On-board Microgrids for the More Electric Aircraft – Technology Review

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***Abstract*—This paper presents an overview of technology related to on-board microgrids for the More Electric Aircraft. All aircraft use an isolated system, where security of supply and power density represent the main requirements. Different distribution systems (AC and DC) and voltage levels coexist, and power converters have the central role in connecting them with high reliability and high power density. Ensuring the safety of supply with a limited redundancy is one of the targets of the system design, since it allows increasing the power density. This main challenge is often tackled with proper load management and advanced control strategies, as highlighted in this paper.**

***Index Terms*—Aerospace engineering, DC-DC Power Converters, AC-AC Power Converters, Power System Management**

I. INTRODUCTION

In the recent years, research has focused in assisting the progressive increase in transportation electrification. Many reasons have driven this effort, including the push for the reduction in pollution (often enforced by international agreements), the research for better performance and the maturity of the technology. The car industry first witnessed the introduction of hybrid cars and then fully-electric vehicles that can be seen today [1]. The cost of the fuel and the sustainability of the market growth were the main drives for this transformation. Regarding the aircraft industry, the idea of the all-electric aircraft (AEA) dates back to more than 30 years. In addition, the concept of hybrid aircraft propulsion has been introduced, giving a route do develop the required technologies for electric propulsion. Nowadays, the gradual substitution of hydraulic and pneumatic subsystem with their electric counterparts on conventional aircraft is already a market reality. This framework takes the name of More Electric Aircraft (MEA), but the propulsion remains completely traditional, in a MEA only the subsystems are electrified [2].

In a conventional aircraft, the fuel is burnt in the jet engine to generate the thrust, in the range of tens of MW, which constitutes the vast majority of the engine power output. The jet engine is coupled to several gearboxes, which drive the electrical generators, the hydraulic pump for the actuators and the fuel pump and hydraulic pump for the engine. About 2-3% of the maximum power output is through a bleed valve in the jet engine that is used to draw high pressure air for the environmental control system. Although this system has proved to be effective for many years, the problems of this architecture are:

I. The presence of the high-pressure bleed valve in the jet engine seriously compromises the efficiency of the turbine.
II. The hydraulic distribution systems is composed of pipes and pumps add up to a considerable amount of weight and can be prone to leaks. A malfunction of the hydraulic distribution system grounds the aircraft, since the corrosive fluids need to be removed and the system repaired.

The bleed valve has for many years represented a good solution to obtain high-pressure air for the pneumatic and the cabin pressurization system. However, the bleed air system deteriorates the performance of the jet engine. In order to obtain the maximum efficiency, engineers have been studying alternatives to the bleed valve and to the hydraulic distribution, looking at the electric and electronic realms. A more electric architecture of the power distribution system would feature engine driven generators that power electrical loads, compressors for the cabin pressurization, electromechanical or electro-hydraulic actuators to remove the central hydraulic pumps and electrical fuel-pumping engine ancillaries.

The aircraft is therefore an isolated grid, where the power must be generated and distributed, ensuring the stability and a high power quality. Although this microgrid shares similarity with the ground-based microgrids, implying that existing methods reported in literature can be transferred to the MEA micro-grid, there are several differences:

- Very high reliability of supply requirement, which implies architectural choices, like the bus isolation and separation.

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- The power density is a priority, since the mass of the EPDS contributes to a considerable amount of fuel consumption over the lifetime of the aircraft.
- Load prioritization: during each flight stage, the loads have changing priority (landing gear, de-icing system).
- Intrinsically hybrid (AC and DC) characteristic with multiple voltage levels.
- Electronic-dominated.

The paper is organized as follows: section II outlines the main characteristics of the on-board microgrids, power systems aspects are described in section III and IV, the Power Electronics is discussed in section V. A description of the control system for the microgrid as well as a discussion on reliability is given in section VI. Protections are outlined in section VII. Section VIII draws the conclusions.

II. ON-BOARD MICROGRIDS IN THE MORE ELECTRIC AIRCRAFT

Power density and resilient operation are conflicting requirements, because a straightforward way to achieve resiliency to a fault in the EPDS is to implement large-scale redundancy. In fact, to avoid a catastrophic power loss that could impair the aircraft, multiple redundant system are implemented. Although it is true that the EPDS must be redundant, the challenge is to minimize this redundancy, i.e., minimize the overall installed power.

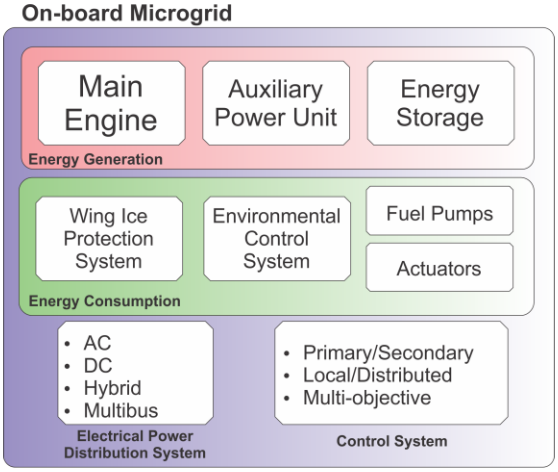

Figure 1 On-board microgrid elements

The EPDS must be sized to provide the peak power in the worst-case scenario, the optimal solution is found when the difference between peak and average power is minimized.

The generators connected to the main engines have a power capability that depends on the engine type, the generator type and on the actual operating conditions [3] and this power is then transferred to the loads through the distribution system. Considering that power electronics converters interface most of the loads, the interactions between the control system makes the stability of the microgrid a challenging task, because the voltage and frequency stability cannot be aided by the presence of large synchronous generator like the traditional grid [4].

Whereas the electrification of existing system would imply in a general efficiency improvement, the passengers' demand are mostly related to an improved comfort and to a better connectivity (laptop, chargers), that increase the unpredictability of the power request and offer a point of access for external power electronics that can constitute a safety risk and could deteriorate the power quality.

Electrifying the propulsion constitutes the next challenge, calling for an increased power density, pushing the technology limits. Hybrid propulsion is already under investigation [5] and some prototypes have been presented [6]. The idea is very similar to hybrid cars: having the engine working at the peak efficiency point and electric motors powering the propulsion.

Figure 1 shows a general representation of the on-board microgrid, where sources/loads and distribution system are listed and will be described in this survey.

III. POWER SYSTEMS ON BOARD

As the result of MEA development, onboard electrical power systems (EPSs) undergo significant changes in order to provide substantially increased power demands whilst meeting extremely strict requirements as for weight and volume, safety and reliability, electric power quality, availability etc. The changes concern both EPS architectures and individual subsystems responsible for energy generation, distribution, conversion, utilization and storage.

A. Energy generation in MEA EPS

Multi-level electric power generation is typically employed and includes primary power sources (main generators, typically ac), secondary sources (auxiliary power unit (APU) which normally is employed on ground but can be used airborne in case of other source failure), and tertiary sources like ram-air turbine (RAT) to be employed in case of multiple failures.

The three-stage synchronous machine is considered as state-of-the-art technology for primary power source for MEA application. This machine is part of MOET MEA architecture [7] and it is employed in Boeing 787 [8]. It is inherently safe and reliable and provides bus voltage control via field using generator control unit (GCU). Aiming for system-level benefits, this machine can also be operated in motoring mode to provide the engine electrical start (due to elimination of pneumatic system in MEA). During engine starting, the machine is controlled by onboard power electronic converter which normally controls ECS compressors. However, with this machine, in order to get the DC voltage, heavy and bulky transformer-rectifier units and filters are required. Voltage control through excitation is slow and may not satisfy requirements of high-dynamic power electronic-driven loads. In addition, wound rotor technology with rotating diodes limits the machine speed, hence limiting space for optimization the machine weight and volume. Therefore, there is a number of studies looking for new machine types and starter/generator system topologies, in particular – based on induction machine, switched-reluctance motor and permanent-magnet machine [9]–[12]. In most cases, new technologies consider introduction of actively controlled AC/DC converters in the main path of energy flow. The new technologies for secondary power sources mainly consider replacement of APU by fuel cells (FC)

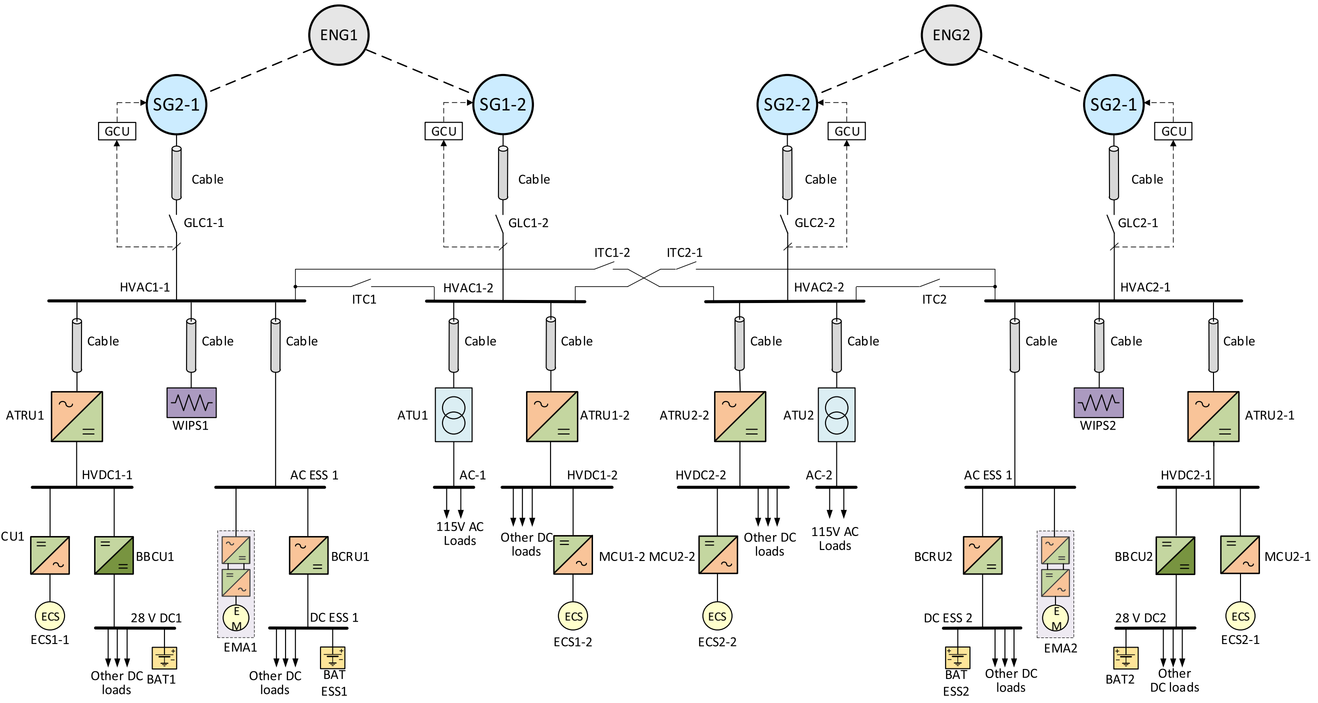

Figure 2. MOET MEA EPS architecture

[13] that offers much better efficiency and are emission-free. However, inclusion of FC onboard MEA require another piece of power electronics – the converter to interface FC with the onboard EPS. There are also reports on development of secondary sources based on combination of lithium-ion batteries with supercapacitors [14]. By coordinated operation with primary sources, it becomes possible to shave peak power demands seen by generators and to manage regenerative energy such that the design point of the main generators can be optimized and in result – up to 15% of their weight saving can be achieved [15].

B. Energy utilization (loads) onboard MEA

New loads in MEA EPS are associated with application of electrically-driven technologies to replace hydraulically- and pneumatically-driven systems of traditional aircraft. These are widely described in many publications therefore here only a short overview with the key references is given. Figure 3 illustrates the placement of the more electrical technologies in a modern aircraft:

- Wing Ice-Protection System (WIPS) utilizing embedded resistive heat mats instead of circulation of hot air off-taken from the engine [7]. For mid-size aircraft this load can require 40-60kW in de-icing mode and up to 200kW in anti-icing mode. WIPS can be smoothly and efficiently controlled by power electronics managing either delivered power or surface temperature [16], [17];
- Electrical Environment Control System (ECS): this system employs electric drive to compress the ambient air and to controls air parameters to provide passengers comfort [7], [18], [19]. For mid-size aircraft several ECSs are required, with typical rating – 70 kW each [8];
- Electromechanical Actuators (EMA) – depending on flight surfaces, the EMA rated power can vary from 2 to 40kW; these are typically based on permanent-magnet machine drives [18], [19]. EMAs can also be employed for landing gear operation (steering, retraction, braking);
- Fuel pumps: being hydraulic-driven on traditional platform, these pumps in MEA are electrically-driven [20]. The system of pumps is required for transferring and feeding the fuel, as well as for controlling location of the aircraft center of gravity, as well as to reduce wing bending and structural fatigue. This system is typically based on induction motor drive, and for mid-size aircraft, the total power of fuel pumps is around 200kVA.

Hence, these new loads (and traditional ones) need to be supplied with the power safely and reliably. This is one of the key function of electrical distribution, which is defined by the EPS architecture. Electrification of propulsion is still at experimental level.

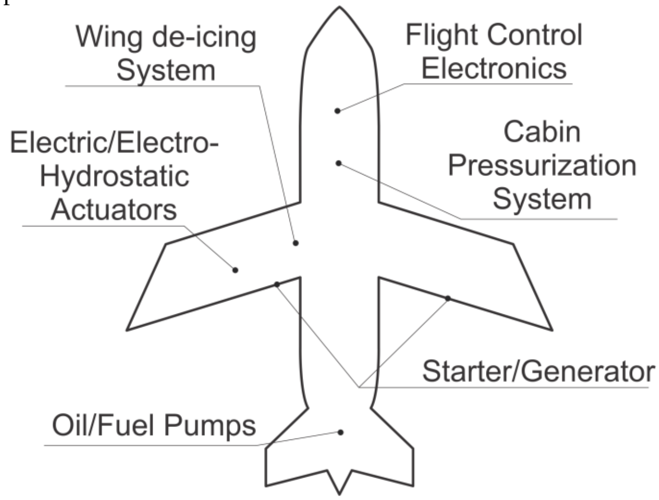

Figure 3. Electrical subsystems in a More Electric Aircraft

IV. MEA ELECTRICAL POWER SYSTEM ARCHITECTURES

MEA EPS architectures are the natural and latest level of aircraft EPS evolution. This is well discussed in many publications including [10], [21], [22], [22], here we just notice that state-of-the-art technology considers high-voltage (230V) variable frequency (360…900Hz) ac primary distribution or high-voltage dc distribution (270Vdc, ±270Vdc or 540Vdc).

An example of hybrid ac/dc MEA EPS architecture is those studies within EU FP6 project MOET [8], [23], [24] and illustrated in Figure 2 and described in details in [25].

This EPS type features an islanded structure under normal conditions: each generator has its own loads and distribution layers, and only under fault scenarios, some of inter-tie contactors can transfer load to healthy primary source. Another particularity of this topology is that it heavily relies on power electronic conversions, i.e. it is power-electronics rich. Since many loads onboard are required only during relatively short period during flight mission, the power electronics utilization rate within this EPS type is low; improving this will allow reducing overall EPS weight and cost significantly.

Therefore, a number of studies investigate alternative MEA EPS topologies. For example [18], [19] investigate so-called integrated modular power electronic concept (IMPEC): the EPS includes a set of identical PECs that supply different loads during different flight stages, with the reconnections established using matrix contactors. The number and the rating of these PECs can be defined in an analytical way according to certain optimization criteria (overall weight, cost, efficiency etc) [26]. The IMPEC idea can be illustrated by architecture in Figure 4.

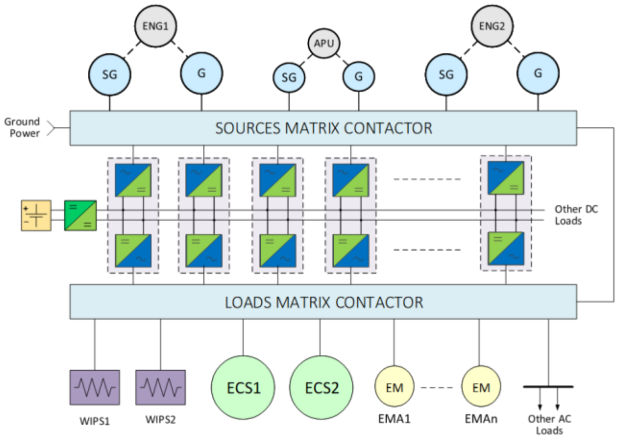

Figure 4. IMPEC concept

Building MEA EPS using “PECs layer” with multiple smaller identical converters leads to the idea of flexible architecture based on modular PEC, as illustrated by Figure 5 [23], [24]. Here, each “small” PEC called “cell” (bidirectional DC/DC) [8], [23], [24] can connect any primary bus to any secondary. No power interruption happens in case of cell fault, cells can operate in parallel with others (number of paralleled cells depends on loading), and significant weight and volume benefits can be achieved since each cell is a small and modular LRU-type unit.

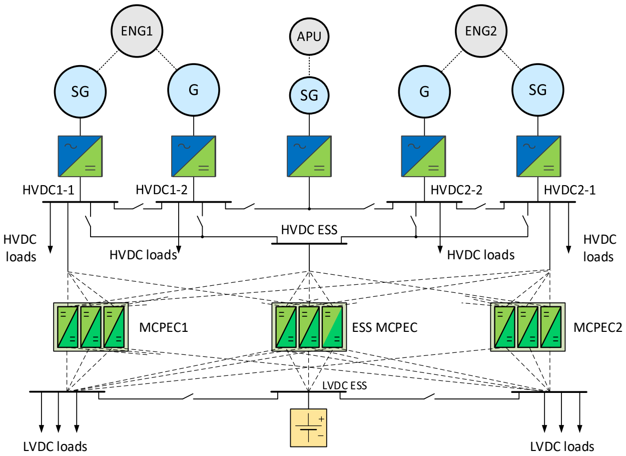

Figure 5. Flexible EPS architecture using modular PEC

Hence, the system provides increased level of power availability to the loads and improved safety. This topology effectively turns the EPS into a smart microgrid with the optimal configuration decided online by the supervision logic in charge of energy management (EM). This logic (supervisor) can be designed in the rigorous analytical way to meet set of optimization criteria. Recently, design of optimized control logic for this type of architectures has attracted a noticeable attention. This the inter-disciplinary area of research combines expertise in both electrical engineering and in optimization mathematics. The most recent reports clearly indicate a significant potential improvements in overall EPS performance, including reliability and safety, power availability, as well as weight minimization, reduction of parts/components count and other criteria [27]–[32].

An important tendency in MEA EPS development deals with the introduction of distributed architectures instead of centralized of traditional aircraft. Distributed architectures allow achieving significant weight benefits by harness optimization. As illustrated by Figure 6, (this approach assumes a number of local distribution units that can be located close to loads with only high-voltage supply to these units.

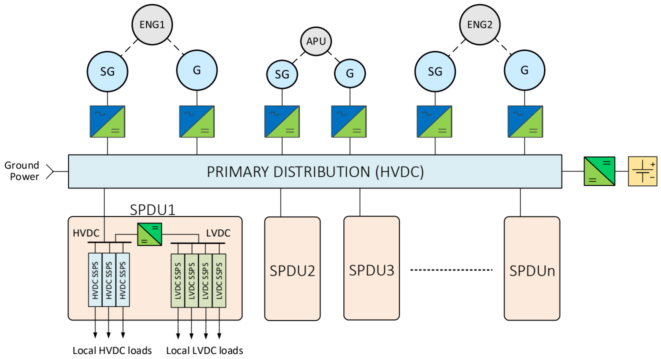

Figure 6. Distributed MEA EPS architecture

Another trend in MEA EPS development considers so-called “single-bus” concept according to which the entire EPS, or its large sections, has a single bus to interface all the loads and all sources [33], [34] (could be of different types and/or physical nature) as illustrated by Figure 7 below.

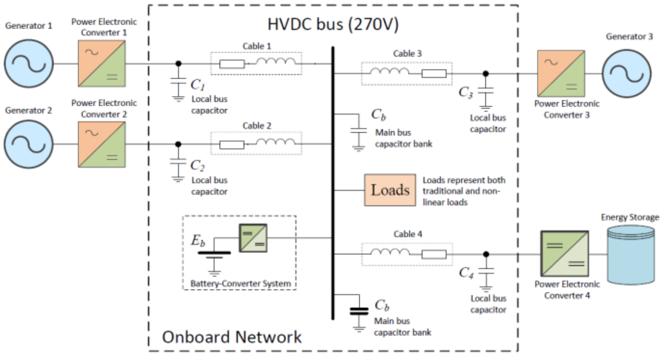

Figure 7. Single-bus MEA EPS architecture

This topology become possible due to introduction of primary sources controlled by active PECs as discussed above. The key potential benefits include ease of establishing the most optimal power allocations using decentralized droop control [35], [36], hence reduction of design ratings for main sources leading to substantial weight reduction. Whilst the control principles for this topology to ensure compliance with power quality requirements are investigated and reported in abovementioned references, the fault protection strategies within this architecture is the key challenge that yet need to be addressed.

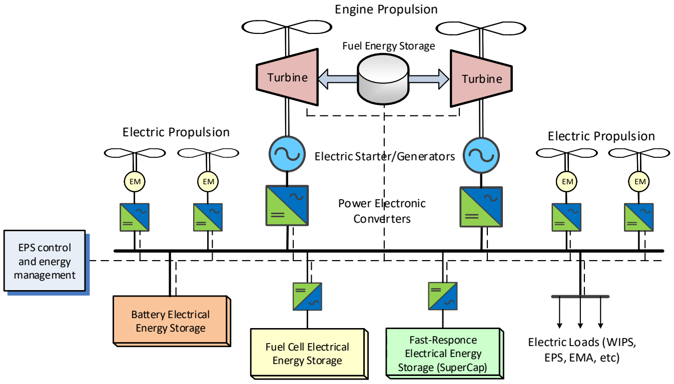

Figure 8. Potential EPS architecture for hybrid propulsion aircraft

Looking towards future EPS architectures for hybrid and full-electric platforms, single bus topology is one of the key candidate studied in recent research. This vision is represented in Figure 8 for hybrid platform [10], [37]: one can easily identify two turbine-driven primary sources and secondary sources based on batteries, fuel cells and super capacitors delivering power to the same high-voltage dc bus, and number of loads (propellers and other MEA loads) fed from the same bus.

On the one hand, the more electric technology can offer advantages regarding functionalities, performance and efficiency, on the other hand, they constitute a challenge for the certification and validation process. Considering the Boeing 787, special evaluation for the most novel systems (Variable Frequency Starter Generators, high-power electrical system, electrically powered spoiler actuators, and composite fuselage manufacturing) were carried out by the Boeing-FAA Critical Systems Review Team [38] to ensure that the criticalities of analysis, design and testing did not constitute a safety issue.

V. POWER CONVERTERS FOR ON-BOARD MICROGRIDS

As detailed in the previous sections, the inherently hybrid AC and DC characteristics of the EPDS implies power electronics conversion stages. Although a different approach to the distribution (e.g., DC distribution) would be possible, the fact that electric motors/generator and DC loads must be supplied makes the power conversion necessary. Many power converter topologies have been proposed and investigated, this section aims at reviewing the most investigated ones for the MEA.

Figure 9 shows a power converter tree, where the main families of DC-AC, AC-DC, AC-AC and DC-DC converters are listed and they are described in the following subsections.

A. AC Power Converter Topologies

In aircraft, there are a variety of applications requiring AC Power Converters. These include:

- Rectifiers – AC to DC
- Inverters – DC to AC
- Direct – AC to AC

Within these classifications, there are a range of topologies and technologies available. This section will consider some of these power converter options for use on existing and future aircraft platform potential.

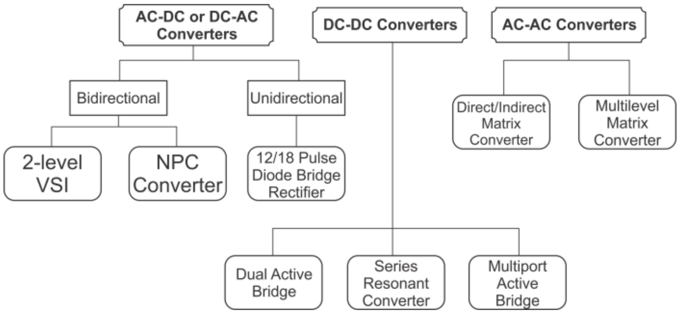

Figure 9. Power electronics converter tree

DC to AC Power Converters

The DC to AC power converter can be one of the most prevalent applications for power electronics on a More Electric Aircraft [2]. These DC to AC power converters are required for the control of AC loads such as electrical machines from a DC bus or supply. In many applications the common six-switch voltage source inverter topology dominates. This is the topology used in the vast majority of industrial motor drives and therefore there is a large amount of knowledge and experience in applying, modulating and controlling this power converter topology and associated loads.

Despite recent advances in power semiconductor devices with the recent practical introduction of Silicon Carbide (SiC) and Gallium Nitride (GaN) [39] materials for switching semiconductor devices there are applications of higher speed electrical machines where the compromise between switching loss and output waveform quality is far from ideal. In these high speed electrical machine applications where high frequency fundamental AC waveforms are required there is therefore consideration for using the three-level Neutral Point Clamped (NPC) power converter topology [40]. The multi-level nature of the output waveform from the NPC means that for the same device switching loss a far higher output waveform quality is possible at the cost of additional semiconductor switching devices.

AC to DC Power Converters

AC to DC power conversion is needed in applications such as connecting an AC generator to a DC electrical system [41] as well as front end power converters for back-to-back AC to AC power converters. Traditionally passive rectifiers using diodes have dominated [42] these applications. Whilst the six pulse diode-bridge has the required functionality, power quality considerations due to low frequency current harmonics mean that in all but the lowest power applications 12 and 18 pulse diode bridge rectifiers are the preferred solution. The addition of more diodes and a phase shifting transformer allows some of the lower frequency harmonics to be eliminated in the AC current waveforms and are the solution assumed in the power quality requirements used in many aircraft [43]. These diode bridge and transformer based solutions are considered to be reliable and effective, but they only allow uni-directional power flow and will therefore always require a braking circuit even if regeneration of electrical energy is allowed by power quality requirements.

An alternative to diode bridge based rectifiers is the use of active power converters in an AC to DC configuration. By turning round the standard inverter circuit and ensuring that there is sufficient inductance on the AC side of the converter it is possible to produce good quality AC current waveforms with just some switching frequency components in the AC current waveforms [42]. If additional power quality is required then an NPC converter can be used in a similar approach as for the DC to AC power converters [41].

AC to AC Power Converters

In motor drive applications on an aircraft with an AC Power system, it is possible to converter the electrical energy and control the load in a single stage converter. This can be a very advantageous solution to enable the weight and volume of the converter to be minimized when compared to the back-to-back connection of a AC to DC and a DC to AC power converter [44]. The dominant power converter technology considered for future applications in this situation is the Matrix Converter [45].

The Direct Matrix Converter uses nine bi-directional switches for a 3-phase AC to AC power converter to ensure that each output phase can be connected to each input phase. There are also a range of Indirect Matrix Converter topologies [46] which offer a different efficiency map and some reduction in device count, although the latter can be at the cost of a reduced operating envelope. The Matrix Converter is a bi-directional power converter, so if regeneration of electrical energy onto the AC grid is not allowed an additional braking circuit is required [47], a slightly more complex solution than those found on traditional back-to-back topologies.

This group of AC to AC power converter topologies have the advantage of minimizing the stored energy within the converter, hence reducing the weight and volume of the passive components. Instead of requiring large DC link storage elements, Matrix Converters require an input filter, usually based on a simple LC single stage filter, to meet power quality requirements. Whilst the number of semiconductor devices increases these devices are generally less stressed so the overall reliability can be shown to be similar [48].

Whilst Multi-level Matrix Converters do exist [49] they are complex topologies and have not been considered for aerospace applications. These topologies have similar advantages as the NPC converter in terms of waveform quality for a particular semiconductor device switching frequency.

B. DC Power Converter topologies

DC-DC power conversion is needed in the MEA framework to:

- Step down the voltage level to feed the low-voltage avionics.
- Regulate the power flow among DC buses.
- Interface the storage.

Hundreds of topology for DC/DC both isolated and non-isolated [50] and it is outside the scope of this manuscript to review them all. From the analysis of the scientific literature on the subject, however, it seems that the isolated topologies, in particular the Dual Active Bridge, has attracted a lot of attention.

The requirements for the MEA constraints the choice of the topology so that only isolated ones are used to interface different buses. In fact, a fault in a DC bus must not propagate to the other ones. Also regarding the voltage conversion between the 270 V DC and the 28 V for the avionics, many efforts have been devoted to isolated topologies.

The most investigated topology is the Dual Active Bridge, that features two H-bridge coupled via a high-frequency transformer. This converter offers galvanic isolation (so that a fault in the LV side does not impair the whole HV bus) and excellent power control. The basic modulation involves the generation of symmetrical square waves at the primary and secondary of the transformer, regulating the power transfer with the phase-shift between the square waves.

The principle of operation is the same as the AC inductive transmission lines, where the voltage angle regulates the active power and the difference in voltage magnitude regulates the reactive power [51], [52].

Soft-switching and high power density constitute additional advantages. The main drawback is the high current ripple in the input/output capacitors, particularly relevant for avionic applications, where electrolytic capacitors are not employed.

Research on the extension of the soft switching range as well as modifications to the basic topology to achieve other optimization targets [53] are reported.

The flexibility offered by the DAB has pushed researcher to extend the concepts to multi-port topologies [54]–[56].

An advantage offered by this kind of concept would be the possibility to interface different buses or different loads while guaranteeing the galvanic isolation.

The advantage of this approach is that in the case of DC distribution, it would be possible to connect the different DC lines without employing solid-state breakers. Once the safety requirement is fulfilled, power can be exchanged between the whole EPDS, allowing for a better utilization of the available resources.

Table 1. Summary of the different kinds of electrical power distribution systems

Microgrid Type	Generator Type	Key aspects	Power Converters
Fixed Frequency	• Permanent Magnet Synchronous Generator	• Conventional system design • Used for low levels of electrification • Need of a constant-speed gearbox	• Transformer-rectifier units • DC/DC power converters to interface with the low-voltage avionics
Variable Frequency AC	• Synchronous generators with excitation control • Induction machines with open-ended windings • Permanent magnet synchronous machines	• Reduced power electronics for the synchronous generator • Used in large commercial aircraft • Starter/generators can be used to provide starting capability to the main engine	• Auto Transformer Rectifier Unit • Transformer-rectifier units • Three-phase DC/AC converters • Matrix Converters
DC	• Permanent Magnet Synchronous Generator	• Reduced number power conversion stages • No reactive power or harmonic instability • Increased complexity in solid-state breakers	• Three-phase rectifiers • Dual Active Bridge • Multiple Active Bridge • Resonant Converters

Table 2. Control systems for the on-board microgrid and their characteristics

Control type	**Control Targets**	**Features**	**Issues**
Primary	• Load current and voltage • DC or AC bus voltage	Local implementation of the inner controls Possibility to use solutions tested in other applications	Customization to the aircraft environment required.
Secondary	• Voltage restoration • Stability improvement • Power flow regulation	Improvement of the distributed control performance. Global network management.	Communication link must be established. Susceptible to single point failure. Several sensors needed.
Storage Management System	• State of charge • Peak shaving • Voltage control	Energy storage scheduling depending on the technology.	Many control targets makes the optimization difficult. Fault isolation required because of the risks.
Multi-objective global optimization	All variables within the specified limits, load prioritization and storage management.	Better performance than distributed control. Possibility to adapt the control targets depending on the flight phase.	Mismatch between predicted and actual mission profile. Computational complexity.

Now, the separate section of the EPDS must be sized based on the peak consumption and power cannot be transferred between sections because of safety reasons. If the whole system is connected, only the overall peak consumption needs to be satisfied. This would probably allow for a reduction of the generators rating with evident benefits in terms of weight.

Power Electronics and Electrical Subsystem mapping

The previous sections have described the power electronics solutions that have been proposed for aerospace application; in this subsection, a brief mapping of the technology to the systems in Figure 3.

- Hydraulic and fuel pumps are directly connected to the distribution (variable AC or DC) without power electronics, the hydraulic systems control the flow.
- Wing de-icing protection are usually connected to the main distribution (AC) by switches without power electronics.
- For cabin pressurization, variable speed drives are adopted, in commercial aircraft, three-phase bridges are used and ATRU provide for the DC Link of the power converters. Matrix converters could be used without the ATRU to provide the same service.
- For the starter/generators, three-phase full-bridge are adopted, although multilevel topologies have been demonstrated in literature [41].
- The low-voltage electronics is supplied by TRU, although DAB or other high-frequency DC/DC converters [57] could be adopted for the same purpose.
- For the actuators, full-bridge converters are commercially used and matrix converters have been demonstrated [58].
- For propulsion in hybrid/electric aircraft, AC drives and motors will be needed; research has been focused on High Temperature Superconductivity [37], [59]. Non-cryogenic solutions have already been proved by using high-power density machines and wide-bandgap semiconductors, as the eFusion aircraft [60], [61].

VI. CONTROL SYSTEM AND RELIABILITY ASPECTS

Control strategies and reliability aspects are strongly connected since a proper control strategy shall be designed in view of achieving high reliability standards.

Control Aspects

As outlined in the previous sections, the on-board microgrid is composed of several components, the distribution system, the storage, and the loads. Control targets are voltage and frequency stability as well as the optimal use of the storage.

The primary controls are embedded in the loads and include the torque/force control for the actuators [58], the control of the rectifier for the electrical generators: synchronous [62], [63], induction [64], permanent magnet [41], [65]. Both standard regulators and more advanced approaches, like predictive control [66] have been proposed.

Regarding the EPDS, the primary control involves the voltage and current control for the regulation of the bus voltage. In this framework, the droop controller has received a widespread attention both for AC and DC microgrids. The basic idea is that a linear characteristics linking voltage/power/current can be embedded in the control system, so that parallel-connected generators can share the power proportionally to their rating. Studies of these approaches are reported in [33], [35], where the different combinations of droop controllers are analyzed.

The droop control allows for a completely decentralized structure of the control, however it is susceptible to steady-state tracking problems, dynamic power sharing and harmonics [67]. For these reasons, secondary controls must be implemented to improve the performance and the stability of the on-board microgrid. Communication between the local controllers and a central one is often required to reach the goals, but communication-less schemes are also feasible [35]. Of particular interest are the control schemes that allow for the reduction of passive components, increasing the power density of the microgrid. In [68] an active stabilization scheme is proposed to ensure the stability of a DC airborne grid in the case of small DC capacitors.

The control of the storage system holds a great importance, because the possibilities of weight reduction and range extensions. The targets of the storage management system are the state of charge, the peak shaving and the voltage support. As different storage technologies have different characteristics in term of energy and power density, the optimal control has been investigated in the literature. In [69], [70] different schemes are evaluated: depending on the optimization target (fuel consumption, component stress) different profiles are generated. Multi-port converters can also be adopted to the purpose of storage interface [54]. Adaptive droop control can be employed to regulate the state of charge and the voltage support without communication between the nodes [71].

Another kind of secondary control is the power flow controller among different bus, that can be realized with virtual resistors and multi-port converter [56]. Virtual resistors can be made adaptive to cope with different bus priority [57].

Global optimization algorithm that include all the targets plus the mission profile knowledge and the storage management are also proposed [72]. As an alternative, off-line optimization based on predefined flight profiles is a viable solution [73], but it is susceptible to errors in the case of mismatch between actual and predicted mission profiles.

The characteristics of the various kinds of control are summarized in Table 2.

Reliability aspects

Regarding the electronic hardware reliability on the aircraft, DO-254 provides the necessary guidance [74]. Accordingly, there are five levels of compliance depending on the effect of failure of a hardware on the operation of the aircraft. The levels and failure rates are summarized in Table 3. The required failure rate of critical loads is 1 FIT for a commercial aircraft.

The FITs are obtained from failure test statistics. 1 FIT corresponds to 114000 years of operation of a component without failure, which does not provide any comprehensive information about the required lifetime of the component. FIT reliability metric is obtained from reliability tests performed on a large number of components and hence, cannot be directly interpreted as the lifetime of a single component. Moreover, the standards are based on constant failure rate λ, which is only applicable in the 'useful life' region of the bathtub curve [76].

Table 3. Failure rate requirement for onboard hardware.

Design Assurance Level	Failure Rate	Remarks
Level A (Catastrophic)	<1 FIT	Loss of aircraft
Level B (Hazardous)	<100 FIT	Fatal injuries
Level C (Major)	<10000 FIT	Discomfort/Injuries
Level D (Minor)	No criteria	May cause inconvenience
Level E (No effect)	No criteria	Safety not compromised

In order to better estimate the lifetime of a component, B_X 'lifetime' is used. It is defined as time at which x percentage of components are failed and is calculated from the unreliability (F(t)) curve given by:

$$F(t) = 1 - exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]$$

Where β, γ, η are the Weibull parameters [75].

However, pure statistics based constant failure rate methods are regarded as inaccurate and too generic for power electronics applications. Hence, Physics of Failure (PoF) based lifetime models are used to explain the wear-out failures in power electronic components such as power devices and capacitors [77]. Since the wear-out process is highly dependent on various factors such as temperature, humidity, mission profile etc., lifetime models are developed to quantify the wear-out of the components. Therefore, the wear-out process determines the useful life of a component. Overcoming the limits of the statistical analysis and tracing the failure down to the root cause is the newest paradigm that is being studied by industry and academia. The goal is to obtain a better estimation of the useful life of the component or the system through comprehensive modeling (Figure 10), allowing for better maintenance scheduling, ultimately resulting in safer flights and reduced cost of ownership.

Regardless the kind of lifetime modeling, as in many other safety critical applications, the goal of the aircraft design is the avoidance of critical conditions (Levels A, B, C in Table 3) that would compromise the safety of the aircraft or the passengers. The Failure Mode and Effects Analysis (FMEA) constitutes the standard tool that is envisaged by the international standards [79]. It is based on the study of the system effects that a failure in a component can cause at system level and takes into account the detectability and the criticality, giving an index of the severity of the issue. Mitigation strategies must be adopted to bring the failures down to the allowed probabilities.

For the on-board microgrid, a catastrophic failure is the loss of power, making it mandatory to have redundant supplies and distribution lines. An hazardous failure is the loss of insulation between appliances that could result in an electric shock, whereas power reduction or power quality issue could cause discomfort (reduced cabin pressurization or temperature, reduction of the cruise speed in hybrid/electric propulsion aircraft etc.).

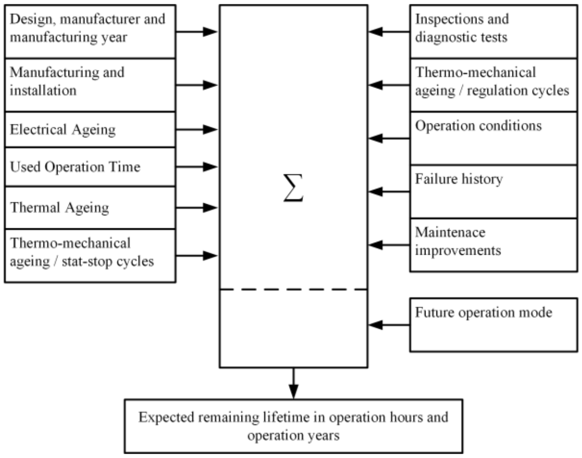

Figure 10. Comprehensive reliability model of a drive system under the physics of failure framework [78].

Regarding the catastrophic failure, as long as the power electronics is concerned, open/short circuit fault handling and fault isolation constitute nowadays an industrial reality.

More difficult is the case of control instability, especially after a partial fault in one or more components of the microgrid. The presence of a high number of intelligent components (loads, power converters, active filters) makes the analysis of the failure effects a difficult task, especially because of the unpredictable interactions between the elements after a failure event. In order to make such complex microgrid a reality, more studies on formal verification of the control are needed [80], [81].

VII. PROTECTION SCHEMES IN THE MEA

One of the MEA concepts uses the DC link (e.g. 270V) as the power supply bus [82]–[84]. Therefore, the onboard power system is operated as a DC microgrid (MG), shown in Figure 11a.

A. Electrical safety and protection schemes

To ensure the safety, proper protection schemes should be designed for the onboard grid. The faults in DCMG can be categorized into line-line fault (FT1 in Figure 11a) and line-ground fault (FT2 in Figure 11a). The protection should be able to locate the fault accurately and to clear the fault fast [85].

The design of the protection affects the topology of DC grid, e.g. the grounding. Two types of grounding, TN-S & IT have been analyzed in different studies [86], [87]. The type of grounding determines the path of the ground fault current and the level of fault current. Other difficulties include e.g. extinguishing arc and the absence of current zero crossing.

The topic of the protection is vast; here one should mention the most important safety protections in MEA EPS which include over- and under-voltage, over- and under- frequency, phase imbalance, overcurrent, power limits, short circuits. Relays have been used to detect the faults [86], [88]. Researches have shown that it is possible to use commercial AC protection devices, such as fuses and circuit breakers (CBs) to protect some types of loads in DC grid. Other methods based on the power electronics such as hybrid DC CB or solid state CB [89]–[91]. Recently, many protections, including I^2t protection to protect wires from excessive currents, overheating and short-circuits, are implemented digitally based on solid-state devices [92]–[95]. The example of deployment of CB is shown in Figure 11a.

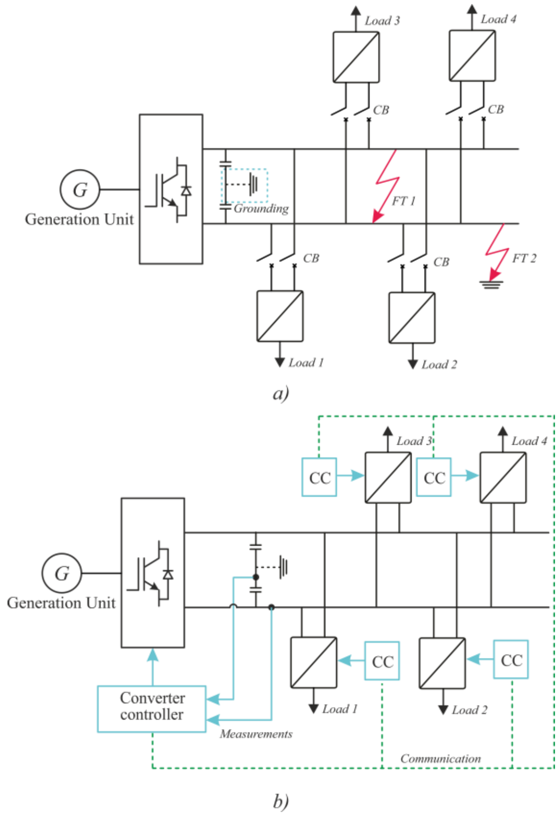

Figure 11 Faults and protection in the microgrid (a), principle of power quality control (CC: converter controller) (b).

B. Power quality to sensitive loads

Regardless the EPS architecture, it should provide the loads with the power quality according to the established standards [43], [96]. One should note that for new platforms an updated standardization documents are required since many requirements of DO-160 and MIL-STD-704F are of legacy nature (harmonic spectrums, emissions, voltage envelopes etc.) and certain aspects of future architectures, such as higher voltage levels or grid frequency range are not covered.

The DCMG proved to ensure a higher power quality, which is a critical issue to sensitive loads. Researches regarding the power quality control have proposed different control strategies [97]–[99].

The principle of power quality control can be summarized as: by means of the multi-functional controllers, the converters in DCMG can regulate the voltage of the DC bus and keep it stable (Figure 11b). In the transient state, the voltage variation is mitigated by the control actions. As an example, in [97], a super-capacitor based energy storage device is proposed: the controller regulates the current flow and state of charge of super-capacitor to meet transient load changes on the DC-bus. DC-bus voltage transients is therefore mitigated and the power quality is maintained.

VIII. CONCLUSION

This overview article has outlined the major aspects of the on-board microgrids for the more electric aircraft: power systems, power electronics and control. The peculiar aspects of this system are the high safety requirements and the absolute need for weight and performance optimization, making it inherently different from a ground-based microgrid.

Considering the actual electrification trends and the future hybrid or electric propulsion aircrafts, emerging research topics in the different research areas can be individuated:

- **Device Level:** high power-density power electronics and machines, fault tolerant converters, DC circuit breakers.
- **System level**: power management system considering fault handling and stability, hybrid microgrids and power flow control, hardware-in-the-loop analysis, reliability-oriented control.

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