

Review of Aircraft Electric Power Systems and Architectures

Zhao, Xin; Guerrero, Josep M.; Wu, Xiaohao

Published in:

Proceedings of the 2014 IEEE International Energy Conference (ENERGYCON)

DOI (link to publication from Publisher):

[10.1109/ENERGYCON.2014.6850540](https://doi.org/10.1109/ENERGYCON.2014.6850540)

Publication date:

2014

Document Version

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Zhao, X., Guerrero, J. M., & Wu, X. (2014). Review of Aircraft Electric Power Systems and Architectures. In *Proceedings of the 2014 IEEE International Energy Conference (ENERGYCON)* (pp. 949-953). IEEE Press. <https://doi.org/10.1109/ENERGYCON.2014.6850540>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Review of Aircraft Electric Power Systems and Architectures

Xin Zhao ^{#1}, Josep M. Guerrero ^{*2}, Xiaohua Wu ^{#3}

[#]Automation School Northwestern Polytechnical University

127 Youyixi Road, Xi'an Shaanxi, 710072, P. R. China

¹xzh@et.aau.dk

³wxh@nwpu.edu.cn

^{*}Microgrids Research Programme www.microgrids.et.aau.dk

Energy Technology Aalborg University

Pontoppidanstraede 101, 9220 Aalborg East, Denmark

²jz@et.aau.dk

Abstract—In recent years, the electrical power capacity is increasing rapidly in more electric aircraft (MEA), since the conventional mechanical, hydraulic and pneumatic energy systems are partly replaced by electrical power system. As a consequence, capacity and complexity of aircraft electric power systems (EPS) will increase dramatically and more advanced aircraft EPSs need to be developed. This paper gives a brief description of the constant frequency (CF) EPS, variable frequency (VF) EPS and advanced high voltage (HV) EPS. Power electronics in the three EPS is overviewed.

Keywords: Aircraft Power System, More Electric Aircraft, Constant Frequency, Variable Frequency, High Voltage.

I. INTRODUCTION

In early stage of the aircraft history, aircraft is driven by mechanical, electrical, hydraulic and pneumatic hybrid systems. At the end of 1970's, the idea of using electricity as dominant power source emerged and during this period the concept of More Electric Aircraft was proposed [1][2][3].

The first commercial aircraft "Fly by Wire" (FBW) was introduced by Airbus with A320 series in 1980's. The FBW technology can reduce the weight and volume of aircraft by replacing part of the mechanical and hydro-mechanical systems into electrical systems. In FBW system, power electrical systems generally use 115V with fixed frequency at 400Hz AC for high power onboard equipment and 28V DC for low power onboard equipment [4][5]. However, some onboard systems like flight control actuation, landing gear, de-icing device and engine starter/generator are still driven by hydraulic, pneumatic and mechanical hybrid systems which are inefficient and heavy [6]. These defects foreshadow the wider implementation of electric power system in aircraft.

In order to remedy these defects and make flights much safer, reliable and environmental friendly, the "Power by Wire" [7] technology emerges as the times require. In PBW technology, most of the inefficient, heavy hydraulic systems were eliminated and replaced by electrical systems which have relatively higher efficiency, stronger fault-tolerant

ability and lower weight. Therefore, the aircraft EPS capacity needs to sprint higher to meet the electrical equipment's requirements. For example, the electrical capacity of Boeing 787 has increased to 1MW during a normal flight [8]. Apparently, compared with conventional EPS, more advanced EPS is needed to achieve high availability, stability, efficiency and low weight, volume in MEA. Besides, less engine noise, emissions and fuel burn can be realized in MEA [9][10].

This paper introduces the structure of conventional and modern aircraft EPS. The advantage of MEA is discussed. Power electronic converters in aircraft EPS is also presented.

II. CONSTANT FREQUENCY EPS

2.1 Structure of Constant Frequency EPS

In constant frequency aircraft EPS, aircraft generators are three-stage Permanent Magnet (PM) excited wound field synchronous machines. A Generator Control Unit (GCU), which is not depicted in Fig. 1, acts as exciter field controller, regulating the output voltage.

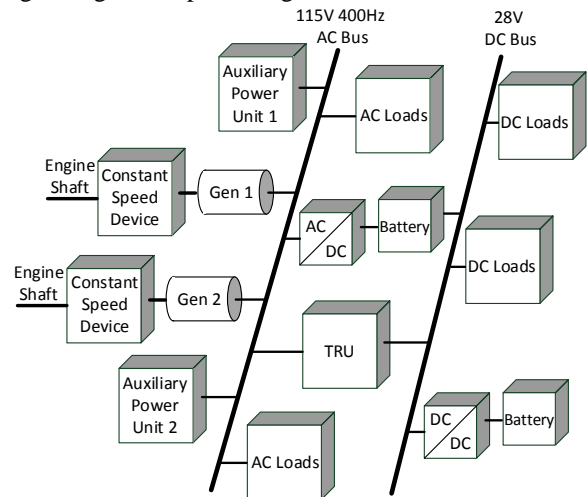


Fig. 1 CF Aircraft EPS

Fig. 1 shows the conventional CF aircraft EPS in which bus voltage is 115V at 400Hz AC and 28V DC. This power system employs constant speed device (CSD) [11] which is a mechanical gearbox. It converts the speed of the engine shaft from variable into constant. And the constant rotating speed shaft connected with the generator will then generate a CF power at 400Hz. As we can see from the figure, AC loads are directly powered by AC bus while the Transformer Rectifier Units (TRU) is used to convert the AC power into 28V DC.

2.2 Power Electronics in Constant Frequency EPS

In CF aircraft EPS, AC/DC converter and TRU are the main power converters. Generally, battery is used as an emergency power source. AC/DC inverter and Bi-directional DC/DC converter will connect the battery with the AC bus and DC bus respectively.

The DC power could be obtained conventionally from a DC generator. However, the space around the aircraft main engine is extremely limited to install other AC or DC generators. In addition, DC cable, which is extremely heavy and long, is also required to connect the generator with the DC bus [12]. For these reasons, TRU [12][13][14] is introduced to convert AC voltage to DC voltage, since it can be installed close to the DC bus, thus weight and volume of EPS could be reduced to a relatively lower level. Besides, TRU could also reduce harmonic currents and achieve lower THD. Topology of a typical 12-Pulse TRU is shown in Fig. 2.

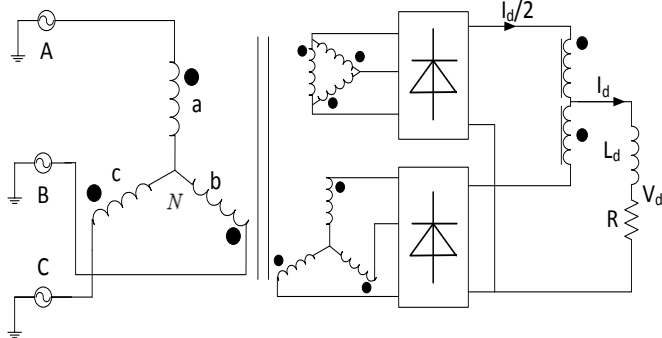


Fig. 2 Topology of 12-Pulse TRU

III. VARIABLE FREQUENCY EPS

3.1 Structure of Variable Frequency EPS

In variable frequency aircraft EPS, shown in Fig. 3, the frequency of primary AC bus is 360Hz-800Hz at 115V since the generator is connected with engine shaft directly. A variety kind of converter is employed to convert VF voltage to multi voltage levels, such as 115V AC and 270V DC.

It's worth mentioning that the frequency of primary AC bus, which varies between 360Hz and 800Hz, is proportional to the engine shaft speed [15]. By using VF power system, the bulky, heavy, inefficient CSD could be removed from the aircraft. Thus, the aircraft EPS could achieve higher performance.

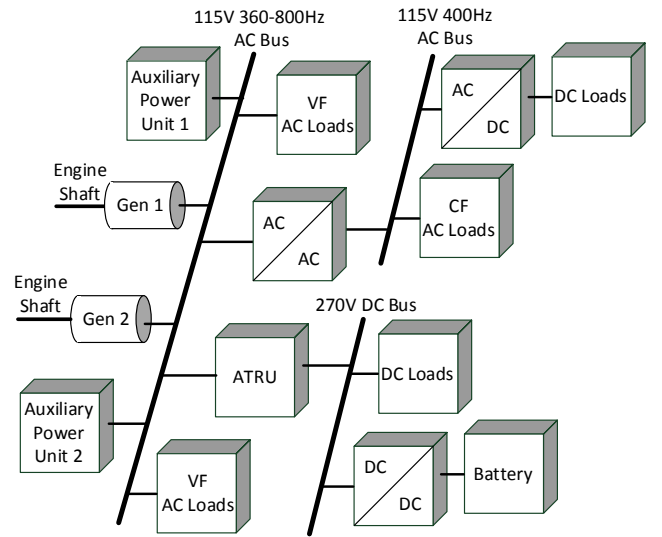


Fig. 3 VF Aircraft EPS

3.2 Power Electronics in Variable Frequency EPS

Since the primary AC bus has a variable frequency, Back-to-Back converter [16] is needed to power CF loads. These converters must be designed carefully to meet the volume, weight and harmonic requirements in aviation standard, such as DO-160 or MIL-704. Its topology is shown in Fig. 4.

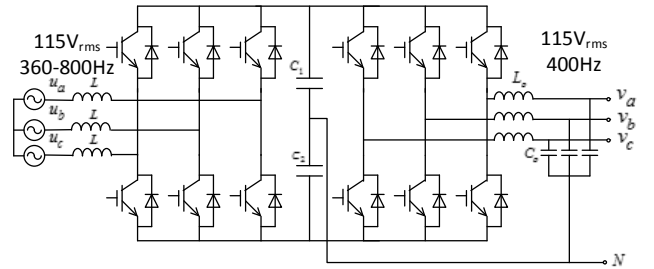


Fig. 4 Back-to-Back Converter Structure

Two PWM converters are employed in Back-to-Back converter. The first stage—high power factor rectifier, which adopt D-Q decouple strategy to control the active and reactive current, can make the power factor approximate to 1. Thus, current harmonic could meet higher standard [17]. The second stage—SPWM inverter could stable the bus voltage and frequency by utilizing voltage-current dual loop.

For DC bus, 270V DC voltage is chosen because it can be obtained directly by rectify 115V AC voltage. DC/DC converter is used to obtain multi DC voltage levels.

As we all know that autotransformer has much smaller size and weight than isolation transformer at same power level. So naturally, Autotransformer Rectifier Unit (ATRU) [14][18] replace the position of TRU. Fig. 5 shows the topology of the 24-Pulse ATRU. The ATRU utilizes phase-shifting windings to generate 4 groups of AC voltage. Each group has 15° phase difference [19], so that the output voltage can reach 270V.

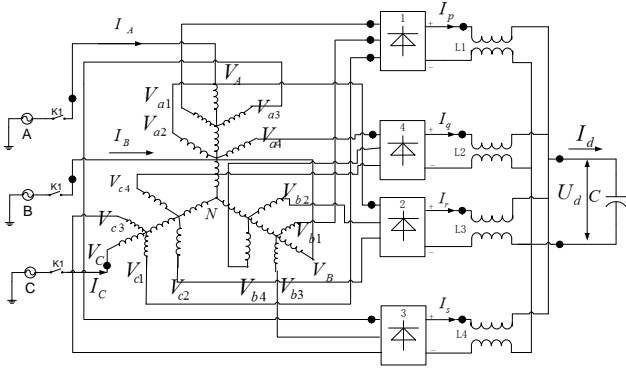


Fig. 5 Topology of 24-Pulse ATRU

Besides the converter aforementioned, Bi-directional DC/DC converter is used in VF aircraft EPS to charge/discharge batteries as the emergency power supply.

IV. FUTURE AIRCRAFT EPS

In later design of aircraft EPS, as the consequence of gradually substitute the hydraulic, pneumatic and mechanical system, there is an obvious trend towards increasing demand of electrical power. However, the feeder cable current in conventional 115V or 28V EPS will increase proportionally to power ratings. And this will definitely lead to higher power loss and cable weight.

As a consequence, increasing the voltage level in future aircraft EPS is an obviously better choice than continuing apply the 115V AC and 28V DC low voltage EPS. By doing this, the feeder cable current could be reduced dramatically. Also, lower cable weight, higher efficiency and lower consumption could be achieved [20][21].

4.1 High Voltage AC (HVAC) Aircraft EPS

Some newer aircrafts have been adopted HVAC power system (230V at 360-800Hz), such as Boeing 787. Compared with the conventional 115V EPS, power transmission loss and converter weight can be reduced by 50.7% and 42.5% respectively [21].

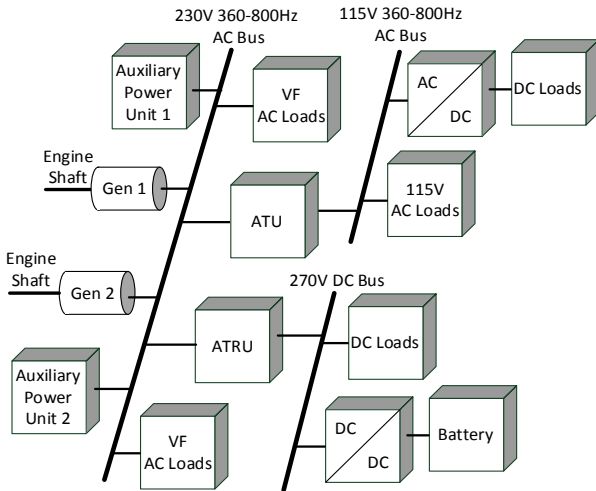


Fig. 6 HVAC Aircraft EPS

An example of HVAC EPS is depicted in Fig. 6. In this system, Auto transformer unit (ATU) is used to generate 115V variable frequency voltage. Buck Boost Converter Unit (BBCU), which consists of 2 DC-AC stages interfaced with a high frequency transformer, is used as the battery charger [22]. Its topology is in the figure below.

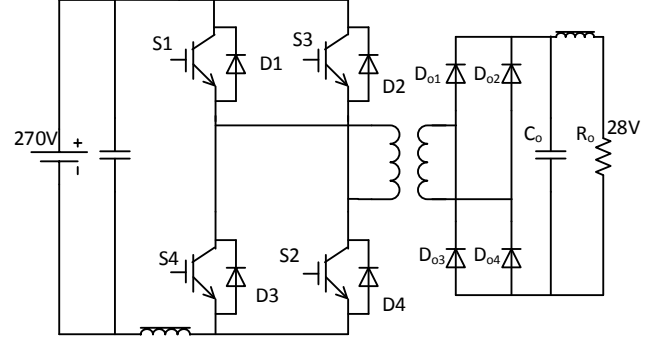


Fig. 7 BBCU Topology

4.2 High Voltage DC (HVDC) Aircraft EPS

Several possible architectures of HVDC aircraft EPS are analyzed in [23]:

- +/- 270V DC 2 phases with ground
- 270V DC 1 phase with ground
- +/-135V DC two phases with ground
- +/- 135V DC 2 phases without ground

The conclusion of [23] certifies that in most cases, HVDC EPS can save weight from 4% (270/0V architecture with 230V AC supply) up to 28% (270/0V architecture with 115V AC supply). Fig. 8 illustrates a typical 270V HVDC EPS.

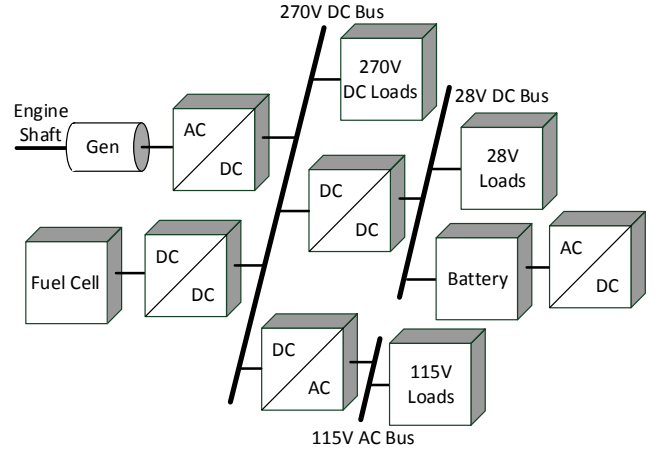


Fig. 8 270V HVDC Aircraft EPS

As we can see from Fig. 8, fuel cell system replaces the position of conventional APU which is driven by turbines. This is because the efficiency of turbine powered APU is typically less than 20% and also has undesirable noise and gaseous emissions [24][25]. Some topology had been proposed in [26] to integrate fuel cell system into aircraft

EPS. One of parallel architecture is depicted in Fig. 9. In this case, bi-directional DC/DC converter is employed.

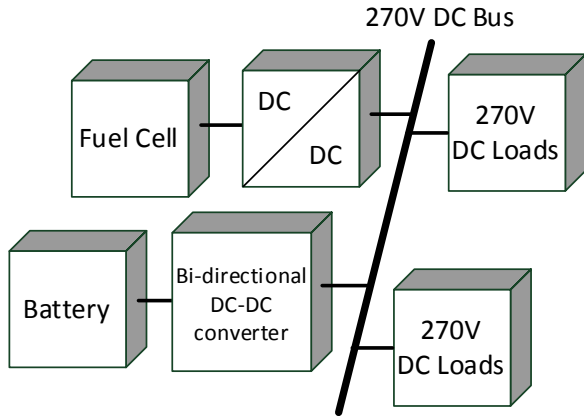


Fig. 9 Parallel Architecture of Fuel Cell System

4.3 Challenges of Future Aircraft EPS

At present, an electrical device cannot offer improved reliability but could increase availability thanks to the opportunity to isolate a subsystem in case of failure [27]. Although it is possible to anticipate failures in the near future through the behavioral modeling of systems coupled with fault-detection algorithms [28][29], but the better way is developing high reliable, high power density power electronic devices. For example, SiC based semiconductor [30][31] device is very promising since it can provide a significant reduction of switching losses, high temperature tolerance and fast switching capability.

In the converter level, the widely used PWM power converters which have a very complicate control strategy may lead to the whole distribution network suffering from an unstable situation. Several studies have been done to guarantee the converter operating in a stable region [32][33]. It's worth mentioning that sharing power electronic converters is an effective way to save mass [29][34].

As to the system level, integrated optimal design will be the major research field in the next decade since the conventional test and error method cannot ensure the system reach its most optimum operation point [29]. The integrated optimal design will balance the system mass, efficiency, thermal stability and power quality through an advance algorithm [35][36].

V. CONCLUSIONS

In this paper, CF, VF and HV aircraft EPS are summarized. The role of power electronic converters is presented. HV EPS will still be the future trend in aircraft as it is an effective way to deal with the increasing capacity of aircraft EPS. Many challenges are also put forward by HV EPS along with the increasing power capacity and power converters. Such as electromagnetic compatibility (EMC) [37], power density, harmonics, high voltage contactors, solid state power controller [38] and so on. To meet and finally triumph these challenges, researchers had proposed

many effective way, such as SiC semiconductors and optimal design at the system level.

REFERENCES

- [1] A. Emadi, M. Ehsani, "Aircraft Power Systems: Technology, State of the Art, and Future Trends," IEEE Aerospace and Electronic Systems Magazine, Volume: 15, Issue: 1, pp. 28-32, Jan. 2000.
- [2] Jones, R.I., "The More Electric Aircraft: the past and the future," Electrical Machines and Systems for the More Electric Aircraft, pp. 1/1-1/4, 1999.
- [3] Quigley, R.E.J., "More Electric Aircraft", IEEE Applied Power Electronics Conference and Exposition, pp. 906-911 APEC '1993.
- [4] G.M. Raimondi, T. Sawata, M. Holme, A. Barton, J. Coles, P. H. Mellor, and N. Sidell, "Aircraft Embedded Generation Systems," International Conference on Power Electronics, Machines and Drives, pp. 217-222, June 2002.
- [5] C.R. Avery, S.G. Burrow and P.H. Mellor, "Electrical generation and distribution for the more electric aircraft," in Proc. IEEE Universities Power Engineering Conference, pp. 1007-1012, Sep. 2007.
- [6] R. T. Naayagi, "A Review of More Electric Aircraft Technology," International Conference on Energy Efficient Technologies for Sustainability, pp. 750-753, April 2013.
- [7] Elbuluk, M.E., Kankam, M.D., "Motor drive technologies for the power-by-wire (PBW) program: options, trends and tradeoffs," National Aerospace and Electronics Conference, pp. 511-522, May 1995.
- [8] Nelson, T., "787 Systems and Performance," The Boeing Company, 2005.
- [9] UK Transport and climate change data, UK Department of Transport Factsheets, pp.1-20, 2007.
- [10] Hoffman A.C., "Advanced Secondary Power System for Transport Aircraft," NASA Technical paper 2463, 1985.
- [11] Elbuluk, M.E., Kankam, M.D., "Potential Starter/Generator Technologies for Future Aerospace Applications," IEEE Aerospace and Electronics Systems Magazine, pp. 17-24, May 1996.
- [12] Lee, J.C., "Aircraft transformer-rectifier units," Students' Quarterly Journal, pp. 69-71, Sep. 1972.
- [13] Cheng, K.W.E., "Comparative study of AC/DC converters for More Electric Aircraft," 7th International Conference on Power Electronics and Variable Speed Drives, pp. 299-304, Sep. 1998.
- [14] Monroy, A.O., Hoang Le-Huy and Lavoie, C., "Modeling and simulation of a 24-pulse Transformer Rectifier Unit for more electric aircraft power system," Electrical Systems for Aircraft, Railway and Ship Propulsion, pp. 1-5, Oct. 2012.
- [15] Chang, Jie, Wang, Anhua, "New VF-power system architecture and evaluation for future aircraft," IEEE Transactions on Aerospace and Electronic Systems, pp. 527-539, April 2006.
- [16] Taha, M.H., Skinner, D., Gami, S., Holme, M. and Raimondi, G., "Variable frequency to constant frequency converter (VFCFC) for aircraft applications," International Conference on Power Electronics, Machines and Drives, pp. 235-240, June 2002.
- [17] IEEE-STD-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," IEEE 1993.
- [18] Jian Sun, Zhonghui Bing and Karimi, K.J., "Small-signal modeling of multipulse rectifiers for more electric aircraft applications," Power Electronics Specialists Conference, pp. 302-308, June 2008.
- [19] Kai Liu, Mingyong Li, "Multiphase rectification technology," Electronic watercraft technology, pp. 26-29, 2005.
- [20] Brombach, J., Schroter, T., Lucken, A. and Schulz, D., "Optimized cabin power supply with a +/-270V DC grid on a modern aircraft," International Conference on Compatibility and Power Electronics, pp. 425-428, June 2011.
- [21] Nya, B.H., Brombach, J., Schulz, D., "Benefits of higher voltage levels in aircraft electrical power systems," Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), pp. 1-5, Oct. 2012.
- [22] L. Rubino, B. Guida, F. Liccardo, P. Marino and A. Cavallo, "Buck-boost DC/DC converter for aeronautical applications," IEEE International Symposium on Industrial Electronics, pp. 2690-2695, July 2010.
- [23] Brombach, J., Lucken, A., Nya, B., Johannsen, M. and Schulz, D., "Comparison of different electrical HVDC-architectures for aircraft

- application,” *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)*, pp. 1-6, Oct. 2012.
- [24] Rajashekara, K., Grieve, J. and Daggett, D., “Hybrid fuel cell power in aircraft: A feasibility study for onboard power generation using a combination of solid oxide fuel cells and gas turbines,” *IEEE Industry Applications Magazine*, vol. 14, Issue. 4, pp. 54-60, July-Aug. 2008.
 - [25] Lucken, A., Brombach, J. and Schulz, D., “Design and protection of a high voltage DC onboard grid with integrated fuel cell system on Toward Optimized Electrical Networks electric aircraft,” *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)*, pp. 1-6, Oct. 2010.
 - [26] Oliver, J.A., Zumel, P., Sanz, M., et al., “High level decision methodology for the selection of a fuel cell based power distribution architecture for an aircraft application,” *IEEE Energy Conversion Congress and Exposition*, pp. 459-464, Sep. 2009.
 - [27] Boglietti, A., Cavagnino, A., Tenconi, A. and Vaschetto, S., “The safety critical electric machines and drives in the more electric aircraft: A survey,” *IEEE Industrial Electronics Conference*, pp. 2587-2594, Nov. 2009.
 - [28] Vohnout S., Goodman D., Judkins J., Kozak M. and Harris K., “Electronic prognostics system implementation on power actuator components,” *IEEE Aerospace Conference*, Mar. 2008.
 - [29] Roboam, X., Sareni, B. and Andrade, A.D., “More Electricity in the Air: Toward Optimized Electrical Networks Embedded in More-Electrical Aircraft,” *IEEE Industrial Electronics Magazine*, pp. 6-17, Dec. 2012.
 - [30] Mostaghimi, O., Wright, N. and Horsfall, A., “Design and performance evaluation of SiC based DC-DC converters for PV applications,” *IEEE Energy Conversion Congress and Exposition*, pp. 3956-3963, Sep. 2012.
 - [31] Pittini, R., Zhe Zhang and Andersen, M.A.E., “Switching performance evaluation of commercial SiC power devices (SiC JFET and SiC MOSFET) in relation to the gate driver complexity,” *IEEE ECCE Asia*, June 2013.
 - [32] Feng, X., Liu, J. and Lee F. C., “Impedance specifications for stable DC distributed power systems,” *IEEE Transactions on Power Electronics*, pp. 157-162, Mar. 2002.
 - [33] Jones, C.E., Barnes, M. and Forsyth, A.J., “Stability analysis of motor drive interactions in aircraft electrical systems,” *European Conference on Power Electronics and Applications*, pp. 1-10, Aug. 2011.
 - [34] Prisse, L., Ferer, D., Foch, H. and Lacoste, A., “New power centre and power electronics sharing in aircraft,” *European Conference on Power Electronics and Applications*, pp. 1-9, Sep. 2009.
 - [35] Hieu Nguyen Huu, Retiere, N. and Wurtz, F., “Optimization of an electrical system using Pareto borders of each component. Application to an automotive drive chain,” *IEEE Industrial Electronics Conference*, pp. 3662-3667, Nov. 2006.
 - [36] Hieu Nguyen Huu, Gerbaud, L., Retiere, N., Roudet, J. and Wurtz, F., “Analytical modeling of static converters for optimal sizing of on-board electrical systems,” *IEEE Vehicle Power and Propulsion Conference (VPPC)*, pp. 1-6, Sep. 2010.
 - [37] Carter, N.J., QinetiQ, “The past, present and future challenges of aircraft EMC,” *IEEE Electromagnetic Compatibility Magazine*, pp. 75-78, July 2012.
 - [38] Izquierdo, D., Barrado, A., Sanz, M., Fernandez, C. and Zumel, P., “Modeling methods for Solid State Power Controllers (SSPC),” *Compatibility and Power Electronics*, pp. 265-270, May 2009.