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# Power Conversion for a Novel AC/DC Aircraft Electrical Distribution System

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**Abstract: This paper proposes a novel and compact AC/DC electrical distribution system for new generation aircraft. In these new aircraft power systems, all loads are fed by two dc bus systems: at 28V and at +/-270V. The electrical distribution system, whose design and implementation are described in this paper, has only one primary AC source (360-900Hz at 230V) with all the required dc voltage levels being derived from this source. This solution enables elimination of the complex mechanical coupling apparatus currently used, for fixed frequency AC systems, to maintain the generator speed at constant level while the engines operate at variable speed. Under the proposed solution, all conversion stages needed to generate the various output voltage levels are implemented using power converters assembled in one unit. Each converter has a current control loop in order to regulate the output current even during output line short circuits and also to limit the inrush current to the circuit at turn-on. To prove the concept a 5 kW prototype was designed and tested, and demonstrated to meet all the specifications within relevant standards regarding input and output power quality.**

**Index Terms: 3-phase buck-type PWM rectifier, DC/DC converter, Multiple DC Network**

## 1. Introduction

Modern aircraft employ an increasing amount of electrical power in place of hydraulic, pneumatic and mechanical power. This has led to the massively increased use of power converters and electrical drives for different on board applications. In fact within the so called More Electric Aircraft (MEA) approach, electrical power is employed for primary and secondary systems, including flight surface actuators, de-icing, flight control, passenger entertainment, cabin air conditioning and engine start. The engine control has also significantly changed, removing the necessity for many hydraulic systems and the bleed air system; thus the MEA will be a lighter and more efficient airplane, resulting in energy and fuel saving, higher reliability and reduced running costs [1]-[4]. To meet the requirements, it is becoming vital to produce lighter, more efficient and more reliable power converters to be installed on board.

Figure 1a shows the state of the art of a modern aircraft AC/DC distribution system. The primary source to generate the 28Vdc power line is the 3 phase AC source1 (115V at fixed frequency 400Hz). A Transformer Rectifier Unit (TRU) generates the 28Vdc. During extreme emergency situations the power source becomes the ram air turbine

(RAT) generator. Figure 1 also shows the presence of a backup battery system and its associated battery charger fed by the same AC source 1. The high voltage DC power line (HVDC), with a nominal voltage of +/270V can be supplied by two different power sources according to design choices: either a high voltage DC generator or an Auto transformer Rectifier Unit (ATRU) powered by AC source 2. This high voltage AC source (HVAC) is 230Vphase to neutral in Variable Speed Variable Frequency (VSVF) systems, with a frequency variation between 360-900Hz.

This paper proposes a novel AC/DC aircraft distribution system, whose structure is shown in figure 1-b. The main differences of the proposed scheme, compared to the traditional one are:

- The main input source is the VSVF (variable speed, variable frequency) AC generator at high voltage (HVAC); there is no need for a 400Hz-115Vac generator.

- The TRU and ATRU (that normally work in a low frequency range <1KHZ with bulky magnetics) are eliminated. Their functions are replaced by isolated DC/DC converter(s) with high frequency transformers (usually within the range 20kHz-100kHz)

All isolated DC/DC converters in the scheme are fed by the output voltage of the AC/DC buck rectifier, at a rated value of 400V [5]-[6]-[7]. Each DC/DC converter includes current control, in order to regulate and limit the output current in all operating conditions (including implementing output $I^2t$ protection).

In this study a prototype of the proposed distribution system has been designed, assembled and tested with all components shown in figure 1-b, with the exception of the battery storage system. The power level is around 5kW and the system features three different DC outputs: two at 28V and 20A (called V1 and V2) and one at +/- 270V at 6 A (called V3). The prototype is shown in figure 2, where it is possible to identify the different elements:

1) The 3-phase PWM buck-type rectifier
2) The main dc link  capacitor (at 400V)
3) The first DC/DC converter from 400V to 28V, 15A (V1)
4) The second DC/DC converter from 400V to 28V, 15A (V2)
5) The DC/DC converter from 400V to +/- 270V, 5A (V3)
6) The digital control unit for all power electronics systems

All outputs have been designed for an overload capability of 30%.

The remainder of this paper describes the design and implementation of the individual power conversion blocks and the comprehensive experimental results obtained. Control strategies for the individual converters are described. Stability analysis of complete DC networks is considered beyond the scope of the paper and has been widely discussed elsewhere, for example [8].

## 2. Description of the system

### 2.1 The 3-phase buck-type PWM rectifier

The circuit of a 3-phase buck-type PWM rectifier [9]-[19] is shown in figure 3. The main characteristics of this converter can be summarised as follows:

- The maximum output voltage is equal to 86.6% of the input phase-to-phase voltage.
- It is capable of achieving almost sinusoidal input currents with the use of a small input filter designed to remove switching harmonic components.
- Capability to control the input power factor (under some limitations relative to the maximum output voltage).
- It does not need any pre-charge circuit.

In recent years this converter topology has generated substantial attention from industry and the research community for aircraft applications particularly for its high reliability [9], [17].

Another important advantage of this topology for aircraft applications is its low weight [9]: the main input filter is not designed to store any bulk energy, but only to filter the switching harmonics, while the output filter can be designed according to different criteria: filtering the switching harmonics (in which case it can be very small) or it can be used to store a sufficient amount of energy to maintain the quality of the output voltage during faults and/or interruption of the input voltage.

In order to meet aerospace power quality standards for the input current and at the same time maintain a reduced size of the input filter, the switching frequency must be chosen as high as possible [19]. This is made possible by using SiC MOSFETs instead of traditional IGBTs without compromising the converter efficiency. The parameters of the input and output filters together with the devices used are listed in Table I.

**2.2 The 400-28V DC/DC converter**

To generate the 28V dc bus voltage, traditional DC/DC converters with transformer isolation (see figure 4) are used [20]. The input stage is represented by a half bridge configuration followed by an isolated centre-tap transformer; the output is a synchronous rectifier using low voltage MOSFETs with a very low drain source resistance $R_{DS}$ to minimize the conduction losses. Hard switching is employed in order to be able to control the output current and voltage in all load situations, from open circuit to short circuit. The switches used on the input half bridge are standard Si MOSFETs rated at 600V, due to the fact that the input voltage is stabilised at 400V. All parameters associated with the input and output filters and the devices are summarized in Table II.

**2.3 The +/-270 DC/DC converter**

In order to power the +/- 270Vdc bus the design choice was to use a standard DC/DC converter with galvanic isolation (Fig. 5) [20] instead of a 3-phase buck rectifier with an integrated boost converter. Even if the latter solution has very good performance in terms of efficiency [13]-[14], in the case of a fault on the load side of the +/-270 dc bus, all other DC outputs would be significantly affected. If a DC/DC converter with galvanic isolation is used instead, it is possible to disable the converter without any extra electronics or mechanical devices.

The input stage employs a full bridge using MOSFETs rated at 600V. In order to attain the required power rating while using ETD transformer cores (for construction simplicity), two transformers were used. Due to the fact that this transformer needs to operate with high voltage rather than high current, it was decided to use two transformers in series. The output rectifier stage uses a SiC diode bridge to avoid recovery losses. In this case the use of synchronous rectification is not desirable because the $R_{DS}$ of high voltage SiC MOSFETs is considerably higher than that of the Si MOSFETs used in the 28V DC/DC converter. Therefore the conduction losses would be similar to that obtained using SiC diodes in parallel. In addition, using SiC diodes avoides the recovery losses that are present in the body diode (Si) of the SiC MOSFETs. This DC/DC converter uses hard switching commutation in order to ensure control of output current and voltage in all load situations. All parameters of the input/output filters and devices are listed in Table III.

**2.4 Control of the converters**

The prototype was implemented using a single control platform; however the control of each unit (the active rectifier and the 3 DC/DC isolated converters) has been implemented separately and is independent. The main task of the 3-phase buck-type PWM rectifier is to control the DC voltage across the main dc link capacitor C8 (figure 3); to do so the converter control system implements a cascade voltage-current loop.

- the external loop is a PI-based voltage control with the voltage feedback signal measured across C8 (figure 8)
- The internal current loop is implemented using a second order controller with plant pole-zero cancellation. The current sensor measures the current flowing through L3 (figure 8)

Full details about the control of the 3-phase buck-type PWM rectifier are reported in [18].

The converter control system for the three DC/DC isolated converters implements a simple cascade voltage –current loop as shown in figure 6:

- the external loop is a PI-based voltage control with output voltage feedback
- the internal loop is a PI-based current control (the current sensor for the 28V scheme is a shunt resistor (see figure 4), while the current sensor for the 540Vdc scheme is located on L6 (see figure 5)

The performance of the control system is shown in detail in figure 7, which depicts experimental results with data recorded by the control platform with a sampling time of 50us. Figure 7a shows the turn on sequence of each dc/dc power converter, while part b) shows the behavior of the low voltage converter when the high voltage one is turned off. It is clear that the 28V rail remains inside the limit line when there are large step loads on the V3 output.

## 3. Experimental results

### 3.1 AC input power quality

Figure 8 shows oscilloscope traces of the AC input line current and line voltage at the rated power condition, when the input frequency is 900 Hz. It clear that the voltage and current are almost in phase: more details regarding power factor values are reported in Table IV. Figure 8b show the spectrum of the line current and figure 8c presents a zoom of figure 8b at lower frequencies, highlighting that the designed system fulfils the aircraft standards specification.

### 3.2 28V DC output power quality

Figure 9 shows oscilloscope traces of the voltage and current at the output of the 28V dc/dc converter, while figure 9b shows the spectrum of the output voltage plotted with the standard limits, highlighting that this part of the designed system also fulfils the aircraft standards specification.

### 3.3 The +/-270V DC output power quality

Figure 10 shows the input current and input voltage of the transformer. Figure 11a shows oscilloscope traces of the positive and negative voltage (+/-270), the differential voltage (540V) and the output current for the +/-270V high voltage DC/DC power converter. Figure 11b shows the spectrum of the differential output voltage plotted with its standards limit; figure 11c show the spectrum of the common mode voltage plotted against the standards limit while figure 11d presents a zoom of Figure 11c on the vertical axis. Both differential and common mode voltage largely fulfill the aircraft standards specification.

### 3.4 $I^2t$ protection for all DC outputs

All DC/DC converters in the proposed distribution system are equipped with $i^2t$ protection at the output. In this implementation, when a short circuit occurs, each single converter control will limit its output current to a fixed value (4 times rated for the low voltage converters and 5 times rated for the high voltage converter) until the computation of $I^2t$ reaches its limit, when the converter is disabled. Figure 12a shows the behavior of the high voltage DC/DC converter during a short circuit, while figure 12b shows the behavior of the low voltage dc/dc converter during a short circuit. This data was recorded by the control unit with a sampling time of 50μs. When the short circuit occurs, the control system has some difficulty to maintain the current level to a fixed value; this is due to two specific factors, firstly there is a limitation due to the controller bandwidth and secondly the short circuit was generated using a standard contactor which has “bounce” and creates some ringing effects.

### 3.6 Efficiency of the whole distribution system

The efficiency of the proposed AC/DC distribution system was measured using two power analyzers (PPA2530), one placed at the input and the second one at the output of the system. Table IV summarizes the measured characteristics of the distribution system under different load conditions and also at different input frequencies. In all tests the power factor is almost equal to 1 and the total efficiency is between 91-93 %. Table V shows the efficiency for the 3-phase buck-type rectifier when the dc output voltage reference has been set to 390V. At low power levels, in order to maintain unity power factor operation, the dc output voltage has been limited so as to compensate the high reactive power of the input capacitor due to the high input frequency [19]. The efficiency of the 3-phase buck-type rectifier including input and output filters is around 96.2%; this means that the high voltage DC/DC converter has an estimated efficiency of around 96.7%, and the low voltage DC/DC converter has an efficiency of around 94%.

## 4. Discussion

The experimental investigation carried out in this paper has demonstrated that it is possible to use an integrated power electronics based solution for an AC/DC distribution system in aircraft applications. At the input (AC) the proposed conversion unit exhibits unity power factor operation for almost all operating conditions, well within the standard limits. The input current has a very high quality with its entire harmonic spectrum up to 150kHz (EMC frequencies were not considered in this study) within aircraft standards specifications; this result was achieved due to the use of high voltage SiC MOSFETs presenting very low switching losses. In addition all DC outputs feature a power quality within the aircraft standards specifications. The DC/DC converters are also easy to control and it is possible to regulate the output current during short circuits with the implemented $i^2t$ protection. Thanks to the configuration of the DC/DC converters with an isolation transformer, the common mode voltage does not contain any harmonics of the supply frequency; however this is not the only advantage given by the galvanic isolation. The more significant advantage is that if a fault occurs on the load side of each single converter, it is possible to disable that particular converter without any extra electronics or mechanical devices, while the DC bus at 400V will still be available to feed the other DC outputs.

Another significant advantage of the proposed distribution system, over a fixed frequency AC generation system, is that it enables the elimination of complex mechanical coupling apparatus currently used to maintain the generator speed at a constant level, while the engines are operated at variable speed. In this way the presence of the TRU and ATRU (that normally work at low frequency <1k Hz) is avoided.

The total efficiency of 91-93% measured during the experimental tests is not particularly high. However there is considerable scop to improve this, since it is possible to increase the efficiency of the power electronic systems by increasing the number of MOSFETs and SiC diodes in parallel to reduce conduction losses [5]. It is also possible to reduce the losses of the passive elements, such as inductors and transformers, through an optimisation including efficiency size and weight, all of which are important targets in aircraft applications.

## 5. Conclusions

This paper has presented a novel compact AC/DC electrical distribution system for new generation aircraft featuring two dc buses at 28V and at +/-270V. The proposed distribution system only has one primary AC source (360-900Hz at 230V), while all the required dc voltage levels are derived from this primary source. All conversion stages needed to generate the various output voltage levels are implemented using power converters assembled in one unit. Experimental results obtained from a 5 kW prototype, demonstrates that all the aircraft standard specifications regarding input and output power quality are met.

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