Flynn, Marie-Claire and Jones, Catherine E. and Norman, Patrick J. and Galloway, Stuart J. (2017) Establishing viable fault management strategies for distributed electrical propulsion aircraft. In: International Society of Air Breathing Engines, 2017-09-03 - 2017-09-08, Manchester Central. ,

Establishing viable fault management strategies for distributed electrical propulsion aircraft

A review of protection and design challenges of viable fault management strategies

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ABSTRACT

Electrical propulsion has the potential to increase aircraft performance. However, this will require the design and development of an appropriate aircraft electrical system to power the propulsor motors. In order to protect this system against electrical faults, which have the potential to threaten the safety of the aircraft, a robust fault management strategy (FMS) is required. The FMS will comprise aspects of system design such as redundancy, reliability and reconfiguration and will rely on a range of protection devices deployed on the electrical system to intercept and manage faults. The electrical architecture will be shaped by the FMS as this will determine the optimal configuration to enable security of supply. The protection system is integral to the system design. Hence it must to be considered from the outset, as part of the wider aircraft concept development. This paper presents a robust framework to develop the optimal FMS for an electrical propulsion aircraft, which is subject to all the relevant aircraft constraints and incorporates the available protection devices for a chosen aircraft for a given developmental timeframe. A case study is then presented in which this protection design methodology is applied to the NASA STARC-ABL aircraft concept in order to demonstrate that the available protection for an electrical propulsion aircraft defines the possible electrical architectures.

Keywords: electrical propulsion; protection; fault management

NOMENCLATURE

CSC	Current Source Converter
CSI	Current Source Inverter
EIS	Entry Into Service
EMI	Electromagnetic Interference
ETOPS	Extended Twin Engine Operations
FMS	Fault Management Strategy
GCU	Generator Control Unit
HVDC	High Voltage Direct Current
MEA	More-Electric Aircraft
MIC	Most Important Constraint
MMC	Modular Multilevel Converter
MVDC	Medium Voltage Direct Current
PWM	Pulse Width Modulation
SFCL	Superconducting Fault Current Limiter
SMES	Superconducting Magnetic Energy Storage
SSCB	Solid State Circuit Breaker
SSPC	Solid State Power Controller
TeDP	Turboelectric Distributed Propulsion
TRL	Technology Readiness Level

1 INTRODUCTION

Electrically driven propulsion has been presented as a possible solution to improve aircraft performance, reducing noise and emissions [1], as global levels of air travel continue to increase by 5% per year [2]. However, much of the benefit of this concept hinges on both the efficient and reliable transfer of electrical power from the generators or energy storage to propulsors driven by electrical motors [3]. As this transmission and distribution network is crucial in ensuring flight safety, electrical fault protection and management is required. This paper will focus on developing a methodology for design of feasible Fault Management Strategies (FMS), which will ensure that electrical power will continue to be transferred from the generators to the motors in the event of an electrical fault occurring. The FMS will be the strategy used to design a robust and resilient electrical power system. The process of selecting an optimal FMS will incorporate the aircraft configuration as well as available protection technologies, and the chosen FMS will influence the possible architecture design for a given aircraft. This design methodology is iterative and would be repeated for any variations in the aircraft constraints and where the final architecture choice has implications for the FMS.

1.1 Fault Management Strategy Requirements

The fault management strategy (FMS) must not reduce the efficiency of the electrical power system below an overall target efficiency, result in an unacceptable weight penalty, abnormally affect the normal operation of the electrical power system (e.g. affect stability) and detect and respond appropriately within an acceptable time frame to abnormal conditions [4]. The FMS may include the use of added redundancy and reconfigurability, along with protection devices which will perform the main fault management functionality in the event of a fault. Therefore, the capability of the available protection devices in terms of operation and potential maximum ratings must be known before the FMS can be defined for a given aircraft. It is particularly important to identify any protection devices that must be omitted from an FMS from the outset, due to unsuitability against a particular constraint, for example unacceptable (anticipated or confirmed) speed of operation or weight of device at the point where the electrical system for an aircraft entering service is finalised. This paper will firstly describe and discuss the challenges associated with designing an optimal FMS. Secondly, a framework for FMS design that seeks to overcome these challenges will be introduced and explained. A case study will then be presented which will demonstrate this proposed FMS design methodology and demonstrate the influence of the FMS on candidate electrical power system design and selection.

2 FUTURE PROTECTION DEVICE CRITERIA

In order to describe the challenges in applying electrical fault management to future aircraft, firstly the paradigm shift between conventional aircraft and electrical propulsion concepts must be considered. There are a number of areas associated with electrical power system design that are affected by this, and for the development of an appropriate FMS, two areas where this is particularly evident are the electrical power ratings and the protection technologies.

2.1 Target Electrical Power Ratings

The electric propulsion power ratings for the aircraft electrical system define the range of suitable power ratings for the protection devices. The propulsive power is derived from the thrust required at take-off and is scaled for each motor and generator according to required redundancy levels. The generated electrical power must also consider losses within the system, with less efficient systems requiring a higher power generation capability. Therefore, it is critical that the overall power train is as efficient as possible. Depending on the number of channels used to supply the load (percentage of maximum power that a section of network must support) and the position of the device on the network, power ratings of protection devices will vary. Since conventional aircraft electrical propulsion systems will be supporting loads in the several MW range [5], if solid state switching components (power electronic converters, circuit breakers) are required, then these must be developed suitable for use in an aero-electrical power system at these high power ratings. These power levels are much higher than is currently supported on current state-of-the-art and More Electric Aircraft (MEA) [6]. Scaling protection devices up to these higher power ratings whilst maintaining high power density remains a key challenge. For example, superconducting Fault Current Limiters (SFCL)s are already rated in the MW range [7], however, the weight and volume would need to be scaled down to utilise this technology on an aircraft application.

2.2 Target Protection Technologies

Current aircraft protection devices are largely unsuitable for use on future electric propulsion aircraft. Due to increased power ratings and increased electrical system complexity, devices such as fuses, breakers and Solid State Power Controllers (SSPC) are likely to require significant specification improvement or be superseded by novel protection technologies. Maintenance of the electrical power system, including the protection system, must also be kept to a minimum to reduce aircraft downtime. Thus fuses are not desirable as they require to be replaced after a fault has occurred. An advantage of SSPCs is that they are able to combine advanced fault detection algorithms with a fault isolation capability. At higher power ratings on a compact network, fault detection functions may be decoupled from the fault isolation technologies to enable flexibility of fault response and to allow centralized control of the protection system [8]. However, the on-state losses of solid state devices such as SSPCs may reduce the overall system efficiency [9] and their susceptibility to EMI failure may be a challenge [10]. Furthermore, there is the possibility of using the power converter switching capability as part of a fault management strategy, to block or limit current [11], as discussed later in Section 3.5.3. Extinguishing of power flow via this mechanism is not currently employed on aircraft systems, but is being developed for HVDC systems [12]. In summary, future aero-electrical protection devices are likely to include:

- AC and DC circuit breakers
- Power electronic converters with current limiting or current interruption ability
- Fault current limiters

3 KEY FAULT MANAGEMENT STRATEGY CHALLENGES

3.1 Architecture Design

There are a number of key challenges to designing optimal and reliable electrical propulsion system architectures. To date, the proposed electrical propulsion system architectures which include a fault management system either have minimal protection [13], a preliminary selection of and/or placement of devices [14][15] or no developed fault management strategy [16][17]. The amount of protection devices which are deemed necessary for a chosen aircraft system also varies considerably [11][18]. Protection devices are often included in system configurations once the network architecture design has been largely concluded. Whilst this may be sufficient for a first pass design to scope novel system configurations, much more detailed design of the electrical architecture is needed to identify the most efficient and reliable configuration. Hence, in the FMS framework proposed in this paper, the choice of FMS determines the key architecture decisions and precedes the architecture design process.

3.2 Constraints

Although some of the limitations of protection devices and protection fault response of electric propulsion systems have been studied [19][20], the authors believe that the identification of the most critical constraint on the FMS should provide the starting point for development of initial solutions. The choice of the Most Important Constraint (MIC) has a significant impact not only on the protection methodology, but also on the choice of protection devices. If, for example, the maximum fault current is excessively large due to the low impedance of the network, then the FMS should focus on fault current limiting devices and the ratings of components in the worst affected areas of the network. If, on the other hand, the speed of response to a fault is the most critical due to the allowable levels of loss of thrust, then the operation time for devices should be prioritised and the control system for protection devices should have minimal latency. As a result, the framework for FMS design proposed in this paper incorporates selection of the most important design constraint for the protection system, and then uses that constraint to drive the choice of feasible FMSs.

3.3 Variation in Standards and Development Targets

The lack of established electrical system designs and power quality standards for future electrical propulsion aircraft [21] results in the situation where different manufacturers and influential organisations are directing developments in a given protection technology towards different end goals and ratings. In addition, if the device specifications (such as rated voltage) are subject to change with the evolution of the electrical design, then it is more difficult to select and develop technologies which will be suitable within the development time frame of the project. This uncertainty in constraints and standards is the motivation to map the interdependencies between constraints from the outset, so that the impact of variation in the range or threshold for a given constraint on the wider FMS design can be identified.

3.4 Time Available for Development

An important factor in the determination of the optimal architecture for a given aircraft is the developmental time frame. If a particular aircraft is not an N+3 or N+4 concept, then there may only be limited time until the electrical system is finalised. In effect, this simplifies the feasible FMS options, since the disparity between current and projected protection devices is reduced. For other aircraft concepts that are less developed and still open to a large degree of variation in configurations and specifications, it is more difficult to accurately quantify the constraints on the system as well as the range of protection technologies which might reach high TRL. In this case, where there is more scope to assess the various merits and challenges posed by different configurations, it is possible that there could be many iterations of feasible FMS solutions leading to a wide range of possible architectures. Thus, depending on the time available, the optimal solution can be derived and moulded by changes in constraints and devices as well as any variation in the aircraft configuration.

3.5 Technology Challenges

There are also a number of challenges in protection system design which result from the projected capabilities of future protection technologies. These are explored below.

3.5.1 DC Circuit Breakers

DC breakers are a standard protection mechanism in many applications. However the DC breakers which are available commercially for state of the art aircraft are typically SSPCs which are not available above 540 V [22]. MVDC breakers developed for other application areas such as naval and terrestrial grids are physically very large [9] and are not available at power density levels which would make them suitable for aircraft. If it is proposed that a DC breaker be used on every cable in the DC sections of a network (or at least in every protection zone) these devices require to be smaller scale and distributed across the network. If this cannot be realised within the constraints of the FMS design then there are important implications for the FMS and the architecture, whereby another means of managing and isolating the DC system fault condition would have to be implemented [11] or DC systems would have to be eliminated as a feasible power distribution method. Another possible solution to meet volume or weight constraints could be to reduce the number of breakers. The availability of DC breakers also has implications for the ratings of the other protection devices on the network in terms of their speed of operation (where there is a coordinated discriminative protection scheme in place), or for the need for current interruption.

3.5.2 Fault Current Limiters

SFCLs have been deployed in a number of terrestrial grid projects [7] and are under development for naval systems [23]. Superconducting electrical power systems are under consideration for larger (> 5-10 MW) aircraft [24]. However, the current weight of the devices and the cooling system prohibits their use in aero-electrical applications, unless the complete electrical system is superconducting and so the additional cryogenic cooling weight is negated by the availability of a systems level cryogenic cooler. An ambient temperature dynamic fault current limiter device for naval systems has been developed [25]. The removal of a requirement for an external cooling system enables a reduction in the overall weight of the system. The recovery time of devices is also a concern [26], especially if there are multiple faults in succession.

3.5.3 Power Electronic Converters

The advantages of achieving electrical decoupling between different sections of the propulsion electrical power system have been reported in the literature [27], such as enabling the electrical machines to operate at their most efficient speed. However, this would entail the use of rectifiers/inverters at the interface of the network and electrical machines, which would have a non-negligible weight penalty. Where the power transmission is AC, then two conversion stages (rectification and inversion) would be required to condition the power fed to the AC bus and maintain frequency synchronisation between machines. Additionally, DC power transmission has been proposed for electrical propulsion aircraft due to the potential to reduce cable weight [28] and losses [29]. It is not yet clear which network configuration will be optimal, particularly in terms of weight, and so this remains an important area of future work.

From an electrical protection perspective, an advantage of using power electronic converters is that they may perform a secondary function as part of the FMS by providing fault current limitation [9]. Whilst this means that the overall number of devices would not have to significantly increase, it does require fault tolerant converter design and may restrict the choice of power electronic converters. If this strategy is employed, then the remaining unfaulted network may temporarily lose power if there is a single fault anywhere on the downstream network served by a single converter. Additionally, the losses in the converters are a significant weight and efficiency constraint on the FMS design. Current state of the art converters for MEA have an efficiency of approximately 97% [30] (but it is estimated that converters with an efficiency of at least 99% are required for electrical propulsion applications [31]).

4 METHODOLOGY FOR DESIGN OF AIRCRAFT FMS

From the discussions presented in Section 3, it is clear that there are a number of constraints which influence the choice of feasible electrical protection devices and solutions for distributed propulsion aircraft. If the protection system is added to the design after the architecture has been selected it may not be possible to satisfy all the constraints, and the resulting protection solution may not be the most optimal given the available technologies within the relevant timeframe. Therefore, the authors have developed an FMS design methodology, shown in Figure 1, which defines the feasible FMS for a given system within a given developmental period and subsequently identifies feasible candidate electrical architectures.

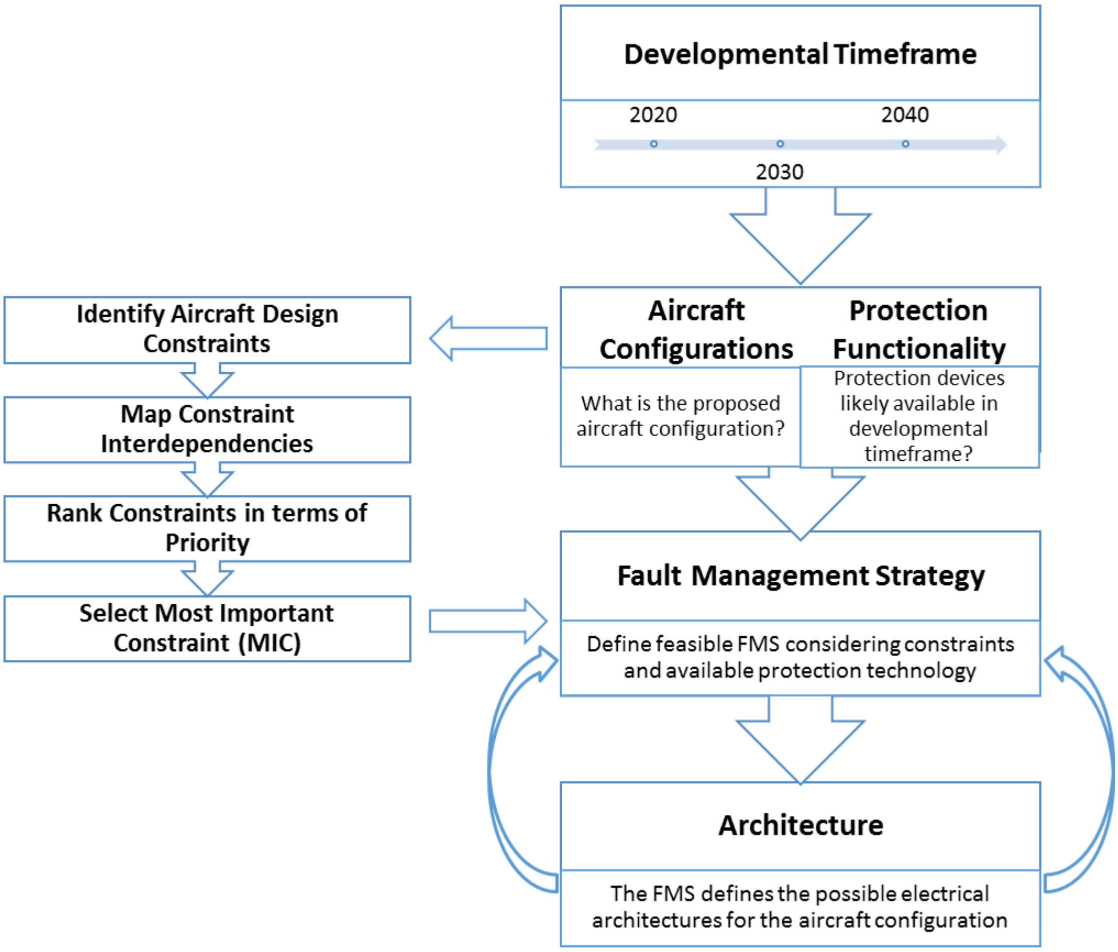

Figure 1 Flow diagram of FMS design concept

On the right hand side of Figure 1, the aircraft developmental timeframe is defined first. This is an important initial step as it will determine the range of aircraft configurations which are being proposed and the protection devices which should be reaching technical maturity by the time the aircraft design is finalised. The next stage is the aircraft configuration and protection functionality, which enables the constraints path to be initiated. To determine the scope of feasible protection functionality, the available protection devices are first identified. The advantages and disadvantages of different technologies or topologies are then assessed to determine the limitations of the available protection options. The protection device trade space can be then be subsequently mapped by combining different specifications of devices in order to identify the feasible regions where a device must exist to be viably incorporated into a FMS for the given aircraft [32].The aircraft concept and the feasible protection functionality and devices (circuit breakers, fault current limiters, as well as power converters and energy storage devices with protection capability) are then fed into the FMS design on the left hand side of Figure 1, which returns the most important constraint (MIC).

To determine the MIC, the constraints are first identified and quantified as far as possible. The constraints may be driven by the physical shape of the airframe (such as where devices will actually fit), certification requirements (such as ETOPS (Extended Twin Engine Operations) criteria [33] or electrical safety standards) or technology limitations (such as the minimum possible time of circuit breaker operation). Once the main constraints are known, the next stage is to map the interdependencies between the constraints. This allows the impact of changes in a constraint set-point to be understood and inform trade-offs between different design criteria. At this point, the constraints can be ranked in terms of priority, with the most critical constraints ranked highest. The most critical constraint with the most significant impact on the FMS design, is then selected as the Most Important Constraint (MIC). The MIC then feeds into the identification of feasible fault management strategies, along with the available protection devices and aircraft configuration. Feasible architectures are then identified, based on the FMS and the necessary protection system.

The process is iterative as a change in developmental timeframe would entail that the process be recommenced whilst the MIC could be varied where there are a number of key constraints, or where the priority level of a particular constraint (such as voltage standards) is dependent on external factors. The mapping of the constraints allows the process to be flexible, adjusting to developments in the aircraft systems or protection technology, at a stage where the important dependencies are already known. Hence the sensitivities of the FMS design to fluctuation in a specific constraint (e.g. chosen network voltage rating) can be anticipated, making the design process more robust.

5 CASE STUDY

To demonstrate the design framework outlined in Section 4 whereby a suitable FMS for an aircraft is derived based on the protection device development and the FMS constraints, this design methodology was applied to a chosen aircraft. The case study could have focussed on either a superconducting or conventional aircraft as the methodology applies to both, but in this instance a conventional aircraft, namely the NASA STARC-ABL hybrid electric aircraft (shown in Figure 2) was chosen.

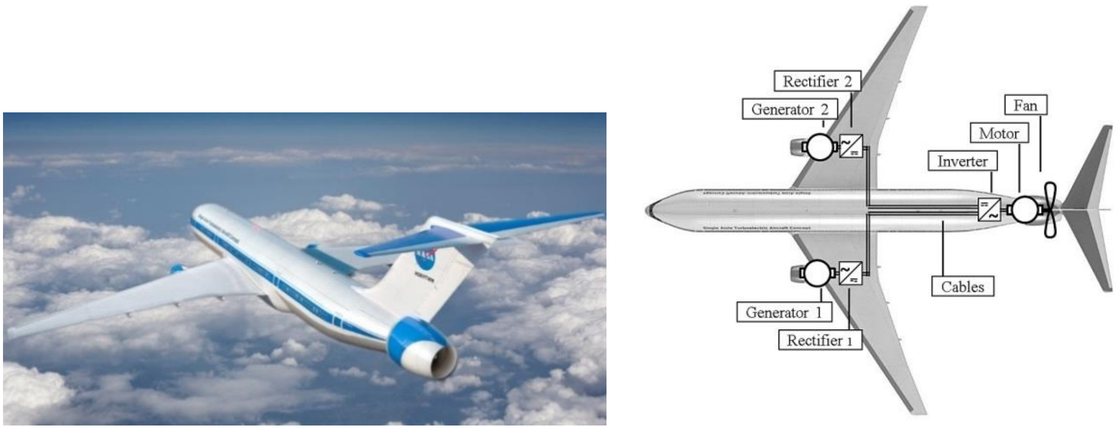

Figure 2 STARC-ABL aircraft concept and proposed electrical architecture [1]

5.1 Developmental Timeframe

This aircraft has proposed point of entry into service of 2035 [1] and can be considered as an N+3 aircraft [34]. Therefore, selection of appropriate protection devices will be based on technologies which have reached high TRL at the point when the aircraft design is finalised, an appropriate length of time before 2035.

5.2 Aircraft Configuration

The chosen aircraft for this configuration is a conventional tube and wing passenger aircraft with two turbofans on the wings and a single propulsor motor housed in the tail cone. This has the benefit of utilising existing aircraft design configurations (as opposed to a blended wing body aircraft [35], for example) and thus providing a technology stepping stone between the current turbofan driven aircraft and future electric propulsion concepts. Power is generated by the generators located on the engines and is supplied to the rear propulsor motor. The electrical system provides 20% thrust at rolling take-off and 44% at the top of climb [1]. This implies that the FMS requires sufficient redundancy and fault ride-through capability in order to continue to provide this level of thrust in an engine-out scenario during take-off.

5.3 Available Protection Devices

With the developmental timeframe for the aircraft chosen, available protection technologies can be identified ahead of scoping possible constraints and the MIC. Since the STARC-ABL is an N+3 concept, the system is almost certainly not superconducting [34]. From the literature [32] it is likely that SFCLs will be too large where the system itself is not superconducting. It is currently unclear whether DC breakers and DC SSPCs will be feasible within the given timeframe. The STARC-ABL has only two generators and a single thruster motor. Therefore as there are only 2 power transmission channels needed (from each generator) and one power distribution (to the load) as shown in Figure 2, the minimum number of circuit breakers that would be required can be found.

In terms of AC network protection, a conventional Generator Control Unit (GCU) could be used at the generator to provide isolation of a generator fault and reconfiguration of power flow between the two generators at the interface to the AC network [36]. This technology is already operational on aircraft; so as a baseline technology, GCUs could be feasibly included in a FMS targeted towards use on an aircraft with an EIS of 2035. However, by 2035 other more advanced technologies may also have reached high TRL. The specific aircraft requirements would dictate whether the GCU technology would be sufficient, or whether an alternative method of achieving this protection functionality is required or desired to overcome any identified functionality deficiencies or to additional aircraft-level benefits.

5.4 Identification of Constraints

The constraints for the aircraft are largely similar to those general electrical propulsion constraints which have already been identified in [32]. Specific STARC-ABL aircraft constraints which are known at present are summarised in Table 1.

Table 1 Known constraints for the STARC-ABL aircraft [1]

Constraint	Expected value or range
Voltage rating	600-4800 V
Power rating	2.8 MW total generation capacity
Electrical system weight	1394 kg
Number of passengers	150
Number of generators	2
Number of motors	1
Location of generators	Pylon mounted on centre of wings behind engines
Location of motors	One single, large motor on tail of aircraft fuselage

Initial studies conducted by NASA for the STARC-ABL aircraft included estimates of the protection system weight and total electrical system weight, based on projections of protection system improvements. However, the actual value of weight is (as indicated in Table 1) is likely to change from these figures as the design evolves.

5.5 Constraint Interdependency

Interdependencies between key constraints will exist and can be identified at this stage of the process. The availability of technology is intrinsically linked to the TRL level and so any delay in the development, testing or certification of a protection device will reduce the chance of that device being available. Another important interdependency is that between redundancy, weight and maximum allowable loss of thrust. Increasing redundancy via parallel or series components will increase the weight unless a redundant component acts as a substitute for an existing component on the network. Higher redundancy reduces the potential loss of thrust, which is an important constraint, but having greater total weight means that the minimum take-off thrust required is also increased. Efficiency and thermal management are also related, as heat losses reduce overall electrical efficiency and have to be safely dissipated from the system. This is more challenging where the power losses are higher and where there are more components with a thermal load. Hence increasing the number of components in order to improve the redundancy of the network may result in an increase in rating of the thermal management system.

5.6 Most Important Constraint (MIC)

The maximum electrical system weight will determine whether or not novel protection devices are feasible for this application. The weight constraint is also the main challenge in transferring technologies from a conventional electrical network or naval application to a future aircraft. This is further verified by the focus given to minimising weight of the entire system in a number of studies for Turboelectric Distributed Propulsion (TeDP) hybrid aircraft [11], [18], [27]. Hence, for this case study weight has been chosen as the MIC for the protection system.

5.7 Choice of Protection Devices and Functionality of FMS

The choice of weight as the MIC eliminates a number of protection options. As discussed in Section 5.3, SFCLs are not appropriate for fault current limiting on an N+3 aircraft and hence alternative methods of providing this protection functionality must be considered. The compact nature of the system results in low levels of intrinsic impedance in the network to limit short circuit fault current levels [20]. Hence either the FMS has to operate before the maximum fault current is reached, or include current limiting converters, or increase the maximum fault tolerance of components [15]. For the purposes of this case study, the chosen option is to operate before peak fault current is reached. This is a viable option as differential DC protection for aircraft has been demonstrated at low TRL to operate within a few microseconds for DC faults [37]. Assuming that the protection is designed for the specific di/dt characteristic of the system, this FMS will be able to isolate an area of faulted network before the maximum fault current is reached which allows the current rating of components on the network to be reduced.

This FMS, however, relies on fast acting and possibly solid state DC breakers on the network which if available, would contribute significantly to the weight of the protection system. However, as there are only two power channels, it is proposed that only four breakers are required. The weight penalty of the circuit breakers could be offset by the component count remaining low. If the weight of the DC breakers was to push the total electrical protection system weight above an allowable limit, then the FMS framework would be used to identify alternative options, either to eliminate the use of circuit breakers from the system or reduce the number used.

As this aircraft seeks to combine conventional aircraft configurations with electrical propulsion technology [38], the FMS for the AC sections of the network (where the electrical machines which are AC interface with the transmission and distribution network) is chosen to be largely similar to current protection systems. A GCU, as discussed in Section 5.3, is selected for each generator and another control unit is used at the motor to prevent propagation of motor faults (realised through effective control of the power converter interface to the motor), effectively removing the motor from the network if a fault is detected. Since there is no back up motor in this configuration, it is assumed for this FMS that if a motor fault cannot be cleared (such as a bird strike damaging the propulsor) then the gas turbine engines would compensate for this fault to provide thrust for a period of time to meet the ETOPS criteria for the aircraft [33]. As the electrical system contributes towards the total thrust requirement but is not the sole source of thrust to the aircraft, the redundancy requirement for the system is somewhat reduced as the engines alone can still provide 80% of the necessary thrust at rolling take-off [1].

5.8 Architecture

Following the framework described in Figure 1, using the chosen FMS it is possible to identify the possible electrical architectures for this aircraft. As there are only two generators each symmetrically located on either side of the fuselage, there must be at least two power channels in the propulsion system, one to serve each of the generators. The chosen FMS in this case implies that the system redundancy will be provided by this dual channel power flow as well as the rerouting capability between both generators, provided by the GCU and the differential protection. Therefore, additional cables, energy storage or parallel redundant converters are not considered for the optimal architecture, based on the FMS. The protection system will incorporate fast DC differential protection, enabling DC power transmission and so rectifiers and inverters are required at the electrical machine interface to the electrical network.

It is acknowledged by the authors that this is one possible solution, from a number of possible, feasible solutions. During the next stage framework studies would be made of the chosen architecture in terms of efficiency, fault response, reliability and adherence to electrical standards. A second iteration of the framework can then begin, feeding back new criteria from the analysis of the chosen architecture design into the choice of FMS. In this way, the architecture is defined by the FMS but also shapes the final selection of the protection strategy. This demonstrates the interdependency between the FMS and the architecture for electrical propulsion aircraft.

6 CONCLUSION

In conclusion, there are number of key challenges which must be considered in the design of an optimal FMS for future electrical propulsion aircraft. It is already evident that the capabilities and limitations of the protection devices and the FMS have a significant impact on the functionality of the aircraft at various points in flight. It is also clear that the physical location of the electrical machines, the quantity of machines that are employed in the system and the percentage of total thrust which comes from the electrical system have implications on the FMS, particularly in terms of meeting aircraft certification criteria and redundancy requirements. Since the protection system design is complex and involves trades between different constraints and FMS options, it must be considered within the wider conceptual design of the aircraft. Therefore, the FMS is a crucial aspect of the aircraft design and must be duly considered from the outset to prevent aircraft configurations being adopted which are impossible to protect without exceeding key constraints such as weight. The framework presented in this paper offers a means to select an electrical system architecture which is based on a robust FMS, subject to all the relevant constraints and incorporates the available protection devices for a chosen aircraft for a given developmental timeframe.

Further studies will focus on performing trades between the various protection system devices, in terms of weight, reliability and functionality. The energy storage on the electrical network also remains an area for future work, as the role of energy storage within both the FMS and the aircraft configuration is still unclear [39]. Since the inclusion of energy storage for either purpose has important implications for the electrical architecture, viable energy storage devices for fault management on electrical propulsion aircraft need to be identified and included in FMS trade studies. Furthermore, a study of various possible electrical power transmission configurations (AC, AC/DC etc.) and the viability of each would inform the design of the FMS methodology.

ACKNOWLEDGMENTS

This work has been conducted as part of the Rolls-Royce University Technology Centre partnership at the University of Strathclyde.

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