ELECTRICAL PROTECTION SOLUTIONS ENABLING INTEGRATED ELECTRICAL POWER AND COMPOSITE STRUCTURE SYSTEMS FOR AIRCRAFT

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Abstract

The combined dual trends for increased use of electrical power for more-electric aircraft (MEA) and carbon fibre reinforced polymer (CFRP) for light weight aircraft structures have been pursued to improve overall aircraft efficiency, reducing fuel burn and hence emissions. However, due to the poor electrical conductivity of CFRP, the CFRP structure and electrical power system (EPS) must be kept physically separate via bulky, heavy cable harnesses and raceways. The closer integration of EPS with CFRP structure offers an opportunity to optimize the weight and volume of the combined electrical power and structural systems, reducing the need for harnesses and raceways. To enable this, there is a need to understand the implications that this will have for electrical power systems design, including approaches to protection. This paper identifies candidate protection solutions for resilient, integrated electrical–composite aircraft structures, by consideration of the interdependent trades between MEA EPS architecture design, CFRP, grounding topology, and electrical fault response. The influence of these interdependent elements on protection requirements is explored, and as a result, design rules for the protection of such resilient, integrated systems are formulated and presented, enabling a focus on the fault response of the system and development of appropriate protection solutions.

1 Introduction

The trend for increased electrification of aircraft systems is leading to higher power levels (1.5 MW more electric aircraft (MEA), multi-megawatt hybrid electric aircraft (HEA)) and higher voltage levels (540 Vdc MEA, multi-kV (HEA)) on aircraft [1]. A parallel trend is for structures with reduced mass, by the use of composite materials, predominantly carbon fibre reinforced polymer (CFRP) [2]. CFRP offers better mechanical performance compared to traditional, metallic structural materials. However, CFRP is a poor conductor of electrical current compared to copper or aluminium [3]. Hence the CFRP structure and electrical power system must be kept physically separate, as sustained electrical current conduction through the CFRP may lead to thermal degradation of the CFRP due to localised Joule heating. The higher electrical resistance of the CFRP will affect the fault response of the electrical power system (EPS) and conventional fault protection methods may no longer be appropriate[4].

Physical separation is achieved via bulky harnesses, raceways, adding weight and volume to the combined structural-electrical power systems [5]. Hence there is a strong incentive to develop appropriate electrical protection systems which enable the closer integration of the electrical power systems with CFRP structures. Achieving this requires understanding of the impact of CFRP forming part of the pathway for electrical fault current, and the influence this that has on fault response, protection requirements and ultimately selection of an appropriate electrical protection solution. In the event of a rail to ground fault in the integrated system, the CFRP structure may form part of the conductive pathway to ground for the electrical fault current, as indicated in Fig. 1, which shows the path taken by fault current, I_f *(A)*, through CFRP to ground, where a fault has occurred due to vibration-induced chaffing of a power cable against a CFRP panel [6].

For a solidly grounded system, the electrical resistance of CFRP can be high enough to significantly restrict the fault current magnitude such that the electrical power system (EPS) may continue to operate as normal, but the level of fault current may still be sufficient to cause thermal degradation of the CFRP structure due to localised Joule heating [4]. As a result, conventional fault detection and protection methods, based on high fault current and resulting low voltages, cannot be relied upon to detect the fault in a timely manner and protect the integrity of the CFRP structure. Therefore, appropriate protection requirements and viable protection solutions must be identified which will enable appropriate management of the conduction of electrical fault current through CFRP, protecting both the EPS and the aircraft structure. To achieve this, the interdependencies between the two systems (electrical, structural), impact on fault diagnostics, EPS design and protection strategy must be better understood.

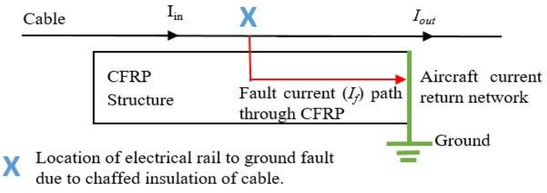

Fig. 1 Path of electrical fault current through CFRP to reach the ground [6]

This paper addresses the need for this understanding of the interdependencies between the EPS and structural systems by providing a set of design rules for integrated electrical–structural systems protection solutions. First, the paper considers the state-of-the-art MEA EPS architectures, existing solutions for current return on composite structure aircraft, the impact of CFRP on fault response, and the resulting protection considerations, to map out the challenges and limitations for integrated systems. Secondly, the interdependencies between the areas of protection considerations, EPS design and CFRP structures will be explored, leading to the identification of design rules for candidate fault protection solutions for integrated electrical power – structural systems.

2 Overview of Aircraft Electrical Power and Structural Systems

2.1 Review of MEA EPS architectures and technologies

The challenge of designing an EPS for an MEA is that it must both meet performance requirements (weight, efficiency) and have sufficient resilience to ensure electrical power can be maintained to flight critical loads at all times, via implementation of an appropriate fault management strategy. This includes the selection and design of an appropriate protection system.

State of the art (SOTA) MEA EPS have a decentralised architecture, significantly reducing cable weight. The higher voltage ratings of the distribution system in the EPS reduce the distribution cable current ratings, and hence cable weight and losses [5][7]. The EPS on a SOTA MEA include sections of network at 115 Vac and 230 Vac at 300 – 800 Hz, 28Vdc and ±270 Vdc. Longer term, a move from AC to DC distribution has been presented to reduce the number of power conversion stages required in the EPS, further improving system performance in terms of weight and efficiency [8]. System parameters such as voltage and frequency are interdependent with choice of technologies. These factors will all directly impact on fault response. SOTA MEA require a mix of AC/DC, DC/AC, AC/AC, DC/DC conversion [9]. Solid state power controllers (SSPCs) offer an alternative approach for protection equipment; however, power ratings of these devices are presently limited.

At present, electrical fault protection methods in MEA for solid faults (arc faults are not considered in this paper) are focussed on fast fault protection for low impedance faults with a high fault current to prevent fault propagation and protect the healthy, non-faulted EPS on the aircraft [10]. However, electrical faults through CFRP present a significant challenge due to the variation in the electrical resistance that the CFRP may add to the fault current pathway [4]. This may result in low magnitude fault currents, which may not affect the EPS operation but may result in thermal degradation of CFRP structure. However, the resistance of the CFRP may also be low enough to result in a high fault current, which may cause damage to both the CFRP structure and the EPS. Hence to enable the design of a more discerning electrical protection solution for integrated electrical power – structural systems, the specification of new protection system requirements is needed. These protection system requirements are influenced by the power system architecture, redundancy considerations and CFRP structure.

2.2 Carbon fibre reinforced polymer aerostructures

CFRP is a composite material comprised of carbon fibres (an electrical conductor) held in place by a polymer resin (dielectric) matrix. More than half of the structures on a SOTA aircraft are constructed from CFRP material (rather than metallic materials) because of their high strength to weight ratio. Epoxy, phenolic and bismaleimide are three main matrix types used in aerospace applications [11]. A critical factor in the selection of the resin matrix is the glass transition temperature (T_g) of the polymer. If a polymer is heated above this temperature, the chains of molecules which form the polymer start to break up, and thermal degradation takes place. The values of T_g depend on the type of resin matrix (for epoxy resin, T_g ~ 100 - 200 °C). For a thermoset polymer, this degradation is irreversible [12][13]. Typically, aerospace grade CFRP has a volume fraction of around 55 – 60 % carbon fibre, with the remainder of the material made from the polymer resin matrix [12][14].

The carbon fibres can be arranged in different lay-ups, and orientations, which directly influences the mechanical, thermal, and electrical properties of CFRP [11]. Due to the high electrical conductivity of the carbon fibres relative to the matrix, the electrical properties of CFRP have been shown to be highly anisotropic, strongly influencing the pathway taken by electrical current through a block of CFRP [15]. As a result, the electrical resistance added to a fault path by CFRP can be significantly higher than for a metallic material. For a solidly grounded system this will result in a low electrical fault current which can be difficult to detect, but high enough to cause thermal degradation of the CFRP [4].

2.3 The current return network and bonding to ground on CFRP aircraft

Due to the low electrical conductivity of CFRP, it cannot perform current return or electrical ground functionality on an aircraft. On aircraft with CFRP structures, the current return is formed from existing metallic structures (beams, raceways) within the aircraft structure, combined with additional cables where required [16]. This current return network provides a solution for an adequate current return path, equipment bonding and used for a failure current return path, protection from lightning and electrostatic discharge protection [5]. CFRP is electrically bonded to the electrical ground to avoid static discharge via bolts, a metal flange or the use of an embedded copper mesh [17].

2.4 Approaches to electrical grounding on aircraft

To date, the electrical grounding method used on aircraft has been a solidly grounded system, TN-C-S: a 4-wire system, with a solidly grounded neutral point [18]. In this grounding system, during a low resistance, short circuit to ground fault, a high fault current will flow. This enables the detection and

Table 1 Summary of fault detection techniques, for Line to Ground (LG) faults, high resistance to ground faults (HRGF), high impedance faults (HIF) for solidly grounded (TN-based), ungrounded (IT) and high resistance grounded topologies

Domain	Application	Technique/ Study	Fault type	Grounding Topology
Time	Land-based grid	Measure sampled values of voltage and current [23]	HIF	Solidly grounded
	Land-based grid	Measure zero-sequence voltage and current [24]	LG	Ungrounded
Frequency	Aerospace	Sliding discrete Fourier Transform [19]	LG	IT
	Marine	Fourier transform [25]	HIF	High impedance
	Aerospace	Spectral analysis of the neutral to the ground voltage over high grounding resistor [6]	HRGF	High resistance
	Land-based grid	Neutral to ground voltage shift [26]	LG	High resistance
	Land-based grid	Fourier Transform [27]	LG	Solidly grounded
Time-Frequency	Marine	Wavelet transform [28]	LG	Ungrounded
	Aerospace	Wavelet multi-resolution analysis (MRA) [29]	LG	Solidly grounded
	Land-based grid	DWT [30]	LG	IT
	Land-based grid	S-Transform [31]	HIF	High resistance
	Shipboard	Differential technique/STFT [32]	LG	High resistance

location of the fault using over current and/or under voltage detection. However higher resistance rail to ground faults in TN-C-S grounded system result in a much lower fault current, which may be difficult to locate and detect. This scenario may occur if the path to ground for the fault current is through CFRP, which may result in a high fault resistance [6]. While the fault current may not be sufficient to damage the EPS, it may be high enough to cause sufficient Joule heating that degradation of the CFRP takes place as the glass transition temperature of the resin matrix of the CFRP is exceeded [4]. Therefore, a significant challenge for the design of an approach to protection with a TN-C-S grounded system is having appropriate sensitivity to detect faults for both higher and lower fault resistances.

Alternative grounding topologies may enable the closer integration of electrical power systems and composite structures, by decoupling the electrical fault response from the fault resistance. For example, in an ungrounded (IT) grounding system, the EPS response to a rail to ground fault is a shift in the neutral voltage relative to ground, for both low and higher resistance faults [19]. Moreover, for a single line to ground fault, it allows for fault ride-through capability which may be particularly attractive for an aircraft EPS with critical loads [20]. However, due to capacitive connections to ground through parasitic connections (e.g., electrical machine casings) and common mode EMC filters, high transient over-voltages may occur during ground faults.

An option to mitigate over voltage transients is to use a high resistance grounding (HRG) topology, in which the neutral point of the system is connected to ground via a grounding resistor which is sized to limit the ground current [18]. However, a significant challenge for both IT and HRG systems is fault location, requiring the development of an approach to protection with appropriate selectivity.

3 Electrical Protection Considerations

3.1 Consideration of protection requirements

Five electrical protection requirements are defined in the literature: sensitivity, speed, selectivity, stability, and reliability [21]. Initially, the focus of the protection design in this paper is on the protection requirements of speed: required speed for the protection system response to prevent damage to the EPS and the CFRP structure; sensitivity: to be able to detect faults with a range of fault resistances; and selectivity: location of a fault to enable appropriate steps to be taken to ensure the healthy sections of the network can continue to operate. The selection and implementation of a protection system for an integrated electrical – CFRP system must be designed to meet these protection requirements. However, at this stage of the design process, the major challenge of the protection system design is addressing the impact of the electrical resistance of the CFRP on the fault resistance for a rail to ground fault. In particular, the resistance added to the fault path by the CFRP can vary from low to high, depending on the location of the fault on a panel, panel dimensions, contact area and method of bonding the CFRP panel to electrical ground [4]. For the case considered in [6] the CFRP added ~ 2.5 Ω to 25 Ω to the fault path. In contrast, the typical resistance for the Electrical Structure Network (ESN) is 0.15 mΩ/m [17].

The second challenge is that the protection system must not only function to protect the EPS, but it must also protect the CFRP from thermal degradation due to localised Joule heating in the event of a fault. By way of an example, for aerospace grade unidirectional (UD) $[0^o]$ CFRP, if more than ~18 W of power is dissipated in the CFRP [4][22], then glass transition temperature will be reached and for levels of power dissipation greater than ~100 W, this will occur within around 2-3 s.

Hence fault diagnostic approaches are needed which enable fault detection and location with a high fault resistance. For a low fault current the speed of detection is not critical, but non-detection of a fault is likely to lead to thermal degradation over time.

3.2 Review of cross application fault diagnostic methods

Table 1 summarises the fault detection techniques presented in the literature, for time, frequency, and combined time-frequency domains, for land-based, marine, shipboard and aerospace power system applications. For each method, the type of fault which it was able to detect is given, along with the grounding topology which strongly influences the fault response of an electrical power system.

4 Interdependent Protection Considerations

4.1 Identification of the key interdependencies

The complexity of the electrical structure network, EPS MEA architecture, impact of CFRP on fault response and protection strategies create several challenging problems in developing a resilient integrated electrical-material system that achieves a competitive efficiency and weight. These challenges can be classified according to three interdependent areas for resilient systems research as outlined in Fig.2.

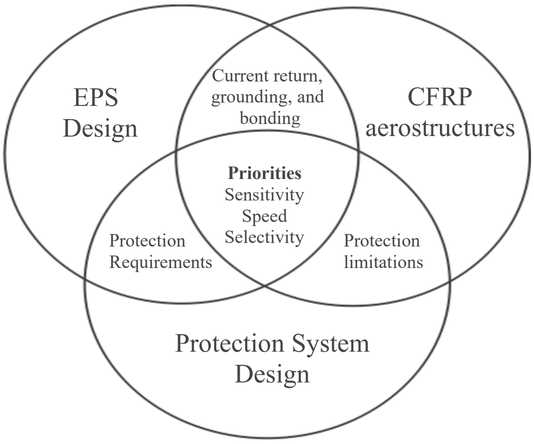

Fig. 2 Key interdependent areas for resilient, integrated systems design

The EPS architectures and CFRP structures both influence the approach to protection system design. There are two sides to protection: one is to protect the electrical power system, and other is to protect the CFRP structure. The contribution to fault resistance by the CFRP, impacts directly on both the sensitivity and speed protection requirements. Sensitivity, because it directly impacts the electrical system fault response and thus methods for fault diagnostics, and speed because the electrical fault must be detected and responded to before damage occurs to the electrical power system equipment, and to protect healthy sections of the network, and it must be detected and cleared before thermal degradation occurs to the CFRP.

The level of power dissipation is a function of both the electrical fault current and the electrical resistance of the CFRP. The threshold level of power dissipated ($P_{threshold}$) will vary depending on the interdependent resistance of the CFRP and the fault current level, and will be influenced by the expected speed of response of the fault protection system and the acceptable levels of localized heating in the environment around a section of CFRP due to the fault. The approach to fault protection system and grounding topology is closely interdependent with CFRP design, due to the impact that all three of these elements have on the electrical fault response of the EPS. However, it may be possible to tune the electrical and thermal properties of CFRP in combination with a wider EPS system design to ensure that the desired fault response is achieved. For example, this may include tuning the electrical resistance added by the fault path by CFRP to below a threshold value, to enable fault detection and location in a TN-C-S grounded network.

5 Ranking and Selection of Approaches to Fault Detection

5.1 Ranking of approaches to fault detection

For the design of protection systems for integrated electrical-structural systems, sensitivity and speed have been considered as the priority protection requirements, ahead of selectivity, and then stability, and reliability. Detection of the fault must be achieved before locating and reacting to the fault in an appropriate time frame. Due to the relatively long time frame (2-3s) identified to detect the higher resistance fault at higher power levels, sensitivity is subsequently prioritised over speed. The variation in fault resistance due to CFRP, from low to high, means that protection systems for the integrated electrical – structural systems cannot be dependent on fault resistance as a primary indicator of a fault occurrence. Stability and reliability criteria of the electrical fault detection can be considered after electrical fault detection and protection solutions have been identified as these are heavily influenced by the choice of primary electrical fault detection methods, protection solutions and devices. Table 2 ranks the fault detection techniques presented in Table 1 based on prioritising the sensitivity and speed protection requirements.

The fault detection techniques ranked in Table 2 are selected on the basis of grounding topology used as they use a HRG or IT topology, which restricts the fault current, thereby decoupling fault response from the fault path resistance which overcomes the issue of variable fault resistance. Implementing a HRG or IT topology may offer a way to reliably detect ground faults through CFRP on an MEA EPS. However, this may also result in implications for the wider electrical power system design such as capacitive connections to ground and over voltages. Moreover, a significant challenge which has yet to be addressed is how these protection and system requirements scale to the higher voltages and power levels. The fault detection methods ranked 1 and 2 propose the implementation of a HRG topology. The top ranked method in Table 2 can detect the fault in 0.5s. Location of a fault is via spectral analysis of the voltage across the grounding resistor. The advantage of this approach is that this decouples the variable resistance of the CFRP from fault response. The disadvantages are that further studies are needed to ascertain whether the spectral analysis can be used to detect a fault in an electrically noisy environment, and second, it requires a redesign of the grounding topology of aircraft, thus impacting significantly on the wider EPS design. Moreover, it requires the EPS to be able to withstand higher voltage levels during faulted conditions, due to the shift in the neutral voltage level of the system, and the fault must be detected before a second rail to ground fault can occur. A flux linkage detection based

Table 2 Ranking of different fault detection techniques based on key priorities set

Rank	**Technique/Study**	**Fault type**	**Grounding Topology**	**Speed**	**Sensitivity (% current change)**	**(AC/DC)**
1	Spectral analysis of the neutral to the ground voltage over high grounding resistor [6]	HRGF	High resistance	0.5s	3.35	DC
2	Neutral to ground voltage shift [26]	LG	High resistance	0.5s	11.11	AC
3	Sliding discrete Fourier Transform [19]	LG	IT	0.6s	3.00	DC
4	S-transform [31]	HIF	High resistance	0.3ms	11.90	DC
5	DWT [30]	LG	IT	0.063s	5.50	DC

HRG fault method for adjustable speed drive systems is ranked at 2, as this has method has not been explored for aerospace applications.

A method using ac current component injection along with the Sliding Discrete Fourier Transform (SDFT) used to estimate the fault impedance is ranked at 3 as it provides accurate implementation for the procedure of first-fault detection with IT grounding in HEA. An S-transform based dc fault detection method is ranked 4. It has been demonstrated to have high sensitivity and speed. The hybrid method ranked 5, with an IT grounding system, detects a ground fault quickly by calculating the detailed coefficient of the discrete wavelet transform (DWT) of the measured current. This method exhibits a constant fault detection time regardless of an increase in the fault resistance.

5.2 Implications for protection solutions and system design rules

For a physically closely integrated electrical-structural system, a fault protection solution is needed which meets sensitivity, speed and selectivity requirements identified in this paper. As discussed in Section 5.1, an approach to fault diagnostics focussing on frequency-based analysis combined with a high resistance or IT grounding topology approach has been indicated to show the most promise. However, diagnostics is one part of protection: a decision must also be made as to how to respond to a fault once it is detected.

Three approaches to the electrical protection are considered here: to isolate, limit or divert the electrical fault current. To isolate in response to a fault requires the timely detection and location of the fault. Unless the electrical resistance that CFRP adds to a fault path can be tuned to be consistent, it is clear that to implement this approach the fault response must be decoupled from the fault resistance. This is possible via alternative grounding topologies, but further exploration of these methods and their wider implications for EPS design is needed.

To prevent damage to the CFRP, the fault current must be limited to low levels of magnitude. It may be possible to tune the electrical resistance of the CFRP, in combination with wider EPS system design to be above the identified threshold, (e.g., HRG or IT grounding topology from Table 2). The use of current source power electronic converters, or fault current limiters could also be investigated as approaches to limit the fault current.

Alternatively, a protection approach may be to divert the fault current along a pre-defined conductive pathway within the CFRP. For example, by adapting the layup of the CFRP, and prevent localised Joule heating. The advantage of this approach is that it would first, prevent damage to the CFRP, and second, potentially facilitate the tuning of the system fault response for the protection requirements. However, fundamental knowledge on how to adapt the properties of the CFRP to enable this functionality, without degrading the mechanical integrity of the CFRP, is needed.

6 Conclusions and Future Work

The design of integrated electrical power – CFRP structural systems offers a number of benefits to MEA applications in terms of reduced overall system weight, but the complex electrical properties of CFRP are a significant challenge to the design and implementation of a protection system for an integrated electrical-power structural system. Opportunities to decouple electrical fault resistance from fault response have been identified, but a major challenge is the impact that such approaches have on wider system design, for example to completely change the established grounding topology of the MEA EPS from TN-C-S to a high resistance or IT grounding topology. By identifying the key protection requirements, aspects of the structural and EPS system which are adaptable and the consequences of adapting these and considering the response of the protection system to a fault, pathways towards establishing viable protection systems for these integrated systems have been identified.

The next step for this work is to develop further fault detection and protection methods for integrated electrical power – structural systems, including exploration of both deterministic and coupled probabilistic-deterministic methods to address the unique challenges of fault detection with variable fault resistance.

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