Application and Challenges of Power Electronics for Variable Frequency Electric Power System of More Electric Aircraft

Shanshan Wu[1], Yongdong Li[2]
[1] Electrical System Department, Shanghai Aircraft Design and Research Institute
[2] Electrical Engineering Department, Tsinghua University
E-mail: wushanshan@comac.cc, liyd@tsinghua.edu.cn

Abstract — The use of electric power is increasing in more electric aircraft (MEA). On-board constant frequency (CF) AC electric power system (EPS) can not provide enough power for MEA increasing electric loads. As a result, EPS of MEA is moving from CF AC to variable frequency (VF) AC systems. Typical CF and VF EPS architectures are presented and compared. The application of power electronics in aircraft EPS is presented. New requirements and challenges for the design of power electronics equipments on VF EPS of MEA are also discussed.

I. Introduction

Today, the primary electric power in most large commercial aircraft is provided by 3-phase 115VAC power at 400Hz constant frequency. The CF AC power is generated by constant speed regulated generators. In these aircraft, subsystems are driven by a combination of mechanical, electrical, hydraulic, and pneumatic systems. Although the conventional aircraft using CF EPS is mature and widely used, different driven sources making the aircraft architecture is very complex and the efficiency is low.

In order to avoid the disadvantages of the conventional aircraft, the concept of MEA is proposed [1]. In MEA, more and more subsystems are driven by electric power. Some loads considered are: flight control systems, electric anti-icing, electric actuated breakers, electromagnetic valve control, air-conditioning system, utility actuators, fuel pumps, and hydraulic pumps [2]. MEA not only reduces the complex of the aircraft, but also enhances the reliability, fault-tolerance, power density and performance. Recent development in the areas of power electronics, electric drives, control electronics, and microprocessors are already providing the impetus to improve the performance of aircraft electrical systems and their reliability. As a result, the MEA concept is seen as the direction of aircraft power system technology.

In MEA, the use of electric power is increasing dramatically. The capacity of the CF generators can not satisfy the increasing power needs because of mechanical restrictions. On the other hand, the CF electric power system is not optimized for many AC loads, such as AC motors that need adjustable-frequency excitation to obtain the desirable speed or torque [3]. For these reasons, many large commercial aircraft, for example B787, A380, etc. are using VF EPS on board. The VF EPS operates with a variable frequency range over a typical range of 360Hz to 800Hz which varies with the engine speed [4]. The change of CF EPS to VF EPS offers many benefits to the aircraft, such as reducing the weight, requiring less maintenance, having lower spare costs and improving the reliability.

The change of primary electric power from CF to VF also induces some changes on EPS configuration. In the conventional aircraft with CF EPS, only single type AC/DC converter and DC/AC inverter are needed. In VF EPS of MEA, multi-voltage level hybrid AC and DC systems are employed. It consequently becomes necessary to employ not only converters which convert electric power from one form to another, but also converters which convert the power supply to a higher or lower voltage level [2]. As a result, in VF EPS of MEA, different kinds of power electronics converters, such as AC/DC rectifier, DC/AC inverter, and DC/DC choppers, are required [2]. Therefore, VF EPS of MEA is mainly in the form of multi-converter power electronics system. For example, B787 EPS uses different power electronic converters to convert 235VAC to 115VAC, ±270VDC and 28VDC to supply power for different AC and DC loads.

The application of power electronics equipments, such as converters, power factor compensators, etc. in VF EPS induces some challenges for power electronics. The existing conventional power electronics equipments developed for industrial applications are not optimized for aircraft applications. They generate harmonics on the power bus, which can not meet the harmonic requirements in the airborne electrical system environmental standards DO-160 and ISO-1540. They also carry size and weight penalties. Therefore, the new power electronics equipments become an essential technology supporting a VF EPS of MEA.

This paper presents a typical CF and VF EPS architecture on aircraft. The application of power electronics on aircraft is presented. New requirements and challenges for power electronics equipments in VF EPS of MEA are also discussed.

II. EPS Architecture

A. CF EPS Architecture

The primary electric power of a traditional CF EPS is usually a 400Hz, 115VAC power which is generated by constant frequency generator (CFG). The frequency of the AC power on board is constant and does not vary as the changing engine speed. One channel of a typical CF EPS architecture is showed in Fig. 1.

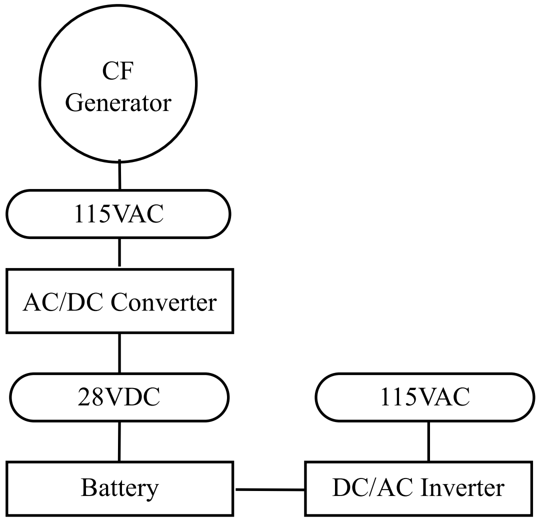

Fig. 1. CF EPS Architecture (one channel)

It can be seen that, the CFG generates CF AC power for the AC loads. Then, TRU converters 115VAC power to 28VDC power for the DC loads. The CF EPS architecture is very simple that it contains only two types of power and only AC/DC converters are used. However, the 400Hz, 115VAC CF power is not the optimized power input for some AC loads, especially the AC pumps. Also, the power loss on the wire is significant because of the low voltage.

B. *VF EPS Architecture*

The primary electric power of VF EPS is generated by variable frequency generator (VFG). The frequency of the AC power will vary in proportion to the changing engine speed. One channel of VF EPS example architecture is showed in Fig. 2.

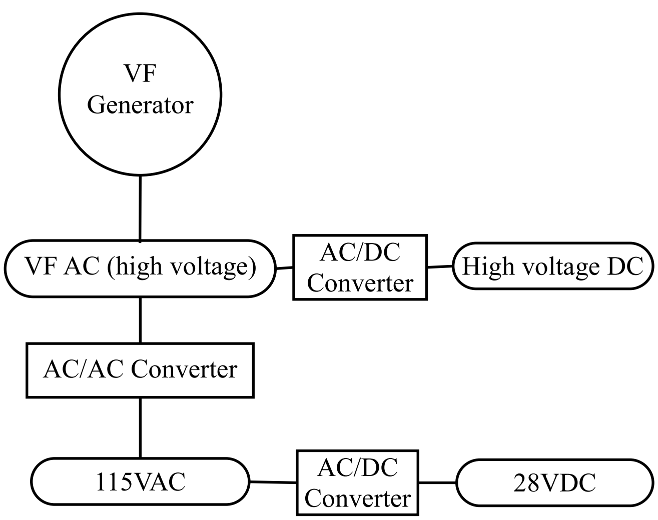

Fig. 2. VF EPS Architecture (one channel)

It can be seen that, the VFG generates high voltage VF AC power first. Then, different power electronic converters are used to receive low voltage AC power and DC power. These powers will be applied to the suitable loads to obtain the best performance and efficiency.

III. Power Electronics Applications In Aircraft EPS

A. *Converters in CF EPS*

In conventional CF EPS, AC/DC converter and DC/AC inverter are used to convert between 400Hz, 115VAC and 28VDC. Usually the DC/AC inverter is used to convert 24VDC battery power to 400Hz, 115VAC for single phase emergency loads. The AC/DC conversion has traditionally been performed by uncontrolled diode rectification circuits. Despite their high reliability, relatively high efficiency, and low cost, diode rectifiers generate large amount of harmonic currents and have very poor input power factor. In order to reduce the harmonic and improve the power factor, multiphase (12- or 18-pulse) transformer-rectifier unit (TRU) is proposed. Fig. 3 is typical 12-pulse TRU architecture. It contains two transformers and two rectifier bridges.

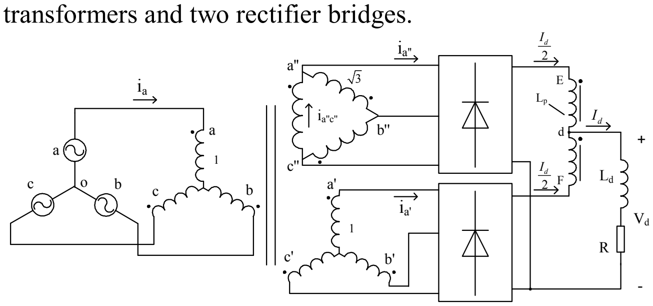

Fig. 3. Typical 12-pulse TRU Architecture

In order to obtain lower harmonic and higher power factor, it can be done by increasing the number of the transformer and rectifier in the TRU. For example, the 18-pulse TRU contains three transformers and three rectifier bridges. However, the weight and volume are big issues on aircraft, higher than 18-pulse TRU is not used.

Besides the AC/DC and DC/AC converters above, bi-directional DC/DC converters are also used in battery charge/discharge units.

B. *Converters in VF EPS*

In order to reduce the power loss and weight, the traditional 115VAC and 28VDC in CF EPS are replaced by multiple types of AC and DC power in VF EPS. For example, the 787 uses an electrical system that is a hybrid voltage system consisting of the following voltage types: 235VAC, 115VAC, ±270VDC and 28VDC[16]. The 115VAC and 28VDC voltage types are traditional, while the 235VAC and the ±270VDC voltage types are the consequence of the MEA architecture that results in a greatly expanded electrical system generating twice as much electricity as previous Boeing airplane models [16]. Higher voltages make the system save weight by reducing the size of power feeders.

As a result, different types of power converters are used to convert power between power buses in VF EPS. In VF EPS, TRU is still used to convert 115VAC (or higher AC voltage) to 28VDC. The disadvantages of bigger size and weight of TRU are obvious. As a result, Auto-transformer-rectifier unit (ATRU) is proposed. Fig. 4 is typical 12-pulse ATRU architecture.

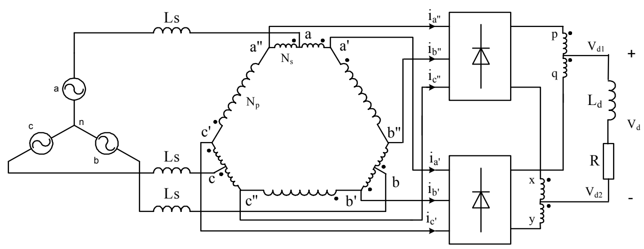

Fig. 4. 12-pulse ATRU Architecture

It can be seen that the conventional transformer is replaced by a self coupling transformer. As a result, ATRU can obtain better performance with lower weight and size than TRU. ATRU has already been used on B787 to convert 235VAC to ±270 VDC.

Moreover, VF-input converters are needed for VF EPS application. The VF-Input PWM converter that needs no input multiple-phase transformer is one choice. The circuit topologies of the PWM converter can be dual-PWM converter [5], AC-AC converter [6, 7] and cycloconverters [8], etc.

Besides the power converters in EPS, the electric load itself also employs converters to justify the input power. The simplest converter used by electric load is non controlled converter. The high harmonic current distortion and poor power factor was not a major concern in the past due to the small percentage of total system power processed by such converters. However, in VF EPS, more and more electric loads have significantly increased the total power of rectification loads, and system power quality will become unacceptable if still using the non-controlled converters. To combat this problem, airborne electrical system environmental standards ISO-1540 introduced stringent limits on harmonic currents which user equipment can draw from the AC source, as well as power factor. The similar requirements are also added in DO-160 from the version D. Detail requirements are discussed in section IV.

C. *Power Factor Compensator*

The cables of aircraft, which connect the electric loads to the electric power source, develop voltage drops due to its impedance. As a result, the voltage at the load terminal is lower than the power source provided and the power factor of the load seen at point of regulation (POR) of EPS is reduced. In order to improve the power factor and reduce the current harmonics, power factor compensator (PFC) is used together with the converters. Many researches have been done for the PFC application on aircraft [9, 10]. Besides improving the power factor, another benefit of PFC is to reduce or eliminate the voltage drop of the cables. This allows the possibility of using high impedance cables with benefits of reduced cable diameter and significant lower weight.

IV. CHALLENGES OF POWER ELECTRONICS IN VF EPS

In order to achieve better performance with lower weight, smaller size and lower cost, VF EPS in MEA requires the power electronic converters and MCs to be specially designed to meet the following requirements: 1) Low-weight. 2) Can directly interface the VF input power. 3) Low harmonics and meet EMC requirements. 4) Highly compact [3]. All these requirements induce big challenges for power electronics application in MEA.

A. *Harmonic Challenges*

The Harmonic requirements for converters and MCs are one of the biggest challenges. The increasing use of converters induces bigger harmonic current in aircraft electrical power network. In order to limit the negative impacts of harmonic currents on airborne electrical power generation and distribution systems, the international standard ISO-1540 and DO-160 introduce limits for input harmonic current distortion of airborne user equipment. ISO-1540 is the first one adding the harmonic requirements. DO-160 adds harmonic requirements later since version D. Now, the harmonic requirements in ISO-1540 and DO-160F are almost the same. Limits for input harmonic currents defined in DO-160 and ISO-1540 is showed in Table I.

TABLE I
HARMONIC REQUIREMENTS IN ISO-1540[11] AND DO-160F [12]

Harmonic Order	Harmonic Limits	
	Single-Phase	Three-Phase
h=3	I_h=0.15I_1/h	I_h=0.02I_1
h=5, 7	I_h =0.3I_1/h	I_h=0.02I_1
h=11		I_h=0.1I_1
h=13		I_h=0.08I_1
h=17,19		I_h=0.04I_1
h=23,25		I_h=0.03I_1
h=29,31,35,37		I_h=0.3I_1/h
Odd Triple Harmonics (h = 9, 15, 21, ..., 39)	I_h=0.15I_1/h	I_h=0.1I_1/h
h=2,4	I_h =0.01I_1/h	I_h =0.01I_1/h
Even Harmonics h>4 (h=6,8,10,…)	I_h=0.0025I_1	I_h=0.0025I_1
where: I_h = harmonic current of order h I_1=maximum fundamental current draw (steady state conditions)		

It can be seen that, the harmonic requirement on aircraft is very strict. Recent research showed that, to meet the low input harmonic current requirements, the converters with active PWM front-end control [13, 14] is an attractive solution for interfacing with the AC bus. However, to effectively control the input current harmonics to meet the very stringent specifications remains a major challenge. It would be more difficult to meet the entire requirement simultaneously without reducing the other performances, such as converter's voltage transfer ratio, input power factor and robustness against unbalanced and/or distorted voltage input [3].

On the other hand, the requirements also present a major design constraint for the filter design of the converters. A relatively small 2nd–order input filter is typically employed in the converters to smooth out the switching ripple current at the power input lines. Alternative topologies for active front-side control and input power filter designs to further reduce the weight and size are also a big challenge [3].

B. *Power Factor Challenges*

Table II is the requirements of steady-state full load power factor of motor loads in DO-160F.

TABLE II

POWER FACTOR REQUIREMENTS FOR MOTOR LOADS IN DO-160F[12]

Frequency	DO-160 Limits	
	Power Factor-Leading	Power Factor-lagging
f>500Hz	PF>0.980	PF>0.7
360Hz<f<500Hz		PF> 2.8571E-3f - 0.72857
f< 360Hz		PF>0.3

The high line fundamental frequency (400 Hz in CF EPS and 360—800 Hz in VF EPS) is a big challenge for the PFC to meet airborne power quality requirements. Achieving low input current distortion and unity input power factor at such high line frequencies require much wider control bandwidth than the widely used industry 50/60 Hz systems. Recent research showed that the primary source of input current harmonics under high line frequency is the zero-crossing distortion, which is the distortion around the zero crossing of the line voltage [15].

Moreover, VF EPS will have more challenges for PFC. It is because that, the cable impedance will vary with the AC frequency in VF EPS. As a result, the PFC shall be designed to providing reactive power vary with the frequency. Another reason is that, because the frequency range of VF EPS is typical 360-800Hz, most of which is higher than 400Hz CF, the voltage drop of cables in VF EPS is higher than that of CF EPS.

C. *Other Challenges*

The power electronics equipments in VF EPS will also meet big challenges of electromagnetic compatibility (EMC) requirement for aircraft application. The EMC requirement on aircraft usually contains electromagnetic interference (EMI), high intensity radiated fields (HIRF) and lightning. As the converters in VF EPS are all high energy electric power equipments and the performance will vary with the power frequency, the EMC requirements are very difficult to meet in the whole frequency range.

Also, the equipment volume and weight is a big issue on aircraft for the limited space and economic reason. Although the harmonic, power factor, EMC and other requirements can be met with adding filters, the volume and weight requirements will have limits on it. Moreover, the AC electric loads with VF input power need to choose suitable design frequency to obtain the optimized performance, as well as volume and weight. So, highly compact electronics equipment with lower weight is another challenge for aircraft application.

Other challenges of environmental requirements, such as temperature, vibration, humidity, etc. will be discussed in the future work due to paper limit.

V. CONCLUSION

Typical CF and VF EPS architecture of aircraft is presented. The application of power electronics in aircraft EPS is presented. New requirements and challenges for the design of new power electronics equipments in VF EPS of MEA are also discussed. The current trend towards VF EPS of MEA presents new opportunities for applications of power electronics.

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