Power distribution in a 13 kW Three-Phase Rectifier system: Impact on weight, volume and efficiency

J.M. Molina, S. Zhao, M. Silva, J. A. Oliver, P. Alou , J. Torres , F. Arévalo , O. García, J.A. Cobos

Abstract—**This paper addresses the power delivery strategy on an aircraft application consisting on seven isolated DC loads to be supplied from the AC grid. Distributed or centralized power processing is evaluated taking into account weight and efficiency. Additionally, the rectifier switching frequency has to be synchronized with an external frequency clock to minimize the interference of the converter harmonics with the loads.**

I. INTRODUCTION

THE aerospace applications have recurrent requirements in parameters as volume, weight or efficiency. These requirements are constrained by the specifications of the system such as the electrical standards MIL-STD-704F, the EMC standard MIL-STD-461E, military derating in the components selection, and galvanic isolation.

The MIL-STD-461E is very restrictive in comparison with others standards for the EMI filter design in terms of frequency range. This standard is applicable from 10 kHz up to 10 MHz. The starting frequency is relatively low compared with the typical switching frequency of the actual rectifiers for applications under 10 kW [1]-[4], increasing the weight and volume of the EMI filter.

In aerospace applications, the optimization of the whole distributed power system, from the electrical generator to the loads, is a common practice [5] analyzing different architectures to optimize the system in terms of weight, volume, losses and reliability.

The system analyzed in this paper supplies seven independent and isolated loads. Different configurations, such as those shown in Figure 1 are analyzed. The configurations are selected to be modular. The effect of using several rectifiers or EMI filters in parallel is analyzed in the following sections.

In section II the requirements of the system are presented. Section III analyzes the system in order to find an optimum solution according to the number of channels in parallel. The EMI filter architecture is studied in section IV.

The experimental results of the power system designed as optimum for the requirements are presented in section V.

II. SPECIFICATION OF THE POWER SYSTEM

The specifications of the system are:

- Input Voltage: 115V RMS phase to neutral point
- Main frequency: 400 Hz
- Nominal Bus Voltage (Vo): 200 V
- Range of Bus Voltage (Vo): 180V to 250 V
- Rated output power: 13 kW (7 isolated loads)
- Comply with MIL-STD-704F
- Comply with MIL-STD-461E
- Military derating
- Galvanic isolation
- Ambient temperature: 70 ºC
- Switching Frequency externally synchronized

The military derating considered is: 70 % in diodes voltage, 75 % in transistor current, 70 % in transistor voltage and 110 ºC as maximum temperature.

To achieve galvanic isolation, the system is divided in two stages, a rectifier stage and a DC/DC stage with isolation. A three phase EMI filter is added at the input to comply with the Military standards. The isolated DC/DC stage used in this application can deliver a power of 2 kW, and it is based on a Phase Shift Full-Bridge [6]. The analysis of the DC/DC stage it is not the goal of this paper.

III. ANALYSIS OF THE NUMBER OF RECTIFIER CHANNELS

The impact of distributing the power in different channels compared with a centralized solution, from the rectifier point of view, is analyzed in this section.

In order to obtain a high power density and high efficiency, the three phase buck type rectifier (Figure 2) is selected [7]-[9].

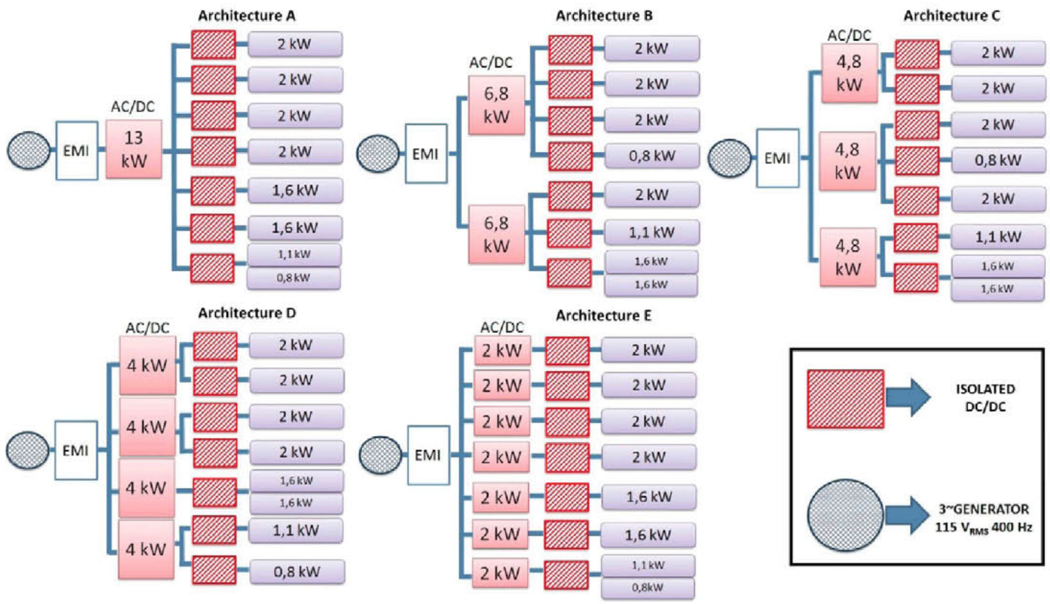

Figure 1. Distributed power solutions proposed for the rectifier

The first step to determine the number of channels is to select the switching frequency, which is conditioned by the synchronization frequency of the loads. The analysis presented in this paper considers two frequency ranges compatible with the load synchronization.

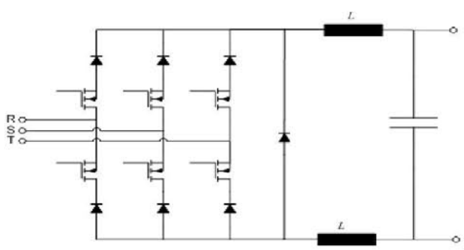

Figure 2. Three-Phase Buck type Rectifier

The rectifier has to operate synchronized in one of the two frequency ranges shown in Table 1.

	FREQUENCY RANGES		
	Min.	Nominal	Max.
LF	80 kHz	**105 kHz**	130 kHz
HF	160 kHz	**210 kHz**	260 kHz

Table 1. Frequency ranges

Figure 1 shows the configurations that have been analyzed, from 1 channel of 13 kW (Figure 1.a), to 7 channels of 2 kW (Figure 1.e), looking for modular solutions of the same rated of power. The analysis of the rectifier does not consider the EMI filter. For the five proposed distributed architectures, the power rating of the rectifiers for each configuration is equal, to simplify the manufacturability. In order to analyze the proposed architectures, weight, volume and efficiency are calculated for each one, and for both frequency ranges. The main differences in weight and volume are due to the inductors of the rectifier. Magnetic component design tool PExprt from ANSYS is used for the inductor design, considering 20% current ripple and the minimum frequency for each case (worst case). The losses in the inductors are calculated taking into account the conduction losses in the wires and the core losses with the simplified Steinmetz equation [10].

	a	b	c	d	e
LF	PM74/59	ETD59	ETD54	ETD54	ETD44
HF	PM74/59	ETD54	ETD49	ETD49	ETD39

Table 2. Rectifier cores depending on the frequency range and architecture

The inductor cores selected for each frequency range and architecture are shown in Table 2. The analysis has been done with ferrites from Ferroxcube [11] and the material selected is 3C92. Only architecture A maintains the same core for both analyzed frequency ranges, this is due to the reduced availability of cores for high power. The calculation of maximum temperature and losses are different. In the LF case the temperature is 105 ºC, and for the HF is 90ºC. The total losses in the inductors are 25 W in the LF case and 14 W for the HF case.

The losses in the semiconductors have been calculated with the equations in [12] for the maximum frequency (worst case). The estimation of the efficiency takes into account the losses in the magnetic components and semiconductors.

Figure 3 shows the results in terms of efficiency, weight and volume. Weight and volume are calculated taking into account the inductors, which is the main differential element among architectures. Low Frequency (LF) solutions (105 kHz) show 1% of variation among architectures in terms of efficiency (95% to 96%) and 40 % of variation in the weight (900 g to 1500 g). However, the High Frequency (HF) solutions (210 kHz) are lighter and smaller and the variation in terms of efficiency is less than 1%. In terms of weight, the variation between the HF architectures is 25%. The differences between LF and HF in the efficiency for the best case (Architecture E) are less than 0,4%. Furthermore, the HF architectures are lighter and smaller than the LF solutions. Therefore, the high frequency (HF) range (160 kHz-260 kHz) is selected. In the following discussion only HF range is considered. The weight of the architectures determine that E is the lightest, with small differences respect to A, B and C. In terms of efficiency C, D and E are similar, while B, C and E are the smallest based on volume. Emphasizing in weight, architecture E is selected.

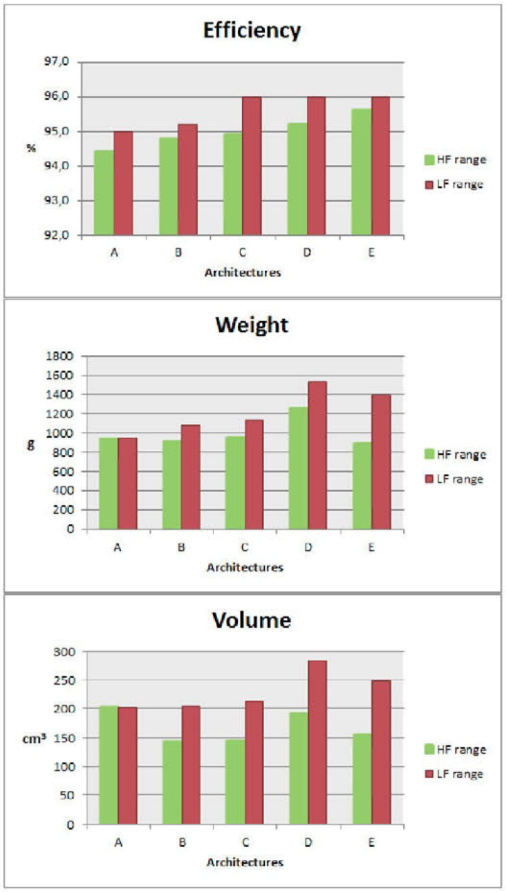

Figure 3. Efficiency, Weight and Volume calculation

IV. ANALYSIS OF THE EMI DISTRIBUTION

The EMI filter represents around 30% of the weight of the system [13]. Once the switching frequency range and the rectifier distribution are selected, three different architectures for the EMI filter are proposed in Figure 4. The selected structure is three differential mode stages and one common mode stage based on the analysis presented in [14]. Centralized Architecture (I) consists of a concentrate EMI filter. The partially distributed Architecture (II) has one differential mode stage for the whole system, and two differential mode stages and one common mode stage are distributed in each power channel. The distributed Architecture (III) presents three differential mode stages and one common mode stage for each power channel.

The current spectrum has been analyzed in order to determine the attenuation needed to comply with MIL-STD-461E. The loads are totally independent; consequently it is not possible to apply interleaving among the loads. The EMI has to be analyzed for the worst case when all the loads are demanding the maximum power at the same time.

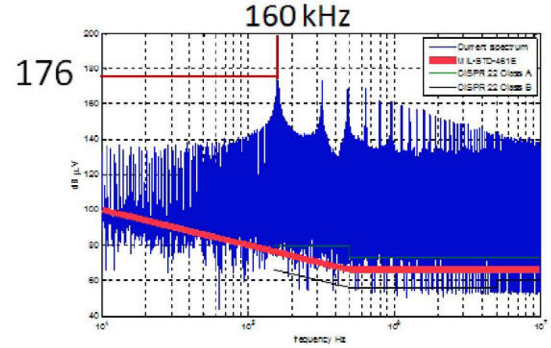

Figure 4. Simulation of the Current Spectrum at 13kW and switching frequency of 160 kHz.

The attenuation required for the whole system in the worst case (13 kW), without interleaving, to comply with MIL-STD-461E in the input of the system is 100 dBuV, based on the simulation carried out in PSIM (Figure 4).
Architecture I has to attenuate 100 dBuV at 160 kHz and the cut off frequency is calculated according to [8]. For Architectures II and III the attenuation necessary for each channel to comply with MIL-STD-461E in the input of the system, is calculated as shown in (1) since each channel will provide in the worst case $\frac{1}{n}$ of the total noise;

$$Att_{channel}(dBuV) = Att_{centralized}(dBuV) + 20\log(n) \quad (1)$$

Figure 5 shows how the MIL-STD-461E limit becomes stricter in the distributed filter for each channel.

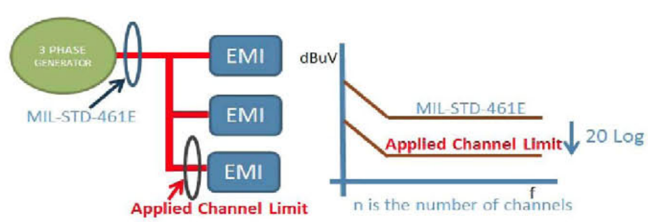

Figure 5. Design Limits in a distributed filter design

Figure 7 shows the results of the calculations for the weight in the EMI filter for the selected frequency range (160 kHz-260 kHz) for the three EMI architectures. The architecture selected is the distributed filter because it is the lightest.

This architecture has 7 distributed channels. The modularity of this solution enhances the reliability. In this Architecture III, the attenuation required for each channel is: 100 dBuV + 20 log (7) =117 dBuV. The three stages of the EMI filter (L=160 uH and C= 0.22uF in delta configuration) attenuate 120 dBuV at this frequency.

Figure 8 shows the schematic of the filter. EMI filter weight has been calculated taking account the core [15], the wires and the capacitors.

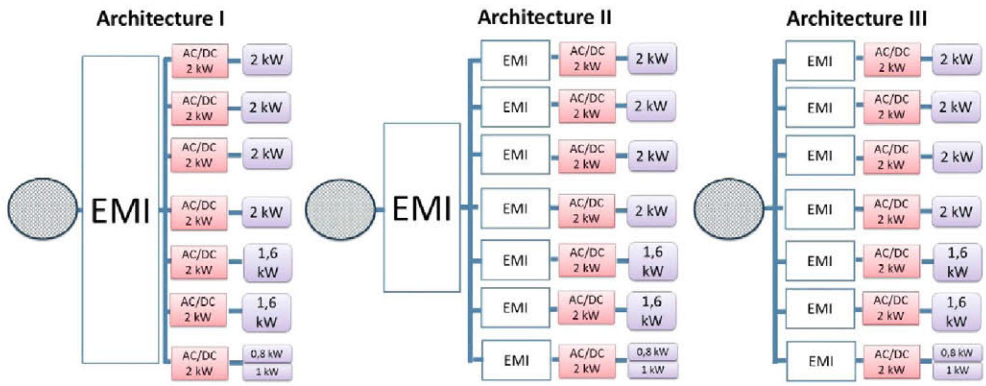

Figure 6. EMI ARCHITECTURES. I) Centralized II) Partially distributed III) Distributed

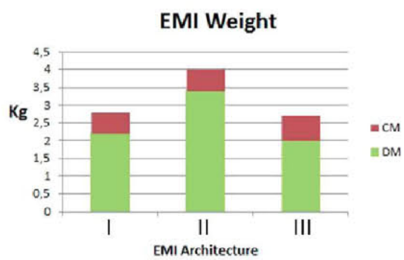

Figure 7. Weight for the EMI architectures.

V. EXPERIMENTAL RESULTS

A 2 kW three- phase buck type rectifier with EMI filter has been built in order to validate the selected architecture complying with the system specifications. The prototype is controlled at nominal frequency (210 kHz) with the DSP TMS320C28346. Figure 9 shows the prototype and the control. The EMI filter inductors have been built with the core 58585 from Magnetics [15], and the capacitor from EPCOS B32652A6. The EMI filter includes R-C parallel damping and R-L parallel damping. The calculated capacitive damping consists of a capacitor of 0.22uF and a resistance of 40 Ω. The inductive damping is calculated as 160 uF (a commercial SMD inductor is used) and resistance of 40 Ω.

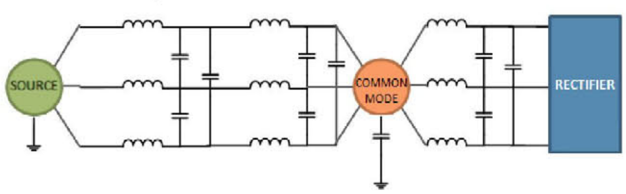

Figure 8. Schematic of the EMI filter

The current spectrum of the current without the filter is show in Figure 10. As it was expected, the system does not comply with the MIL-STD-461E, and the second, third, and fourth harmonics of the switching frequency are higher than the fundamental. This effect needs further investigation.

Figure 11 shows the current spectrum with the EMI filter complying with the standard. As it has been explained in section IV, in a distributed configuration, each channel should be attenuated at the switching frequency 20log(n) dBuV more than the centralized architecture to comply in the input of the whole system, with the seven rectifiers in parallel.

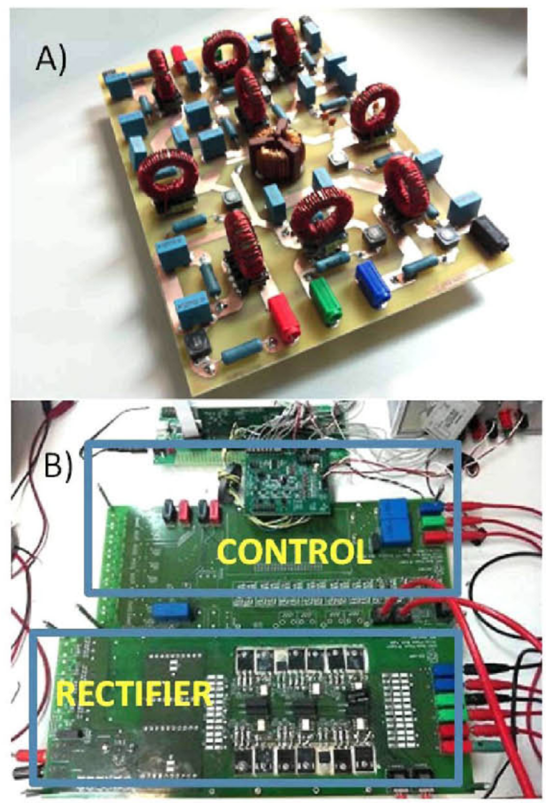

Figure 9. A) EMI filter prototype..B) Rectifier

Waveforms of the line to line input voltage and phase current of the rectifier with the EMI filter are shown in Figure 12. Figure 13 shows the current through the output inductor and the output voltage of the system working at 2 kW (Vin=115 V, Vo=205). The measured efficiency is 96% in agreement with the calculation in Figure 3. Figure 13 shows the phase current and phase voltage keeping a power factor of 95%.

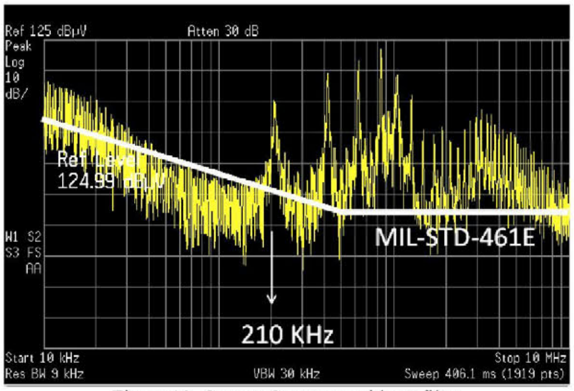

Figure 10. Current Spectrum without filter

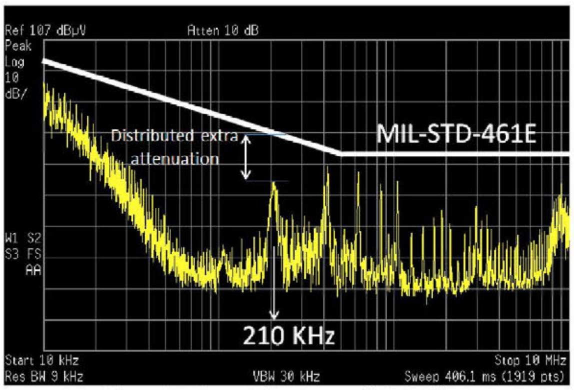

Figure 11. Current Spectrum with EMI filter

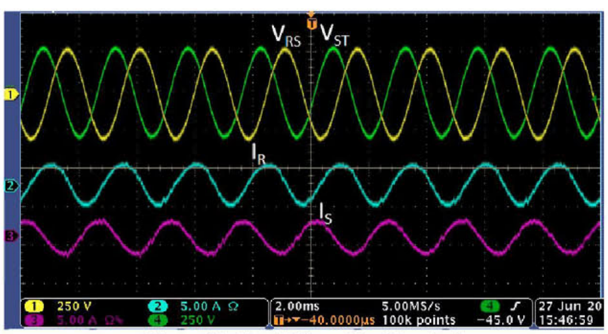

Figure 12. Line Voltage V_{RS}, V_{ST}, I_R, I_S

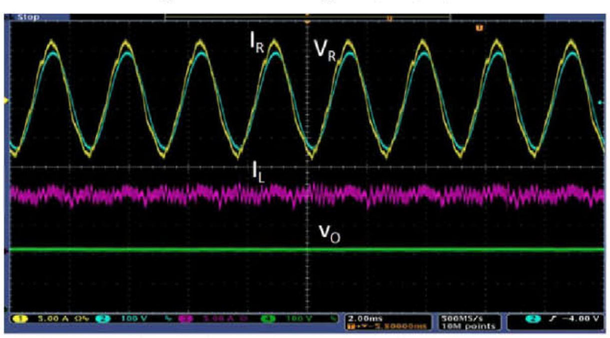

Figure 13. . Phase voltage and current. Inductor current (I_L). Output voltage(V_o)

VI. CONCLUSION

The impact of distributing the power in different channels for an AC/DC rectifier and EMI filter to supply independent and isolated loads is presented. The loads impose the switching frequency to the rectifiers and two different frequency ranges have been considered in the analysis. The frequency analysis of the rectifier shows that in this application, doubling the switching frequency improves weight in the high frequency range, and the differences in the efficiency are less than 1%. Therefore, high frequency range is selected. Five architectures for the rectifier have been analyzed. In terms of weight, volume and efficiency the architectures do not show significant differences, being Architecture E the best in terms of weight and efficiency. Consequently, Architecture E is selected with the advantage of the modularity, increasing the reliability of the system. Three architectures for the EMI filter have been analyzed in terms of weight and the distributed architecture (III) is selected. In addition, this architecture provides modularity thus increasing the reliability. Considerations for the attenuation required in the distributed filter are analyzed and applied. Prototypes for the EMI filter and rectifier are built and experimental results validate the presented analysis.

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