Interleaved Multi-Cell Isolated Three-Phase PWM Rectifier System for Aircraft Applications

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***Abstract*—Recently there has been an important increase in electric equipment, as well as, electric power demand in aircrafts applications. This prompts to the necessity of efficient, reliable, and low-weight converters, especially rectifiers from 115VAC to 270VDC because these voltages are used in power distribution. In order to obtain a high efficiency, in aircraft application where the derating in semiconductors is high, normally several semiconductors are used in parallel to decrease the conduction losses. However, this is in conflict with high reliability. To match both goal of high efficiency and reliability, this work proposes an interleaved multi-cell rectifier system, employing several converter cells in parallel instead of parallel-connected semiconductors. In this work a 10kW multi-cell isolated rectifier system where each cell is composed of a buck type rectifier and a full bridge DC-DC converter has been designed. The implemented system exhibits 91% of efficiency, high power density (10kW/10kg), low THD (2.5%), and n-1 fault tolerance which complies, with military aircraft standards.**

I. Introduction

During the last decade the More Electric Aircraft (MEA) concept has been gaining more and more relevance both in the industrial and military aircraft world [1]. This has been caused by the replacement of pneumatic, mechanic, and hydraulic actuators by electric actuators. With this change, the reliability of the system is increased and the maintenance is reduced. Furthermore, the losses in the energy conversion are minimized, causing an increment in the overall efficiency.

All these innovations have increased the demand of electrical power in airplanes, which has prompted the incorporation of a new level of distribution power in military aircrafts. The classical aircraft distribution is a three-phase grid with 115V at 400Hz and in direct current at 28VDC. The new high DC voltage distribution is 270VDC. The main benefit of using a high voltage is that it decreases the current level to 10 times lower than the traditional low voltage; hence, the section and the weight of the cabling is considerable reduced [2]–[6]

In a typical aircraft, power generators provide three phase grid of 115VAC. The simplest way to obtain 270VDC is using a diode bridge; however, in this way the total harmonics distortion of the grid current (THD_i) is around 30% [7], which is unacceptable in aircraft applications. In order, to obtain low THD, high power density, and control capability of the output voltage, an active rectifier needs to be used.

Within the active rectifiers there are two families, the buck type and the boost type [8]. Since the DC voltage obtained with a simple diode bridge on a three phase grid changes from 115VAC to 270VDC, it is not possible to obtain the same voltage with a buck or boost type active rectifier. With a buck type rectifier, the output voltage is lower than 240VDC and the boost type is higher than 290VDC. Hence, it is necessary to utilize a two stage topology by using either a three-phase buck type rectifier plus a DC-DC boost converter or a three-phase boost type rectifier plus a DC-DC buck converter. Both architectures are shown in fig 1(a).

In [9], [10] both topologies have been analyzed and compared. It has been shown that the buck plus boost configuration possesses advantages over the boost plus buck; such as: higher efficiency and power density. This is due in part to the fact that the output inductor of the buck stage and the input inductor of the boost stage can be integrated into one single component. In addition, the buck rectifier does not need a pre-charge circuit and this type of rectifier can reach very high efficiency [11]. The fig 1(b) shows the topology of the buck rectifier plus boost converter.

When isolation between AC and DC is a requirement, the isolation can be provide either with a low frequency heavy transformer in the input of the rectifier (fig 2(a)), or using smaller high frequency transformer that usually leads to a two stage solution by using an isolated DC-DC converter (fig 2(b). Despite the fact that the complexity of a two stage configuration is higher than a single stage converter, the weight in aircraft applications is the most important factor; thus, the most appropriate solution is using two converters in cascade.

In applications at relatively low frequency, decades of kHz, one way to obtain high efficiency is to increase the number of semiconductors in parallel in order to decrease the conduction losses [12]. For instance, in [11] an extremely high efficiency buck type rectifier has been presented employing six MOSFETs and six diodes in parallel. However, this amount of semiconductors has a negative effect on reliability because when one of theses semiconductors fails, the complete system can fail; thereby a configuration with many components in parallel is not recommended for aircraft applications.

To combine the need for many semiconductors to obtain high efficiency and the need for high reliability, the system can be separated into a number of individual converters in parallel of smaller power (Fig3), hereafter called converter cell. In this case if one semiconductor fails, only one of the cells

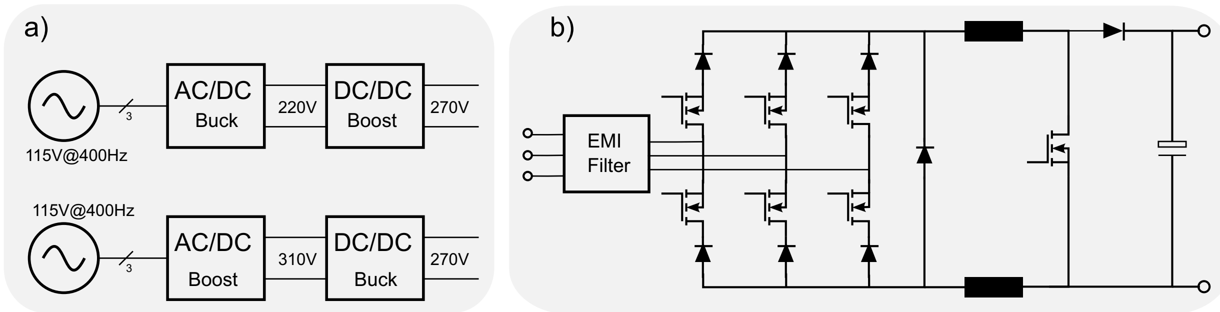

Figure 1. (a) Two-Stage Rectifier system. buck-type rectifier plus DC-DC boost converter, and boost-type rectifier plus DC-DC buck converter. (b) Three-phase Buck type Rectifier plus DC-DC boost Converter Topology

fails, and the rest of the system can still operate at lower power. In addition, using interleaving technics in a multi-cells configuration, both the input filter and the output filter effort is reduced leading to smaller volume and weight and therefore higher power density of the full system.

This work proposes an interleaved multi-cell isolated three-phase PWM rectifier system for aircraft applications. This topology allows high efficiency using multiple cells in parallel and high reliability with n-1 fault tolerance. In addition, this work shows an optimization process for the system in terms of number of cells, switching frequency, and weight of the system to obtain a good balance between all these features. Finally, a comparison between the isolated and a non-isolated configuration is performed to show the cost to pay in terms of losses and weight when the isolation is required.

II. Rectifier System Architecture

A. Specifications system

The isolated rectifier system presents in this work has been designed to comply with the following specifications:

- Input Voltage: 115V RMS phase to neutral point
- Main frequency: 400Hz
- Output Voltage: 250V to 280V where the nominal voltage is 270V
- Rated output power: 10kW
- Comply with MIL-STD-704F
- Comply with MIL-STD-461E
- Military derating
- forced air ventilation

The rectifier system is designed for aircraft applications. MIL-STD-704F is an aircraft standard related to the power quality and MIL-STD-461E is related to the electromagnetic interference. The military derating applies considers : an ambient temperature of 70°C, 70% in voltage diodes, 75% in transistor current, voltage and maximum junction temperature and 110°C maximum temperature in magnetics.

Additionally, these applications require a rectifier system with high efficiency, high power density and high reliability. These three characteristics are in generally opposing parameters between them. For instance, to obtain high efficiency normally is necessary to place semiconductor in parallel to decrease the conduction losses, but the higher is the number of components the lower is the reliability. In case of power density and efficiency, the higher is the switching frequency the higher are power losses and the lower is the weigh and volume in magnetic components.

One way to deal with high efficiency and reliability is instead to use several semiconductor in parallel, to use several smaller rectifiers or cells in parallel, thus when one component fail the fail cell is disabled and the system can still operate at rate of the nominal power. In addition, if in each cell the PWM carrier signal is phase shifted to achieve interleaved, the grig current spectrum is moved to $n \cdot f_{sw}$ where n is the number of cells and f_{sw} is the switching frequency, hence the input

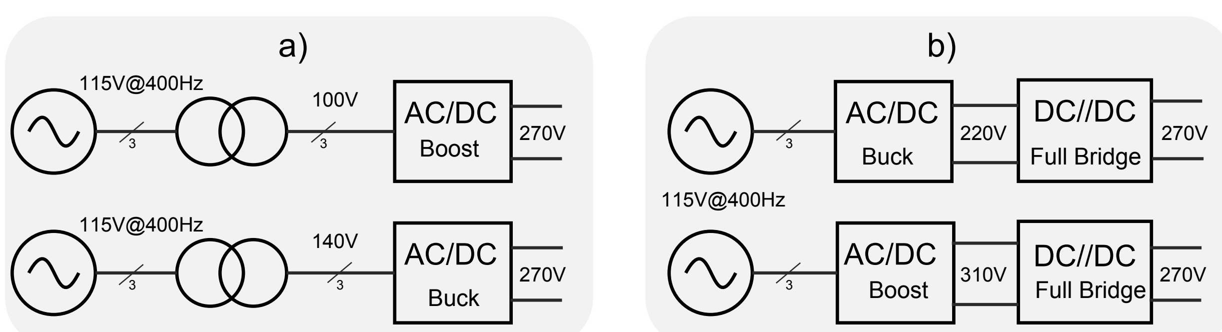

Figure 2. Isolated rectifier systems, (a) 400Hz transformer with an active rectifier. (b) Active rectifier with a DC-DC full bridge converter .

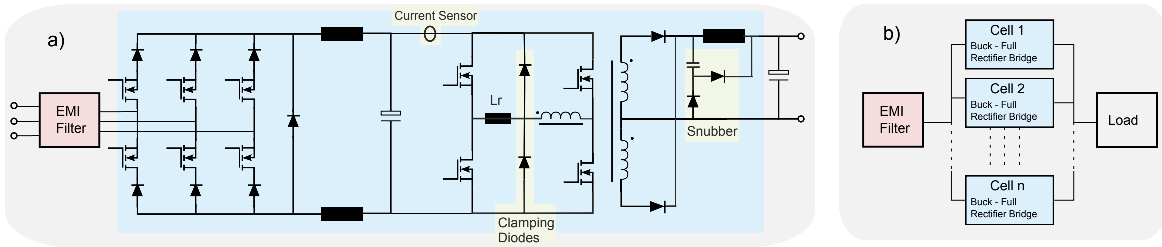

Figure 3. Interleaved multi-cell isolated rectifier system.(a) Buck type rectifier and DC-DC full bridge topology corresponding a one cell. (b) 10kW 3 cells rectifier system.

filter effort is reduced leading to a smaller EMI differential mode filter, and therefore smaller volume and weight.

Each cell of this multicell architecture is compose by a three phase buck-type rectifier and a DC-DC full bridge converter. While the EMI differential mode and common mode filter is unify in only one.

B. Topology Selection

1) Active Rectifier: The three phase buck-type rectifier (fig 1 b) is an appropriate unidirectional topology when a high power density and high efficiency are required. This current source converter has been presented in [13] and proposed for use in aircraft applications [14].

The main advantages of this topology are: it does not need a pre-charge circuit, it can still operated with power factor correction when one main phase fail [15] and it is easy to control. In the secondary stage there is controlled converter, the rectifier can be operated in open loop, just a two voltage sensor are needed for the main grid and without the necessity of any current sensor.

Different modulation methods for this rectifier have been studied in [16], [17], differences between these modulations are the ripple in the DC inductor and in the switching losses. In this work has been selected the modulation method 1 which has lower switching losses to obtain higher efficiency.

2) Isolated DC-DC Converter: For the second stage of this system, the Full Bridge Phase Shift (FBPS) topology has been selected. The Full Bridge is the most popular DC-DC converter topology for this power range of a few kilowatts [18]. The main requirements of this application are: galvanic isolation, high efficiency, high power density, zero voltage switching achievable, and high reliability. The FBPS can satisfy all these requirements.

The simple control is another feature of this converter. The most common control method in FBPS topology is the peak current mode control [19] since it is very fast and provides the capability of operating the converter as a current source. The current is measured at the input of the converter, as it is shown in fig 3(a)

In order to maintain a high efficiency and low EMI emission, it is important to achieve Zero Voltage Switching (ZVS) in the primary side MOSFETs over a wide load range [20]. Full Bridge converters can achieve ZVS at high power loads by using the leakage inductance of the transformer. To obtain ZVS at light loads an additional inductor (Lr) is needed [21].

During operation a resonance between the leakage inductance of the transformer and the parasitic capacitance of the rectifier diodes occurs, which causes an overvoltage oscillation across the rectifier diodes. To avoid this problem, two methods have been applied. The first one is to place two clamping diodes in the primary side, and the second is to placed a non-dissipative snubber in the secondary side (cf Fig 3 (a)).

III. Rectifier System Optimization

In order to simplify the overall optimization the complete system is divided in three parts: the EMI filter, the active rectifier, and the DC-DC converter. Each subsystem is optimized separately. The active rectifier and the DC-DC converter optimization considers: a database of available semiconductor components (MOSFETs and diodes), different switching frequencies, and the number of semiconductors in parallel. The EMI filter optimization considers a database of toroidal cores, wires, and capacitors. Each part of the system is optimized for one, two, and three cells in parallel. The aim of the optimization is to achieve a good tradeoff between power density, efficiency, and reliability of the whole rectifier system.

Table I
Summary table for Weight and losses estimated for 1, 2 and 3 cells configuration.

N° Cells	Element	Weight	Losses	MOSFETs	Diodes
1 Cell	Filter	4.3kg	79W	-	-
	AC-DC	1.54kg	470W	18	14
	DC-DC	5.3kg	241W	24	12
2 Cell	Filter	2.5kg	65W	-	-
	AC-DC	1.0kg	404W	24	14
	DC-DC	1.6kg	252W	32	12
3 Cell	Filter	2.9kg	38W	-	-
	AC-DC	1.04kg	400W	18	21
	DC-DC	1.4kg	256W	36	12

A. Buck Rectifier optimization

From of the point of view of the number of MOSFETs, for single cell configuration the minimum number of MOSFETs in parallel is three to decrease the conduction losses to comply with the derating temperature in transistors (112°C). In the same way for two cell configuration, at least two MOSFETs are required since the rectifier power, however, the global number of MOSFETs is higher than the single cell configuration. In the case of a three cell configurations, parallel MOSFETs are not needed what is positive from of the point of view of reliability; the total number of MOSFETs is lower than the two cell configuration and using three cells one failure tolerance is possible assuming a rate of the nominal power.

In terms of the power density, one cell configuration is 50% weigher than two and three. Two and three cells configuration provide practically the same weight in magnetics components leading the same power density. In addition according to the losses three cell configuration is lightly more efficient than two, and much more than single cell configuration.

According to the rectifier the best configuration is with tree cell, due to the number of semiconductors, reliability, power density and efficiency.

B. Full Bridge optimization

C. EMI filter optimization

The EMI filter is one of the most important system components, regarding weight and volume [22]. The interleaved operation of n individual converter cells results in an n times higher apparent switching frequency of the converter system in the conducted EMI spectrum [14] (cf Fig 4 for an example of three interleaved cells). This translates into a higher cutoff frequency of the input filter and therefore smaller and lighter filter components can be used. An optimization has been performed regarding the filter architecture which considered the number of filter stages as well as the possibility of distributing the filter among the individual converter cells or employing a single concentrated filter [23]. The resulting filter is a single concentrated filter with three differential mode filter stages including damping networks and two common-mode filter stages.

D. Global optimization results

The system optimization results in a one-failure-tolerant design with three converter cells in parallel, an expected efficiency of 92% and a weight of approximately 10kg.

IV. Experimental Results

In order to validate the design of the rectifier system, a 10kW three cells rectifier system has been designed. In Fig. 5(a) and 5(b), pictures of the active rectifier and the full bridge are shown. Both converters have been built on different PCBs to accelerate the prototyping process. In addition, a boost converter has been built to analyze and compare the power density and the efficiency of an isolated (Fig 3(a)) with a non isolated system (Fig 1(b)). The results of the comparison is going to be shown in the final paper.

The 10kW filter, three buck type rectifiers, and one full bridge have been built and test at nominal power of converters and under load steps. In Fig 7(a) and (b) negative and positive load steps of 2.3kW are shown respectively. The constant slope for the positive step (green line in Fig 7(b)) is given by a limitation of the electronic load used. Both steps have

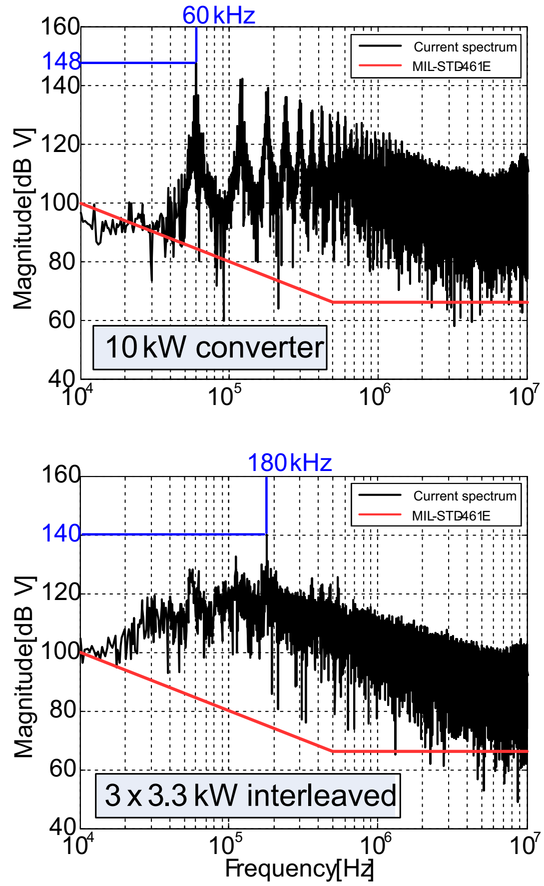

Figure 4. Input current spectrum of a single 10kW converter (left) and 3 interleaved converter systems of the same total power (right. One can see that the apparent switching frequency (coinciding with the most important peak in the frequency spectrum) is three times higher in the interleaved converter system (180kHz compared to 60kHz).

Table II
Selected components for rectifier, FBPS and Boost converter topologies.

System	Element	Device Description
AC-DC 60kHz	MOSFET	Si IPW60R041 600V CoolMOS
	Rec Diode	Si STTH30R04 Ultrafast recovery diode
	FW Diode	SiC C3D10060A Z-Rec Schottky
	L_{out}	126μH, core ETD49, gap 2.5mm, ETD3C90 10 parallel wires of 0.6mm diameter
	C_{out}	6x0.56μF Murata X7T 450V
	C_{in}	3x0.56μF Murata X7T 450V
FBPS 180kHz	MOSFET	Si IPW50R140CP 600V CoolMOS
	Clamp. Diode	SiC C2D20120D Schottky diode
	Snubb. Diode	Si VS-8ETU04PbF Ultrafast diode
	Rect. Diode	SiC C2D20120D Schottky diode
	Trafo	ETD59, N1/N2 = 5/11, Litz wire 400x0.07mm. N1 2 parallel wire
	L_{out}	60μH, core ETD49, gap 2.5mm, ETD3C90 2 parallel Litz wire of 200x0.07mm
	L_r	2.5μH, core E55, gap 2mm, ETD3C90 3 parallel Litz wire of 400x0.07mm
Boost 60kHz	MOSTEF	Si IPW50R140CP 600V CoolMOS
	Diode	SiC C3D10060A Z-Rec Schottky
	L_{in}	126μH, core ETD49, gap 2.5mm, ETD3C90 10 parallel wires of 0.6mm diameter

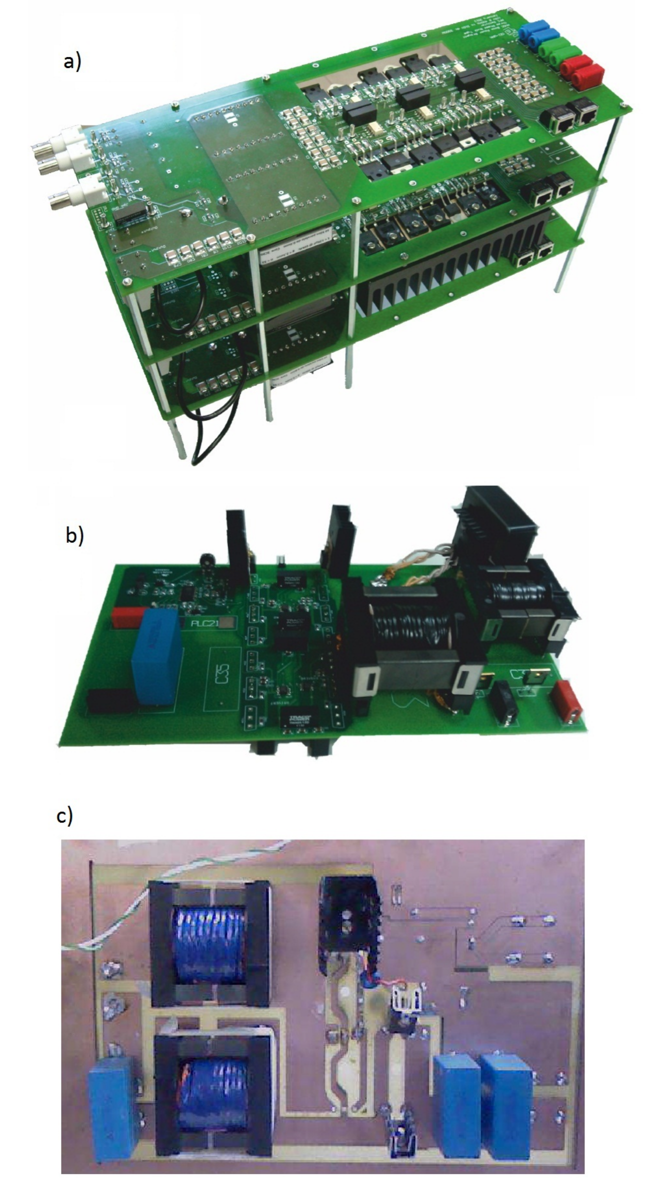

Figure 5. Pictures of the prototypes built. (a) Three 3.3kW rectifiers. (b) One 3.3kW Full bridge

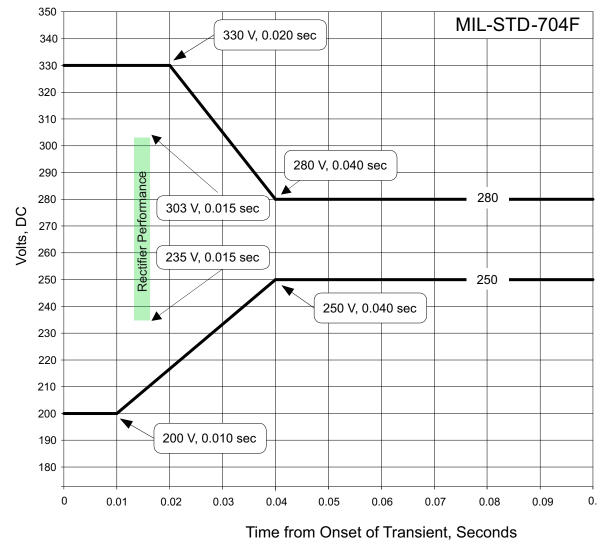

Figure 6. (a)Military standard 704F, envelope of normal voltage transient for 270 volts DC system.

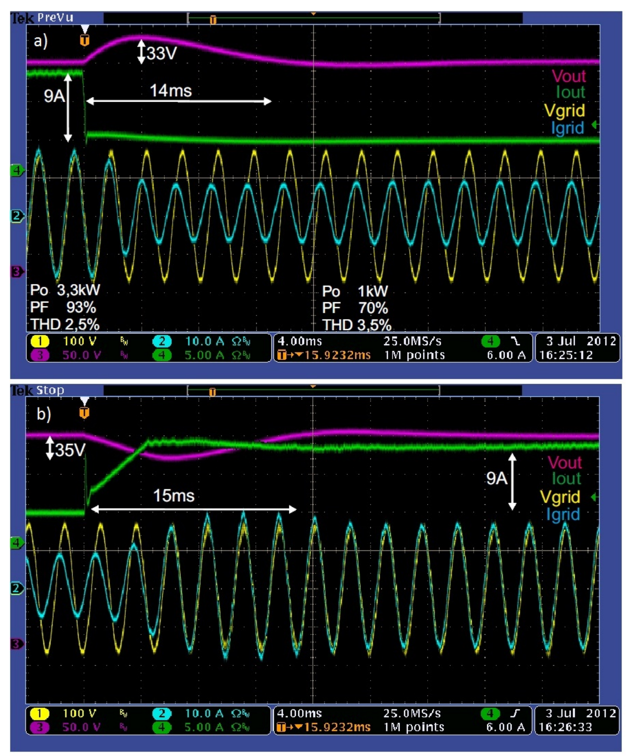

Figure 7. Experimental results for single cell, Power load steps using a constant power load (a)Negative power step from 3.3kW to 1kW. (b) Positive power step from 1kW to 3.3kW.

a voltage deviation around 35V and transients shorter than 15ms. The aircraft standard [24] permits up to 30ms transient for a deviation of 35V (Fig 8 (a)). The filter is designed to obtain a unitary power factor at 10kW, but as is can be seen in the experiential results Fig 7(a) and 7(b), at a third of the nominal power it is 93%. The limit for the THD_i is 5%; at full power it is 2.5% and during the whole power range it is lower than 4%.

The fig 8(b) shows the efficiency of the active rectifier and the DC-DC. The efficiency of one cell at full power is 91.6% corresponding to 96.5% for active rectifier and 95.0% for the DC-DC converter. The voltage derating in aircraft applications need to be 75% for all semiconductors, which heavily penalizes the efficiency of the system.

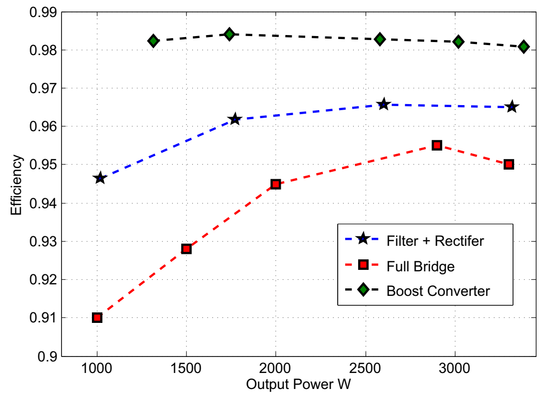

Figure 8. (a)Military standard 704F, envelope of normal voltage transient for 270 volts DC system. (b)Efficiency of the rectifier and the DC-DC from 1kW to 3.3kW

V. Conclusions

Aircraft applications require power converters with high efficiency, power density, and reliability. These are opposing requirements since high efficiency normally requires many semiconductors connected in parallel, resulting in low reliability.

This paper presents a three phase 10kW rectifier composed of three independent cells. Each cell is composed of three phase rectifier and DC-DC converter with isolation, while the EMI filter is common for all three cells. The size/weight of the filter is drastically reduce due to employed interleaving technic. Normally high efficiency is obtained by placing several semiconductor components in parallel. However this reduces the reliability of the system. A multi-cell approach enables high efficiency and high reliability at the same time. High efficiency is obtained by employing highly optimize low power cells. In the case of a failure of one semiconductor component the system can still provide power to the load by switching off the cell with the failure (supplying 66% of the full load). The implemented prototype has 91% of efficiency and 2.5% of THD_i at full power. The total weight of the rectifier system is, approximately, 10kg. The obtained power density and efficiency are heavily influenced by the military standard that has to be fulfilled.

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