1. DESIGN OF MODULAR, CFRP-ENCASED ELECTRICAL POWER SYSTEMS FOR MORE-ELECTRIC AIRCRAFT APPLICATIONS

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ABSTRACT

Decarbonisation of aviation is directly supported by the twin trends of electrification of aircraft, and use of light-weight, carbon fibre reinforced polymer (CFRP) aircraft structures. The concept of creating a modularised electrical power system (EPS), with EPS equipment encased in CFRP opens up new design opportunities for electrification of aircraft systems; reduced weight and volume, reduced time out-of-service due to maintenance. Such systems necessitate an understanding of how electrical and structural systems interact, and the design boundary between the CFRP providing combined electrical and structural functionality, versus CFRP with a purely structural functionality, with a separate electrical system encased in CFRP.

A power electronic converter (PEC) is an enabling technology for the more-electric aircraft EPS. The paper identifies the key design interdependencies, trades and integrated systems design levers for design of a CFRP casing for a PEC module through a conceptual case study. This includes the capture of high and low frequency electrical functionality, thermal management requirements, and their interdependencies with the topology and functional role of the PEC and the wider EPS architecture. This knowledge is combined to present a design methodology for the design of composite casings for PEC in modularised, on-board electrical power systems.

2. INTRODUCTION

Electrification of on-board aircraft systems on more-electric aircraft (MEA) offer a route to more efficient aircraft systems, for reduced fuel burn and emissions [1]. A significant challenge is that the weight of the EPS must not mitigate the benefits of electrification. In parallel to electrification of aircraft systems, carbon fibre reinforced polymer (CFRP) has been increasingly used for aircraft structures due to its superior mechanical performance compared to metallic materials such as aluminium. More than 50% of the structure of a state-of-the-art MEA is formed from CFRP, reducing the weight of the structure by around 20% [2]. A significant challenge is that CFRP is ~1000 times less electrically conductive than aluminum (e.g. reported as ~30 kS/m in [3]). Hence electrical and CFRP structural systems must be kept physically separate on aircraft. This requires additional infrastructure, adding weight and bulk to the combined systems.

The identification of methods to enable the closer integration of the electrical power and structural systems offers a route to lighter weight, more compact systems. This includes encasing EPS equipment in CFRP, to form a compact, modular EPS. Additional benefits of this concept are the reduced part count, and ability to more easily swap equipment in and out of a system, reducing time out of service due to maintenance [4], similar to a line replaceable unit.

A design methodology is needed to identify and combine the interdependencies between the electrical equipment topology, CFRP design and the wider electrical power system (EPS) to find a viable solution space for the casing design. The component casing must have appropriate electrical and thermal characteristics, while maintaining mechanical strength. Consideration

must be given to how the casing will interact with high and low power rated electrical components, across the low (<MHz) to high MHz frequency spectrum.
To enable the design of these casings, it is necessary to capture the requirements of the casing, exploring these interdependencies in detail and understanding which design parameters the system design is sensitive to, and which can be adapted. This paper will use the casing design for a power electronic converter (PEC) as a case study to explore this design process and identify the key areas for future research to enable these casings to be designed, bringing the lightweight benefits of these solutions.

3. OUTLINE OF PROPOSED METHODOLOGY

The design of a casing for a sub-section of the EPS is an interdependent design process, incorporating the equipment to be encased (in this case a PEC), the wider EPS and the layup and design of the CFRP forming the casing, as indicated in Figure 1. The viable solution space is indicated by the blue area in the centre of Figure 1. The aim of the methodology is to determine pathways to the manipulation of that viable design space.

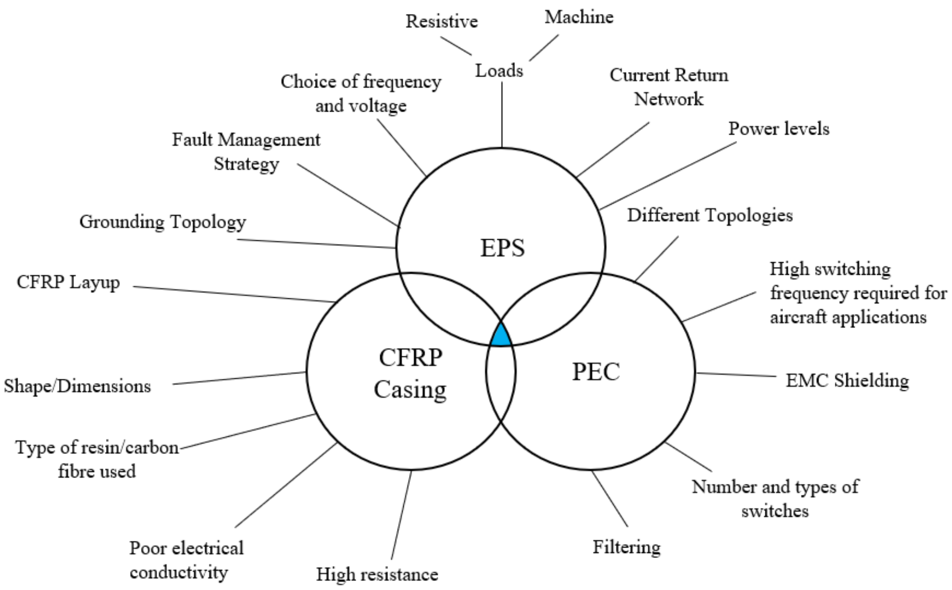

Figure 1. Influences on the CFRP electrical equipment casing design space

A number of different design considerations which affect the viable design space are indicated in Figure 1 for each of the three main areas. Decisions made at a full systems level will determine the role of the PEC in the EPS, and hence the required functionality of the PEC, choice of PEC topology and associated filter design. For example, the approach to fault management strategy will influence whether the PEC must provide current limiting functionality. The choice of voltage and frequency for power distribution influences the levels of electrical insulation required, size of cables and operating temperatures. This influences physical layout, and approaches to thermal management: higher power rated equipment may require liquid cooling, whereas at lower powers natural air cooling may be sufficient.
A significant challenge for the use of CFRP as an electrical casing is the low electrical conductivity of CFRP. At low frequencies, conduction of electrical current results in localised Joule heating, and hence at present, CFRP cannot form part of the EPS. The EPS on composite aircraft has a metallic current return network (CRN) [5]. Adaption of the approach to low frequency grounding on the EPS impacts on the current carrying requirements of the CRN.

To ensure that the PEC meets the industrial standards on EMI, RTCA DO160 [6], the casing must have appropriate electro-magnetic (EM) shielding effectiveness (SE). The ability of EM shielding to be provided by carbon fibre is demonstrated in [7], where 75 dB is reported at 1GHz.

Therefore the casing design space is hugely complex, with multiple interdependent factors. In order to find viable solutions, the design process in Figure 2 is proposed.

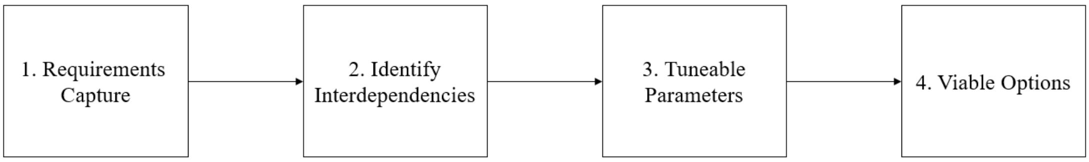

Figure 2. Methodology for the development of key design rules for CFRP casing

The first stage ("1" in Fig. 2) is to capture the requirements of the casing. The focus of this paper is the electrical design, this is interdependent with thermal and structural requirements. The physical location of the PEC in the aircraft will influence both structural and thermal requirements. Thermal requirements will also be influenced by the approach to thermal management, which is driven by the level of losses (dissipated as heat) from the encased electrical equipment. From an electrical perspective, there are several requirements that must be captured: the range of frequencies that the equipment will work with, including fundamental frequency of any power distribution and the switching frequency of the converter; the electrical voltage and power level of the equipment; the approach to fault management and grounding topology.

In stage 2, the interdependencies between the EPS, PEC and CFRP layup design, are mapped out. At this stage, two critical elements must be determined. First, what are the elements of EPS, PEC and CFRP design which influence and drive design decisions in other areas. For example, the required functionality of the PEC is determined by a decision made at systems level. Second, which of these interdependencies are the design of other systems very sensitive to, and which are less critical. For example, the choice of a high voltage, DC transmission system drives the need for a multilevel PEC topology.

Following on from identifying and understanding interdependent interactions (stage 2) which occur when designing a casing to meet the requirements from stage 1, in stage 3 the tunable parameters which enable manipulation of the viable design space are determined. When all tunable parameters have been determined they will be ranked in terms of ease of implementation and effectiveness. The level of tunability of individual parameters must be assessed. Some parameters will be more tunable than others: for example it may be possible to adapt the choice of PEC topology, but it may not be possible to change the type of fibre used in a layup from polyacrylonitrile (PAN) to pitch (to improve electrical and thermal conductivity) without disrupting the whole CFRP supply chain.

Stage 4 determines the final viable options for the CFRP casing. During this phase, candidate solutions are verified to meet the design requirements set out at Stage 1. While the full design process is currently conceptual, in the future it is expected that it will be supported by a mixture of computer simulation modelling, and where necessary experimental testing.

4. CONCEPTUAL PEC CFRP CASING DESIGN

4.1 Capture of design requirements

4.1.1. Influence of EPS architecture on casing requirements

Figure 3 shows one channel of a dual channel EPS for an example state of the art MEA, based on published information for the EPS on the Boeing 787 [8]. The full EPS is rated at ~1.5 MW, and incorporates a wide variety of power levels, power conversion stages, energy sources and electrical loads. The main AC distribution system is rated at 230 Vrms, with a variable frequency (350 – 800 Hz) to match variations in engine speed. This voltage is converted to +/- 270 Vdc via an auto-transformer rectifier unit (ATRU). This busbar is used to supply dedicated loads on the aircraft. A DC-DC converter steps the voltage down from 270 Vdc to 28 Vdc. The AC-to-AC PEC provides an AC voltage of 115 Vrms at 400 Hz. A transformer rectifier unit (TRU) converts 230 Vrms to 28 Vdc. The loads supplied by the EPS are a mix of rotating electrical machines, such as the environmental conditioning motor (80 kVA), EMA (electromechanical actuators) and EHA (electro-hydrostatic actuators) (2 – 40 kW), fuel pumps (200 kVA total), wings ice protection systems (up to 200 kW [9]), galley loads and avionics.

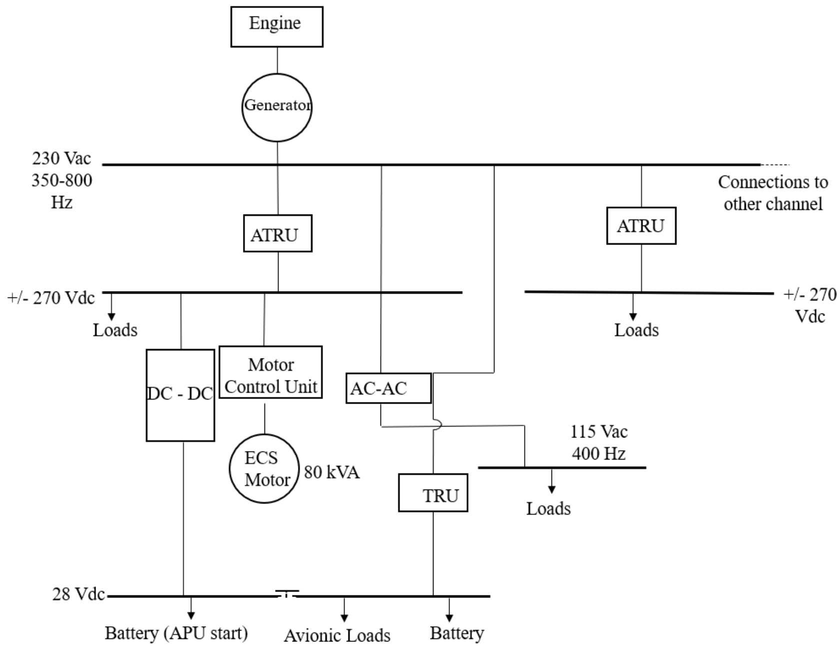

Figure 3. Example EPS Architecture for MEA

Aircraft electrical power systems are grounded using a TN-C-S grounding topology [10]. This topology uses a 4-wire system with a solidly grounded neutral point. In the event of a low impedance short circuit to ground fault a high fault current will flow as a result of the low impedance of the grounding point. This enables detection of the fault using the over-current or under-voltage methods [11]. This fault current can be limited through different grounding topologies. The current return network on the aircraft must be as close to equipotential as possible [12]. Due to the low electrical conductivity of CFRP, it cannot form part of the current return network. Any electrical bonding between the electrical equipment and metallic (conductive) casing, must have a maximum resistance of 2.5 mΩ, if fault current is expected to be greater than 5 A [13]. On existing aircraft with composite structures, the current return network is formed from metallic cables and straps, combined with existing metallic components [5]. In existing aircraft, cable harnesses are used to ensure physical separation between electrical cables and the CFRP structure. The detection of electrical faults through

CFRP is challenging, due to the variable electrical resistance which CFRP adds to the fault path, depending on the grounding configuration. A possible solution is the use of a high resistance grounding topology, to decouple fault response from fault resistance. However, methods to locate the electrical fault in these system topologies require further exploration.
Therefore the EPS influences not only the voltage, power and frequency rating of cables passing into, and within the encased equipment, but also the approach to fault management and grounding directly influences changes to system parameters in the event of a fault. Combined these impact on methods to control (or prevent) electrical current conduction through the casing, the physical size and temperature of cables that may be routed on or through the casing, and the associated required electrical and thermal properties of the casing.

4.1.2. Influence of PEC on casing requirements

The ATRU, used to convert from variable frequency AC to +/-270 Vdc in the MEA architecture in Figure 3, is an example of a PEC in the aircraft which uses uncontrolled switches. The auto-transformer windings are needed to improve power quality by reducing the ripple in the output voltage. The advantage of using uncontrolled diodes, rather than controlled devices, such as integrated bipolar transistors (IGBT), is the lower losses and robustness of the diodes. The TRU offers galvanic isolation between input and output voltages, the ATRU does not offer this functionality. When considering the impact on the casing design therefore, the devices first, do not require accommodation of control units and associated cabling. Second, galvanic isolation impacts on pathways that fault currents may take through casing to reach electrical ground.
In cases where a higher level of control is needed of output current and voltages, converter topologies with controlled switches can be used. These devices switch at much higher frequencies than the fundamental system frequency (10s of kHz and higher) and as such losses are higher. However, increasing the switching frequency reduces the size of the required filters. Neutral point clamped (NPC) converters provide a natural neutral point that can be connected to the electrical ground. Multilevel converters with more than 2 levels provide a route to rating converters for higher voltages. Switching devices made from Silicon Carbide (SiC) and Gallium Nitride (GaN), rather than silicon, offer potential for higher switching frequencies with low losses for different voltage levels [14]. However, a faster switching frequency increases EMI emissions which must be taken into account [15]. This offers a pathway to increase power density of the PEC.
Therefore the choice of PEC topology impacts directly on the casing requirements, at a fundamental level by influencing the physical size of the casing. The casing must accommodate passive components for filters, circuitry associated with control, and the switching devices. Due to the large number of components housed within the casing, it must be of sufficient size so that the components are evenly distributed across the base so that localised heating does not occur in components or casing. The losses of the PEC are dissipated as heat, and therefore these influence the thermal management system and how this is incorporated into the packaging. Methods for thermal management of PEC are either natural cooling (heatsink), forced air cooling (air blown across heat sink) or liquid cooling. The converter topology and the approach taken to electrically connecting a neutral point to ground, directly link to how the casing is bonded to the current return network and paths taken by fault and zero sequence currents.

4.1.3. Influence of CFRP on casing requirements

The electrical and thermal properties of CFRP are strongly influenced by the orientation of the fibres within the CFRP, the carbon fibres and resin matrix forming the layup, the physical dimensions of the CFRP component, and the location, and method used (bolt, flange) for any electrical bonding of the casing to the current return or metallic structural network. A critical requirement for the casing is that any localised heating of the CFRP does not result in the glass transition temperature of the resin matrix being reached, as this may lead to thermal degradation of the CFRP layup. Heating may be due to external, environmental conditions, thermal losses from equipment in the casing, or due to conduction of electrical current in the CFRP (e.g. under electrical fault conditions).

Unless methods to adapt CFRP to increase the electrical conductivity of the CFRP to high enough levels suitable for low frequency electrical conduction can be developed, the casing cannot conduct electrical current. Hence methods to ensure cables can be routed through, or over CFRP are needed. The influence of the CFRP on electrical fault conditions, and approaches to fault management must be considered. At high frequencies, it may be possible to adapt the casing to provide appropriate EM shielding. This is demonstrated in [16], where the initial shielding effectiveness for the CFRP layup was 12 dB at 1MHz. An aluminium coil is used to create a Faraday cage to improve the shielding effectiveness to 80 dB at 1 MHz.

4.2 Identification of interdependencies between EPS, PEC and CFRP design

From identifying the requirements on the casing design from the perspective of the EPS, PEC and the CFRP, the next stage in the design process is to map out interdependencies between these three areas. Table 2 provides a selected sample of these interdependencies for the design of a CFRP casing for a PEC.

Table 1. Influence of casing requirements on EPS, PEC and CFRP layup

	Design interdependencies		
Casing Requirement	EPS	PEC	CFRP Layup
Appropriate electrical conductivity for EMC shielding	• Requirement for controllable PEC to enable desired functionality of EPS.	• Choice of switching frequency, linked to choice of topology and type of switch.	• Appropriate layup of CFRP to enable EMI shielding [7].
Known electrical resistance at low frequencies	• Ability to estimate range of fault resistance supports appropriate selection of Approach to fault management and grounding topology.	• PEC topology directly influences fault response.	• Choice of layup for which low frequency electrical properties are known.
Appropriate physical size to accommodate electrical equipment	• Power, voltage and frequency ratings directly influence size of components.	• Topology and switching frequency influence filter size, thermal	• Impact of casing shape and size on mechanical and electrical properties.

		management requirements.	

4.3 Capture of tunable parameters and viable options

Stages 1 and 2 of the process outlines in Figure 2 provide the understanding of the influences and interdependencies within the design space for the CFRP casing design. In stage 3, the parameters which enable manipulation of that design space are captured and assessed. These are known as the "Tunable Parameters". The assessment takes two forms, the sensitivity of the design space to adaption of a particular parameter, and secondly how practical it is to adapt a particular parameter.

Table 2 lists the tunable parameters identified for the PEC casing. The table includes an initial ranking of how adaptable each parameter is estimated to be. A ranking against sensitivity is not given, as further research is needed to better understand the sensitivity of system design to the parameters. From Table 2, the most adaptable tunable parameters are the PEC and the EPS. The layup of the CFRP can be adapted to tune electrical and thermal parameters by orientation of plies, and by the addition of additives between plies. However appropriate mechanical integrity of the casing must be maintained. Changing the choice of resin is possible, however, if this requires a non-standard resin to be used then this may necessitate a complete change in the method of manufacturing the CFRP. For example if a standard pre-preg can no longer be used. For this reason, adapting the choice of fibres is ranked as low for adaptability.

The move towards electrification of power and propulsion systems on aircraft provides a huge opportunity to re-design the EPS. Hence adapting the EPS to enable the design of PEC with composite casings is ranked as highly adaptable. PEC requirements are driven by the EPS requirements, and hence are less adaptable. However, further research is needed to fully understand this design space, and understand the interaction with the CFRP casing, to capture these interdependencies and design sensitivities. This will then enable the translation of the tunable parameters into viable options for casing design.

Table 2. Identification and assessment of adaptability of tunable parameters

Design area	Tunable Parameters	Adaptability
CFRP layup	Carbon fibre layup	Medium • Closely dependent on mechanical requirements • May be able to interleave electrically and thermally conductive materials to tune CFRP properties.
	Choice of resin	Medium • Depends on mechanical requirements • May necessitate change of pre-preg
	Choice of fibres	Low • Impact on mechanical requirements

		• Necessitates changes to standard pre-preg materials
	Component size and shape	Low to high • Limited by minimum size driven by equipment size
PEC	Topology	Medium - high • Driven by required functionality from EPS • Limited by technology readiness level (TRL) of novel converter topologies
	Filter size	Medium • Driven by switching frequency and power quality requirements.
	Type of switches	Medium • Limited by technology maturity.
	Thermal management	High • Variation of layout may offer flexibility
EPS	Power distribution (frequency and voltage levels)	High • New architectures and approaches for MEA EPS offer flexibility. • Challenges with industrial standards and technology maturity
	Fault Management Strategy	
	Grounding topology	
	Physical location	

5. CONCLUSIONS AND FUTURE WORK

Design of CFRP casings for EPS equipment offers a route to integrated EPS – CFRP structural systems, for light weighting of systems in weight critical applications, such as aircraft. The requirements and design of the composite casing for a PEC is closely interdependent not only with the PEC topology, but the wider EPS design. The most promising routes to adapting the viable design space for this technology require the exploitation and manipulation of these interdependencies driven by requirements from the EPS. Further research is needed to establish the sensitivity of casing design to the tunable parameters identified in this paper as adaptable. Fundamental knowledge of low frequency, electrical characteristics is limited, and research is needed to capture this knowledge to support the manipulation of the design space for integrated electrical power and CFRP structures.

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