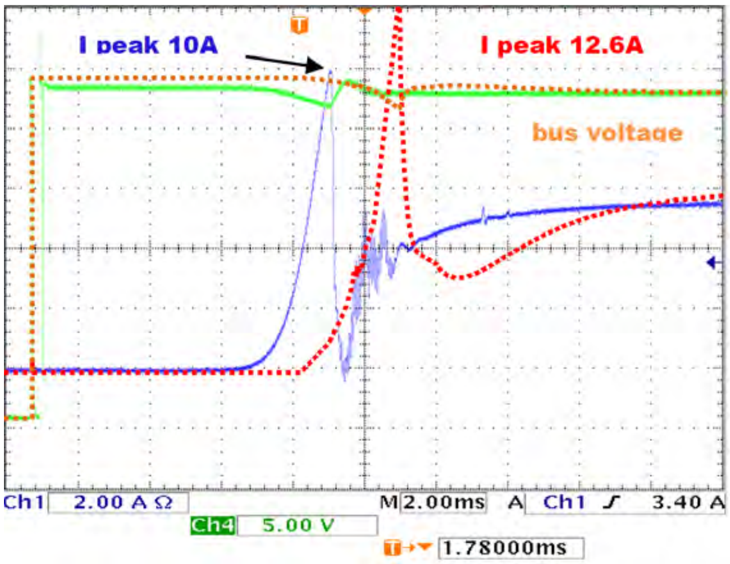

Figure 4.18: The measured inrush current compared to the simulation (dashed line) value after the protection implementation.

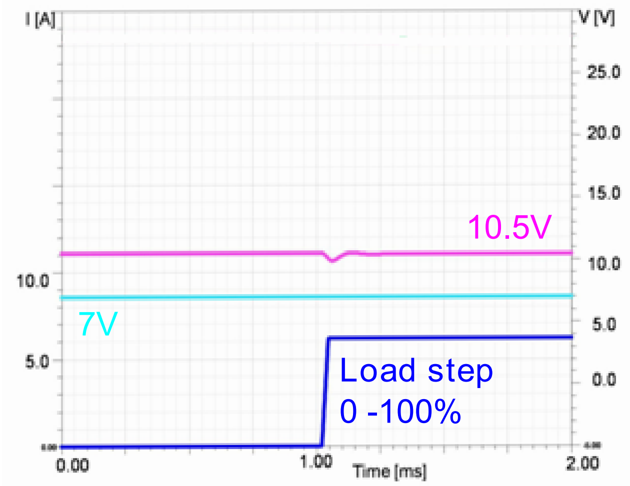

Figure 4.19: Simulated load step from no load to full load introduced at the 10.5 power module output.

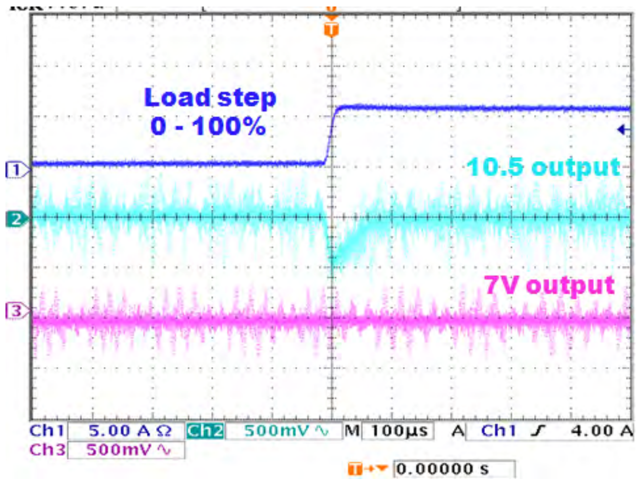

Figure 4.20: Introduced load step from no load to full load at the 10.5V module at ac- measurement.

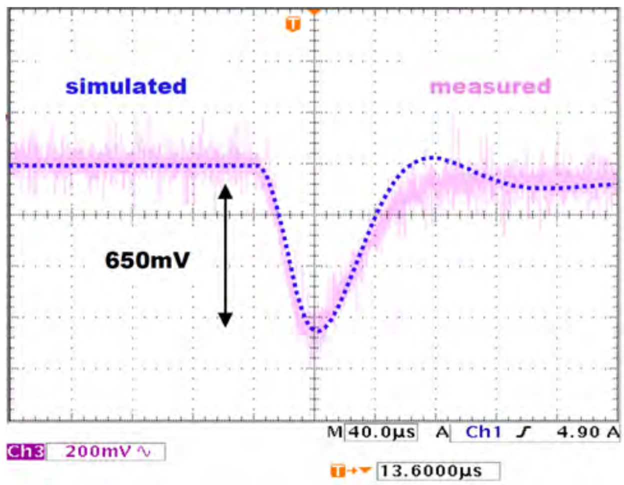

Figure 4.21: A detailed comparison of the output voltage deviation under transient between simulation and measurement values.

Chapter 5

Analysis Guidelines for a Given Architecture

Various architectures exist depending on the particular application and its requirements. The objective of this chapter is to provide system analysis guidelines, independent of the utilized architecture. The optimum design architecture- selection lies outside the scope of this thesis. These recommendations are based on the designed system for an avionic application presented within this thesis. References are made to the previous chapters in order to better demonstrate the design methods. These provided instructions are applicable to any dc distributed power system albeit the focus lies on avionic power systems, concentrating on the restrictions provided by the applicable standards. The relevant power system requirements can be separated as illustrated in Figure 5.1.

The design initiates by recognizing the relevant authority constraints concerning the application conditions of electric power and electromagnetic compatibility. Equally essential is to comprehensively understand the limitations and restrictions introduced by the system functionality requirements. Each specific application has its own individual functional requirements, which the system needs to fulfill. Moreover, the system is required to comply with certain authority regulations depending on the intended application field. The analysis procedure of a distributed power system is divided into two separate parts:

- System component selection
- Analysis procedure

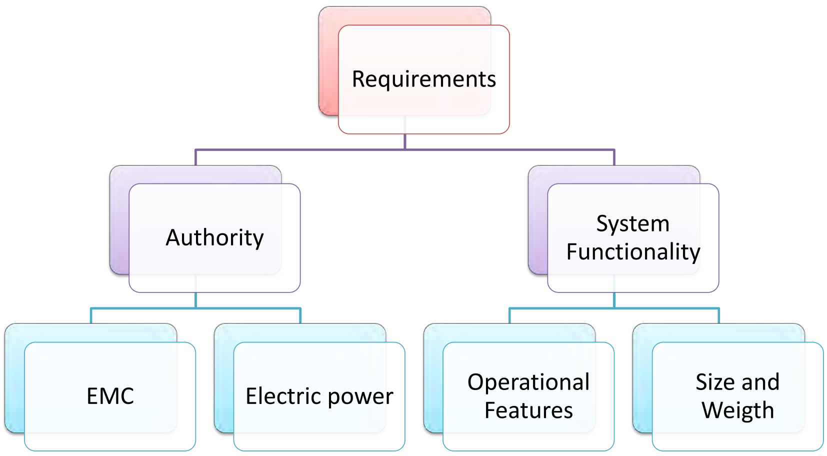

Figure 5.1: Recognition of the relevant requirements aimed for distributed power systems.

Multiple restrictions and constraints within the system affect on the component selection. A detailed principle on discovering the most relevant requirements, covered within next section, assists the optimum component selection.

By following the described analysis procedure, proper performance characteristics under every operating condition can be confirmed. This chapter comprehensively describes both, the component selection as well as the system analysis procedure. Furthermore, detailed analysis steps for the system operation verification are described.

5.1 System component selection

Component selection is based on the on the relevant requirements concerning the system aiming to an optimal design solution. The regulatory requirements and particular system restrictions for avionic applications provide the constraints as presented in Figure 5.2.

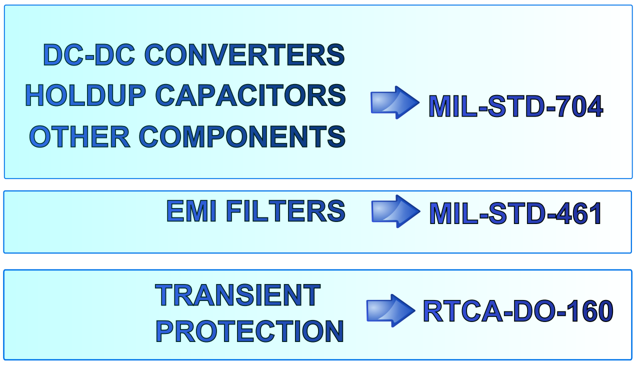

Figure 5.2: Authority requirements affecting the component selection.

Military standard, MIL-STD-704, provides the operating conditions for the bus voltage and influences on the required component voltage stress. In addition, it specifies undervoltage and power interrupt conditions for the system, according which the holdup capacitors are measured. The system EMC requirements are covered in MIL-STD-461 and the compliance with this standard demands the usage of additional EMI filters. Regarding the transient suppressor, standard RTCA-DO-160 defines in detail the requirements for transient threats within avionics.

Within the following sections, comprehensive instructions for the main system component, dc-dc converters, EMI filters, holdup capacitors and transient suppressors, selection and design are provided.

Dc-dc converters

The most fundamental system components are the dc-dc converters. Due to the strict regulatory constraints and restrictions, the utilized power supplies are COTS converters. Multiple requirements are targeted to the power supplies as illustrated in Figure 5.3.

Each of the presented features contributes to the converter selection and prioritizations are required. The most significant criteria for the power supply selection are the compliance with the relevant application standards as well as the load demands. Within any power system, small size and weight are attractive features and within some power systems are the most essential requirements. The additional functionality and provided protections depend on the manufacturer thus an opti-

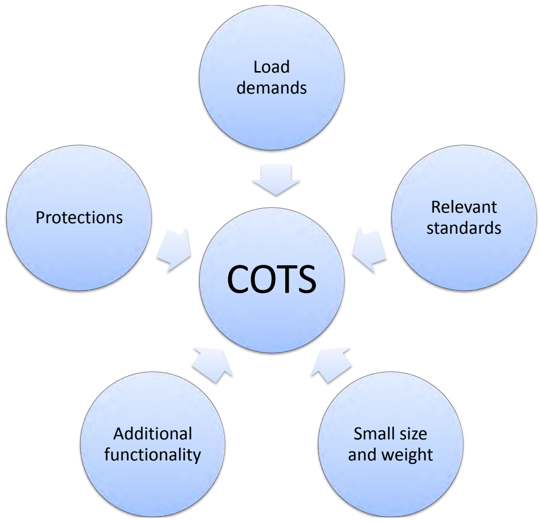

Figure 5.3: Requirements aimed for commercial dc-dc converters.

mized converter solution for particular application might be challenging to find and compromises are required.

A detailed description of the necessary characteristics within COTS converters is shown in Figure 5.4.

A fundamental requirement for a power supply is to provide proper output voltage level and power according to the load demand. This is not, however always obtainable with a single power supply. Thus in order to supply the load in a proper way the dc-dc converters might be required to be connected in series or in parallel to obtain desired output voltage or power. Nonetheless, the manufacturer needs to provide this feature in order to guarantee safe operation when the converters are connected in series or parallel. It should be emphasized that parallel connection of the converters further introduces adverse interaction to the system [Luo, 2005]. Furthermore, output voltage trimming feature enables the possibility to adjust the voltage level to match special load demands.

Additional functionality refers to the possibility to control a power supply with an external signal through an *enable pin*. In the case this feature is not provided within the converter, it needs to be changed if this feature is relevant within the system. However, if the converter is not fulfilling the protection requirements, supplementary protection circuits can be implemented within the system without

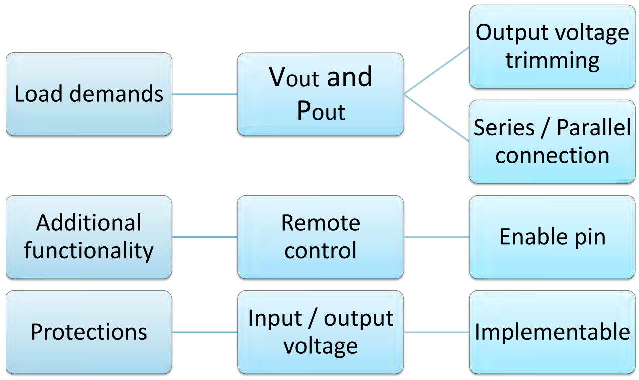

Figure 5.4: Specific features of COTS components aimed to avionic applications.

the necessity of changing the component.

EMI filter solution

Finding an optimum EMI filter solution for a distributed power system is a demanding task. Various possible configurations exist depending on the design architecture. Regarding the designed power system, due to the critical design time, a conventional distributed filter placement was selected. The advantages of this solution are:

- Compliance with the standards
- Design time
- PCB design

EMI filter optimization is of significant interest within Distributed power systems. Therefore, a concentrated EMI filter based on the same constraints as the distributed solution is designed. This new solution comprises of a single input filter instead various. The two EMI filter solutions are illustrated in Figure 5.5.

An EMI filter should always locate at the close proximity of the dc-dc converter. Therefore, within distributed solution the filter placement on the PCB is more flexible than with the single filter. Comparisons between these solutions are shown

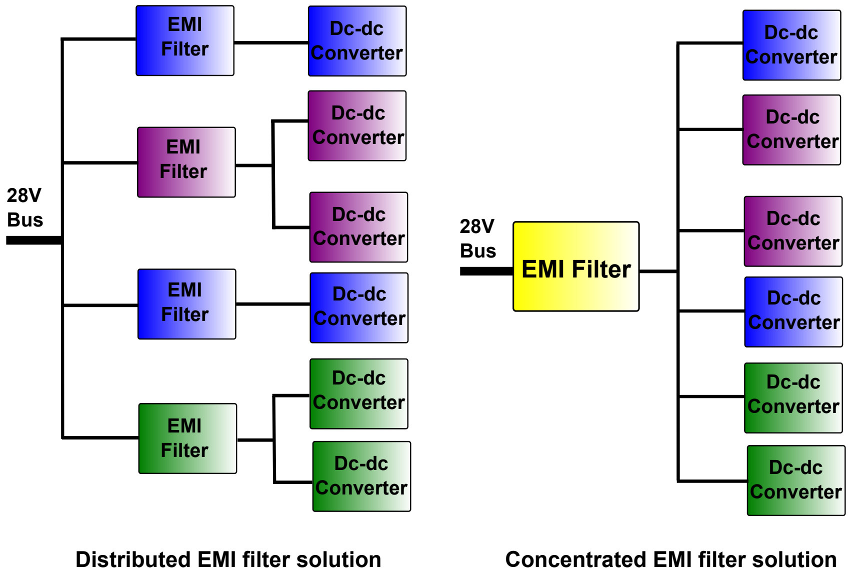

Figure 5.5: Designed conventional distributed EMI filter solution and the designed concentrated EMI filter.

in Table 5.1 where the component values for the distributed solution are obtained from the created equivalent circuits.

Comprehensive

Table 5.1: Comparison of the EMI filter solutions

Parameter	Concentrated	Distributed
Capacitance	273uF	190uF
Inductance	0.36uH	39.3uH
Inductor energy	6.5uJ	31.2uJ
Capacitor energy	107mJ	75mJ

This comparison provides an interesting starting point for further analysis. For this particular system, the distributed EMI filter solution employs less capacitance than the concentrated one thus resulting in a smaller size. However, this solution is limited to the commercial components the manufacturers provide and further design optimizations are not possible. Whereas, a customized filter design is possible to be improved adjusting the design parameters. Furthermore, more filter placement possibilities exist for design optimization. As further analysis is executed, more fundamental recommendations considering the optimized filter solution can be provided.

Other components

A fundamental requirement for the holdup capacitors is the required time to provide energy to the system during a power interrupt. The defined bus voltage conditions contribute to the needed capacitance along with the required energy and holdup time. Figure 5.6 summarizes the relevant capacitor features to be considered while selecting the actual component.

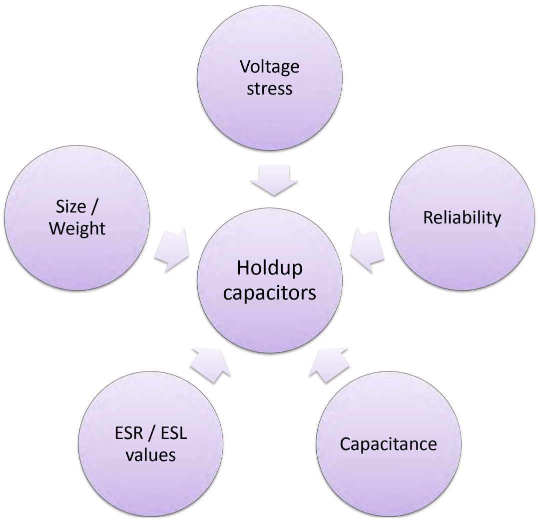

Figure 5.6: Relevant features within holdup time capacitors.

The capacitor value is generally large thus introducing difficulties while selecting the component. This is due to the size constraints within avionic applications, as big capacitance typically indicates large volume. Within some applications, height is a critical parameter thus some special-purpose capacitors are required. While these most critical features have a major contribution on the component selection, other aspects such as reliability, parasitic values and required voltage stress need a profound analysis.

Transient suppressor is essential feature to protect the sensitive electronics from lightning strikes in avionic applications. While these devices are selected, important issues to cover are:

- Required threat level
- Applicable transient waveform
- Parameter conversion

Primary importance is to recognize the intended location and threat level due to their influence on the suppressor selection. Parameter conversion is required for the selection of the most suitable transient protection device based on the datasheet information.

5.2 Analysis procedure

Subsequent to the component selection, an important phase within the analysis procedure is to create adequate simulation models for the components. Hence, the most fundamental part of the system analysis, stability and proper system operation validation can be executed. This further contributes to a reduced design time and costs due to the possibility to discover the potential stability problems and design errors prior to the prototype implementation. Instructions for consistent operational system design are illustrated in Figure 5.7. In case a design error is discovered within the analysis, recommendations to solve the problem are given.

Component models

Prior to the analysis execution, simulation models for each commercial component are needed. Considering the proper system performance estimation, the most essential components, dc-dc converters and EMI filters are to be modeled according to Chapter 2.

The dc-dc converters can be configured for multiple system applications. These commercial components typically can operate at nominal or light load with standard or trimmed output voltage. However, the information provided in the datasheets regards the converter behavior at the nominal conditions, which is applicable for majority of applications. Hence, in case the power supply is utilized within an application with specific operational requirements, more accurate information of the converter behavior is required for the creation of better model. Therefore, further measurements regarding the converter behavior in particular operation condition is required.

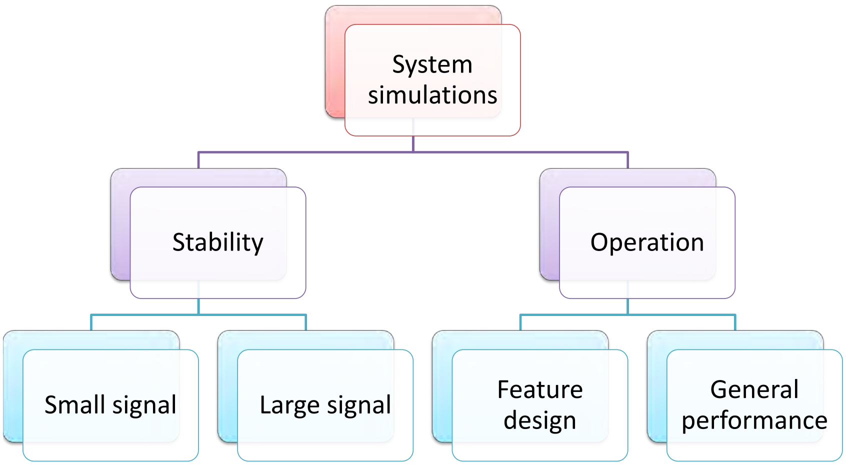

Figure 5.7: Recommended design procedure for consistent distributed power system analysis.

An example of the model parameter adjustments for a utilized power supply within the system is provided in Table 5.8. This improvement is carried out in order to better imitate the actual converter behavior in specific operation condition.

Datasheet provides an output voltage deviation during a load step from 50% to 100% for a power module of $V_{out} = 15V$ and $I_{out} = 8A$. Within the system, the utilized converter has the $I_{out,max} = 6A$ and a standard output voltage of 12V, which is trimmed to a voltage level of 10.5V. Thus, the datasheet information is not sufficient to create an accurate component model concerning transients. From the provided datasheet curve, the maximum voltage deviation is approximately 440mV whereas according to the measurements it is 650mV within the system.

Therefore, through the measurements improved models can be created in case the information within the datasheet is not accurate enough.

Parameter	Datasheet	Actual component
Output voltage	15V	10.5V With output voltage trimming
Maximum output current	8A	6A
Load step	Provided: 50% to 100% From 4A to 8A	Required: 0% to 100% From 0A to 6A
Vout deviation	Provided: 440mV	Measured: 650mV

Figure 5.8: Parameter comparison between datasheet values and actual system requirements.

Stability

Stability is a major concern in any electric power systems. Complex distributed power systems consists of various components introducing adverse interactions within the system and possibly causing instability. Stable operation is the most fundamental design issue and is a vital starting point to a comprehensive system analysis. Figure 5.9 describes the stability analysis procedure within the system design.

First two steps within the stability analysis are to create the component models for the dc-dc converters, through the provided information on the datasheet or measurements, and for the EMI filters through measurements. Thereafter, small signal stability, i.e. impedance interactions between the converter and the input filter, can be evaluated.

Contrary to local stability, large signal stability is a global design issue analyzed through system level simulations. The performable simulations depend on the implemented system specifications while estimating the potential instability sources. In case a potential stability problem is discovered at this phase, it is possible to solve it at the design level.

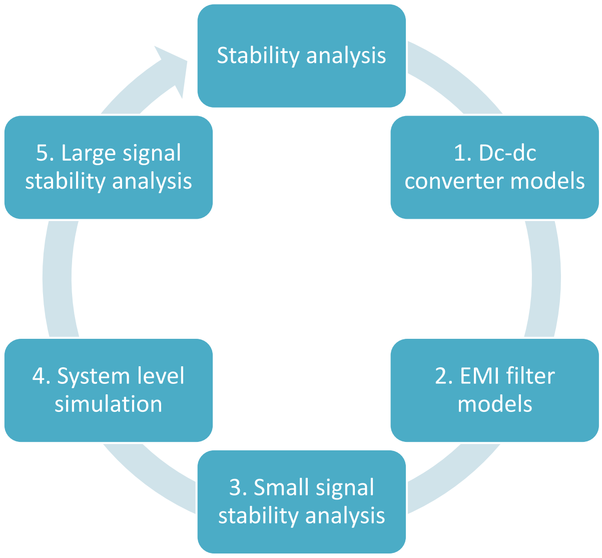

Figure 5.9: Stability analysis procedure.

Performance

Along with stable operation, equally important is the correct system performance according to its specification. Executing simulations as provided in Figure 5.10, proper operation under various conditions is estimated.

Recommendations are provided in case potential problems are discovered within the simulations. It should be emphasized that the simulations to be performed, depend on the applied system due to different operational features and specifications.

A significant advantage is the ability to execute comprehensive simulations concerning various operating conditions. Especially the analysis of worst-case situations is a significant asset. This reduces design costs considerably as it is possible to discover errors at the design stage rather than at the prototype phase. Subsequent to the systematic execution of the recommended simulations and validation of the proper system operation, a prototype can be implemented.

System feature	Simulation	Recommendation
Output voltage	15V	10.5V With output voltage trimming
Maximum output current	8A	6A
Load step	Provided: 50% to 100% From 4A to 8A	Required: 0% to 100% From 0A to 6A
Vout deviation	Provided: 440mV	Measured: 650mV

Figure 5.10: Power system features and recommended simulation analysis.

Chapter 6

Conclusions and Future Work

Analysis and simulation of dc distributed power system are explored comprehensively within this thesis. The obtained results are based on behavioral COTS component models enabling a profound system evaluation. The most fundamental design aspects, operation verification according to the specifications as well as the overall system stability, are investigated in detail. Utilizing this analysis procedure, faster time-to-market is obtained due to the ability to discover design errors prior to the prototype implementation.

Distributed power systems comprise of various components thus increasing the system complexity. Various adverse interactions between the components present design difficulties at the system level. This introduces multiple problems within the design complicating the overall analysis. The main objective of this thesis is to facilitate the design by providing comprehensive system analysis guidelines for a given architecture based on a designed power system for an avionic application.

The designed system is based on architecture presented in Figure 6.1. The system components are selected according to the recommendations provided within this thesis. A detailed modeling procedure for the main system components, dc-dc converters and EMI filters required for the simulations, is described. Thereafter, a profound operational analysis is executed verifying the stability as well as the performance characteristics. Local stability is verified by analyzing the impedance interactions between a dc-dc converter and EMI filter. The analysis is performed by utilizing simulations hence validating the global stability as well as proper system operation. A potential instability problem was discovered and solved prior to the prototype implementation. The theoretical system analysis and the simulated operation are verified in practice within the designed distributed power system for avionic application.

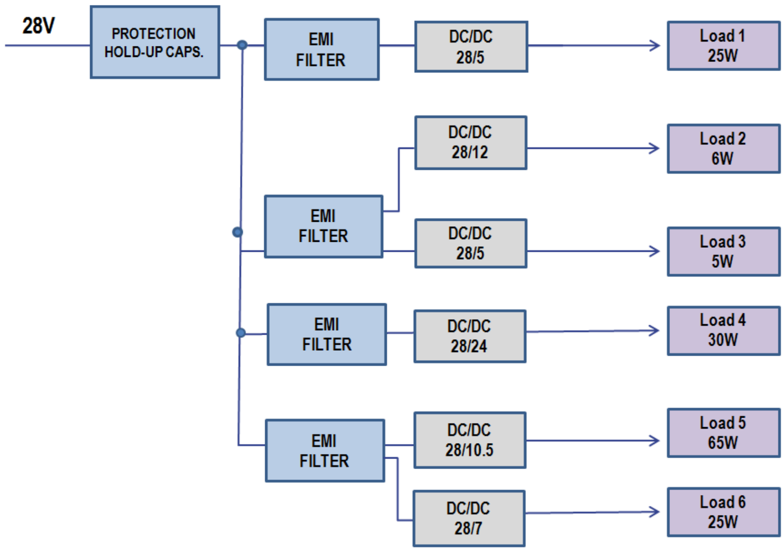

Figure 6.1: A block diagram of the designed distributed power system for avionic application.

Analysis guidelines for existing distributed power architectures are provided within this thesis, dividing the instructions into component selection and analysis procedure. Figure 6.2 concludes the recommendations and design methods based on the implemented system.

Primary importance lies on recognizing the relevant requirements for the applicable system. Based on these constraints, the system components are selected aiming to an optimized design solution. System level simulations are executed subsequent creating the component models. Significant asset with simulations is that the proper system operation can be verified prior to the prototype implementation. However, the final success of the designed system is verified through the prototype measurements.

The provided recommendations are generally applicable for the analysis of any given distributed power system architecture. However, the focus lies on the avionic application and its specifications and constraints. Therefore, it should be empha-

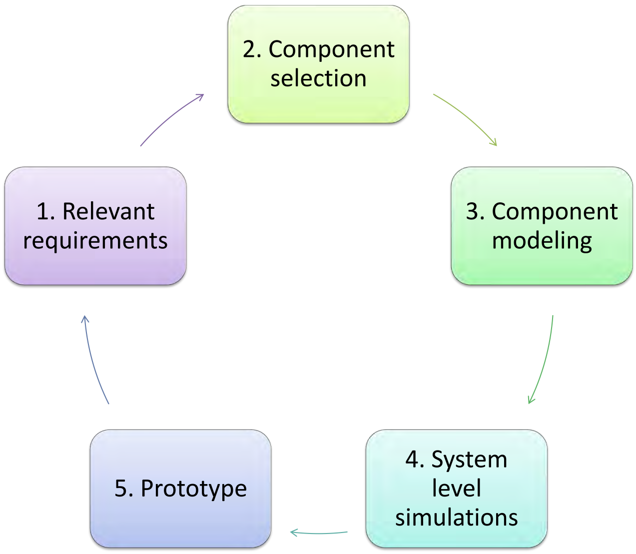

Figure 6.2: Concluded steps on the system analysis process.

sized that the origin of the component requirements is based on the relevant standards of the intended design.

Future work

Plenty of work exists on the analysis and deeper understanding of the distributed power systems. In order to better investigate and analyze the design, improvements and further model development concerning:

- System soft start characteristics
- Typical protection features of the commercial converters within the distributed power systems
- Remote on / off control of the dc-dc converters

is required. By including more features, improved models for special applications are developed in order to better evaluate the actual system behavior.

Further stability analysis concerning small and large signal stability has always a significant importance within the power system design. Especially regarding the global stability analysis, various interesting issues such as:

- Power up
- Power interrupts at the bus voltage
- Sequencing
- Soft start
- Load transients

are essential to be covered in detail. These features are typical operations within distributed power systems.

Main interest on the future work lies on optimizing the EMI filter solution. The analysis is initiated by designing a concentrated EMI filter as a comparison to the conventional approach. Various alternatives for the EMI filter placement exist. Interesting future work is to investigate these possibilities providing comparisons regarding different design parameters. Essential issues within the EMI optimization concerning:

- Stability
- EMI filter optimization within various system architectures
- EMI filter placement in case of parallel connected converters

Bibliography

[MIL, 2004a] (2004a). *MIL-STD-461F, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*. Department of Defense Interface standard.

[MIL, 2004b] (2004b). *MIL-STD-704F, Aircraft Electronic Power Characteristics,*. Department of Defense Interface standard.

[Brush, 2004] Brush, L. (2004). Distributed power architecture demand characteristics. volume 1, pages 342 – 345 Vol.1.

[Cho and Lee, 1985] Cho, B. and Lee, F. (1985). Modeling and analysis of spacecraft power systems. pages 523 –534.

[Cho and Lee, 1988] Cho, B. and Lee, F. (1988). Modeling and analysis of spacecraft power systems. *Power Electronics, IEEE Transactions on*, 3(1):44 –54.

[Emadi, 2004] Emadi, A. (2004). Modeling and analysis of multiconverter dc power electronic systems using the generalized state-space averaging method. *Industrial Electronics, IEEE Transactions on*, 51(3):661 – 668.

[Erickson and Maksimovic, 2000] Erickson, R. W. and Maksimovic, D. (2000). Fundamentals of power electronics, second edition.

[Gaia, 2010] Gaia (2010). October. http://www.gaia-converter.ca/.

[Interpoint, 2010] Interpoint (2010). http://www.interpoint.com.

[Luo, 2005] Luo, S. (2005). A review of distributed power systems part i: Dc distributed power system. *Aerospace and Electronic Systems Magazine, IEEE*, 20(8):5 –16.

[Mammano, 1993] Mammano, B. (1993). Distributed power systems. In *Unitrode Power Supply Design Seminar 1000. Unitrode Integrated Circuits.*

[Mel Clark,] Mel Clark, M. C. . S. Micronotetm 127, lightning protection for aircraft electrical power and data communication systems. http://www.microsemi.com/micnotes/127.pdf.

[Middlebrook, 1976] Middlebrook, R. (1976). Input filter considerations in design and application of switching regulators. pages 336 –382.

[Oliver et al., 2009] Oliver, J., Prieto, R., Cobos, J., Garcia, O., and Alou, P. (2009). Hybrid wiener-hammerstein structure for grey-box modeling of dc-dc converters. In *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*, pages 280 –285.

[Oliver et al., 2008] Oliver, J., Prieto, R., Laguna, L., and Cobos, J. (2008). Modeling and simulation requirements for the analysis and design of dc distributed power electronic systems. In *Power Electronics Congress, 2008. CIEP 2008. 11th IEEE International*, pages 204 –209.

[Oliver et al., 2006] Oliver, J., Prieto, R., Romero, V., and Cobos, J. (2006). Behavioral modeling of dc-dc converters for large-signal simulation of distributed power systems. In *Applied Power Electronics Conference and Exposition, 2006. APEC '06. Twenty-First Annual IEEE*, page 6 pp.

[Prieto et al., 2008] Prieto, R., Laguna, L., Oliver, J., and Cobos, J. (2008). A parameterization tool for power electronics design at system level. In *Power Electronics Congress, 2008. CIEP 2008. 11th IEEE International*, pages 210 –214.

[Prieto et al., 2009] Prieto, R., Laguna, L., Oliver, J., and Cobos, J. (2009). Dc/dc converter parametric models for system level simulation. In *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*, pages 292 –297.

[RTCA, 2004] RTCA, I. (2004). *RTCA/DO-160, Environmental Conditions and Test Procedures for Airborne Equipment.*

[Sanders et al., 1991] Sanders, S., Noworolski, J., Liu, X., and Verghese, G. (1991). Generalized averaging method for power conversion circuits. *Power Electronics, IEEE Transactions on*, 6(2):333 –340.

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División de Ingeniería Electrónica

ESCUELA TÉCNICA SUPERIOR DE INGENIEROS INDUSTRIALES
UNIVERSIDAD POLITÉCNICA DE MADRID

José Gutiérrez Abascal, 2. 28006 Madrid
Tel.: 91 336 3060 Fax: 91 561 8618
info.industriales@upm.es

www.industriales.upm.es