Recent Technologies and Control Methods for Electric Power Systems in More Electric Aircrafts: A Review

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Abstract*: This paper is aimed at discussing the current trends in the design of Electric Power Systems (EPS) architectures which are intended to be implemented in More Electric Aircrafts (MEAs). Various EPS architectures such as HVAC, HVDC, hybrid HVAC/HVDC etc are studied and compared. Various control techniques which are implemented in order to control the EPS are also reviewed and they are compared on the basis of power quality, ease of installation and maintenance, possibility of future expansion of EPS, need of active power filters and so on. On the basis of the evaluation of various EPS architectures, the need of fuel cell installation in the EPS to be used for MEAs is explained and various ways to incorporate the fuel cell in the said EPS are discussed. Further the need of DC to DC converters in the power grid of a MEA is discussed and various possible choices for the topologies of DC to DC converters are compared on the basis of the parameters such as efficiency, transient response, reliability, electromagnetic emissions, size, weight and so on. Moreover, various controllers such as PI controller, PID controller, Sliding Mode Controller etc which can be used for a closed loop control of DC to DC converters are discussed.

***Keywords*: More Electric Aircrafts, Fuel Cells, DC to DC converters, Sliding Mode Controller**

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I. INTRODUCTION (*HEADING 1*)

Global warming and Carbon dioxide emissions from transportation systems are constantly becoming a topic of concern for all humanity. According to Intergovernmental Panel on Climate Change, about 2% of total emissions are due to aviation systems working globally. Although aviation is a relatively small source of the emissions contributing to global warming, it is of significance because it is probable that high-altitude emissions are disproportionately damaging to the environment. It is essential to limit the Green House gas emissions for maintaining the environmental balance. Moreover, the fossil fuels are non-renewable sources of energy and are depleting at an alarming rate [1].

The “Advisory Council for Aeronautics Research in Europe” has set a few goals to be achieved by 2020 which include 50% reduction of CO2 emissions through drastic reduction of fuel consumption, an 80% reduction of Nitrogen oxide emissions, a 50% reduction of external noise and a green product life cycle in terms of design, manufacturing, maintenance and disposal. The goals set by the International Civil Aviation Organization are to improve fuel efficiency by an average 2% per year until 2050 and to keep the global net carbon emissions from international aviation at the same level beyond 2020 [2].

It is often claimed that 1 kg saved on each flight could save roughly 1,700 t of fuel and 5,400 t of CO2 per year for all air traffic. Furthermore, a decrease in mass would also be profitable in terms of cost: each kilogram of systems costs approximately US$1,000. Furthermore, mass saving would be profitable: a gain of 1 kg on the systems increases the price by approximately US$1,000. Thus, the aircraft manufacturing industry is placing greater emphasis on the use of technologies that can influence both the overall costs (design, operation, and maintenance) and fuel consumption. In addition to the aerodynamic structure and the engine optimization, equipment systems will also play a major role, especially in reducing operation costs with minimum maintenance and maximum availability.

In this context, the rationalization of power sources has led engineers to an electrical aircraft design in which conventional devices are replaced by electrical systems. This trend is depicted in Figure 1, which displays the evolution of electrical power needs [3].

So far, a conventional aircraft has four different integrated energy vectors (see Figure 2):

- pneumatic power for air conditioning, the wing ice protection system (WIPS) and engine start-up
- electric power for commercial loads and avionic systems
- hydraulic power for pumps and flight control actuators
- mechanical power to drive hydraulic or fuel pumps directly from the engine gearbox.

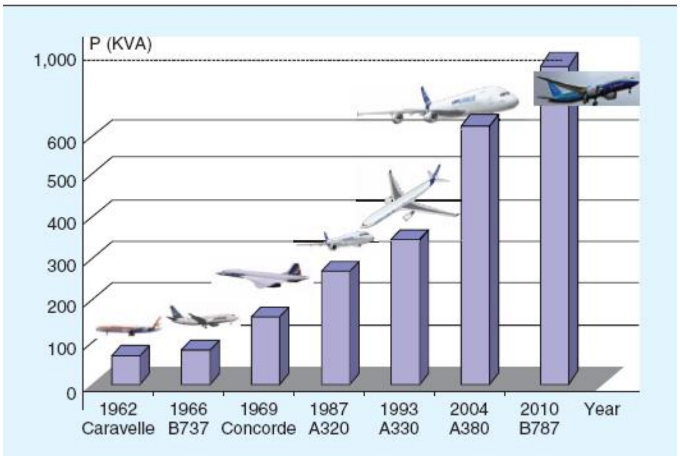

Figure 1 Evolution of electrical power needs

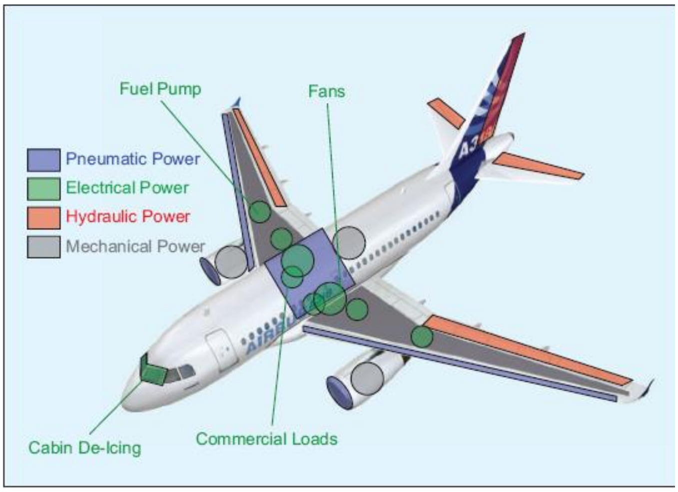

Figure 2 Current architecture with four different energy vectors

In a traditional airplane, the jet engine is designed to produce thrust and to power the pneumatic, hydraulic, and electrical systems, as shown in Figure 3. The pneumatic power is used for pressurizing and cooling the cabin, starting the main engines, and de-icing the wings. The hydraulic power is used mainly for flight control actuators. The electrical power is used for supplying the power to all of the electrical loads, including the computers and avionics systems. In addition, the engines drive the gearbox-mounted units, such as fuel, oil, and hydraulic pumps.

This paper aims at discussing the current trends in the design of Electric Power Systems (EPS) architectures which are intended to be implemented in More Electric Aircrafts (MEAs). Various EPS architectures such as HVAC, HVDC, hybrid HVAC/HVDC etc are studied and compared. Various control techniques which are implemented in order to control the EPS are also reviewed and they are compared on the basis of power quality, ease of installation and maintenance, possibility of future expansion of EPS, need of active power filters and so on. On the basis of the evaluation of various EPS architectures, the need of fuel cell installation in the EPS to be used for MEAs is explained and various ways to incorporate the fuel cell in the said EPS are discussed. Further the need of DC to DC converters in the power grid of a MEA is discussed and various possible choices for the topologies of DC to DC converters are compared on the basis of the parameters such as efficiency, transient response, reliability, electromagnetic emissions, size, weight and so on. Moreover, various controllers such as PI controller, PID controller, Sliding Mode Controller etc which can be used for a closed loop control of DC to DC converters are discussed.

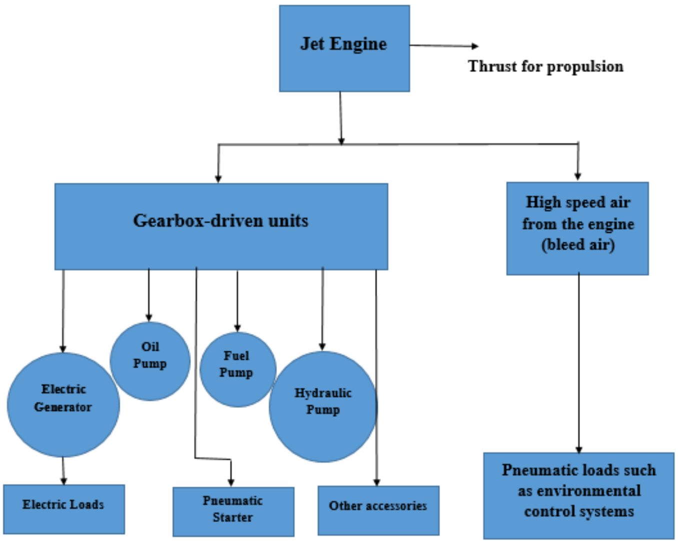

Figure 3. A traditional aircraft system

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II. ABOUT MORE ELECTRIC AIRCRAFT

The More Electric Aircraft (MEA) initiative aims to increase the penetration of electrical systems in aircraft to decrease weight and further develop overall efficiency and reliability. Newer aircraft, such as the Boeing 787 and the Airbus A380, have more electrical power installed compared with older models, and this trend is not expected to change any time soon. Although most aircraft feature some amount of electrical power, this is often limited to the electronics (i.e., flight or entertainment systems) or auxiliary systems (i.e., lighting or anti- icing). The core systems of the actuation still rely on hydraulic power. The power density and reliability of the hydraulic actuators are known to be high; however, the oil distribution system is bulky and prone to leaks, and this counterbalances the advantages of the actuators. Another relevant issue of the hydraulic distribution system is that a bleed valve on the main engine usually powers the main oil pump, which deteriorates the efficiency of the main engines. Other systems that normally rely on the bleed air, such as those for environmental conditioning, can be substituted by a compressor powered by the electric system, as has been done on the Boeing 787 [4], [5], [6].

Beyond mass or fuel consumption reduction, the advantages of the more electric aircraft are found in power/energy rationalization and subsequent gains in terms of power management. The aircraft's operation costs include both the direct operating costs (fuel consumption, etc.) and the indirect costs linked to maintenance and availability. For example, 75% of late flights are due to system faults. An electrical device will not offer improved reliability but would increase availability thanks to the opportunity to isolate a subsystem in case of failure. On the contrary, a hydraulic leakage in a device leads to the isolation of the entire circuit, which provokes a "No Go" fault. The failure of a hydraulic circuit is equivalent to an electrical bus bar failure, whose probability is 100 times less. It may even become possible to anticipate faults in the near future through the health monitoring capacity. Anticipating failures of an electrical network would be possible through the behavioral modeling of systems coupled with fault-detection algorithms [7].

Gains are also expected on the ground. On the one hand, an electrical ground card may replace all ground power services (air starters, aircraft hydraulic system, cabin pressure testing, etc.) by offering a better power rationalization. On the other hand, oversized "green" electrical ground services could be used instead of the auxiliary power unit (APU), which approximately burns 100 kg/h of fuel. Furthermore, using the landing gear system as a motoring system on the ground during the taxi phase, so as to allow airplane engines to idle back during this phase, would allow replacing pushback tugs with the expected triple benefit of reducing ground noise, fuel consumption, and CO2 emissions. The required power is almost 100 kW, which is compatible with the APUs of more-electrical aircrafts.

III. Electric Power System Architectures for More Electric Aircrafts

With increased onboard power generation, the problem of power distribution arises. Because the aircraft is an isolated system with generators and loads, the distribution system can be considered an onboard microgrid. Different paradigms are possible depending on the amount of power electronics installed and the characteristics of the actuator. These have been standardized in *Aircraft Electrical Power Characteristics*, Department of Defense Interface Standard: Aircraft Electric Power Characteristics MIL-STD-704F as constant voltage/constant frequency, constant voltage/variable frequency, and dc distribution.

In the case of constant voltage/constant frequency, a constant speed gearbox is powering the generator, and a power is distributed through a three phase 115 V, 400 Hz system. This solution can not be widely adopted since the constant speed gearbox used to provide the constant speed shaft is complex and bulky. In the case of constant voltage/ variable frequency, electrical generators with controllable excitations are connected to variable-speed shafts supplied by the main engines. However to achieve the variable frequency systems, frequency converters are required which again raise the weight of the aircraft. Moreover the problem of synchronization of multiple generators connected on the main shaft makes the system more complex. Finally, with a dc distribution, an AC to DC converter converts the generator power into a high-voltage (HV) dc supply and then all the auxiliary systems are designed to operate with dc voltage. DC to DC converters are needed to be designed for the LV side but still this solution simplifies the actuation system, since standard voltage source inverters can be adopted instead of back to back or matrix-based converters. The standards have contemplated voltage levels of ±270 V DC [8]. Figure 4 illustrates various possible power generation strategies which can be used in more electric aircrafts.

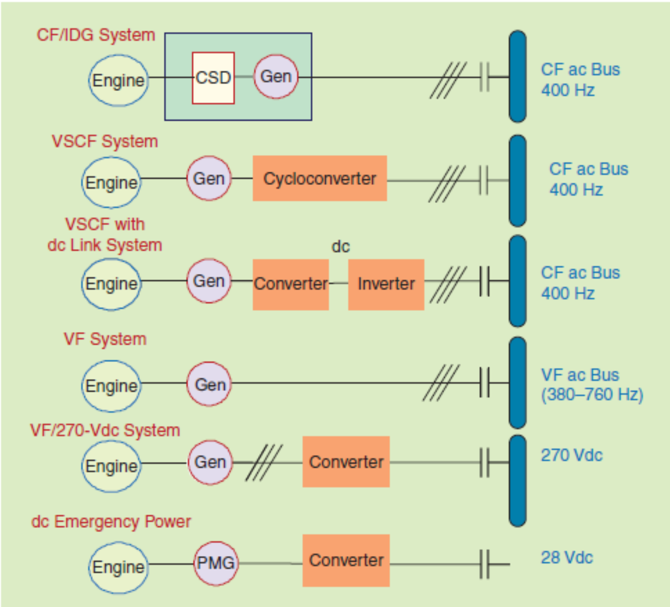

Figure 4. Various electric power generation strategies in more electric aircraft

A lot of research is being done about what type of architecture should be adopted for the power system to be used in a more electric aircraft. As mentioned above, the choices are constant voltage/constant frequency, constant voltage/ variable frequency or dc distribution. Moreover, a mix of these choices can also be implemented to get benefitted by the positive traits of each of these topologies. Reference [9] suggests use of pure HVDC architecture as compared to a hybrid HVAC/HVDC architecture because even though both the architectures give almost same volume and weight to the power system, the former offers a better system stability and a smaller dc capacitor is sufficient to stabilize the system. Therefore a DC distribution system seems like the most suitable option so far as MEAs are concerned.

IV. Integration of Fuel Cells in More Electric Aircrafts

Replacing pneumatic and hydraulic components of an aircraft with the corresponding electrical ones make the use of an electric power source obvious in case of emergencies. Besides, replacing crucial actuators of an aircraft with their electric counterparts makes the choice of the power source issue more sensitive and of much more importance. Current auxiliary power unit (APU) systems being used in aircrafts are heavy, noisy and inefficient, so a new form of power source to replace the engine mounted generator technologies is in demand. As a green power source, fuel cell seems like a tangible solution to the problem mentioned above. Many research articles like [39],[40],[28],[41],[23],[42]-[46] focus on the use of a fuel cell as a potential power source to replace the conventional APUs and the studies suggest that fuel cell based system performs better in the aspects of specific energy, specific power, efficiency, complexity and so on. With the development of the fuel cell stack, power electronics and hydrogen storage technologies, the fuel cell based APU is hopeful to be applied for MEAs. A hybrid electric power supply system also seems like a good option as per research paper [42] in which the energy management system is suggested to be chosen depending on the operating life of each energy source, to either minimize the stress on the fuel cell system, the battery system, or the supercapacitor system, hence maximizing the life cycle of the hybrid power system.

Paper [39] discusses the advantages and disadvantages of fuel cell and batteries. The advantages of fuel cells are that they generate power as long as fuel is supplied, they have zero emissions, are silent, and they have no moving parts (and thus function reliably). Their disadvantages include their long start-up time and slow dynamics. On the other hand, the advantages of batteries are their dynamic response time, on the order of milliseconds, and that they can charge and discharge for up to 1000 cycles. Batteries' disadvantages include their long recharge time, low specific energy compared to a fuel cell and limited discharge time.

Paper [40] investigates the feasibility of the fuel cell as an APU. The qualitative analysis in the paper shows that proton exchange membrane fuel cell (PEMFC) system performs the best. Then a PEMFC based APU system is proposed and designed theoretically. Comparisons between the new APU system and original one in B787 suggest that fuel cell based system performs better in the aspects of specific energy, specific power, efficiency, complexity and so on. With the development of the fuel cell stack, power electronics and hydrogen storage technologies, the fuel cell based APU is hopeful to be applied.

Papers [41], [42], [43] discuss the current trend in aircraft batteries, hybrid nature of the power supplies being used in aircrafts and their pros and cons. With all the gathered information, fuel cell seems like the most feasible option for implementation in aircrafts owing to their specific energy, specific power, efficiency and eco-friendly nature.

V. Various Control Techniques used in More Electric Aircrafts

A lot of study has already been done about various possible power system architectures which can be used in more electric aircrafts. Different power system topologies call for the use of various power electronic converters such as inverters, matrix converters, DC to DC converters etc. Research papers like reference [47],[48] illustrate the incorporation of inverters in the electric power system structure of a more electric aircraft.

The authors of paper [47] have developed a prototype of 50-kW SiC two-level three-phase voltage source inverter with a gravimetric power density of 26 kW/kg. The converter is operated at a switching frequency up to 100 kHz and a narrow dead band of 250 ns.

In reference paper [50], a three phase three level diode clamped inverter operating at 400Hz frequency has been designed and developed, having lesser distortion factor. Use of inverters and rectifiers, however, arise a question of harmonics mitigation and power quality improvement. Hence a lot of rigorous study has been done regarding these issues and all the possible solutions are investigated in papers [49]-[52].

In paper [49], a feedforward compensation path of load current is proposed which is based on the analysis and modeling of the shunt APF with close-loop control. Authors claim that it improves the dynamic performance of the APF. As mentioned above, the increase of power electronic subsystems in more-electrical aircrafts (MEA) brings severe challenges to aircraft power distribution in terms of power quality on board.

Paper [50] tries to address to this issue by suggesting a five-level active shunt filter topology with an enhanced deadbeat current controller for a fixed frequency 400 Hz aircraft power grid. The proposed controller features a high bandwidth of the current control loop, capable of high frequency harmonic compensation, using a reduced devices switching frequency. The proposed topology is tested for a Variable Speed Constant Frequency (VSCF) aircraft electric power system.

Reference paper [51] presents the design, simulation and implementation of a Multilevel Aeronautical Active Power Filter (AAPF) for a Variable Speed Variable Frequency (VSVF) advanced aircraft electric power system. AAPF are most commonly used to mitigate current harmonics, improve the source power factor and to mitigate the effects of unbalanced loads. The Aircraft Electrical Power System (AEPS) is very different than the residential and industrial power systems, in this systems, the frequency may vary between 360 Hz and 900 Hz, and the load dynamics is often modified. Therefore, for aircraft purposes an enhanced filtering technique is required, especially if an AC power system architecture is adopted.

In paper [52], A Shunt Active Filter (SAF) based on modular multilevel converter (MMC) topology is proposed that can be used to track and compensate the harmonic contents of the load currents in an aircraft power distribution system. The implementation of the SAF is conducted with current control scheme utilizing finite control set-model predictive control (FCSMPC) algorithm. The authors have emphasized on system transients and steady-state behaviors is considered through variations in loads, supply impedances and operating frequencies.

Reviewing such references related to an AC power structure alongwith the required power quality enhancement modules once again highlight the fact that the HVDC architecture seems to be the simplest choice for aircraft applications. Figure 5 shows the block diagram of the DC architecture mentioned above.

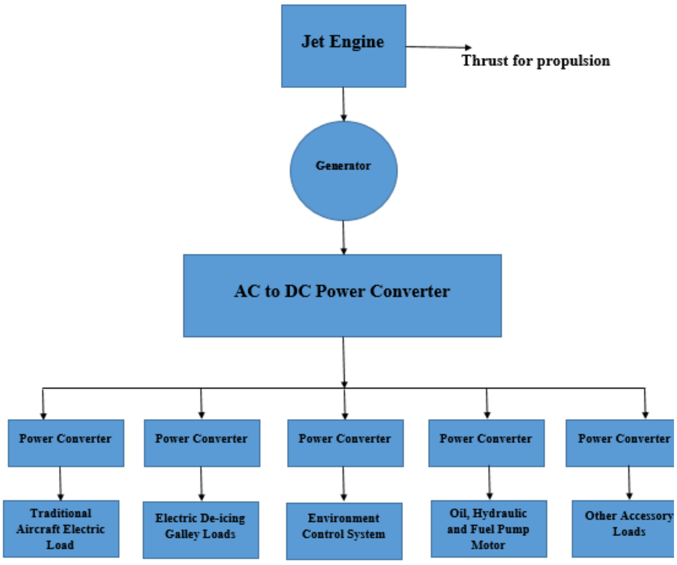

Figure 5. More Electric Aircraft with DC electric power system architecture

Figure 5 shows that the power generated by the turbines mounted on the shaft of the engine will be first converted to DC power using a suitable rectifier and then the power will be fed to all the loads through suitable (DC to AC or DC to DC) power converters. Figure 6 shows the typical DC power distribution system in case of more electric aircrafts.

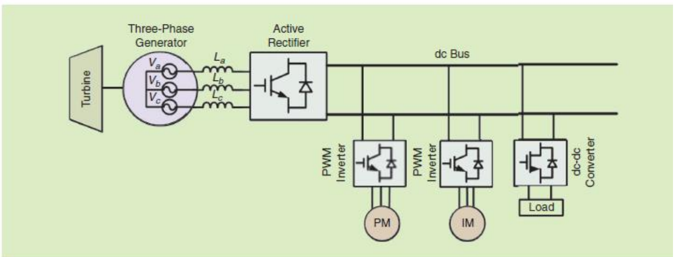

Figure 6. DC power distribution system in MEA

VI. DC TO DC CONVERTER TOPOLOGIES

The scenario where multiple high voltage and low voltage buses are present, a power electronic converter installation becomes mandatory. Many novel topologies and control techniques of DC to DC converters have been suggested in the research papers [10]-[16] to minimize the fuel consumption, improve system efficiency and to ensure a faster transient response, a reduced electromagnetic emission and an improved reliability. Paper [17] introduces an advanced DC-link variable voltage control methodology that improves significantly the fuel economy of series Hybrid Electric Vehicles (HEVs). The DC-link connects a rectifier, a Dual Active Bridge (DAB) DC-DC converter and an inverter, interfacing respectively the two sources and the load in a series HEV powertrain. The introduced Dual Phase Shift (DPS) proportional voltage conversion ratio control scheme is realized by manipulating the phase shifts of the gating signals in the DAB converter, to regulate the amount of DAB converter power flow in and out of the DC-link. Dynamic converter efficiency models are utilized to account for switching, conduction, copper and core losses. The authors conclude that the dual phase-shift control method remarkably offers persistent DC-DC converter efficiency improvements that approach 10% over the single phase-shift control, and fuel economy improvements that approach 4% over the constant voltage control.

Paper [18] suggests the use of interleaved boost converter (IBC) in several applications which require increasing the output voltage such as fuel cells, photovoltaic cells and batteries that can be installed for EPS in More Electric Aircrafts. Thanks to the advantages related to the conventional boost converter, there are low input current ripples, a higher efficiency, a faster transient response, a reduced electromagnetic emission and an improved reliability in the topology proposed by the authors.

Paper [19] investigates a novel pulse width modulation (PWM) scheme for two-phase interleaved boost converter with voltage multiplier for fuel cell power system by combining alternating phase shift (APS) control and traditional interleaving PWM control. The APS control is used to reduce the voltage stress on switches in light load while the traditional interleaving control is used to keep better performance in heavy load.

Focus of paper [20] is on the topologies of galvanically isolated impedance-source dc–dc converters. These converters are particularly appropriate for distributed generation systems with renewable or alternative energy sources, which require input voltage and load regulation in a wide range. Authors of this paper conclude that quasi Z source inverter based DC to DC converters have advantages over the impedance source based converters for emerging applications.

In paper [21], an interleaved reduced-component-count dc/dc converter is proposed for power management in fuel cell powered vehicles with a multivoltage electric net. This converter features better capability to handle high power levels and a reduced component count.

In paper [22] a fixed frequency operated bidirectional series resonant (BSR) converter is proposed for energy storage system in dc microgrid. The proposed system possesses the desirable properties such as bidirectional voltage and power flow regulation, buck and boost voltage conversion capabilities in both forward and backward modes, smooth and automatic mode transition etc.

In paper [23] a power density optimised DC/DC-converter for the integration of a multifunctional fuel cell system (MFFCS) to a +/- 270V bipolar high voltage DC (HVDC) grid in a more electric aircraft is presented. A hard switching cascaded buck-boost converter module with optimised power density for aviation has been developed with silicon MOSFETs. At the worst combination of input voltage and load scenario the power module is still capable of converting 24kW output power. Without EMC filters, housing and other components the pure power module including the gate drivers has achieved a power density of more than 8.3 kW/kg. The stability of the system has been tested for several hours at a liquid cooling temperature of 80 degree celcius. The efficiency of the proposed DC/DC-converter was determined by measurement and has been at least 95% in all specified operating points.

In paper [24] the design of a dedicated power convertor, within a future aircraft with a 270 V dc based Electrical Power System is considered. The power convertor is required to supply an Electronic Engine Controller (EEC), a mid-power aircraft electrical sub-system which resides in a non-pressurised environment.

In paper [25], a non isolated dc–dc converter with high voltage ratio is proposed to interface between the fuel cell and high-voltage dc bus. An energy control structure has been proposed to manage the transfer of energy in the system based on flatness principle. The authors suggest implementation of a nonlinear current controller to improve robustness of the proposed system and to make is feasible for critical applications like in case of MEAs.

Many other research papers like [26]-[31] suggest the use of Dual Active Bridge Converters, Triple Active Bridge Converters or Quadraple Active Bridge Converters in the architecture of power system for a MEA. These can effectively be used as a storage manager for the MEA, guaranteeing the galavanic isolation between the ports and prioritizing the energy consumption from the fast energy sources depending upon the load priority and power availability. The main challenge in such topologies is to control the power flow between different sources in a highly coupled structure of the QAB. In research paper [31], the authors put forward the problems of power coupling and strong non-linearity in traditional three-port triple active bridge (TAB) converters, and propose a decoupled TAB topology, which has the feature of decoupled power flow. The topology is compatible with ±270 V DC, 28 V DC and energy storage system with high-power density and efficiency.

In paper [26], A 270/28 V SiC MOSFET DAB converter has been proposed for MEA applications. An investigation about the thermal behavior of the converter in case of high ambient temperatures has been provided in order to verify compliance with harsh environments conditions. Feasible operation of the DAB converter can be guaranteed for ambient temperatures over 300 °C thanks to the superior performances of the SIC MOSFETs.

VII. Control Techniques for DC to DC converters

Design and implementation of a closed loop efficient dc to dc converter becomes the most important aspect while designing a microgrid with all the mentioned qualities. Papers [32]-[35] discuss various control techniques like PI, PID, fuzzy controllers etc for closed loop control of DC to DC converters. Papers [36]-[38] talk about use of sliding mode controller for DC to DC converters. Sliding mode controllers are non-linear controllers originally used for variable structured systems. The major advantages of SMCs are the guaranteed stability and the robustness against parameter, line, and load uncertainties. The SMC method is particularly suitable for handling non-linear systems with uncertain dynamics and disturbances because of its order reduction property, which relaxes the burden of the necessity of exact modeling. Also, the main advantage of SMC over a PI controller is smaller response time and no overshoot. Moreover, being a controller that has a high degree of flexibility in its design choices, the Sliding Mode Controller is relatively easy to implement as compared with other types of nonlinear controllers. Such properties make it highly suitable for control applications in nonlinear systems. Incidentally, characterized by switching, dc-dc converters are inherently variable-structured. It is, therefore, appropriate to use Sliding Mode Controllers for the control of dc-dc converters Instead of using conventional PI controllers for the control of output of DC to DC converter which have problems like overshoot, larger rise time and settling time etc, Sliding Mode Controller seems like a good option which has much better transient response as compared to that of the conventional controllers.

VIII. Conclusion

From the review of the research papers in the field of the current trends in the design of Electric Power Systems (EPS) architectures which are intended to be implemented in More Electric Aircrafts (MEAs), it seems that implementation of an HVDC system in the EPS architecture of a MEA is the most feasible option owing to its small size, low maintenance, high reliability and ease of installation and control.

Implementation of HVDC microgrid calls for a reliable dc source-batteries and fuel cells being the options. A rigorous review of the research papers associated with the two options shows that fuel cell is going to be the future of the EP in MEAs because of specific energy, specific power, efficiency and eco-friendly nature. A significant work has already been done in the area of fuel cells, passive components, and EMI technologies by the industries involved in automation of electric and hybrid electric vehicles. The fuel cells being developed for automotive propulsion could be used as APUs for powering a dedicated load, such as the galley or wing de-icing load, in MEAs. Because of the similar voltage and power ranges in EVs/HEVs and MEAs, the electrical systems for aircraft could be developed using similar technologies with modifications to meet the MEA requirements, particularly related to high-altitude conditions, wide temperature variations, and safety.

Various control strategies necessary for an EPS used in MEAs are discussed considering both AC as well as DC EPS and it seems that using an AC EPS for MEAs will complicate the system architecture owing to the problems like harmonics mitigation and power quality improvement associated with AC architectures. As against that, using a DC power system will automatically keep these problems at bay and make the structure simple.

Further the need of DC to DC converters in the power grid of a MEA is discussed and various possible choices for the topologies of DC to DC converters are compared on the basis of the parameters such as efficiency, transient response, reliability, electromagnetic emissions, size, weight and so on. The current trend show the implementation of dual or triple or quadruple active bridge converters have all the merits mentioned above and can be implemented in MEAs. Moreover, various controllers such as PI controller, PID controller, Sliding Mode Controller etc which can be used for a closed loop control of DC to DC converters are discussed and sliding mode controller seems to be the most appropriate controller for the application in DC to DC converters.

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