Electrical Fault Management Orientated Design of Future Electrical Propulsion Aircraft

PhD Thesis

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September 2019

Abstract

Electrical propulsion aircraft (EPA) have been cited as the future of aviation, enabling greener, quieter, more efficient aircraft. However, due to the stringent requirements surrounding aircraft certification, these novel EPA concepts will need to demonstrate high levels of safety and reliability if electrified flight is ever to become a mainstream mode of passenger transportation. Therefore, robust electrical fault management (FM) is necessary to maintain critical levels of aircraft thrust and to enable high confidence in the reliability and safety of future EPA designs. To date, electrical FM for EPA has been done at a first-pass, minimal level or not at all. For electrical FM to be effective, it must be integrated into the aircraft design from an early stage. This dictates that a novel approach to the design of electrical architectures for EPA is required which addresses the current uncertainty in the availability of suitable FM technologies for future EPA electrical architectures. Therefore, a first-of-kind FM strategy map is presented which identifies projections on the progression of key areas of future EPA-specific FM technology development and acts as a pre-cursor to future FM technology roadmaps. Furthermore, the FM orientated early-stage electrical architecture design methodology presented in this thesis derives feasible, FM-capable electrical architectures for a given EPA concept and captures significant assumptions which impact the down selection process. Since any novel EPA electrical architecture will require some form of testing in hardware, a novel framework for strategic FM demonstrator development is then proposed and the FM test goals for different levels of demonstrator are identified. This strategic development of critical aspects of FM and early integration of FM requires a portfolio of FM demonstrators and test beds for EPA and is crucial if unproven, future EPA electrical architectures are to reach high confidence.

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Acknowledgements

I would firstly like to thank my supervisors, Dr Patrick Norman and Dr Catherine Jones, for giving me the opportunity to undertake this PhD and for all the encouragement and support I have received from them. I am very fortunate to have had such approachable, knowledgeable and dedicated supervisors, whose guidance and technical expertise in navigating a systems engineering PhD has been truly invaluable.

I would like to thank Prof. Graeme Burt and colleagues at Rolls-Royce, especially Paul Miller and Mark Husband, for providing valuable guidance and support.

I am also very grateful to past and present members of the wider Strathclyde Aero-team, long-standing members of the AES group and fellow TIC occupants, without whom I could not have had such an enjoyable and memorable PhD experience.

I am sincerely grateful to friends near and far who have been alongside me at different times throughout the PhD, and to my extended family for faithfully supporting, upholding and encouraging me. I would like to express my heartfelt gratitude towards my siblings, [redacted], for their enthusiasm for my research over the years and for sustaining me in the final stages of the PhD. I would most especially like to thank my parents, [redacted] for all their wisdom and love. This thesis is dedicated to them.

Acronyms

ATI	Aerospace Technology Institute
BLI	Boundary Layer Ingestion
BRS	Ballistic Recovery Systems
CAN	Controller Area Network
COTS	Commercial Off-the-Shelf
CSC	Current Source Converter
DFIGs	Doubly Fed Induction Generators
DLRs	Demonstrator Level Requirements
EMCB	Electromechanical Circuit Breaker
EMI	Electromagnetic Interference
EPA	Electrical Propulsion Aircraft
ESS	Energy Storage System
EV	Electric Vehicle
EVTOL	Electric Vertical Takeoff and Landing
FM	Fault Management
FMS	Fault Management Strategy

HIL	Hardware-in-the-Loop
HTS	High Temperature Superconducting
IRL	Integration Readiness Level
LEAPTech	Leading Edge Asynchronous Propeller Technology
MEA	More Electric Aircraft
MIC	Most Important Constraint
MTOP	Maxiumum Take-off Propulsion
MVDC	Medium Voltage Direct Current
NEAT	NASA Electric Aircraft Test Bed
NRA	NASA Research Announcement
PAX	Passengers
PLRs	Platform Level Requirements
PRS	Parachute Recovery Systems
SFCL	Superconducting Fault Current Limiter
SFR	Strategic Fault Response
SOA	State-of-the-art
SRL	Systems Readiness Level
SSCBs	Solid State Circuit Breakers
SSPCs	Solid State Power Controllers
STARC-ABL	Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer
TeDP	Turboelectric Distributed Propulsion
TRL	Technology Readiness Level

Chapter 1

Introduction

The safety of any aircraft is paramount, especially where any critical failure of the aircraft puts the lives of passengers and crew in jeopardy. Safety is rightly woven into the culture of the aviation industry with rigorous safety regulations applied to all aircraft. As a result of this need to demonstrate exceptionally high levels of reliability, the aircraft industry has often been risk-adverse and cautious in adopting innovation. In recent years, commercial aircraft developers have incorporated incremental improvements to established designs, thereby limiting the possibility of new root causes of aircraft failures and accidents [20].

Where innovation in aircraft performance has been accepted by the regulators and welcomed by customers, this has come after rigorous testing, and even then there have been a number of high-profile catastrophic failures. The recent crashes involving the B737 MAX 8 aircraft first in the sea near Indonesia [21] and then several months later in Ethiopia [22] have drawn a significant amount of public outcry due to the fact that an identified design issue first detected after the initial crash was part of a chain of failures that led to a repetition of such a tragic loss of life[1]. This is certainly not the only example of an aspect of a new aircraft's design leading to a critical failure (e.g. the DeHavilland Comet crashes [23]) and nor is it always easy in such complex aircraft systems to fully identify all the factors that ultimately caused an accident.

Any fault in an aircraft design discovered in operation is costly in terms of lives, as

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[1] From initial FAA findings and media reports, publication of full investigation pending

well as commercial reputation and economic performance. Yet beyond this immediate impact, there are wider implications for future aircraft design across the industry after any occurrence of a catastrophic failure. There is a heightened and renewed determination to improve the safety and fault tolerance of aircraft. Inevitably, the safety measures in the aircraft design are scrutinised to identify any potential source of failure or oversight, and decisions and assumptions reaching back to the early design phases of the aircraft are reviewed. As it is estimated that 70 to 90 percent of the design decisions which will affect safety are made at the initial stages of concept development [20], this early design phase is critical to the future safety of the aircraft. Electrical Propulsion Aircraft (EPA) are currently at this key stage of development, and given the huge emphasis on safety in the aerospace industry, in-depth consideration of safety and electrical Fault Management (FM) for EPA is timely, necessary and high priority (an expanded definition is given in Section 2.2).

The importance of integrating safety requirements from the very outset of conceptual design is well established in system safety engineering [24] and in the aviation industry. Integration of safety-driven FM from the outset is all the more critical when the proposed novel aircraft concept is unproven at scale and will rely on a range of technologies which are still in development [25]. Therefore, if it is possible that unknown failure modes and oversights in safety-critical design and operation can occur even in conventional aircraft concepts with incremental design improvements, then this begs the question whether the aviation industry would ever adopt novel EPA concepts for passenger transport when there is likely to be an even greater risk of unknown unknowns in the design leading to a critical failure? Then, even if the safety of such novel aircraft is acceptable, how can FM be effectively integrated into the early conceptual design stages to ensure that the current aviation safety levels can be maintained?

The answer is partly that the ambitious targets to reduce aircraft noise and emissions will not be met with incremental improvements in existing aircraft [26]. Despite the risk and uncertainty posed by EPA in terms of safety and robust FM, the projected environmental and noise benefits of EPA in comparison to current State-of-the-art (SOA) More Electric Aircraft (MEA) are clearly a strong motivator. However, it is expected that future EPA will only be certified for flight where EPA can demonstrate a level of safety and reliability comparable to, if not better than, current SOA MEA aircraft. In any EPA the electrical architecture is critical to maintaining aircraft thrust yet the decades of experience in high reliability design of aircraft turbine engines simply do not exist for aircraft electrical propulsion systems. This then requires that safety mechanisms and robust electrical FM is incorporated from the very outset through the entire electrical propulsion architecture.

The challenge, however, is that there is currently no established method by which to effectively apply FM to future EPA design and development. The safety standards regulating EPA design are not yet detailed and there is limited experience in developing FM capable electrical architectures for EPA. EPA represent a step-change in aircraft electrical architectures with a significant increase in power generation required to supply large propulsive loads and the critical aircraft thrust levels increasingly being provided by the electrical propulsion system. Many of the technologies which are crucial to the realisation of EPA aircraft, especially preferred FM technologies, are immature and untested in an aircraft environment. Therefore, the novelty of the proposed EPA concepts together with the lack of suitable FM technologies currently available require that a novel approach to FM is adopted. This work aims to address the need to integrate electrical FM into the design and development of novel EPA concepts, around which there is much uncertainty, limited data and stringent aircraft-specific requirements.

1.0.1 FM Design Challenges Specific to Future EPA

Whilst electrical propulsion powered transport is certainly not a novel concept, as it is currently used in traction, naval, marine and electric vehicle (EV) applications [27], the specific challenges of FM for EPA are distinct from those of existing electrical propulsion applications.

In particular, EPA design must consider safety-critical electrical loads, mass production of highly reliable aircraft systems and stringent weight constraints, all of which entail that simply transferring technologies and configurations from other applications may not be feasible. Furthermore, the level of uncertainty surrounding the design of future EPA is another differentiating factor compared to existing electrical propulsion applications. As these aircraft are at the early stages of development and initial demonstrator testing, there is no established approach to the electrical architecture design. This coupled with the critical propulsive loads and the weight constraint drives the need for a novel approach to a fault tolerant design for EPA.

Another significant challenge specific to FM for future EPA is the current lack of available electrical protection devices. EPA electrical architectures require devices rated for higher power levels, capable of operating within an appropriate time frame, suitable for use in the harsh aircraft environment and of a weight and volume viable for EPA. Devices developed for other application areas will require adaptation before they can be certified for flight and novel technologies will need to reach a high Technology Readiness Level (TRL) well ahead of the aircraft's point of EIS. This then induces an added level of uncertainty into the development of effective FM for EPA. As the choice of FM will impact strongly on the configuration of the electrical architecture, this uncertainty is a significant factor in the complete aircraft design. Yet it is not feasible to wait until FM technologies are better developed and there are less unknowns before commencing the FM design, since FM needs to be considered from the outset of the aircraft conceptual design. Thus, the solution is to identify a means of reducing uncertainty in the electrical architecture design by identifying key areas of FM development that will be necessary, and by integrating current FM requirements into the early design phases of EPA concepts.

1.0.2 Integration of FM into Aircraft and Demonstrator Design

Although electrical protection and FM has historically been highly important in the design of electrical systems for aircraft, there is a lack of detailed FM design in the published literature on novel EPA concepts (see Chapter 4.3). Despite there being proposed targets for energy storage, power converters and electrical machines (all of which are key technologies for EPA), no developmental goals for FM devices or FM specific roadmaps have yet been published for this application.

Furthermore, given that FM is a crucial step in the development of robust electrical propulsion systems, any architecture will require some form of testing in hardware before the final electrical system is chosen. Thus, a method for integration of FM into the EPA demonstrator design is required together with a systems-level view of the progression and variety of FM orientated demonstrators which are likely to be required. Detailed FM development in existing published EPA demonstrators is limited, especially for any of the larger scale test beds or flying demonstrators for which there is information available in the public domain. Therefore, timely integration of strategic FM into the development of EPA concepts and demonstrators will enable high confidence in the reliability and safety of future EPA designs.

1.1 Research Contributions

The thesis provides the following contributions to knowledge:

- Capture of critical FM requirements for future EPA. Such requirements have until now been implicit in the presented FM solutions or have been studied in terms of initial trade studies but the impact on the design of the protection system has not been well understood.

- Identification of key FM technology bottlenecks which if not addressed severely limit the range of feasible FM solutions.

- Proposal of an FM orientated early-stage design framework to derive feasible, FM-capable electrical architectures for a given EPA concept. The framework presented in this thesis addresses the uncertainty in the availability of suitable FM technologies for design of future EPA electrical architectures and captures significant assumptions which impact the down selection process.

    - This novel design methodology also identifies key Platform Level Requirements (PLRs) which impact the choice of FM design.
    - On the basis of this novel FM approach, new terminology related to FM in EPA is defined and FM is considered as a combination of technologies and

oversizing, as opposed to the application of individual electrical protection devices.

- Development of a methodology to define FM strategy maps and presentation of a first-of-kind strategy map of the projections on the progression of future EPA-specific FM technology development, aspects of systems overrating and increasing complexity of FM goals. The need for an FM-specific strategy map as a pre-cursor to future FM technology roadmaps is demonstrated.
- A novel framework for strategic FM demonstrator development is proposed and the FM test goals for different levels of demonstrator are identified. This requires a portfolio of FM demonstrators and test beds for EPA. This strategic development of critical aspects of FM and early integration of FM into larger EPA demonstrators has not yet been proposed in the literature and is crucial if complex FM systems are to reach high confidence.
- The concept of Demonstrator Level Requirements (DLRs) is proposed and a suite of candidate DLRs are defined, which are relevant for determination of FM test goals for future EPA demonstrators and test beds.

1.2 Publications

The following publications have been completed in the course of the PhD:

1.2.1 Journal Articles

M.-C. Flynn, M. Sztykiel, C. E. Jones, P. J. Norman, G. M. Burt, P. Miller and M. Husband, "Protection and Fault Management Strategy Maps for Future Electrical Propulsion Aircraft," IEEE Transactions on Transportation Electrification **(Accepted 27th August 2019)**.

M.-C. Flynn, C. E. Jones, P. J. Norman, and G. M. Burt, "A Fault Management-Oriented Early-Design Framework for Electrical Propulsion Aircraft," IEEE Transactions on Transportation Electrification, vol. 5, no. 2, pp. 465–478, Jun. 2019.

1.2.2 Conference Papers

M.-C. Flynn, C. Jones, P. Norman, and S. Galloway, “Fault Management Strategies and Architecture Design for Turboelectric Distributed Propulsion,” in Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS) Conference, Toulouse, November 2016.

M.-C. Flynn, C. Jones, P. Rakhra, P. Norman, and S. Galloway, “Impact of key design constraints on fault management strategies for distributed electrical propulsion aircraft,” in AIAA Energy and Propulsion Conference, Atlanta, July 2017.

M.-C. Flynn, C. E. Jones, P. J. Norman, and S. J. Galloway, ”Establishing viable fault management strategies for distributed electrical propulsion aircraft”, in International Society of Air Breathing Engines, Manchester, United Kingdom, September 2017.

1.3 Thesis Outline

An overview of the structure of this thesis and the key research questions and FM concepts addressed in each chapter is given in Figure 1.1 and explained in further detail in this section.

Chapter 2 presents an overview of the relevant literature. The electrical architectures, FM approaches and key protection technologies for future EPA concepts are discussed. The interdependency between the electrical architecture and the FM strategy is highlighted in the existing literature. A review of specific aspects of the literature pertaining to the contribution identified in each chapter (such as current EPA demonstrator aircraft in Chapter 6) is included at the beginning of the relevant chapter.

The main contributions to knowledge are in Chapters 3, 4, 5 and 6. Chapter 3 first identifies preliminary requirements for protection technologies evident in the literature and discusses the impact of each requirement on the choice of protection technologies.

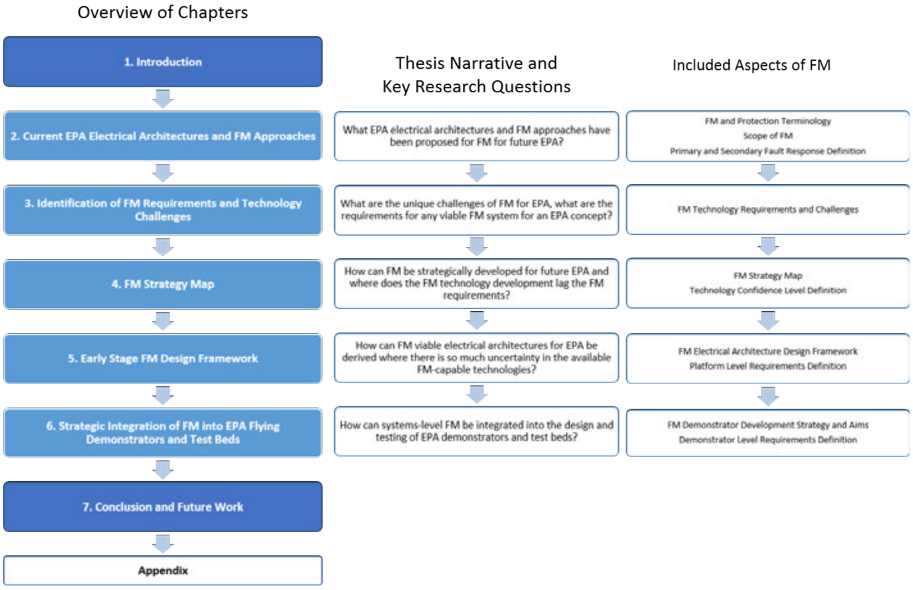


Figure 1.1: Overview of thesis chapter headings, FM concepts included in each chapter and narrative

This enables a number of significant FM technology bottlenecks to be identified. The chapter concludes by proposing the combination of individual protection technologies into FM solutions to overcome these technology challenges.

In Chapter 4 a new method to compile a systems-level strategy map for the development of future FM technologies for EPA is then derived. This method is then used to compose a novel FM strategy map which identifies the discrepancies between the current SOA FM technologies and the expected future specifications and functionalities for FM technologies. The strategy map also highlights the projected development in the FM system goal which has not been addressed in existing literature, as well the interdependency between the FM system and both electrical and Rest-of-System oversizing.

An early-stage design framework for determining viable FM orientated electrical architectures is introduced in Chapter 5. The various stages that contribute to down selecting feasible FM architecture features and which shape the FM requirements are discussed. The framework is also demonstrated by means of a case study design of FM orientated architectures for a given future aircraft concept. The chapter concludes with a process of verification and validation of the proposed methodology. More detail on the way in which the FM framework presented in Chapter 5 was developed and the rationale behind its configuration is given in Section A of the Appendix.

The design method proposed in Chapter 5 is then further developed and applied to the design of FM capable EPA demonstrators in Chapter 6. Key Demonstrator Level Requirements (DLRs) are then identified and a logical progression of FM testing is then proposed. Given the importance of FM goals identified in Chapter 5, the various FM test goals specific to different scales and developmental stage are then identified and discussed.

Chapter 7 concludes the thesis by discussing the impact of FM on the choice of protection technologies, feasible electrical architectures for future EPA concepts and the development of demonstrator aircraft and test beds.

Chapter 2

Current EPA Electrical Architectures and FM Approaches

2.1 Introduction

This chapter presents and discusses the relevant background material and published literature on FM for future EPA concepts. Further literature review on specific aspects of FM (such as design frameworks and demonstrator aircraft) is included in the relevant chapters later in the thesis. An overview of the included aspects of literature review throughout the thesis is given in Figure 2.1.

The chapter begins by defining key FM terminology in Section 2.2. In Section 2.4, an overview of the future EPA concepts, electrical architectures and FM approaches which have been proposed in the literature is given and the interdependency between the electrical architecture and the FM strategy is discussed. Given the importance of the FM system objective, a review of goal-based FM approaches being developed for other applications is discussed in Section 2.6, as this has direct relevance to the approach advocated in this thesis. To provide a complete overview of the status of FM for EPA, a review of the safety standards in development for EPA is then presented in Section 2.9.

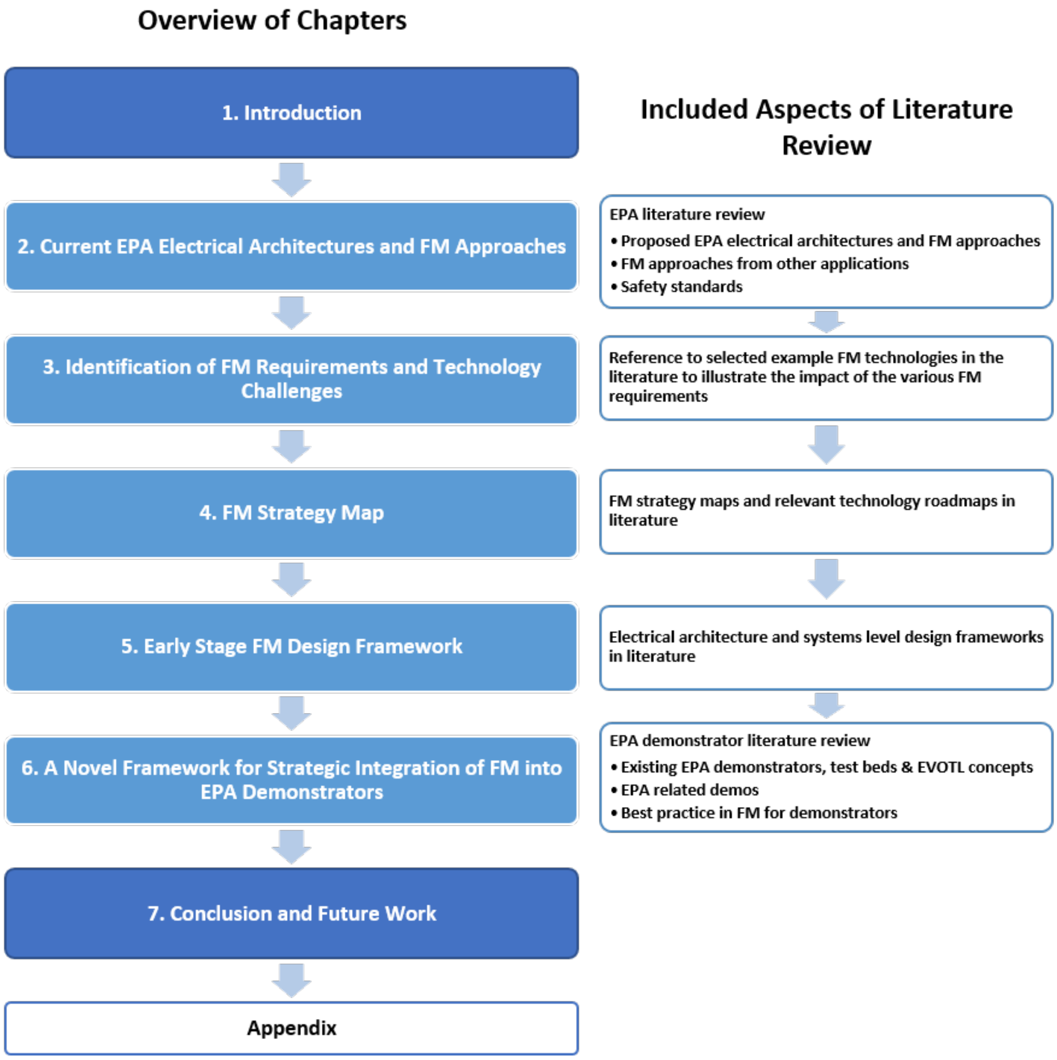


Figure 2.1: Overview of aspects of literature included in chapters throughout the thesis

2.2 Defining Key FM Terminology

There is a paradigm shift required not only in the design of EPA electrical architectures but also in the terminology which is used. Conventionally, *electrical protection design* considers the possible faults that could occur at a given location on the network, and then uses that knowledge to select appropriate fault protection devices and schemes to protect against the range of anticipated faults. The proposed alternative (*fault management*) applies much of the same technical understanding of electrical faults, but aims to configure whole the electrical architecture from the outset with a view to the integration of effective, prioritized electrical fault protection. This enables the electrical architecture to implement a robust fault response from a combination of FM-specific devices (such as circuit breakers) and other components with possible FM functions (such as power electronic converters), as well as any inherent fault management capability of the architecture itself (such as cable overrating).

It is certainly not novel to consider the upstream/downstream impact of a fault and to include some level of redundancy and overrating into the EPA electrical design process. Yet the stringent weight constraint and the complexity of the electrical system for an EPA, even in comparison to the level of electrical power installed on current aircraft, together with the compact configuration of the electrical system and the harsh aircraft operating environment, all require that FM must take a wider scope than conventional electrical protection.

Fault management approaches this problem with a view to only employing the devices which are proven necessary for a given FM goal, strategically locating them on the system for maximum benefit. Ratings of the non-fault management specific components and subsystems are specified to complement the chosen Fault Management Strategy (FMS), acknowledging the limitations of devices and using technologies in clusters to achieve required functions where a given technology is limited.

The process of fault detection, diagnosis and location are not considered in detail in this thesis, although these are important functions which would form part of the detailed FM design at a later point in the design process. The scope of FM as a whole does include these aspects, yet these will come into greater focus as the primary fault response technologies develop further and the different electrical subsystems are integrated together into a complete system. FM enablers (which perform the fault detection, diagnosis and location) are of course highly important components of an FMS, but are not currently considered as a technology challenge on the same level as the FM technologies which will enact a strategic fault response. Further discussion of FM enablers is provided in Chapter 6.

In conventional terminology, *load management* is the strategic optimization of electrical loads during flight, especially when there is an insufficient power supply [28].

However, aside from the auxiliary or hotel loads which will of course still feature on the fully developed electrical architecture for any passenger aircraft, any form of unplanned load shedding of the large propulsive loads on the electrical system would only be implemented in a critical fault scenario. Therefore, load management becomes part of the wider FM system.

Furthermore, the electrical protection system also now has novel interfaces with the mechanical design and configuration of the aircraft (as discussed in the Appendix Section B.3) and so a systems-level understanding of how an electrical fault might then impact the design of other neighbouring dependent systems is required. Since in EPA the propulsion is integrated into the airframe, any electrical fault will undermine the optimal performance of the aircraft. More importantly, however, electrical faults may threaten the ability of the aircraft to maintain the minimum propulsive power, and the safety and integrity of the aircraft structure as a whole.

In the context of future EPA, FM is relevant to the design of the architecture at the conceptual stages but also in the operation of the system when a fault occurs during flight. It seems therefore useful to allow a distinction between these two facets of fault management, fault management during system design and fault management during live system operation. Thus it is possible to define the fault detection, isolation, reconfiguration functions that are triggered by the occurrence of a fault as forming the Strategic Fault Response (SFR). The fault management capability incorporated into design, on the other hand can be defined as the FMS.

2.2.1 Primary, Secondary and Wider System Fault Response

A typical electrical FM response will have primary and secondary operations depending the scale of the fault and the time since the fault occurred. An overview of the primary and secondary fault responses is shown in Figure 2.2.

Figure 2.2 breaks down a typical fault response into three stages, ordered chronologically by point of operation relative to the time when a fault occurs:

1. Primary response (*FM Devices Operation*)

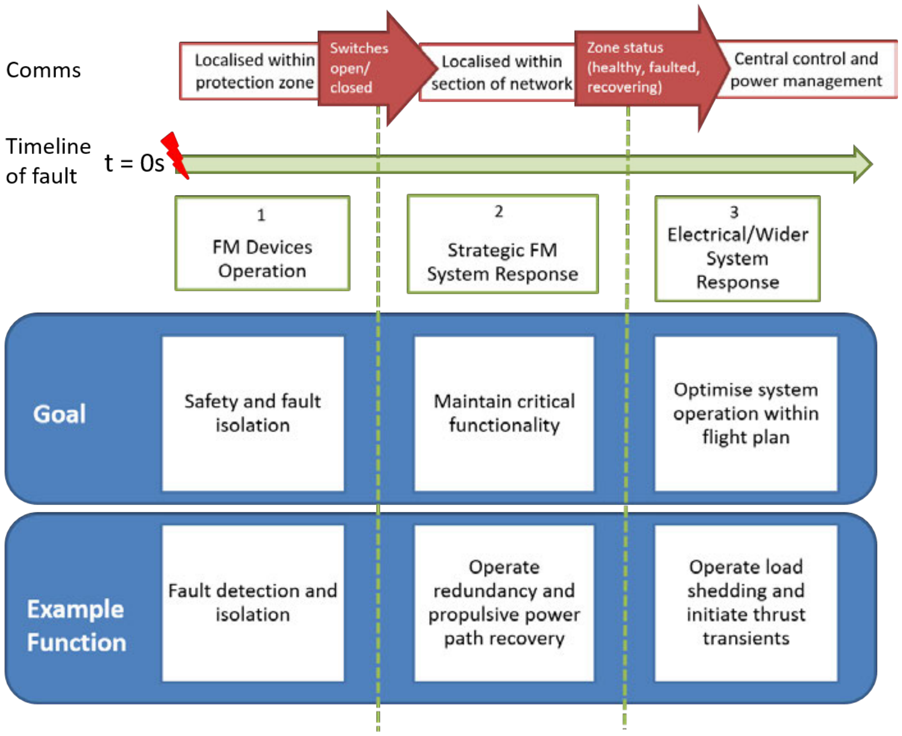


Figure 2.2: Operation of Primary and Secondary Fault Responses

2. Secondary Response (*Strategic FM System Response*)
3. Electrical/Wider System Response

For each of these stages an example generalised goal of the fault response is indicated to allow comparison. Example FM functions which would be expected to operate within each of the fault response phases is shown at the bottom of Figure 2.2. The flow chart at the top Figure 2.2 in red also describes the communications required to be passed between the different levels of the FM system. During a primary response communications are localised to the area of the electrical architecture or protection zone where the active fault response occurs. For a secondary response the required communications during the fault response are wider due to the need to coordinate multiple FM devices, with the status of a section of network being reported to a centralised FM control.

The definition of primary, secondary and wider system fault responses is derived from protection logic. The primary and secondary classification of responses are determined by the time frame in which the FM response occurs and the relative complexity of the FM system response which is required. The *Electrical/ Wider system response* tertiary phase in the aftermath of the fault is critical to the aircraft safety but as it demands control of the other non-electrical systems, this is addressed in the latter stages of FM testing (see right hand yellow box in Figure 6.4). The goal of each phase and the corresponding function are also given to demonstrate the different layers of FM response that will be necessary for an EPA electrical architecture. The communications between devices and systems which generally will be needed at each stage of the FM response are outlined at the top of the figure.

2.3 Scope of FM and FM Technologies

It is also important to define the scope of FM technologies. In this thesis, FM technologies include FM-specific technologies and FM-capable technologies. FM-specific technologies are technologies (such as switchgear) whose primary purpose is to perform conventional electrical protection. FM-capable technologies includes components, systems and aspects of the electrical architecture (such as redundant cables) which can perform FM functions (such as fault current interruption) but which may be included in the electrical architecture for other reasons. A summary of the FM technologies which are referred to in 4 and considered throughout this these are listed below:

- Resistive Superconducting Fault Current Limiters (SFCLs)
- Saturated Core Superconducting Fault Current Limiters (SFCLs)
- Solid State Fault Current Limiters (FCLs)
- Power Electronic Converter
- Solid State Power Controller(SSPC)
- Z-source Breaker
- AC and DC Electromechanical Circuit Breakers (EMCBs)

- AC and DC Solid State Circuit Breakers (SSCBs)
- Hybrid Circuit Breakers (CB)
- Bypass Switch
- Bus Tie Switches
- Pyrofuse/switch
- Mechanical Contactors

Whilst there is discussion later in the thesis around the challenge of DC FM technologies for future EPA, FM here is considered and for both AC and DC systems, and FM technologies includes both AC and DC devices. Much of the conceptual design work for EPA in the literature focuses on DC systems, there is no specification yet that exists which stipulates whether a DC or AC system is optimal or preferred. Both AC and DC systems are identified in the literature review presented in this chapter, however in the later case study in Chapter 5 an arbitrary choice of a DC architecture is made for the purposes of demonstrating the design framework.

2.4 Current EPA Concepts

2.5 EPA Configurations

Electrical architectures for future EPA could adopt a range of generalized configurations, defined as follows [29]:

- All electric (e.g. Maxwell [3], EVTOL and air taxi concepts [25])
- Parallel hybrid - where electric drive and mechanical drive combine at the turbine shaft (e.g. SUGAR [6])
- Series hybrid - where electric drive and turbo-electric drive combine at the electric bus

- Turboelectric - when all the turbine energy is converted to electricity used to power electric motors (e.g. ECO-150 [4] and N3-X [8, 30], STARC-ABL [29] partially turboelectric)

A visual representation of these configurations is shown in Figure 2.3. The term EPA is used to refer to any aircraft where a proportion or all of the critical thrust required for flight is derived from an electrical propulsion system. EVTOL aircraft and small scale EPA demonstrators have, to date, opted for all electric propulsion, where the propulsive power demands of the EPA are supported by energy storage or fuel cells [31]. Larger demonstrators (such as the E-Fan X), single aisle (such as ECO-150 and STARC-ABL) and twin aisle future (such as N3-X) concepts proposed in the literature combine gas turbine or combustion engines with electrical propulsion motors in different hybrid configurations to supply the total required aircraft thrust levels.

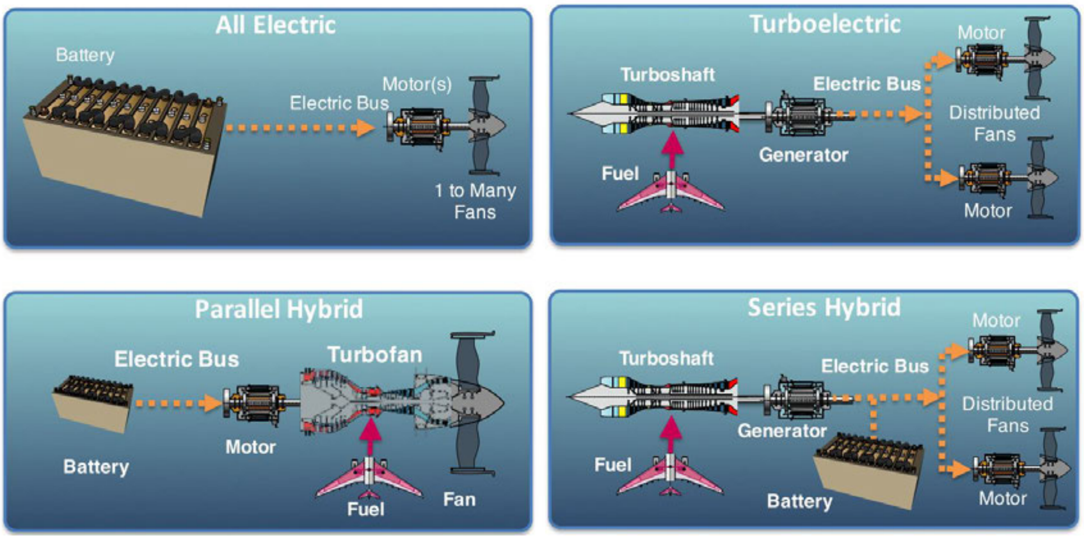


Figure 2.3: Overview of various EPA configuration schematics [1]

Although all EPA concepts inherently require electrical systems design, not all proposed EPA concepts in the literature are sufficiently developed that an initial electrical architecture exists. Yet given that many EPA concepts have projected dates of EIS of 10 or more years in the future [25], those electrical architectures that are currently proposed are likely to undergo significant changes. The most detailed architectures have been derived for turboelectric (such as [8]) or partially turboelectric aircraft [29], although parallel (such as [6]) and series hybrid configurations have also been proposed in the literature. However, even in these early configurations, the interdependency between the conceptual design, the choice of electrical architecture and the FM approach is evident.

2.5.1 Electrical Architectures and Fault Management Approaches

The electrical architectures and the corresponding FM approaches for EPA concepts ordered by power level/configuration (see further discussion in Section 4.5) in the literature are discussed in the following sections.

2.5.2 HYPSTAIR

The Siemens HYPSTAIR aircraft electrical architecture [2] applies systems level FM, although on a small-scale all-electric demonstrator EPA. Although a detailed architecture is not presented, the block diagram description shown in Figure 2.4 indicates the level of redundancy in the choice of power channel configuration and dual wound electrical machines. In [2], the FM approach is discussed as well as reconfiguration options and overrating of the power channels to allow this.

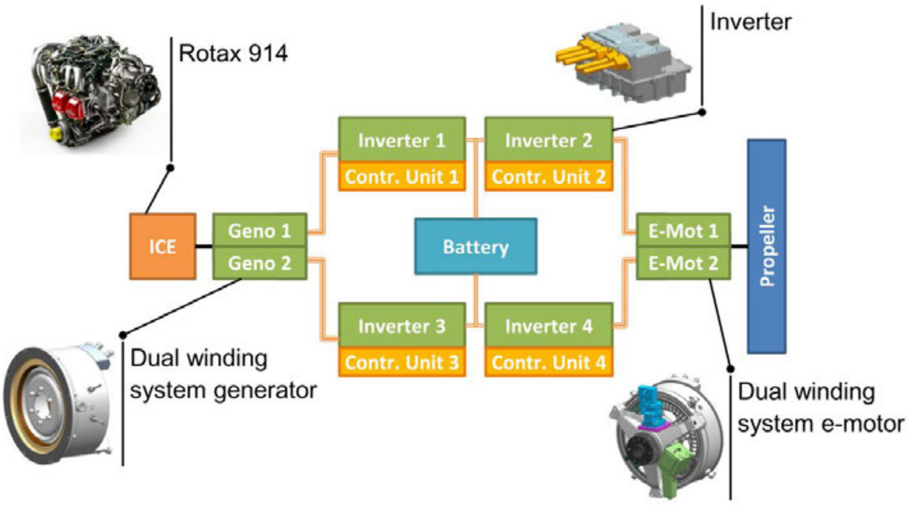


Figure 2.4: HYPSTAIR electrical architecture [2]

2.5.3 Maxwell

The proposed electrical architecture for NASA's Maxwell X-57 details a near-term, pilot only EPA experimental demonstrator [3]. The electrical architecture features all electric propulsion by means of batteries supplying an array of propulsion fans on the aircraft wing. The FM approach involves isolation of power channels to prevent propagation of faults, de-energising or de-rating faulted sections of network to maintain symmetry of thrust. As this aircraft is part of a *build-fly-learn* research project, the FM approach is geared towards ensuring safe testing of technologies and increasing confidence in the reliable operation of the chosen electrical architecture. A detailed discussion of FM approaches and requirements for EPA demonstrators is given in Chapter 6.

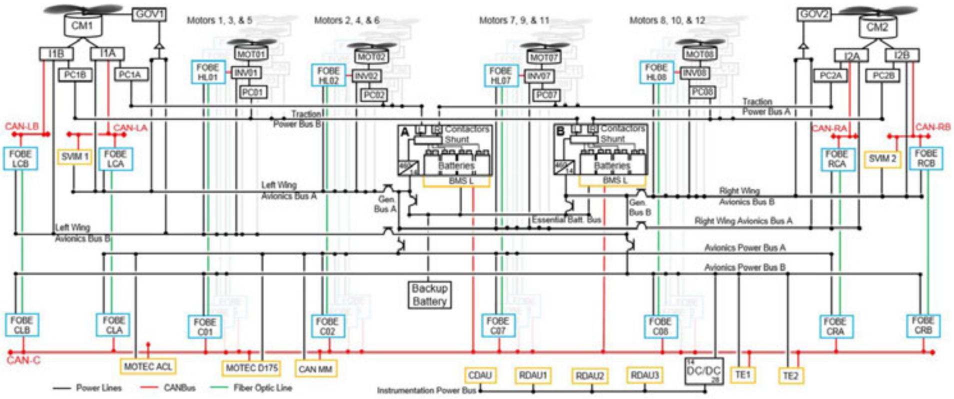


Figure 2.5: NASA Maxwell X-57 electrical architecture [3]

2.5.4 STARC-ABL

The electrical architecture for NASA's STARC-ABL aircraft [29] is presented in Section 5.12.5. The electrical architecture powers a 2.61 MW propulsive load via two power channels from each generator to a single inverter. The DC circuit breakers are not shown on the diagram, but the proposed FM strategy is to utilise circuit breakers on both the DC and AC sections of the architecture for fault interruption and inclusion of dual feeders to the downstream inverter for redundancy. As this is a notional architecture from an early study, the voltage level of the system is not specified, the FM inclusion is minimal and there is little justification for the FM approach adopted.

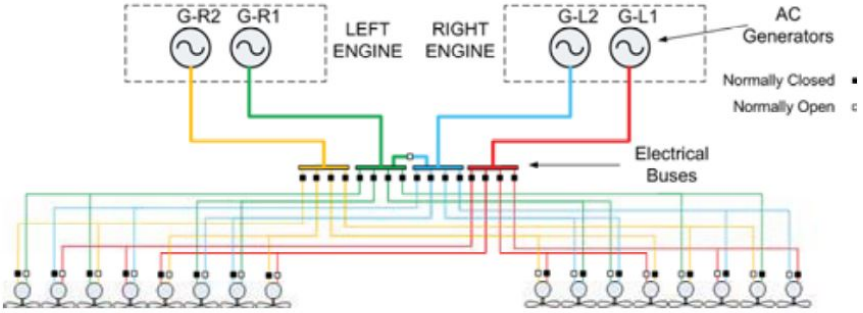
2.5.5 ECO-150

The ECO-150 concept is under development by ESAero and NASA, with more recent trade studies between AC synchronous, DC distribution and hybrid configurations of the ECO-150 conducted by Rolls-Royce [4]. These initial studies focused on the electrical architectures shown in Figure 2.6, which include an array of propulsive fans on the wings fed power from four generators through a distribution network, for which there are a range of preferred configurations.

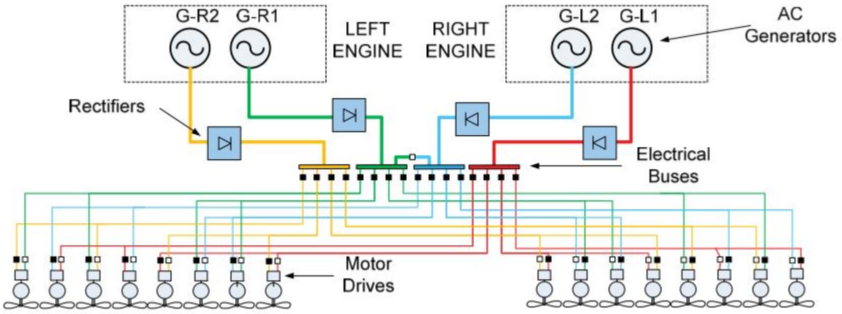
This publication specifies the protection strategy which provides the basis for the choice of protection technologies and their placement on the network, and is summarised as follows: *a lightweight and highly flexible reconfiguration system which only acts in a de-energized state. The only components which must act under faulted conditions are the power source isolation components at the generators or energy storage* [4]. This FMS is one option applied to the electrical architecture in the Case Study demonstration of the proposed FM framework in Section 5.4. The inability of the protection devices to interrupt fault current at the loads or on the distribution network is a major limitation of this approach, yet is chosen as it provides a weight saving. This is evidence of the lack of fault current interruption devices which are expected to be readily available for this application type and the interdependency between the chosen FM approach and the electrical architecture.

2.5.6 Quadfan

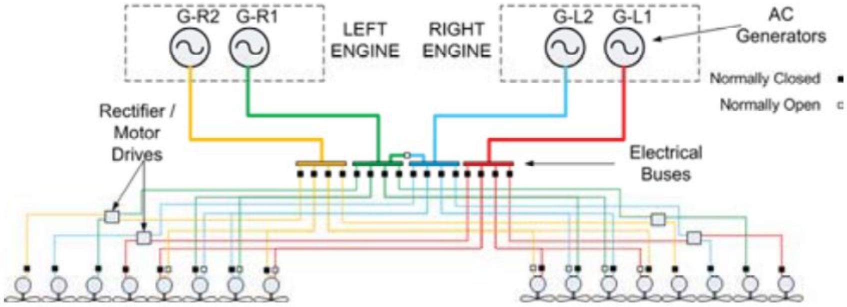
The architecture presented in [5] and shown in Figure 2.7 was derived from conceptual studies for hybrid electric transport, and therefore was not an electrical architecture focused publication. The minimal dual-channel architecture identifies Solid State Power Controllers (SSPCs) for fault protection, but does not give reasoning for this choice of technology, verification of the feasibility of this technology for the chosen concept nor rationale for the choice of power channels and location of devices.



(a) AC synchronous distribution configuration



(b) DC distribution configuration



(c) Hybrid distribution

Figure 2.6: Proposed Architectures for the ECO-150 Aircraft Concept Early Trade Studies [4]

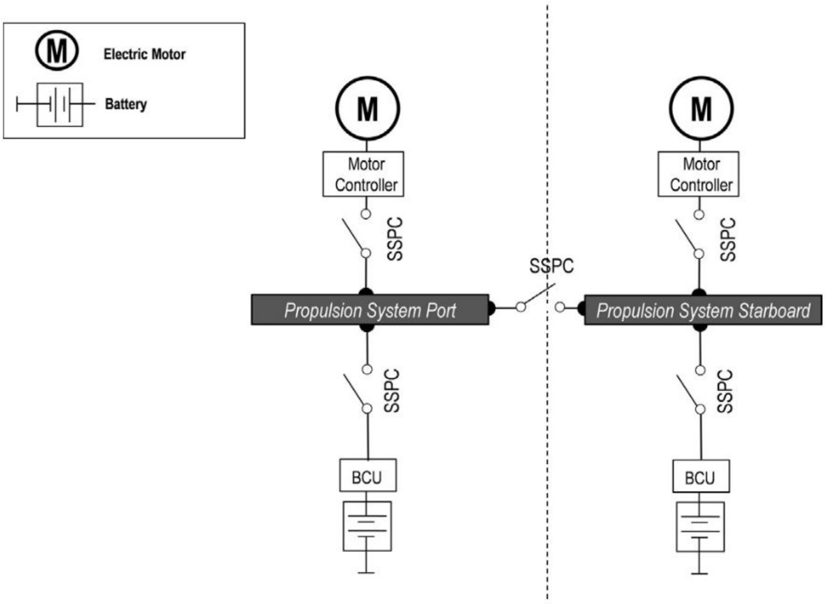


Figure 2.7: Quadfan electrical architecture [5]

2.5.7 SUGAR

SUGAR Volt [6] is one of a range of N+4 future concepts (as defined in [25]) generated by initial performance studies on EPA focused on assessing the relative merits of different hybrid or all electric configurations. This particular sub-concept has been proposed in both conventional and superconducting configurations yet no complete electrical architecture was published as part of these studies, and the only electrical protection mechanism identified was Solid State Circuit Breakers (SSCBs). The outcome of the paper focused on one configuration requiring a 1750 HP motor (approximately 1.3 MW) and the other requiring a 7150 HP motor (approximately 5.3 MW). The stated weight of the electrical system does not specify the non-negligible weight of the protection devices. Therefore, this early study does not capture the impact of FM on the feasibility of the initial conceptual design.

2.5.8 DEAP Project

An alternative superconducting EPA architecture is proposed in [7] (shown in Figure 2.9), and is assumed to deliver 9 MW. This AC synchronous network with cryocoolers

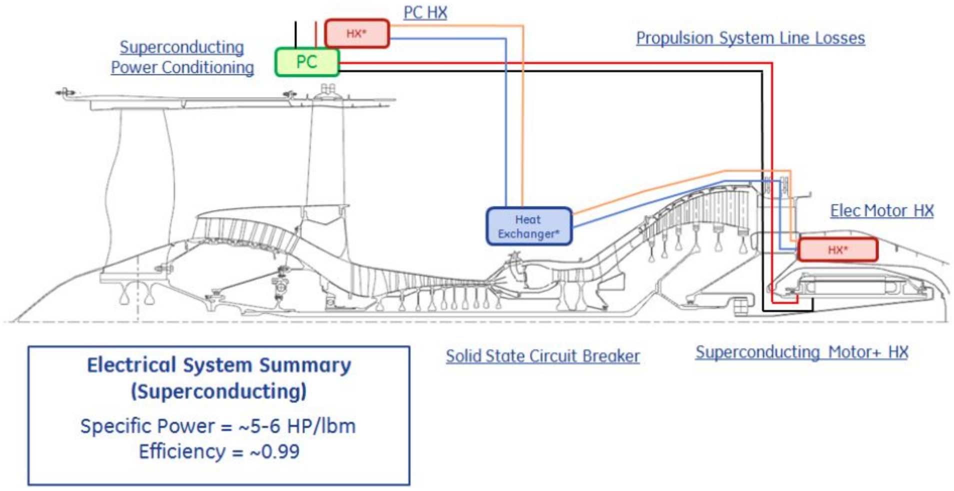


Figure 2.8: SUGAR aircraft engine and superconducting electrical system configuration [6], (HX = heat exchanger)

and distributed propulsion is presented as part of a discussion of the challenges surrounding implementing High Temperature Superconducting (HTS) electrical configurations in aircraft, such as the requirement for high efficiency in the power electronics and high power density (and reliability) of the cryocoolers [7]. Further challenges include the fact that many of the cryogenic technologies such as HTS cables are technically immature and unproven for use in an EPA application. The use of HTS electrical architectures in aircraft such as this concept is considered for larger, twin aisle EPA concepts [8,32]. The benefit of adopting an AC synchronous system is the lack of power electronic converters (leading to a weight saving) and FM being achieved through AC fault current interruption (use of natural zero crossing). However, the FM implications of this type of architecture configuration are not well understood. For example, the need for reconfiguration of power channels, bus-ties and physical isolation of faults is identified yet the means by which this could be achieved is not described, nor is the feasibility of AC synchronous electrical architectures for Turboelectric Distributed Propulsion (TeDP) concepts verified.

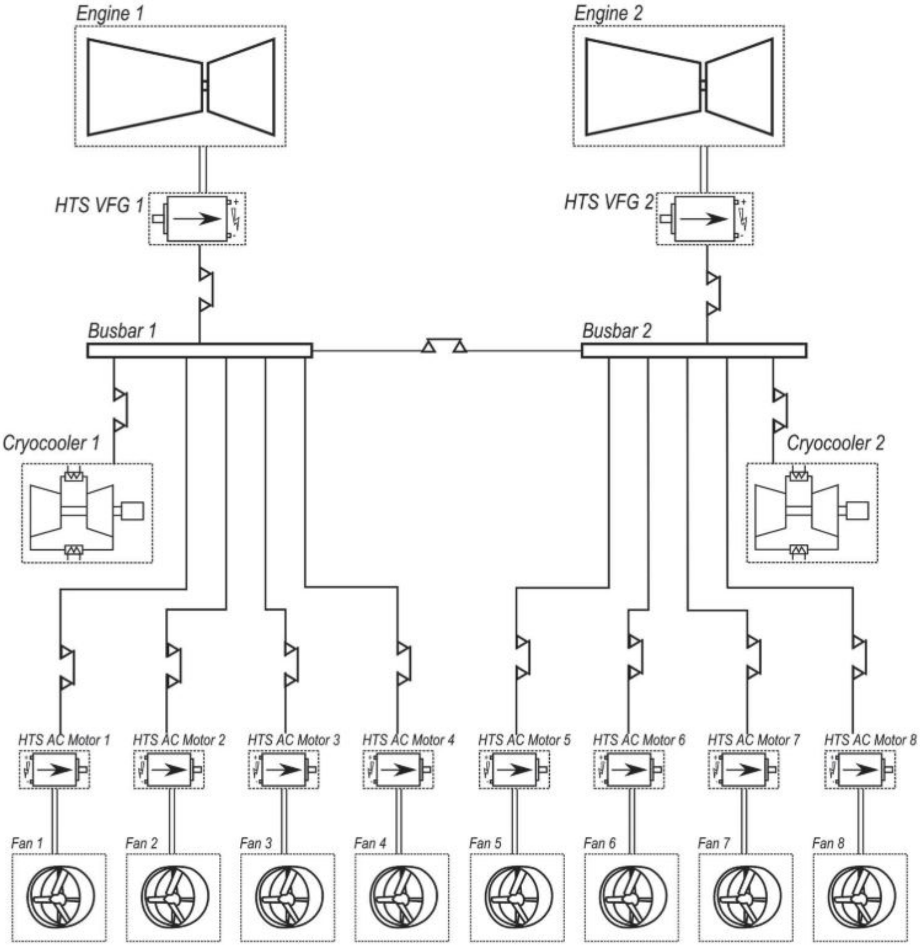


Figure 2.9: Airbus and Rolls-Royce DEAP electrical architecture [7]

2.5.9 N-3X

The N-3X concept proposed by NASA is a large twin aisle, 300 Passengers (PAX) superconducting blended-wing body concept. A number of early studies were conducted to perform trade studies of various electrical architectures for the N-3X concept. These configurations are presented and discussed in the following sections.

Cross-Redundant Radial Architecture

This FM approach uses Superconducting Fault Current Limiters (SFCLs) placed each channel of the network to restrict fault currents to below critical current levels. However in order to interrupt the fault current, Solid State Circuit Breakers (SSCBs) are included at the protection zone interfaces. Energy storage is also included on the distribution busbars and cross-redundant feeders to the propulsive loads enable flexibility of reconfiguration after a fault. The architecture in Figure 2.10 is the baseline architecture from which further similar configurations were derived and evaluated. However, the FM approach here is based on providing maximum functionality across the entire electrical architecture. The feasibility of the FMS proposed here remains unclear due to the excessive weight of protection devices and the lack of maturity of supporting technologies (such as communications between FM devices).

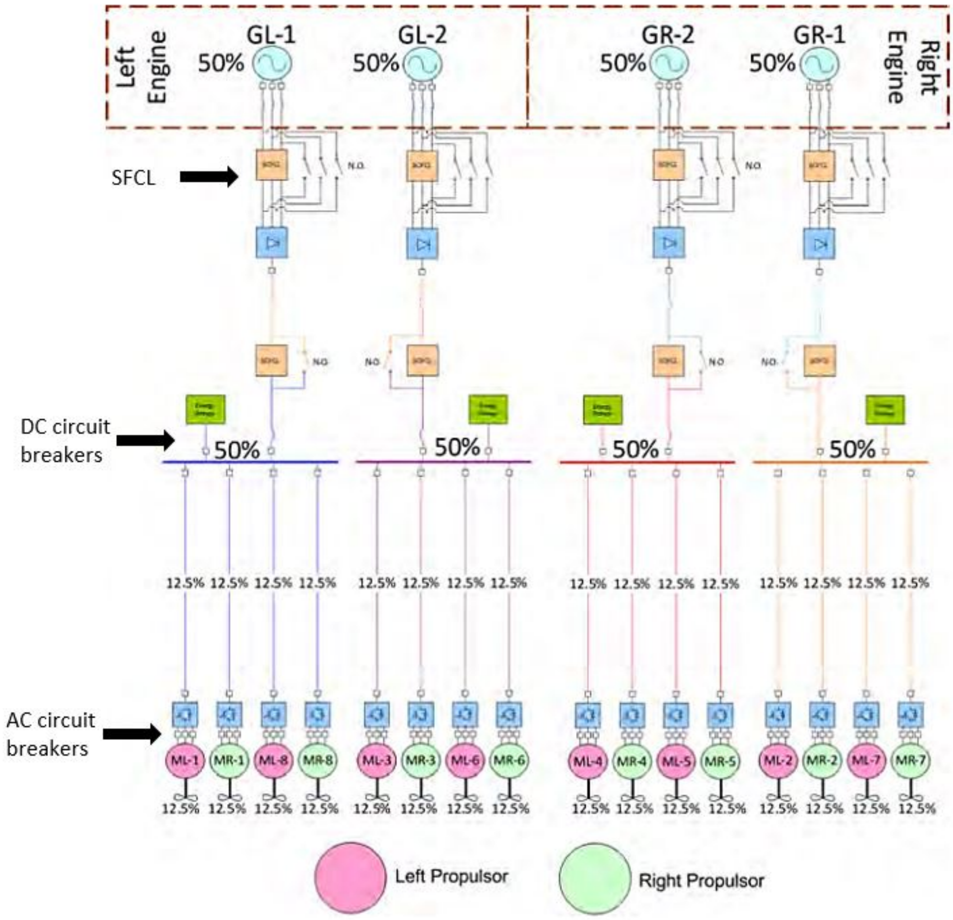


Figure 2.10: Rolls-Royce N-3X baseline architecture [8]

Voltage Source Architecture with Fast Disconnects

The *Voltage Source Architecture with Fast Disconnects* architecture shown in Figure 2.11 [30] has been designed with *Super Fast Disconnects*. These are used to reconfigure the de-energised network to isolate the faulty section, only after all fault current producing elements have been disconnected by the circuit breakers. The circuit breakers are then reclosed to restore power to healthy sections of network. The FM response for this configuration may be more complex than the network in Figure 2.10, as the disconnect switches must wait until the fault has been isolated to operate since they have no current interruption capability. This sequential operation may increase the total fault response time. A detailed discussion of the impact of sequential or layered operation of FM is given in Section 2.2.1.

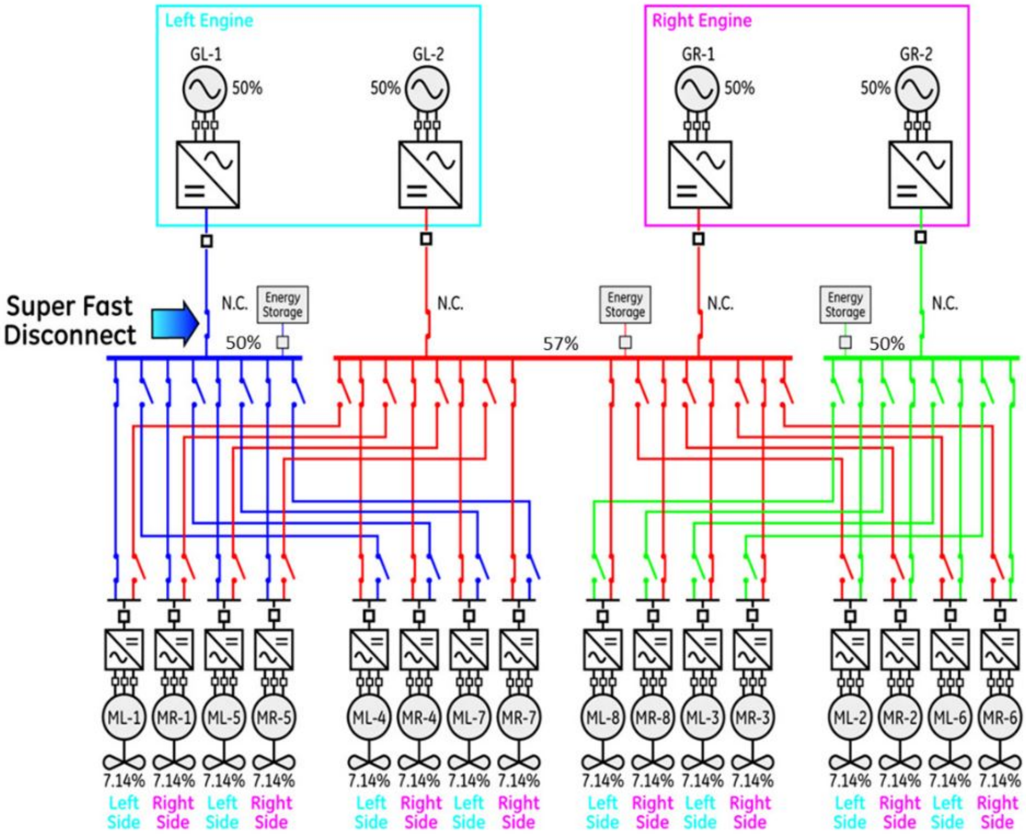


Figure 2.11: GE N-3X voltage source converter electrical architecture

Ring Architecture

An alternative electrical architecture proposal for the same concept [30] (shown in Figure 2.12) proposes a ring architecture and Current Source Converter (CSC) topology. Here, the chosen FMS aims to bypass the faulted section of the network. This FM approach requires a CSC interfaced DC system, to enable a constant current to be maintained, including during system disturbances. This approach avoids the weight associated with DC fault current interrupters, and has advantages of reduced peak fault current and bi-directional voltage blocking capability during a short circuit DC fault [33]. However, these FM system benefits are likely to be offset by the fact that the filter components for a CSC can lead to a large converter weight and volume and a current source system (and associated converters and control) is not proven in an aircraft environment [33]. A further technical issue with this proposed architecture is the large loss of propulsion that would occur if there was a fault on the GL-1 or GR-2 generators which may be critical at times of flight when the maximum output propulsion power is required.

2.5.10 FM Approaches for the N-3X Summary

The different FM approaches for the N-3X aircraft are further discussed in [18]. It is evident from these early studies that there is a close interdependency between the FM approach or design which is adopted and the resulting electrical architecture. Furthermore, there are critical trades to be made between the aircraft performance (weight, efficiency etc.), the level of functionality available in the FM system and where various FM technologies can be physically located on the electrical architecture.

2.5.11 Summary of Proposed EPA Electrical Architectures and FM Approaches

The data on available electrical architectures and the level in the proposed FM approaches for future EPA is summarised in Table 2.1:

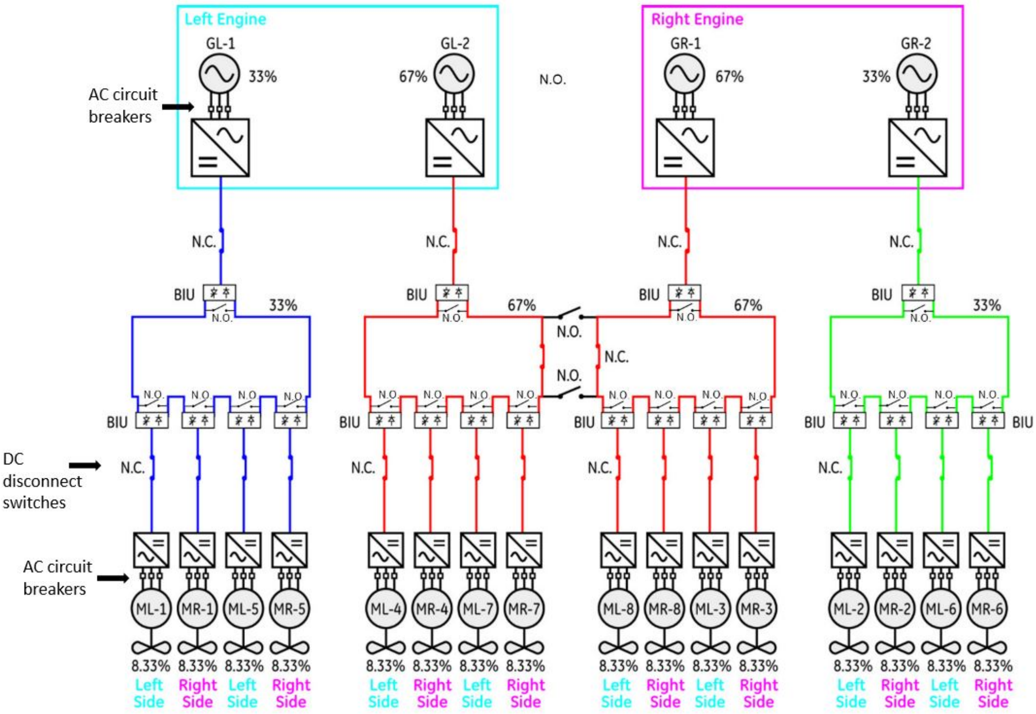


Figure 2.12: GE N-3X CSC ring electrical architecture

Table 2.1: Summary of current EPA electrical architectures and FM approaches

EPA Concept	**Developer**	**Target EIS [25]**	**Configuration**	**FM Approach Specified?**
HYPSTAIR	Siemens	N	All electric	Yes, systems level FM design
Maxwell X-57	NASA	N+2	All electric	Yes, detailed FM design
STARC-ABL	NASA	N+3	Partial Turbo-electric	FM technologies identified
ECO-150	Empirical Systems Aerospace, NASA	N+3	Turboelectric	Yes, protection strategy identified
Quad-fan	Bauhaus Luftfahrt	N+3	All electric	FM technologies Identified

SUGAR	Boeing, NASA	N+4	Parallel hybrid	No, possible technologies suggested
DEAP	Airbus, Cranfield University, Rolls-Royce	N+4	Turboelectric	No, but key FM functions identified
N-3X	NASA, Rolls-Royce, GE	N+4	Turboelectric	Yes, possible FM approaches identified

From Table 2.1 it is evident that the initial conceptual and electrical architectural EPA designs have not focused on electrical FM. To date, electrical FM for EPA has been done at a first-pass, minimal level or not at all. The weight of FM-capable components for any future EPA will be non-negligible, and without robust electrical FM no EPA can hope to achieve aircraft safety statistics comparable with current MEA. Current approaches in the literature (such as [34]), whilst highlighting some of the technical challenges around FM-capable electrical architectures for EPA, have not proposed a design methodology which integrates FM from the outset. Furthermore, in the design of EPA concepts in Table 2.1 the availability of particular technologies has often been assumed, thereby foregoing the opportunity to highlight the key technologies which require development now if such EPA concepts are to be realised in the future. This dictates that a novel approach to the design of electrical architectures for EPA is required which addresses the current uncertainty in the availability of suitable FM technologies for future EPA electrical architectures. However, for electrical FM to be effective, it must be integrated into the aircraft design from an early stage. Therefore, the lack of FM integration in the electrical architectures in the literature provides a strong justification for the requirement of an FM-orientated design approach for future EPA.

2.6 FM Approaches for Other Critical Propulsion Applications

As EPA are a novel concept, the electrical FM approaches described in Section 2.4 are technologically immature and require further development. Therefore, in order to derive FM approaches for future EPA concepts which are viable, it is useful to review electrical FM approaches in other applications.

This thesis proposes that systems-level FM is integrated into the early design of critical EPA systems. Whilst this is a novel electrical FM approach for EPA, a similar concept has been proposed for spacecraft and space propulsion and navigation systems. Although this is a different application area, these systems are also required to fulfil a safety-critical mission and demonstrate high reliability of all systems. In particular, *Goal-Based Fault Management* developed in relation to the software embedded in such systems advocates that it is more important for the FM system *to respond to a loss of function, not matter how it occurs, than only a set of anticipated faults*, since the lack of faults successfully being detected does not necessarily mean that the system is at 100% health [35]. This approach to FM marks a deviation from the approach where a defined set of failure modes and fault effects are identified for which the FM system has a set of mitigation responses.

For complex architectures where there may be conflicting control requirements, this approach to FM which identifies the system goal(s) and responds to any goal failure allows for a more robust FM system. This is especially important where there is uncertainty in terms of the exact failure modes that the system may exhibit, as is the case in novel EPA electrical architectures. This goal-based approach to FM advocates consideration of the electrical architecture in terms of acceptable system behaviour and a success criterion that needs to be achieved. This is particularly relevant to EPA electrical architecture design where the desired response to a fault will depend on the state of the system (e.g. point in flight path) as well as the key system intent at that moment in time (e.g. preference for operation of electrical thrust over mechanical thrust to minimize noise). Therefore, the response of the EPA system to an electrical fault needs to be cognisant of a number of factors which vary in time. FM-orientated design of the electrical architecture is then dependent on a number of whole aircraft level variables which need to be understood if the aim of the system under faulted conditions is to be effectively determined.

This idea in [35] that FM *should not be merely to react mechanically to some a* *priori list of failure modes with rote responses, but instead to acknowledge any threat to objectives, striving to preserve functionality no matter what the cause* is discussed in detail and with a large degree of insight in [36]. Although in [36] the application is Guidance, Navigation and Control of spacecraft, the concept is highly applicable to future EPA. These are novel aircraft concepts which are expected to employ SOA technologies and electrical architecture configurations which have not been extensively tested over decades of flight. This leads to uncertainty in the failure modes and likely fault scenarios in the electrical propulsion system, coupled with a critical level of dependence on the same system to maintain flight safety. Therefore aiming to preserve key functions instead of just performing reactionary fault protection is a useful approach to FM where the functions are critical. Furthermore, a systems-level approach to FM is proposed in [36] since any robust FM system needs to capture the complexity of the complete system. This is a significant aspect of integrating FM into the design of EPA, since it is acknowledged that the electrical FM system will interface with wider aspects of the mechanical and conceptual design. Therefore, this FM approach established in the aerospace sector and advocated by the wider NASA FM community [37], has informed and significantly impacted the defined scope and terminology associated with FM which are proposed in this thesis in Section 2.2. Furthermore, determining FM goals is a crucial stage in the FM framework presented in Section 4.5.5.

Strategic FM, as opposed to protection has been proposed for use in future naval electrical systems where there are increased electrical loads. There is limited data in the literature on the development of naval specific FM due to the nature of the application area. For example, in [38] FM at both localised and centralised levels on an MVDC naval electrical architecture is presented. This shows that the coordinated use of FM devices is required for systems requiring protection against short circuit DC faults. The FM approach in [38], whilst relevant to EPA electrical architectures, is not currently at high TRL and so there is uncertainty as to whether this mode of fault response could feasibly be certified for use on a future EPA. Although there are similarities in the design of electrical propulsion architectures for naval ships and commercial EPA, there are a number of key differences in the FM approach which validates the need for a new approach. Commercial EPA are a novel concept which remains relatively immature, whereas naval ships incorporating electrical propulsion are well established (e.g. Royal Navy Type 45 Destroyer). The requirement for minimal weight is more stringent for an EPA than for a naval ship (although weight is a key aspect of the design in both). Furthermore, any FM technologies used in a naval application would need to be proven to withstand the harsh aircraft environment (see Section 3.3.6) and would need to achieve safety certification for use on an aircraft.

Therefore, a new approach to the design of electrical architectures for EPA is required, which draws on the experience of applying systems-level FM in other application areas but which addresses the aircraft-specific FM requirements (see Section 5.4.1).

2.7 Current Rest-of-System FM Approaches

It is evident that the advent of small-scale EVTOL aircraft flying at low altitude over built up areas pushes the boundaries of current defined safety standards. Since many of the EVTOL concepts in development by both established market players and smaller scale start-up or spin-out companies are targeted towards a near term EIS, it is expected that non-electrical FM will be crucial, due to the current immaturity of EPA-specific electrical FM technologies. This FM capability of the EPA coming from the wider, non-electrical system is defined as "Rest-of-system" FM (this is further discussed in Section 4.5.3).

The electrical FM which will be developed for larger scale EPA concepts may not scale down (in terms of technologies such as SFCLs or cost) and may not be available where developers are keen to bring an aircraft quickly to market. Therefore EVTOL concepts are likely to employ Rest-of-system FM such as Parachute Recovery Systems (PRS) and/or Ballistic Recovery Systems (BRS) [39]. Currently available whole aircraft PRS only work above 250 to 300 ft (approximately 76 to 90 m), which would leave the system vulnerable to faults on take-off and landing below this altitude [40]. BRS systems are also only useful above 100 to 150 ft (approximately 30 to 45 m) [40], and so there is a question of the safety of these aircraft should a critical fault occur at an altitude outwith the BRS or PRS safety window. The limitations of depending on

Rest-of-system FM is further discussed in Section 4.5.3 in order to demonstrate the need for targeted development of key electrical FM technologies.

However, even with these safety systems available, there is still a requirement for these EVTOL aircraft to integrate effective electrical FM into the design. The electrical propulsion system is even more critical where an aircraft has minimal gliding or autorotating capability, since the safe landing of the aircraft largely depends on the FM system's ability to maintain sufficient power to critical propulsive loads. Larger single aisle or twin aisle aircraft are unlikely to depend on PRS or BRS based safety, and so development and integration of more robust electrical FM is key. An initial electrical safety *Special Condition* published by the European Aviation Safety Agency (EASA) highlights these key differentiators, whilst specifying the need for enhanced safety requirements for such aircraft which are intended for operation over congested areas [41]. In [39] a new EPA developer identifies the following safety target: *VTOL aircraft need to be safer than driving a car on a fatalities-per-passenger-mile basis.* Yet this overlooks the existing stringent safety standards for passenger aircraft and the need to protect lives in the vicinity of airports and under flight paths, as well as the passengers on board. Hence it is unclear whether the wider safety and electrical FM requirements are being successfully integrated into the development of small-scale near-term EPA for which there is a limited amount of operational maturity and established electrical FM design best-practice.

2.8 Safety Critical Design

Since the main airframers and naval manufacturers do not publish the robust design methodologies and frameworks, it is difficult to establish the current state-of-the-art in safety critical electrical architecture design. In the publicly available literature on robust architecture design, uncertainty has been considered in [42] for unmanned aircraft and in [43] for the civil aerospace sector but from a high-level, project management perspective. Neither of these publications address the issues of robust architecture design for novel aircraft where the component technologies are unproven in an aircraft environment, and hence the complete design process is subject to a large level of uncertainty and risk of infeasibility of chosen solutions. The safety critical requirements for EPA are different from that of existing aircraft as the electrical system is even more significant to the safety of the aircraft but is less mature than the engines and other critical technologies on MEA. Therefore, a novel approach to managing uncertainty in the design process for EPA is necessary. This has led to focus being given to identifying assumptions and risks throughout the design process, enabling the impact of uncertainty to be monitored as the electrical architecture design progresses.

2.9 Current UK and International Safety Standards Development for EPA

Recently there have been efforts to develop the necessary safety standards for the electrical architecture in future EPA concepts [1]. The MIL-STD-704F standard published in 2004 [45], whilst highly detailed, does not address the unique FM challenges for future EPA at higher voltage levels where the electrical architecture is an intrinsic part of the aircraft propulsion system. It is evident that new safety standards and regulations are necessary to drive the development of reliable EPA concepts.

It was announced in 2018 that a new SAE International Committee was being established for Aircraft Hybrid/Electric Propulsion [46] to *standardized nomenclature, define applicable terms and fundamental architectures, and address considerations for endurance and other performance criteria, safety, high voltage/high power, aircraft integration and installation, and interfaces between equipment.* This marks an important progression in the realization of EPA as cross-industry engagement in defining key standards is required if any proposed FM systems and technologies are to be certifiable for future flight.

Furthermore, a new ASTM Standard Specification for Electrical Systems for Aircraft with Electric or Hybrid-Electric Propulsion was recently published [47]. Although

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[1] Although there is currently a lack of clarity as to which and by what means a regulatory body would determine and enforce safety standards in the design and operation of future EPA if the UK (and hence the Civil Aviation Authority (CAA)) were to cease membership of the EASA as part of the Brexit process [44], it is assumed in this thesis that the UK would continue to align its regulatory standards for the design and certification of EPA with that of EASA.

not mandatory, this standard offers a benchmark in terms of the expected requirements for any EPA electrical architecture. However, the standard has a minimal specification of FM requirements. The standard states that power to essential loads must be maintained when there is a loss of a single power source or ESS, yet it is unclear if a large loss of network would be acceptable, if rerouteing power is allowed or the transients that the system must be able to withstand if such a severe power fluctuation were to occur. Whilst electrical loads and sources are defined, the electrical distribution system is not defined in detail, and so it is not evident whether power converters, sensors and switch gear might be included in this category. *Protection devices* are mentioned in the context of the need for crew to disconnect sources from the distribution systems, yet the rationale for this requirement is not explained in that any fault isolation should occur within an appropriate time frame, and certainly faster than a typical human reaction time. Therefore, it seems that such actions, as well as the stated 30 minute time period in which *to recognize the loss of primary power and take appropriate load shedding action*, would occur as part of the systems-level fault response after the main electrical FM had operated (see Section 2.2.1). The standard does however, indicate the need to demonstrate that the system can maintain security of electrical supply to loads for probable durations which emphasises the importance of integrating FM testing into the development of EPA (discusses in detail in Chapter 6).

The standard also specifies that *a protective device for a circuit essential to flight safety may not be used to protect any other circuit.* This stipulation is clearly intended to limit possible fault propagation, yet from the architectures in the literature, it is possible that a single upstream device may protect zones of the electrical architecture downstream, especially where the instances of physical fault isolation are limited. If a power converter is used to perform an FM function then this may protect multiple cables or busbars to which it is connected. In stating that *circuit protective devices must be installed in all electrical circuits other that circuits in which no hazard is presented by their omission*, the standard does not specify what kind of device is required and for what function (e.g. fault current interruption, fault current limitation). Therefore, these examples highlight that this standard does not yet address the complexity in the design of FM capable electrical architectures, nor does it currently satisfactorily specify requirements for FM devices.

Given the lack of substantial safety standards for the design of electrical architectures for EPA, a novel approach to the integration of FM into the design process is required (as also highlighted in Section 7.2). Safety standards relevant to a given EPA concept are considered in Phase 1 of the FM framework presented in Section 5.4.1. Ideally, safety regulations should provide targets for operating capabilities of FM technologies, target areas for research and development as well as a metric against which different, competing design solutions can be assessed and down-selected.

2.10 Summary

Currently, FM is not considered in detail in the proposed EPA concepts in the literature. Electrical fault protection devices are identified in some instances, however, there is not a clear rationale given as to the selection of technology types, their location on the electrical architecture and the ultimate aim of the electrical FM system when a fault occurs. FM approaches which have been proposed in other applications can inform the development of robust FM for EPA - in particular, by determining the FM goal and by adhering to a systems-level FM design process. The safety standards for the electrical system on an EPA are still in development, and initial standards published recently do not satisfactorily address the complexity and interdependencies that underpin the design of FM capable electrical architectures. Therefore, a novel approach for FM design for EPA is required to manage the uncertainty and to catalyse development of both FM technologies and the supporting safety standards.

Chapter 3

Impact of Critical of FM Requirements and FM Technology Challenges

3.1 Introduction

It is crucial that the protection technology requirements are identified at an early stage in the electrical architecture design so that the range and complexity of each requirement can be fully understood. A comprehensive process of FM requirements capture has not been conducted in the existing EPA literature and so this thesis offers a novel contribution by reviewing and analysing the impact of critical EPA FM requirements on the choice of FM solutions. The selection of protection technologies in the proposed electrical architectures in the literature in Section 2.4 is largely driven by the available protection functionality of a given device, and not whether such technologies are actually feasible for an EPA concept. Therefore, there is a risk that the FM approaches and the electrical architectures proposed in the literature which are assumed to be viable are not in fact feasible when the protection technology requirements are thoroughly scoped. This key FM design assumption is acceptable at the early stages of conceptual design, but needs to be verified as part of a more detailed consideration of effective FM design.

There are a range of FM technology challenges associated with integrating effective FM into future EPA electrical architectures, such as scaling of current protection technologies and ensuring that novel technologies can operate reliably in the harsh aircraft environment. Furthermore, on the one hand, the weight of the electrical system must be minimized as far as possible, and on the other, the FM system must be reliable, robust and contend with a large variety of complex requirements. These challenges have not yet been addressed in detail in the literature but are likely to have a significant impact on the future choice of protection devices for EPA. The identification of these key technology challenges and FM requirements for future EPA are important contributions and lay the groundwork for the major contributions of this thesis, including the electrical architecture design framework (see Chapter 5) and the FM strategy map (see Chapter 4).

In order to overcome the technology challenges identified in this chapter, a new FM approach is proposed. Protection devices must be considered in combination and strategically applied to a given electrical architecture, if a range of FM functions are to be available and if the FM system requirements are to be met. A key contribution then is made in proposing the shift from *protection* to *fault management*, from a component and subsystems level to a systems level design of FM. This was first put forward by the author in [18] building on initial EPA electrical protection studies such as [48]. In subsequent, recent publications in the literature [4,49] there is evidence of this strategic fault protection using FM technologies in combination being considered where FM requirements are challenging.

This chapter first identifies pertinent requirements for protection technologies evident in the literature and discusses the impact of each requirement on the available protection technologies in Section 3.3. This then leads to the identification of a number of FM technology bottlenecks in Section 3.5 and the need to implement FM with a combination of technologies is proposed in Section 3.6. A summary of the key outcomes of the chapter are then discussed in Section 3.7.

3.2 Protection Technology Database

In the literature, it is stated that: *Rather than delivering "first time right" information - which is not available so early in the development life cycle for these complex products - initial assumptions about the aircraft design are incrementally refined on the way towards an global optimum within the interdependencies of involved engineering disciplines like Flight Control, Aerodynamics, etc.* [50]. The initial assumption in the literature (as discussed in Chapter 4.3), which now needs to be refined, is that the specified protection devices will actually be available and will satisfy the stringent FM requirements which are later highlighted in this chapter.

There is evidence in the literature [51, 52] to suppose that there is a large degree of uncertainty around the availability of suitable technologies to meet the FM system requirements within the available developmental time frames. This leads to the need to assess the current status of protection devices which could be used in future EPA applications against the key FM system requirements which are identified in Section 3.3.

A database of current protection devices categorised by function and assessed in terms of their technical maturity for an aircraft application is presented in Appendix C of this thesis. This database was first compiled and presented in [51]. The initial focus was on protection devices which were relevant to future DC configurations and superconducting protective technologies as this reflected the key technology challenges in the available detailed literature on EPA electrical architectures at that time. Since then, this database has been further developed within the Strathclyde University Technology Centre (UTC) research team for a Rolls-Royce internal project and now includes AC devices. The original database has been updated and expanded due to its value as a reference point for FM studies for EPA within the research group. For example, one of the technologies identified in the original database [53] was recommended in the project deliverable, whilst others (such as [54]) that had not been considered were given due review. The database in its current format is no longer the sole work of the student. Therefore, the original database comprising the student's work is given in the

Appendix C and reference is made in the discussion of requirements to technologies in this database in the following sections. Therefore, the data in Appendix C can be read in conjunction with the discussion of the key FM requirements for EPA.

3.3 Identification of Requirements for Protection Technologies

Feasible protection technologies for EPA must meet a number of key FM and aircraft system requirements. Therefore, in order to fully scope the future viability of any FM approach, an understanding of the relevant requirements is necessary. The FM requirements flow down from the initial electrical architecture requirements and also the wider EPA concept requirements (see definition of PLRs in Section 5.4.1). Whilst there are many requirements that will influence the choice of protection devices, it is important to prioritise those which are specific to an EPA application (such as weight) as well as those which may be especially challenging, given the current status of protection technologies. A number of requirements which are evident in the literature and are discussed in the following sections:

- Voltage rating
- Weight budget
- Component power density
- Volume
- Availability
- Tolerance of Altitude Effects
- Thermal management

It is also important to highlight that these design requirements for a given EPA concept are subject to change. For example, the expected point of EIS for a EPA may shift due to governmental pressure to reduce emissions from aircraft sooner, or may be pushed back where there are financial challenges within the industry or insufficient technology progress. As an example of the possible variation in EIS, NASA delayed the expected EIS date of some of its developmental aircraft in 2016 [55], compared to previously released roadmaps, although the specific cause, if any, was not stated. There may also be aspects of particular technologies (e.g. superconducting cables) whose more detailed requirements will become apparent in the future but are at the moment unknown. Thus the choice of protection devices which satisfy the EPA requirements is subject to a degree of uncertainty resulting from both known unknowns (e.g. whether AC or DC distribution is preferred) and unknown unknowns.

Although the detailed specifications and safety standards for a given future EPA electrical architecture may not yet be fully defined (see Section 2.9), it is possible to identify from the literature and current standards possible ranges or a threshold value for a particular requirement.

3.3.1 Voltage Rating Requirement

Two of the most immediate requirements are the system voltage and power ratings. Voltages on conventional aircraft have not yet matched increases in railway or naval system ratings and the existing standards for aero-electrical systems are only for lower voltage levels up to 270 V_{dc} [45]. However, the probable shift from present aircraft systems rated at 115 V_{ac}, +/- 270 V_{dc} and 28 V_{dc}, 230 V_{ac} to 700 V_{dc} line-to-line in the medium term [56], then to voltages in the kV range [5, 57] in order to supply high power propulsion loads with minimal losses is one of the key design factors that differentiates current protection systems and those of the future. Projections of EPA voltage and power ratings for different generations of aircraft are described in Chapter 4 and mapped in Table 4.3.

The voltage ratings for Boeing's SUGAR Volt aircraft is taken from the input parameters to the system model [6]. The voltage rating of the bus bar in the study was initially set to 10 kV with the power converters rated for 500 V_{dc} and 120 V_{ac}. As an electrical system architecture is not provided, it is assumed that the protection devices for this aircraft should be rated for the bus bar voltage, although it is not clear from this minimal data why there is a difference in the boundary values for the bus bar and power converters. Further work is needed to fully understand the electrical system which would support the propulsive motors and batteries in this design.

The STARC-ABL system in [29] was not defined for a specific voltage value, but rather was assessed over a range of voltages from current state-of-the-art aircraft levels to kV-level naval system ratings. Although the cables in this design were rated at 1000 V, the protection devices were scaled for power densities at 6500 V [29]. Therefore, it is likely that the voltage range identified in the literature for this and other concepts will be reduced or better defined based on trades between efficiency and system weight.

The FM classes (see Figure 4.1 in Chapter 4) under 1kV are split at 750 V as it is expected that aircraft systems will match the voltage levels of electric vehicles [58] in the first instance as there will be electrical protection devices developed at this rating.

As mentioned already, the exact voltage ratings for an aircraft may not yet be decided, but reviewing the literature gives an indication of likely ranges (greater than 1 kV range for superconducting systems, less than 1 kV scale for nearer term ambient temperature aircraft).

3.3.2 Weight Budget Requirement

The requirement for the system to be within a given weight budget is particularly important as the weight of the protection system will form a non-negligible component of the overall electrical system weight. A review of published EPA electric aircraft literature reveals that there is little understanding of the impact of the protection system weight upon the feasibility of the overall electric system, since protection system weight is at times not included in aircraft weight breakdown figures [5, 6, 59]. Focus is in some cases instead given to the significance of battery weight and design sensitivities to battery improvements and availability. However, the protection system weight must also be given consideration at this design stage, in view of the need for security of power supply to the propulsors and the weight of current protection devices. In [4] the total weight budget for the ECO-150 aircraft (including SSCBs) is assessed for a variety of configurations, as it is shown that the weight of the complete electrical architecture varies with the voltage rating. This already indicates the interdependency of the various EPA requirements (see Section B.3).

It is anticipated that larger aircraft will require larger power systems and hence higher rated protection devices. Furthermore, the possible change in electrical configuration from conventional electrical systems to superconducting (STARC-ABL [60]/ Quadfan [5] to N3-X [8, 30]) for larger aircraft implies an increase in total protection system weight. Published literature on Boeing's SUGAR Volt aircraft and BHL's Propulsive Fuselage aircraft heavily discussed aeronautical system design but did not state electrical system weight breakdown in sufficient detail for an effective comparison to be made. Therefore, there is a need for all proposed architectures to consider electrical protection devices before commencing more detailed system design, as this will shape other aspects of the electrical propulsion system and form a component of the maximum take-off weight.

3.3.3 Component Power Density

Power density of protection components is an important point of comparison between technologies. Aircraft concepts which are less developed and targeted towards the far term may not have a defined total system weight budget, and so it may be difficult to derive the weight requirement for individual components. In this case, the target component power densities are a useful metric to enable assessment of the feasibility of technologies. This bottom-up approach to quantifying requirements does overlap with the top-down approach based on the PLRs (see Section 5.4.1), yet both are useful means of determining feasible protection technologies.

At present, the power density of silicon based power electronics for aircraft is around 2.2 kW/kg [25]. Advances in silicon carbide (SiC) switching devices are expected to increase the power density to 9 kW/kg for aircraft power electronics applications by around 2035 [25]. In these power density values it is not clear if this includes filters, packaging and thermal management components. These values stated in [25] are still less than the 19 kW/kg target for complete power converters on the N+3 NASA STARC-ABL aircraft, and the 13 kW/ kg for the N+1 SCEPTOR aircraft [60].

Raytheon have begun developing novel High Temperature Silicon Carbide power modules specifically targeted towards a More Electric Aircraft (MEA) power system [61]. Although the exact power densities of these devices are not yet published, this demonstrates that SiC power electronics are already being investigated as an enabling technology for future EPA.

Moreover, Thales are developing Power Electronics Modules (PEMs) for MEA applications with a current power density of 2-3 kW/kg for today's devices, 6 kW/kg for next generation modules and ultimately 9-15 kW/kg for N+2 devices [62]. This is in a similar range as the values quoted about for NASA's Maxwell project and is further verified by the N+2 PEMs reaching TRL 5 in 2015. The modularity of this design may be useful for scaling up these power converters for higher power rated systems.

Furthermore, a state-of-the art rectifier developed by ETH Zurich aimed at MEA applications achieved a power density of 9.44 kW/kg and a volumetric power density of 14.1 kW/m^3 rated for a 10 kW system [63]. Almost half (48%) the total volume of this device was derived from the Electromagnetic Interference (EMI) filter, which highlights the fact that the bulky filter components are an area in need of improvement for future power electronic devices. Clearly there are trades to be made between the size of filter and the switching frequency if this has has a significant impact on the total volume. The rated voltage for this device was in the range of 320-480 V$_{ac}$, which is more suitable for powering electrical subsystem networks on EPA aircraft as opposed to electric propulsion loads. However, if the stated power density could be scaled to the kV range, this would make AC-DC conversion with DC transmission more attractive.

In the literature it is not always clear if the quoted power density value for a component or target includes all packaging and associated thermal management. Therefore, a key requirement for all FM devices is that the weight of all housing, insulation and cooling systems is minimised, and also taken into account in calculating power density.

Automotive Converter Power Density Case Study

Whilst advances in aircraft-specific high power density converters have yet to be fully realised, the automotive industry has already seen an increase in power converter ratings for electric and hybrid vehicles over the last decade [64]. It is possible that a similar level of development could be achieved in EPA power converters, if a similar level of investment is achieved. Furthermore, power electronics in Formula 1 electric vehicle systems also give an indication of technology improvements that might be possible, as this is an area of the automotive industry in which the constraints on weight and volume are particularly stringent, yet where there is funding and motivation to develop means of overcoming such challenges. The comparison to Formula 1 converter capacities, however, should take into account the expected reliability and life span on devices in motor-sport. Components are often and easily replaced and so the requirement for high reliability and maximum life span is not as important in this particular application.

One example of a SOA high power density motor-sport device would be McLaren's Motor Control Unit (MCU) which contains a 14 V DC-DC converter using SiC MOSFETS [65] which offers greater power density (over 20 kW/kg [66]) and reduced cooling requirements in comparison to previous models and is a market leader. This shows that SiC power electronics are already being exploited in DC automotive systems to increase efficiency and power density, the benefits of which may be transferable to DC aircraft electrical architectures.

Power Density of SFCLs Case Study

The SOA power density of SFCLs is very low (ranging from 0.66 to 15.9 kW/kg depending on the technology type [48]), due to the fact that they are typically one-off installations on terrestrial grids used to protect critical sections of a network. The lowest weighted SFCL published in the Electric Power Research Institute Technology Review [67] as of 2012 was 907 kg rated at 22.9 kV (weights of other SFCL devices are presented in Appendix C.2.3). If this weight were to be linearly scaled as a very basic metric for a 10 kV aircraft system (such as the N-3X) then the expected weight would be in the region of 396 kg. This significantly higher than the 2.8 kg weight of the 11.19 MW rated SFCLs required for the cross redundant multi-feeder architecture suggested for the N-3X aircraft [48].

However, the SFCLs installed currently on the grid must have their own cryogenic system, which adds to the overall weight. Devices on a superconducting aircraft may be able to benefit from weight savings due to a centralised cryogenic system supplying all the superconducting devices. Furthermore, SFCLs developed for aircraft would naturally have a reduced weight due to components being chosen specifically to minimise weight, which may not be the case in SFCL technology demonstrators. However, the reductions in SFCL weight which are required to increase power density ratings from ≈ 4 kW/kg of TRL 5-6 devices in 2013 to the 4000 kW/kg mentioned in the same study [48], imply that SFCLs are not likely to feature in any FMS for N+1 or N+2 aircraft. Whilst naval SFCLs currently under development [68, 69] are expected to reduce weight and volume compared to terrestrial systems, it is expected that this technology will need to be developed and demonstrated in naval systems before being adapted and further reduced in size for a EPA aircraft. This demonstrates the significant discrepancy in examples of SOA FM power density and the expected FM technology requirements.

Power Density of DC Fault Current Interrupters Case Study

Another weight sensitive design technology is the DC fault current interrupter. A comparison of protection system total weight and the projected weight of DC fault current interrupters across a number of proposed EPA electrical architectures which specify this device as part of the electrical architecture is shown in Table 3.1, where the values are either from data in the literature or calculated from stated power densities of the protection equipment.

Although SSPCs form part of the architecture for the Quad-fan concept [5] outlined in Table 3.1, they are not currently available rated at 3 kV, and currently have a maximum rating of 375 V_{dc} at 10 A [70]. Whilst an SSPC prototype for MEA systems operating at 540 V_{dc} has been demonstrated (see protection device database entry [71] in Appendix C.2.1), the assumption that N+3 EPA systems could utilise SSPCs for DC FM (i.e. [5]) would require very significant development in solid state switches suitable for SSPCs (in terms of V/I ratings and on-state losses) and on the energy dissipation capacity of the switch. Therefore, there is a challenge to realising DC fault current interruption with devices of an appropriate power density when the required operating voltage is greater than current SSPCs.

The remaining table entries have stipulated a DC breaker power density of 200 kW/kg which was identified in a recent NASA study as a best case scenario rating [8]. However, given that example solid state DC breakers of TRL 5-6 (verified in a relevant environment) had a power density of 14 kW/kg in 2013 [48], this infers an increase in power density more than ten times the SOA achievement. Whilst some of this could be achieved by improvements in solid state switches, operation at higher power will demand greater cooling which may offset these improvements (thermal management requirement is discussed in Section 3.3.7). At present, individual IGBT modules from Mitsubishi and Infineon have a maximum voltage blocking rating of 6.5 kV and a maximum current rating of 1.5 kA [30], which means that these devices would not be suitable for use in larger N+3/ N+4 designs, but may be suitable for smaller scale, near-term EPA. Other DC solid state and hybrid breakers in the protection device database in Appendix C.2.1, such as [72] and [73], have suitable voltage ratings for future EPA electrical aircraft but have not yet been adapter for use in an aircraft environment.

Furthermore, Electro-Mechanical Circuit Breakers (EMCBs) may not be suitable for all future EPA applications. For example, commercially available vacuum DC breakers from ABB rated at 12 kV and nominal current 2 kA have a weight of 121 kg and require between 33-60 ms to open in response to a fault [74]. Whilst this device is rated in similar voltage and current ranges for larger N+4 EPA such as the N-3X, the speed of operation of the breaker may be too slow for compact, low-impedance aircraft electrical architectures, and the current weight without any future adaptation is almost certainly too large given the estimated target weight of 20–72 kg [8, 30].

Alternatives to DC Circuit Breakers

Therefore, while it is important to identify target values of power density, it must be understood that such ideals may not be realised in the chosen development time frame. Alternatives to DC breakers need to be sought in order to ensure that protection of DC distribution on aircraft can be achieved. One such alternative to both SSCBs and

EMCBs are DC disconnect switches. These switches do not interrupt the fault current, but rather isolate a fault and allow reconfiguration of the network after the fault has been cleared by an appropriate fault current interrupter device. Thus the device must only interrupt small leakage currents in the order of mA which reduces both the volume and mass of the overall device.

The weight of DC disconnects has been estimated as 6.49 kg for a 10 kV, 10 MW rated disconnect, which could be scaled with a power density rating of 1540 kW/kg [30]. This power density is significantly higher than the current ratings of DC circuit breakers, and the weight is much less than the estimated DC breaker weight of 71.84 kg described in the same study. Although disconnects with a superconducting repulsive disc are still at low TRL, the possibility that some of the DC breakers on a network will be replaced by DC disconnects (or a similar non-current interrupting technology) in order to reduce the protection system weight has implications for the FMS as well as the architecture design, since greater sections of network must be de-energised during a fault clearing process [18]. Devices will have to operate in sequence with coordinated responses which is more challenging. There will also have to be high confidence in the sensors detecting the fault as fault current interruption devices may have to be remotely tripped where the fault and the fault current interruption functionality are not located in the same section of the network. Communication and coordination of FM devices increases the total fault response time so this FM approach (driven by the use of DC disconnect switches) has to be weighed against the improvement in electrical system weight.

The impact of DC circuit breakers being unavailable at high confidence level is further discussed in the down selection of FM solutions in the case study presented in Section 5.4.

3.3.4 Volume Requirement

The volume of devices is also a concern, given the limited space which is available within the airframe. This is particularly pertinent for converter devices which may require large filtering components, thermal management or insulation. For example, one DC-DC converter study highlighted that there was a volume utilization of around 50% in the converter, which was due to large isolation distances and material needed to achieve galvanic isolation [75]. The volume of converters is also sensitive to the choice of topology e.g. approximately half the comparatively large volume of MMC converters is occupied by the capacitors. Yet the converter topology dictates fault response, and so a converter may be a preferred choice of FM technology in terms of its FM capability but may be infeasible due to the requirement for minimal volume.

Minimal volume is also an important requirement in existing DC circuit breakers since the components that stretch and extinguish the arc are bulky and contribute to the overall large volume of the device [76]. Solid state devices are an alternative; however, they are susceptible to higher conduction losses. Therefore, the constraints on the protection device trade space may influence the technology types which are feasible.

Depending on the level of propulsion distribution, devices may have to be located in a variety of positions. Larger devices are more difficult to accommodate, especially where integration with novel aircraft configurations (such as Blended Wing Body or Double Bubble [77]) is required.

Figure 3.1: Transformer and rectifier device shown to indicate scale [9]

Volume Constraint Case Study

A recent prototype AC-DC-AC converter tested by ABB in a Swiss shunt locomotive was rated at 1.2 MW although able to operate at a slightly higher level for a short time [9]. The device has a weight of 4500 kg and the scale is evident from Figure 3.1. This highlights the discrepancy between the current status of converters rated around 1 MW, and the reduction in scale that would be required in order to transfer this technology to an EPA application. Furthermore, the cooling of this device benefits from the natural convection of the train draft. If used in an EPA environment, an alternative cooling mechanism such as liquid cooling would be required to replace the train draft cooling. This example shows some of the complexity which can arise in transferring technology across application areas.

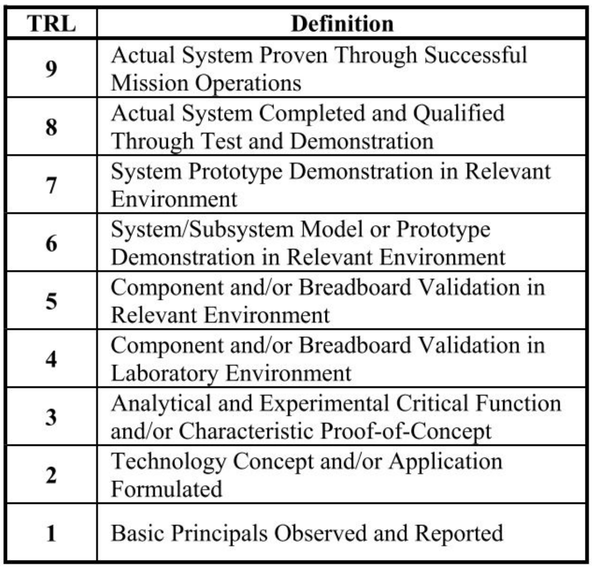
3.3.5 Availability Requirement

Regardless of the aircraft concept, there is a fundamental requirement that FM technologies are available. Devices must have reached high TRL to be certified for use on an aircraft at the point where the aircraft and its subsystems are reach the final design stages ahead of the EIS or they cannot be part of the FMS. TRLs are defined in [10] as shown in Figure 3.2.

The exact TRL (0-9) for some technologies is difficult to ascertain based on the published data, so in this thesis the TRL rating has been simplified into three broad stages as follows:

- Low TRL (1 to 3) – evidence of patents, computational modelling and simulations or conceptual description
- Medium TRL (4 to 6) – evidence of lab based prototype, hardware testing or scaling up of initial testing
- High TRL (7 to 9) – evidence of extensive in-field testing or commercially available

These simplified TRLs are therefore used as an indication of the required level of development remaining before devices can be certified and used in a future EPA.



TRL	Definition
9	Actual System Proven Through Successful Mission Operations
8	Actual System Completed and Qualified Through Test and Demonstration
7	System Prototype Demonstration in Relevant Environment
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment
5	Component and/or Breadboard Validation in Relevant Environment
4	Component and/or Breadboard Validation in Laboratory Environment
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
2	Technology Concept and/or Application Formulated
1	Basic Principals Observed and Reported

Figure 3.2: TRL defintions [10]

In pursuing novel protection devices, there is a risk that the technologies may not reach maturity within the required time frame. Given the risk adverse nature of the aircraft industry, there is also the possibility that airframers may be reluctant to adopt technology that has not demonstrated long term reliability in an aircraft environment. Also, devices may theoretically be commercially available, yet the cost or complexity in manufacturing may entail that there is a limit on the number of units which can feasibly be used on an aircraft. Therefore, it is possible that the TRL of a given device may render it available from the electrical system design perspective, yet the aerospace industry may choose not to employ such a technology.

There is also added uncertainty in the design of EPA electrical architectures where novel technologies are being developed or adapted from other application areas. There may be an unknown limit in the TRL progression that is possible for a particular technology or topology which in regards to a future EPA application. This then further indicates the importance of early development of FM devices specifically for EPA and methodical testing of individual FM technology capabilities (see Chapter 6).

AC Breakers Availability

AC breakers are an established technology which are already in use on conventional aircraft [78], as well across other applications such as naval systems where AC transmission is in use. Therefore, it is anticipated that it will comparatively less challenging (compared to DC breakers) to source AC breakers of suitable rating and power density for EPA propulsion aircraft, and indeed, published TeDP electrical architectures utilise AC breakers at both the generator and motor sides of the network [8, 30].

DC Circuit Breakers Availability

DC circuit breakers, however, are far more challenging to realize on a future EPA. This is due to the fact that in order to interrupt the power flow in the high power density circuit, the current needs to be reduced to zero. AC circuits exhibit inherent zero crossing behaviour, which allows physical disconnection of the circuit at the point of zero current. In DC breakers this is of course not possible, which means that additional circuit complexity must be incorporated to deliver a near zero current. Existing methods used to achieve disconnection and energy dissipation, some of which involve arc chutes, others requiring large capacitors and inductors to create a resonant circuit, are typically bulky [79] and may not be suitable for high power density systems.

DC Breaker Case study

State-of-the-art naval and marine power system designs have increasingly employed DC power, which has led to a growing need for suitable DC breakers. In order to support the use of a DC bus supplying multiple high power AC drives, Siemens developed a method of splitting sections of the network to minimize the impact of short circuits. The IGBT bus circuit breaker (called *Integrated Load Controller*) is capable of $\leq 20\ \mu$s interrupt time, trips at 7 kA, is rated for 930 V_{dc} and has a recovery time of 10 ms after a short circuit has occurred [80]. Since this technology has reached high TRL (already been implemented on first operational vessels) [80] and is capable of very fast response to DC faults, this may be a device that has potential cross-over to a future aircraft application if it could be suitably adapted and certified. An alternative choice for future naval fault current interruption is the use of “z-source breakers” which force fault current backwards through a switching device [54], and two such z-source technologies [54, 81] are identified in the protection device database in Appendix C.2.1.

3.3.6 Altitude Requirement

Another major challenge for the safe operation of electrical aircraft systems is the impact of high altitude on component operation. Aircraft systems have traditionally been limited by Paschen’s law which describes the breakdown voltage of parallel metal plates in air versus the product of the distance between the conductors and the pressure [82]. Since the minimum breakdown voltage for any pressure-distance value is approximately 327 V, conventional aircraft voltages have been limited to less than 327 V. However, with much higher propulsive electrical loads it is likely that the voltage rating of future EPA electrical architectures will be well above this conventional limit (see Table 4.3 and discussion in Chapter 4). Novel protection devices which have been developed for other applications may not have been proven at high altitude, and may not have appropriate insulation thickness [83]. It is advantageous, therefore, to develop aero-specific protection devices from the outset and to begin to understand the complexities introduced to the design of effective FM as a result of operating at higher voltages in an aircraft environment subject to vibrations and variations in temperature and pressure.

3.3.7 Thermal Management Requirement

The required thermal management for a chosen aero-electrical power system may have a significant negative impact on performance (weight and efficiency) [84]. There may also be requirements on where devices can be located if there is risk of the heat transfer from devices interfering with or causing damage to surrounding components. An example of a technology type for which thermal management is important are SFCLs since a sufficient coolant mass flow rate must be maintained. Thermal losses from protection devices lower the efficiency so requirements on the maximum allowable heat transfer may apply. If batteries are to be used on the electrical network, then there may also be an optimal temperature for the environment surrounding the battery which would also pose a potential thermal management requirement.

Table 3.1: Overview of total protection device weight for a selection of EPA

Aircraft	Developer	Time Frame [25]	Total Weight of Protection Devices (kg)[a]	Protection Devices on Network	Individual DC Breaker Weight (kg)
Maxwell [29]	NASA	N+2	3.8	10 DC circuit breakers	0.4
STARC-ABL [29]	NASA	N+3	13.6	4 DC circuit breakers	6.87
Hybrid Quad-fan [5]	Bauhaus Luftfahrt	N+3	252	5 SSPCs (DC)	50.5[b]
N-3X [8]	Rolls-Royce and NASA	N+4	5438[c]	60 AC breakers, DC breakers (18 high power & 128 low power), 134 fault current limiters	62.5[d]
N-3X [30]	GE and NASA	N+4	1237[e]	20 Hybrid AC breakers, 20 Hybrid DC breakers (16 low power & 4 higher power), 68 disconnects	71.84[f]

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[a] Does not include the converter weights

[b] Based on 44 kW/kg power density and 2220 kW electric propulsion power26, assuming SSPCs are rated for full motor power

[c] Weight for Multi-Feeder architecture base line weight [8] (page 145 in reference)

[d] Based on a high power SSCB rated at 12.5 MW and with a 200 kW/kg expected power density

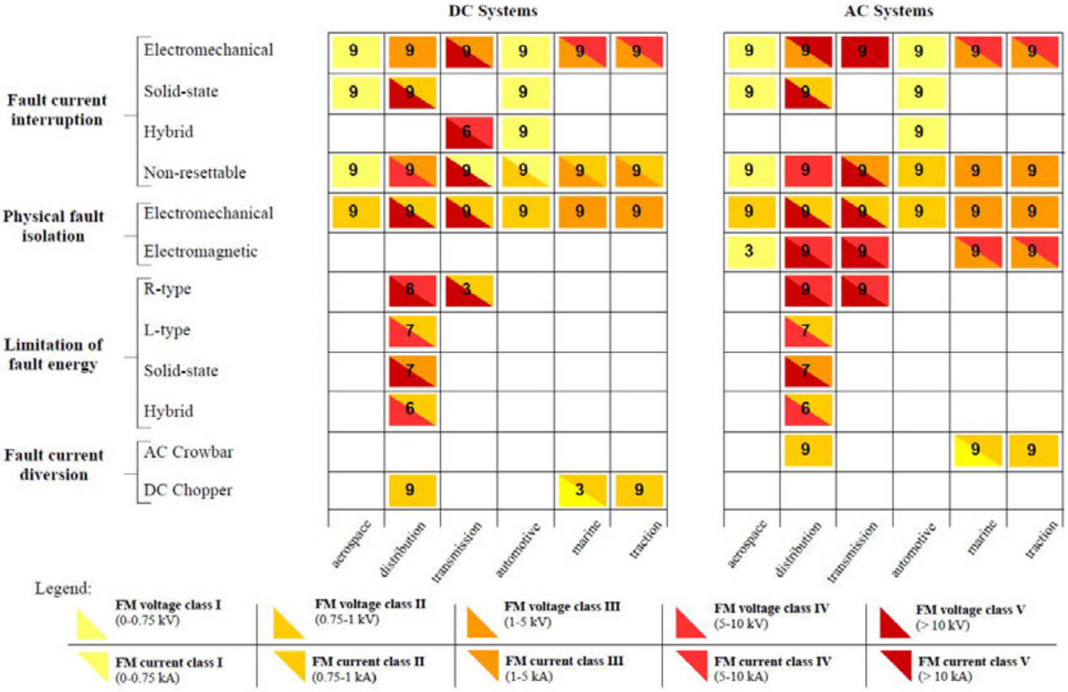
[e] Total protection weight for 8 kV system to optimise overall weight, but individual DC breaker rated for 10 kV

[f] Hybrid DC breaker scaled to 10 MW rating

3.4 Summary and Requirement for Novel Approach to FM for Aircraft Environment

Given the FM requirements discussed in Section 3.3 and the lack of development in key FM technologies, a novel approach to FM for future aircraft is necessary. This review of the impact of requirements highlights the value of the work undertaken in this thesis. It is clear that the requirements that determine what is needed from the FM system are fundamentally different from those that exist for current aircraft and for similar power rated electrical architectures from other application areas. In particular, the harsh aircraft environment and the increased power levels entail that current FM solutions will not be feasible and a novel approach to FM is needed.

The desired technologies and FM functions for EPA which are available to other application areas do not yet have the levels of maturity needed to be used with confidence in future EPA. An overview of the technical maturity and level of challenge anticipated in developing and adapting each technology for use in an EPA is given in Figure 3.3. This clearly indicates the lack of maturity and limited ratings of a number of FM technologies. This again indicates that existing FM solutions will not be suitable as the component FM technologies on which they rely may not be available. The risk of key technologies being unavailable at the required specification and the impact that this has on the wider electrical and system design is further discussed in Chapter 4.



		DC Systems						AC Systems					
		aerospace	distribution	transmission	automotive	marine	traction	aerospace	distribution	transmission	automotive	marine	traction
Fault current interruption	Electromechanical	9	9	9	9	9	9	9	9	9	9	9	9
	Solid-state	9	9		9			9	9		9		
	Hybrid			6	9						9		
	Non-resettable	9	9	9	9	9	9	9	9	9	9	9	9
Physical fault isolation	Electromechanical	9	9	9	9	9	9	9	9	9	9	9	9
	Electromagnetic							3	9	9		9	9
Limitation of fault energy	R-type		8	3					9	9			
	L-type		7						7				
	Solid-state		7						7				
	Hybrid		6						6				
Fault current diversion	AC Crowbar								9			9	9
	DC Chopper		9			3	9						

Legend:

FM voltage class I (0-0.75 kV)	**FM voltage class II** (0.75-1 kV)	**FM voltage class III** (1-5 kV)	**FM voltage class IV** (5-10 kV)	**FM voltage class V** (> 10 kV)
FM current class I (0-0.75 kA)	**FM current class II** (0.75-1 kA)	**FM current class III** (1-5 kA)	**FM current class IV** (5-10 kA)	**FM current class V** (> 10 kA)

Figure 3.3: Overview of Individual Technology Maturity and Availability [11]

3.5 Expected Technology Bottlenecks

From reviewing the current proposed electrical architectures in Chapter 2.4 and identifying the relevant FM requirements for future EPA electrical architectures, it is clear that there are a number of technology challenges which may undermine the feasibility of any future EPA concept.

3.5.1 Target Weight Budget

Based on the protection device database and the review of requirements, the target weight budget is a significant challenge. Whilst weight could be considered as a constraint on component selection or a systems level target, the available weight budget for aircraft with later points of EIS sets a requirement which has implications for the choice of FMS. The weight budget as a requirement is therefore useful in eliminating inviable FMSs at an early point in the design process. Furthermore, reduction in weight is one of the main Core Activities (see Table 4.2) which must be achieved before technologies developed for other applications can be transferred to an aircraft system. Weight is also one of the most challenging requirements to physically implement as typically improvements made to system performance or reliability lead to an addition of weight. This is made yet more difficult by the increasing power levels in aircraft, resulting in the situation where a reduction in weight needs to be achieved while the system power ratings increase. Fundamentally, the fact remains that EPA have been pursued as a means to reduce aircraft emissions and this can only be achieved where the effect of adding electrical propulsion is offset by a reduction in fuel burn. Therefore, the challenge is that on the one hand the weight of the electrical system must be minimized as far as possible, and on the other the FMS must be reliable, robust and contend with a large variety of complex requirements.

3.5.2 Step-Changes in Electrical Architecture Requirements

A number of important possible shifts in the system requirements have been identified in Table 3.2 and are discussed in the following sections. These are possible changes in the system design that would catalyse the development of protection devices and/or eliminate the effective use of current SOA protection devices. The limitations of each of the technologies have been identified, since it is anticipated that particularly for near term aircraft the rating and functionality of available devices will be severely limited. Finally, the operation of each device within an FMS is also highlighted. Many of the electrical architectures proposed for future aircraft concepts have been designed with this ideal FM scenario (e.g. [8]), and so it then follows that the electrical architectures which are actually feasible are likely to be limited where key technologies are insufficiently progressed.

Table 3.2: Technology Challenges

FM Technology Challenges	**Up to the Present**	**1. Possible shift in System Requirements**	**Projected Near Term Development and Limitations**	**2. Possible shift in System Requirements**	**Projected Mid-term Development and Limitations**	**Long Term Development Goal**
Power Electronic Converters	Power electronic converters required as part of the electrical architecture with internal FM mechanisms but not used for wider electrical system FM	Power switching/ diversion functionality of converters needed in fault response, use of DC network between electrical machines	Power electronic converters can be used for secondary fault isolation of wider network after peak fault current cleared and for FM of converter itself. Limited by: • Number that can be used or power ratings due to • Low power density • Insufficient improvements in thermal management/ efficiency • Requirement to operate in series with devices providing initial fault isolation • Requirement to operate in series with devices providing physical fault isolation • FM may only be feasible in either rectifier or inverter **AND/OR** specific converter topology	Multiple points of fault current interruption required, limited FM weight budget	Power electronic converters can be used for FM at critical points in the wider network. Limited by: • Low power density • Insufficient improvements in thermal management/ efficiency • Physical integration (volume, cooling system) with airframe where multiple converters are used • Requirement to operate in series with devices providing physical fault isolation • Possible requirement for parallel redundancy to prevent converter failure causing failure of fault isolation	Power electronic converters used as part of a strategic fault response for: • Fault current limitation and interruption at critical points on the network • Interfacing energy storage to the network • Effective fault ride through during fault within converter

Table 3.2: Technology Challenges

FM Technology Challenges	**Up to the Present**	**1. Possible shift in System Requirements**	**Projected Near Term Development and Limitations**	**2. Possible shift in System Requirements**	**Projected Mid-term Development and Limitations**	**Long Term Development Goal**
Energy Storage	No energy storage on the propulsion network OR Energy storage not used for FM in the electrical network	Increased requirement for security of supply to critical loads	Energy storage used as a supplement or substitute power source at a single or limited number of locations where the electrical system is operating for a prolonged time in a faulted or depleted state. Limited by: • Capacity of energy storage • Length of time power can be supplied and the percentage of power from energy storage • Physical location and co-ordination of energy storage devices • Speed of the response due to network reconfiguration prior to power being supplied from the energy storage	Increased number of loads, greater flexibility of architecture required	Energy storage rapidly brought online to supply power to specific area of network/load suffering loss of nominal power source. Limited by: • Capacity of energy storage • Bandwidth of energy storage and associated converter • Physical location and co-ordination of distributed energy storage devices • Speed of the FM response due to the converter limitations and network reconfiguration prior to power being supplied from the energy storage	Energy storage used as part of a strategic fault response as: • Single large energy storage device at strategic location on the network • Multiple coordinated, distributed energy storage devices at strategic locations Providing alternative or additional power during faulted conditions

Table 3.2: Technology Challenges

FM Technology Challenges	**Up to the Present**	**1. Possible shift in System Requirements**	**Projected Near Term Development and Limitations**	**2. Possible shift in System Requirements**	**Projected Mid-term Development and Limitations**	**Long Term Development Goal**
DC Fault Current Interruption Devices	DC distribution not feasible/ not preferred OR DC network limited to voltage ratings of ± 270V to enable use of current SSPCs and fuses	Increase in network voltage rating or preference for a DC network	DC distribution > ± 270V not feasible/ not preferred due to lack of available FM technologies **OR** Higher voltage (> ± 270V) DC distribution used but FM response limited by lack of available resettable fault current interruption technologies on DC network. FM response dependent on fault current interruption from: • Pyro-fuses/fuses **AND/OR** • Power converters **AND/OR** • AC breakers - coupled with non-fault current interrupting breakers on the DC network which operate once the network is de-energized	Increased rating and number of loads, larger aircraft, standards developing	DC fault current interruption devices available but limited by: • Speed of operation **AND/OR** • Low power density **AND/OR** • Functionality: – Requirement for sequential operation of devices & sophisticated control **AND/OR** – Additional devices for physical fault isolation required on same network zone (where devices are solid state)	DC fault current interrupters used as part of a strategic fault response for: • Rapid fault current interruption at all zones on DC network Enabling: • Strategic isolation of upstream/downstream zones • Effective reconfiguration of healthy network and use of redundant power paths

Power Electronic Converters

Since power electronic converters feature in many proposed baseline electrical architectures (e.g. [4, 8, 13, 30]) and are heavy, it would be beneficial to exploit the dual functionality that these devices offer: both power conditioning and switching. Yet given that power conversion is a critical electrical architecture function, and that failure of these devices would impact on both the faulted and normal operating conditions of the system, further development is required to ascertain whether these technologies can be actively used as part of a FM strategy within the stringent aircraft operating standards. EPA configurations have been proposed which are converterless [7] to reduce the weight of the electrical system, but require synchronous operation of the generators and motors, thus introducing another technology challenge.

FM Optimized Energy Storage Devices

Most electrical architectures proposed for future EPA and demonstrators feature some form of energy storage, although it is not always clear if the energy storage plays a role in the FM response or only during normal operation. Yet energy storage as part of a rapid fault response to maintain critical propulsion, especially where the network is DC, has not been fully proven in a scaled EPA application. Therefore, there is uncertainty as to whether the power converter interfacing the energy storage to the rest of the network would be capable of ensuring fast supply of power from the energy storage to the critical propulsion loads, while the upstream or unfaulted system is reconfigured or recovers and during which points of flight this mechanism would be used.

DC Fault Current Interrupters

DC fault current interruption devices are a critical technology for architectures with DC distribution, where components cannot be rated to withstand maximum or prolonged fault current. However, given the lack of aircraft suitable DC switchgear in the kV range (see database in Section C.2.1) there is a risk that this technology may not be available and so may limit the use of DC networks in future EPA.

3.6 Combination of Devices

Thus far, protection devices have been discussed individually, yet there are advantages to be gained by combining different types of devices, such as greater redundancy and more flexible reconfiguration. However, there are also trades to be made between the increased security of supply gained from the use of multiple devices on a section of network against the weight and efficiency penalty associated with increasing the number of devices. For example, reducing the maximum fault current rating for circuit breakers and cables by the addition of fault current limiters to the network [18, 48]. Thus, the use of multiple, varied devices may lessen the impact of some requirements (maximum fault current in this case) yet makes others more difficult to achieve (minimal total weight), thus also posing a technology challenge. Therefore, this demands that design of protection for critical, high power electrical architectures takes a systems-level view to determining protection devices which can feasibly meet the FM system requirements. Given the FM requirements and the current status of protection devices, any viable FM approach for future EPA concepts will need to look beyond individual protection devices towards strategic fault management. This is further discussed and new terminology is defined in Section 2.2.

3.7 Summary

The presented FM requirements for EPA electrical architectures have highlighted the range and complexity of the technology challenges facing the design of robust FM systems for future EPA. A number of key technology bottlenecks have been identified which at worst threaten the viability of certain EPA concepts, and at best will severely limit the choice of FM solutions available. In highlighting and discussing the impact of these technology challenges which have not been well understood in the literature (evidenced by the lack of clear FM rationale in the proposed FM approaches) an important contribution is made.

In particular, there is currently no obvious technology solution which can perform physical DC fault isolation for larger scale EPA meeting the likely power, volume and density requirements. Further targeted development of FM devices is required to address these identified technology challenges, and an FM approach is required which goes beyond specification of individual protection devices towards identification of complete FM solutions. This has led to the development of an FM strategy map, as described in Section 4.

The availability, TRL and range of capability of protection devices at an aircraft's point of final electrical design will have a significant impact on the feasible FMSs, and hence the available electrical architectures. The requirements surrounding the design of an electrical propulsion FM system are demanding, particularly in regard to those which are specific to aero-electrical systems (such as altitude), and prioritising the correct requirements at an early stage in the design to achieve an optimised system design is not straight forward. It is these stringent EPA requirements on the specification, design and capability of the protection devices that results in so few currently being suitable for future EPA. It is also clear that although some devices do exist at high TRL (e.g. SSPCs), this may be for only a limited range of specifications or scale. This then indicates that TRL alone is insufficient to determine the feasibility of using a given protection device within an electrical architecture. This has led to the use of the term *Confidence Level* in the later chapters of this thesis (see Section 5.7.2) as a metric of technology and system maturity.

In light of these requirements and the range of current technology challenges, it is imperative that the FM system is considered from the outset of the electrical architecture design to ensure the viability of the chosen FMS. Therefore, by applying a design process that is driven by the aircraft level requirements and informed by the available FM devices, an FM capable electrical architecture can be achieved. On this basis, a novel electrical architecture design methodology is proposed in Chapter 5 which derives the critical FM requirements for future EPA and which ensures that only viable electrical protection technologies are selected as part of an FMS.

Chapter 4

FM Strategy Map

4.1 Introduction

The identification of key FM requirements in Chapter 3 highlighted the fact that targeted development of protection technologies for EPA is required. In order to strategically develop a wide range of suitable protection technologies in line with the range of proposed EPA concepts, an FM strategy map has been developed.

Robust, effective FM solutions for complex EPA electrical systems require the integration of a number of protection technologies in combination with various aspects of electrical and wider system oversizing. The functional limitations of the various FM devices and FM clusters (groups of FM devices, non-FM devices and aspects of the electrical architecture which perform specific FM functions) need to be taken into account and assessed alongside the development of the FM system goal, in order to identify areas requiring targeted development. Critical to this is the determination of the FM confidence level, an indication as to whether the specific technology will be available at suitable ratings within the developmental time frame. This assessment of confidence level represents a novel metric of FM technology readiness and suitability which enables a clearer understanding of the feasibility of FM solutions.

FM strategy maps provide a mechanism by which to identify points where the desired FM system goal and aircraft level requirements do not align with high confidence in the availability of the required FM technology functions. Any limitation of confidence level in particular FM solutions informs decisions on the choice of electrical architecture and wider aircraft design. Therefore, the presented strategy map provides timely insight into key FM technology challenges which does not yet exist in the literature, enabling targeted development of FM technologies where the current status of technology lags the projected requirements for future EPA FM design.

In order to outline a vision of the future development of FM solutions, a method of compiling an FM strategy map is required which captures the unique challenges associated with the development of FM for EPA and will form the basis of future FM technology specific roadmaps. A method for compilation of an effective FM strategy map does not exist in the published literature, and so the proposed process of structuring, gathering relevant data and populating an FM strategy map is an important contribution.

The presented strategy map demonstrates that while electrical FM solutions remain limited by the availability and capability of technologies, significant levels of rest-of-system (non-electrical) oversizing will continue to be required. There is a risk, however, that some aspects of rest-of-system oversizing may not scale up for larger scale EPA concepts, and that a reliance on alternative safety measures detracts focus from the much needed developments in EPA specific FM solutions. This has not yet been adequately addressed in the literature, and so the strategy map highlights this challenge and the potential impact on the feasibility of future EPA.

This chapter is structured as follows: Section 4.2 defines requirements for effective FM strategy maps, then Section 4.3 presents a literature review of the current status of the development of FM technologies. Section 4.4 describes the proposed strategy mapping approach. Thereafter, in Section 4.5 strategy maps for key FM solutions are presented and discussed in Section 4.6 and finally in Section 4.7 a summary of the strategy map is given.

4.2 Definition of FM Strategy Map

In [85] roadmapping is defined as a technique used to support technology management and long-range planning. Numerous power density targets and technology roadmaps (such as [1, 31]) exist for electrical machines, power electronic converters and energy storage for EPA applications, however within these there is a lack of detailed developmental goals for FM devices, and no FM specific roadmaps have yet been published for this application. Therefore, an FM strategy map is required in the first instance as a pre-cursor to FM technology roadmaps.

The concept of strategy mapping is well established in business management as a tool enabling organisations to conduct forward planning and communicate a clear strategy. This original formulation of a strategy map is defined as: *"A strategy map provides a visual representation of the organization's strategy"* [86] and is usually shown on a single page. Presenting a high-level strategy in this format is effective when used to *"align organisational and individual targets and initiative with a defined mission and desired strategic outcomes"* [86].

The definition of *strategy map* which is proposed for this thesis incorporates the same purpose of visualising clear future goals and strategic aims. However, a key additional feature of this strategy map is the identification of areas where there are concerns about the possibility of *not* achieving the desired outcomes. Thus the contribution here is not only drawing together projections of technology development, oversizing requirements and FM goals but going further to show mismatches and discrepancies between the current status of development and the ultimate EPA *strategic outcome*, which is to realise a range of EPA concepts in the desired developmental time frames. More specifically, an FM strategy map is a vision of the future FM landscape which maps out the development of the technologies required for the realization of critical FM functions within an FMS. Furthermore, a *strategy map* lays the groundwork for specific technology roadmapping (more common strategic planning tool in engineering applications) by giving an overview of the future development of a wide range of interdependent technologies and the critical stages of progression that are expected.

In the presented strategy map, identification of viable technologies is achieved by scoping the landscape of FM devices ranging from conceptual designs to commercially available products across a range of industry applications (presented in detail by the authors in [11]). However, an effective FM strategy map cannot consider FM technologies in isolation, rather the impact of combined FM solutions must be taken into account, where various FM specific technologies and non-FM specific electrical components are used together with aspects of electrical or rest-of-system-oversizing to enable a desired fault response [52]. Hence, an FM strategy map for future EPA must outline the progression of the FM system goal against time as proposed EPA concepts increase in power rating with increased level of, and reliance on, electrical propulsion.

4.3 Overview of Current Fault Management Technology Strategy Maps in the Literature

Since there are currently no FM strategy maps or roadmaps for FM-specific technologies related to EPA in the literature, an overview of existing technology roadmaps relevant to EPA electrical architecture development is instead presented.

A recent report published by the Aerospace Technology Institute (ATI) [31] identifies key research areas for future EPA, but FM technologies and solutions are not explicitly highlighted as key focus areas. Whilst “sensors and protection” and “system architecture” are identified as requiring development, all of which are very relevant to FM design, the critical interdependency of the FM system [18] and the electrical architecture development is not identified.

“Integrated, fail-safe mechanisms” are stated as being required for the time frame approximately 2018-2022 in [31], but no indication is given of which FM technologies such mechanisms would depend on, whether such technologies are available, or the process by which FM could be integrated into the wider electrical system development. Protection and fault tolerance are rightly identified as technology challenges, yet only in the area of power electronics is FM elevated to a “major challenge”.

In [25], the lack of FM technologies suitable for future EPA and the lack of devices actively in development for this specific application are acknowledged. Power density targets are identified for a number of key technologies including converters, energy storage and electrical machines, yet similar targets for the required range of future FM devices are not presented. Furthermore, the lack of understanding of the developmental requirements of FM in relation to other aspects of the electrical system design is shown by the fact that FM is a identified as a sub-category of power electronics development.

Developers of future EPA [1, 6] have published roadmaps for target developmental conceptual aircraft. However, none of the high level roadmaps which have been published to date have outlined the progression of the FM and safety systems, or the means of integrating FM development into the wider aircraft design.

In studies undertaken as part of the early development of the N-3X and ECO-150 conceptual aircraft [4, 8, 30], possible FM solutions and variations in electrical architectures are proposed. This relies on projections of expected development in individual FM technologies such as hybrid circuit breakers and estimations of the weight budget available to the FM system. However, it is acknowledged that the feasibility of the complete FM solutions proposed for each aircraft using a combination of technologies remains unclear.

The authors in [87] highlight the need for development of electrical machines and batteries as well as the challenge of integrating all these components on an aircraft, yet this broad assessment of the technology challenges facing the aerospace industry does not address in detail the development of effective FM solutions. Arc faults are identified as a potential hazard which needs to be mitigated against, yet it is not said how this will be achieved, nor is the impact of higher voltages (discussed in terms of cable weight) assessed in regard to the impact that this may have on the choice of FM devices or solutions. This is a significant omission in [87] and in the literature in general, since early studies have shown that protection and FM will form a non-negligible proportion of the total electrical system weight for EPA [8, 13, 30].

In [88] a number of high-level control technology challenges are identified, including “Fault detection, isolation, and reconfiguration/redundancy management”. This highlighted the need for integrated fault modelling and fault tolerance analysis as part of the development of future hybrid electric aircraft, yet it did not describe how this might be achieved.

4.4 FM Strategy Mapping Approach

As an FM strategy map for EPA does not currently exist in the literature, a logical methodology for compiling the available technology and EPA concept data into a useful format is first presented. Whilst the strategy map draws on existing data and wider EPA roadmaps, the process of developing an FM specific technology strategy map is novel.

The purpose of the proposed FM strategy mapping approach is to enable identification of promising FM solutions suitable for accelerated adaptation for EPA as well as key future FM technology challenges. An FM strategy map must take an aircraft systems level perspective of the development of FM, due to the novel interfaces between the FM system and the wider aircraft in EPA design (as described in the identification of PLRs in Section 5.4.1). A comprehensive FM strategy map must go beyond technology-focused development targets to determine viable FM solutions. This enables early integration of FM technologies into the electrical architecture and identification of priority areas of FM development, as well as highlighting technology challenges and any disparities in developmental time-frames between the point where an FM solution is required at high confidence level, and when it becomes technically mature. This approach is summarized in Figure 4.1.

Figure 4.1: Proposed approach to FM strategy map development

Although fault detection will be required as part of any FM solution, FM enabler technologies (such as sensors, metrology and communications) are an aspect of future work, and so fault detection has not been selected as a “Key FM Function”. FM enablers (see Chapter 6 for further discussion) are important in a FMS, but are not considered currently as a technology challenge since inclusion of FM enablers does not have as significant an impact on the total electrical system weight as the EPA concepts increase in scale.

Since electrical FM technologies specific to EPA are at an early development stage or do not yet exist (as discussed in Chapter 3), key FM technologies have been identified from six different existing industry sectors: aerospace, marine, traction, automotive, terrestrial grid transmission systems and distribution systems, based on relevance and technology overlap [51]. The technologies from each sector are then assigned to the corresponding voltage and current FM classes that represent four ranges of ratings, as defined by the authors in [11] and shown in Table 4.1.

Table 4.1: FM classes as defined in [11]

	Voltage Classes	**Current Classes**
Class I	0 - 0.75 kV	0 - 0.75 kA
Class II	0.75 - 1 kV	0.75 - 1 kA
Class III	1 - 5 kV	1 - 5 kA
Class IV	5 - 10 kV	5 - 10 kA
Class V	$>$ 10 kV	$>$ 10 kA

This classification is used to allow comparison between technologies, especially across different application areas. Therefore, there is a degree of uncertainty in the exact boundaries of the FM classes which allow the most effective categorisation of FM technologies. However, for the current FM strategy map, engineering judgement by the authors of [11] and peer reviewers have determined that these classes are logical and valid.

The *"Core Activities"* (as defined in [11] and shown in Table 4.2) required to adapt a given technology for an aircraft electrical propulsion system are then compared against the current TRL status (as defined in [10]) so that the estimated developmental time can be determined.

To determine the viability of an FM strategy for a particular aircraft electrical architecture, the TRL of the combination of devices operating to achieve a particular FM goal needs to be assessed. FM devices will be clustered with interdependent FM technologies, FM enablers such as sensors, control functions, redundancy in the electrical system and aspects of oversizing in the rest of the aircraft that supports the electrical FM system. Thus the feasibility of a complete FM solution must also take into account the Integration Readiness Level (IRL) [10] of each technology in the electrical architecture, and relate that to the anticipated level of redundancy in the wider aircraft system. This is assessment of feasibility is subjective and requires engineering judgement (until more detailed data on the capability of FM strategy components is available), and oversight of the different technology confidence levels. In Section 5.8, an example down selection of viable FMS options is demonstrated and discussed.

Table 4.2: Core Activities for Technology Adaptation [11]

Core Activity	**Rationale**
Adaption to higher voltages	Required either series-connection arrangement of the devices with a synchronized tripping command, or awaiting development of a higher voltage rated device.
Adaption to higher currents	Required either parallel-connection arrangement of the devices with a synchronized tripping command, or awaiting development of a higher current rated device
Prototyping and integration	Assembling all parts and sub-systems into a single functional unit. This includes all packaging and stacking arrangements.
Sizing/scaling devices	Reducing weight and volume of devices including packaging and thermal management systems.
Adaption to aerospace environment	Required hermetical enclosure for sealing a device against environment and radiation susceptibility.
Testing and development	Testing against environmental conditions and validation of functionality for EPA systems.

4.5 Proposed FM Strategy Map

Building on the FM technology status appraisal outlined in [11], Table 4.3 presents the proposed FM strategy map for future EPA. This first-of-a-kind FM strategy map combines the progression of proposed EPA concepts and demonstrators in the published literature and the required FM development for EPA. Thus the presented strategy map incorporates the associated requirements established in Section 4.2 and goes beyond existing EPA technology roadmaps (as discussed in Section 4.3). The confidence level (defined in [52]) in the availability and suitability of key individual FM technologies under development (grouped by FM function), are mapped against the expected developmental time frame. The required aspects of oversizing and the progression of the projected FM goal are also presented alongside the FM technologies, EPA concepts and demonstrators targeted towards each development phase.

Developmental stage is used rather than a defined time frame as this is a more useful metric of development and enables the strategy map to automatically take into account any variation in projections of technology maturity. More electric aircraft (MEA) and previous very small scale demonstrator aircraft are used as a bench mark to show current electrical propulsion capability and the step-change between commercial MEA and future EPA concepts. Future demonstrator aircraft (proof of concept or technology testing aircraft) are distinguished from commercial concepts here since the final commercial aircraft will require a different FM strategy from a demonstrator.

4.5.1 Classifications in Strategy Map

A tabular strategy map format [85] has been adopted due to the large volume of discrete data, with additional annotations and colour coding to show priority or confidence ratings. In Table 4.3, the confidence levels for each technology are defined as follows: pink = low, amber = medium and green = high confidence level. The fault response function within an FMS of a given technology is classified as primary, secondary or both. Primary fault response is defined as the initial response of the FM system, which will normally operate within an appropriate time frame to isolate/bypass the fault. Secondary fault responses occur after the primary response usually to support network recovery e.g. to reconfigure power paths or to physically/galvanically isolate a de-energised section of faulted network. In classifying the rest of system oversizing, pink indicates "not part of system design", amber indicates "possibly part of the design" where there is uncertainty and green indicates where a "feature is included in concept design".

4.5.2 Determination of Technology Confidence Level

Where technologies are not currently available at high TRL and certified for use in aircraft, it is necessary to determine the level of confidence that the technology will become available in the future at suitable ratings. The factors which determine FM technology confidence level are defined in [52]. To indicate the means by which the confidence level of the technologies in Table 4.3 was derived, *"High confidence level"* would equate to an FM technology meeting at least some of the following criteria:

- Established EPA technology at high TRL, well proven in an aircraft application where scaling of SOA power, voltage or current ratings is feasible
- High TRL technology from a non-aircraft application, with minimal core activities required
- Technology requires modest level of development for an aircraft application but is the focus of industrial and academic research efforts, with key performance targets being achievable within the available developmental time frame
- Evidence of high IRL, i.e. technology expected to be integrated without significant redesign of the systems and components in the vicinity or wider concept design
- Technology already well adapted or suitable for reliable operation in harsh aircraft environment
- Technology provides a priority aspect of FM functionality for a future EPA electrical architecture (see Section 5.6), so although not currently available at high TRL and/or suitable for EPA, the technology is at a reasonable TRL already with respect to the timescales of the target EPA application

This process is subjective and is applied based on engineering judgement, drawing on available literature. For near term concepts, the confidence level of technologies may be more strongly influenced by the SOA devices and the identified core activities, since there is comparatively less uncertainty as to the future availability of suitable devices. Yet for longer-term FM design, the wider criteria identified above which determine the confidence level will feature more strongly in the projected classification of confidence level, especially where the devices do not yet exist for an EPA application and there is less certainty that present TRL levels are indicative of future availability for larger EPA.

Factors Determining Confidence Level

The TRL of SOA or best available devices is the first, and key indicator of future availability for an EPA FM system. However, there needs to be a caveat applied if the SOA devices which are available have been developed for another application area. Where a particular technology has reached a particular TRL of less than 9, there is also no guarantee that the technology will be able to surpass the current rating.

The confidence level is also impacted by any challenges which exist in transferring a technology from one application area to another. This has already been identified in the "Core Activities" defined by the authors in [11] and shown in Table 4.2. The core activities are not necessarily all equal in terms of impact on the required developmental time. Therefore, to determine the confidence level the core activities for adapting a given technology need to be identified and the associated time quantified. Where there is an identifiable risk that even with a significant developmental time frame a particular technology will be difficult to adapt to an EPA application at the likely identified ratings, then this would justify down grading the confidence level.

Related to the transfer of technologies is the IRL of the technology. If integration issues exist (such as integrating a superconducting component into a conventional, non-superconducting electrical architecture) this would affect the developmental time frame in which the technology would progress to higher confidence level.

The impact of the harsh aircraft environment on the selection of FM technologies was highlighted in Section 3.3.6. Where a particular technology is susceptible to failure due to arcing, vibration, EMI or temperature fluctuations this would lead to the need for more testing in an aircraft representative environment to increase the confidence level of the technology for use within an FM EPA, which in turn would limit the confidence level of the technology to low or medium until the technology is sufficiently developed.

Where a device performs a high priority FM functionality (see Section 5.6 on FM actions) which is challenging to provide by other means (such as physical fault isolation), then this would support higher confidence in the technology being available subject to any key EPA requirements being met. The assumption behind this is that where a device is lacking in TRL or IRL, the functionality that it offers may "buy its way" onto the aircraft. In this case the confidence level of the device is primarily a reflection of its capability, and then its suitability in the absence of any better technology solutions.

The confidence level of an individual technology would have to be heavily scrutinised if there was a significant risk to the electrical architecture design if suitable ratings of the technology were not to become available within the assumed time frame. Any uncertainty as to the classification of a technology where the criteria placed it on a boundary would have to take into account the impact of an erroneous confidence level classification. Opting for a lower confidence level where there is conflicting data between two possibilities ensures that a realistic understanding of the complete FM cluster is maintained and the negative effect of the uncertainty is limited.

The time frame in which a particular technology reached an upgraded level of confidence would likely be reduced where there was a large degree of industrial and academic focus and key technology targets have been identified. This would support accelerated development of a particular technology and increase the probability of key core activities being performed.

These factors (in particular, IRL, effects of the aircraft environment and technology transfer) which determine the confidence level of a particular technology for EPA are discussed in further detail in Chapter 6 as part of the required progression of FM testing to develop high confidence FM solutions.

Example Determination of Confidence Level

Where the criteria for *"High confidence level"* cannot be met, a logical decision must be made as to whether there is *"Medium"* or *"Low"* confidence. Technologies have been attributed a *"Low confidence"* rating where such a technology is deemed by the student to be wholly unfeasible for the EPA configuration and developmental time frame (and where this rating has been verified by panel review by authors of [11]). For example, all fault current limiter technologies are at *"Low"* confidence level for N+1 and N+2 concepts, due to their weight and cooling requirements causing integration challenges. However, FCLs have been included in the proposed electrical architectures for N+4 concepts and provide useful FM functionality. Resistive SFCLs are the most compact SFCL technology [89] (hence the *"Low"* confidence levels for saturated core FCL technologies across all developmental stages), and are the focus of most research and development activities [89]. Therefore, resistive SFCLs are deemed to be at *"High"* confidence for N+4 concepts due to the lengthy developmental time available and possibility of EPA electrical architectures benefiting from a range of SFCLs expected to complete field testing become commercially available in the interim [90].

In the case that there is evidence so suggest that a technology is possibly feasible for a given EIS, yet insufficient criteria are met to justify a *"High confidence"* rating, the technology is designated as *"Medium confidence"* level until more data is available.

The aspects of electrical and rest-of-system oversizing which populate the lower sections of Table 4.3 are derived from logic and from the available literature relevant to each proposed future EPA concept or demonstrator.

4.5.3 Inclusion of Systems Oversizing

The *"Rest of System Oversizing"* section of Table 4.3 identifies key non-electrical safety features which would compensate for the complete or partial loss of electrical propulsion. *"Oversizing"* is defined as increased or additional rating, capacity or redundancy in components, systems or subsystems above the required baseline specification included in a system to support FM. This systems oversizing is required as it highlights the increased redundancy associated with an increase in percentage hybridization. These functions should increasingly become less critical or even redundant as EPA become more mature and there is increased use of electrical systems oversizing.

4.5.4 Inclusion of Electrical Systems Oversizing

The electrical system oversizing section of Table 4.3 identifies priority aspects of system oversizing relative to the aircraft concept and Platform Level Requirements (PLRs). PLRs are requirements relevant to the electrical architecture design which flow down from the whole aircraft design, and form the fundamental basis of the electrical system design [52].

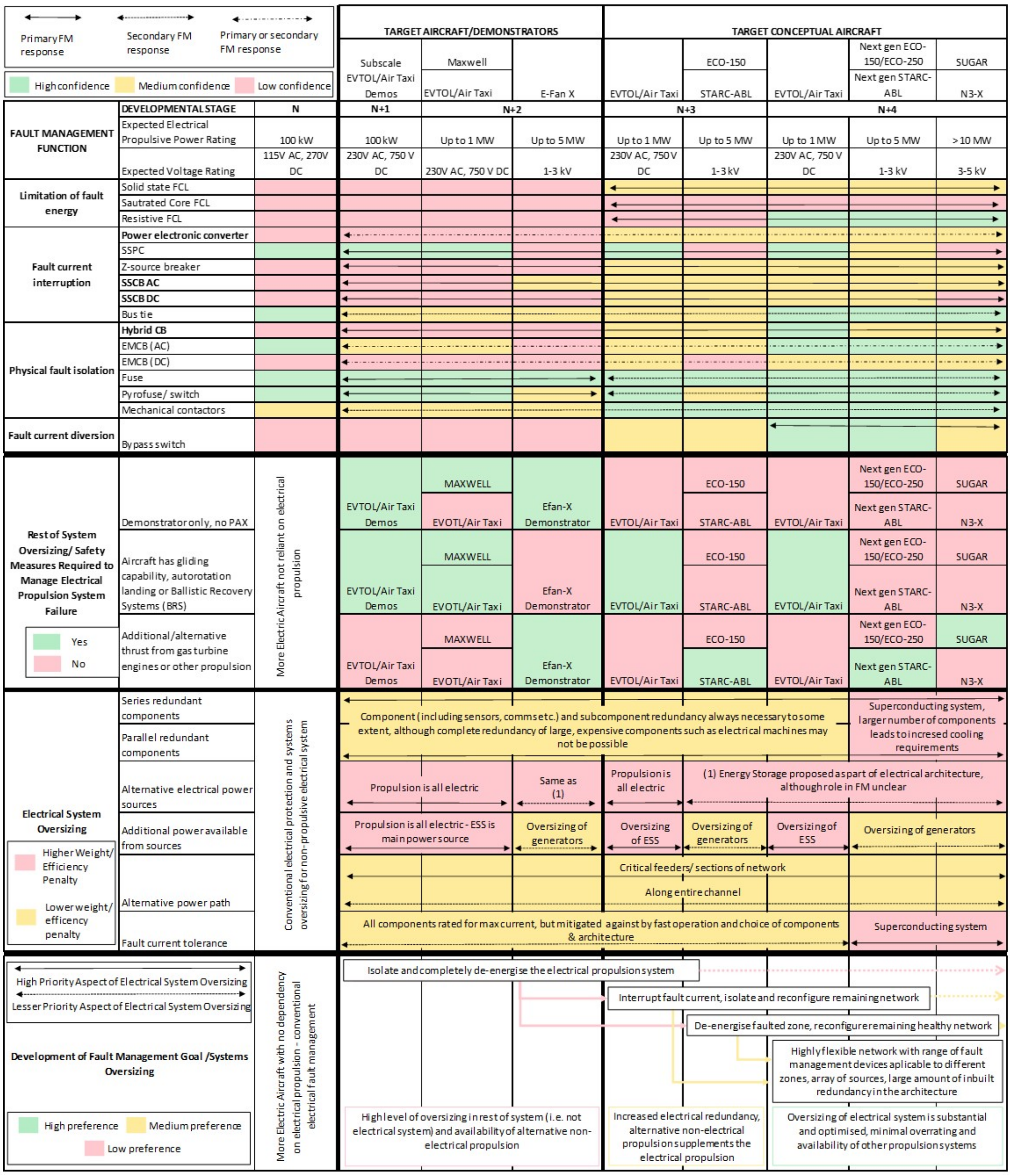
The rationale for attributing different levels of priority to various aspects of oversizing is noted in each cell in Table 4.3 against the reference class of aircraft. This weighting informs the possible impact (in terms of weight, flexibility and complexity of architecture) of oversizing on the electrical architecture design. The relative weight and efficiency penalties associated with each aspect of electrical system sizing are based on the comparative weights of components such as electrical machines, energy storage and cables, and the impact on the system performance expected with the chosen redundancy measure. Furthermore, this also shows that there is a trade-off required between very distributed oversizing (e.g. increased fault current tolerance of a number of components on the network) and single, large instances of oversizing (e.g. additional energy storage), or a combination of both.

4.5.5 Importance of FM Goal in FM Strategy Map

Besides mapping various aspects of system oversizing, a key feature of the proposed strategy map is the inclusion of the projected developments in the FM system goal. In Section 5.5 the aircraft system goal under fault conditions is shown to determine the FM system goal. From the operation of the architectures described in the literature [3,6,8,13,30,91], the FM goal is identified and mapped at the bottom of Table 4.3. For example, in [4] the system goal is maintain power to the array of propulsor motors during a fault, and the electrical system is configured such that the FM reconfiguration can only occur in a de-energized state after all the power sources connected to the faulted bus have been isolated. Thus the FM goal is to detect and isolate the faulted bus within an appropriate time frame before reconfiguration of remaining healthy network. The FM goal will become increasingly complex as the EPA concepts develop (particularly where the electrical network is extensive and supports multiple propulsive loads) and the FM control system must decide in real time between a range of possible fault responses. Hence, an FM strategy map must incorporate the priority weighting of the various available functions and technologies, directing the key FM areas for future development.

System goals and FM goals that have been selected or established for near-term, smaller scale aircraft remain valid for future concepts (as indicated by the arrows in the bottom section of Table 4.3), but these are expected to be superseded by more sophisticated system responses. The green-amber-pink colour coding indicates the preference of each general FM goal. Therefore, mapping the progression of current FM goals against the availability of FM devices and the constraints on the use of oversizing allows viable FM solutions to be identified.

Table 4.3: FM Strategy Map



Primary FM response · Secondary FM response · Primary or secondary FM response

🟩 High confidence 🟨 Medium confidence 🟥 Low confidence

FAULT MANAGEMENT FUNCTION	DEVELOPMENTAL STAGE	N	N+1 (TARGET AIRCRAFT/DEMONSTRATORS)	N+2	N+2	N+3 (TARGET CONCEPTUAL AIRCRAFT)	N+3	N+4	N+4	N+4
			Subscale EVTOL/Air Taxi Demos	Maxwell EVTOL/Air Taxi	E-Fan X	EVTOL/Air Taxi	ECO-150 STARC-ABL	EVTOL/Air Taxi	Next gen ECO-150/ECO-250 Next gen STARC-ABL	SUGAR N3-X
	Expected Electrical Propulsive Power Rating	100 kW	100 kW	Up to 1 MW	Up to 5 MW	Up to 1 MW	Up to 5 MW	Up to 1 MW	Up to 5 MW	> 10 MW
	Expected Voltage Rating	115V AC, 270V DC	230V AC, 750 V DC	230V AC, 750 V DC	1-3 kV	230V AC, 750 V DC	1-3 kV	230V AC, 750 V DC	1-3 kV	3-5 kV
Limitation of fault energy	Solid state FCL	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨
	Sautrated Core FCL	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Resistive FCL	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩
Fault current interruption	**Power electronic converter**	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨
	SSPC	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟨	🟥
	Z-source breaker	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨
	SSCB AC	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨
	SSCB DC	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟥
	Bus tie	🟩	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
Physical fault isolation	**Hybrid CB**	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟨	🟨
	EMCB (AC)	🟩	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩
	EMCB (DC)	🟥	🟥	🟥	🟥	🟨	🟥	🟨	🟨	🟨
	Fuse	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Pyrofuse/ switch	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩	🟩
	Mechanical contactors	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩
Fault current diversion	Bypass switch	🟥	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟨

Rest of System Oversizing/ Safety Measures Required to Manage Electrical Propulsion System Failure

🟩 Yes 🟥 No

Demonstrator only, no PAX	More Electric Aircraft not reliant on electrical propulsion	EVTOL/Air Taxi Demos 🟩	MAXWELL 🟩 EVOTL/Air Taxi 🟥	Efan-X Demonstrator 🟩	EVTOL/Air Taxi 🟥	ECO-150 🟥 STARC-ABL 🟥	EVTOL/Air Taxi 🟥	Next gen ECO-150/ECO-250 🟥 Next gen STARC-ABL 🟥	SUGAR 🟥 N3-X 🟥
Aircraft has gliding capability, autorotation landing or Ballistic Recovery Systems (BRS)		EVTOL/Air Taxi Demos 🟩	MAXWELL 🟩 EVOTL/Air Taxi 🟩	Efan-X Demonstrator 🟥	EVTOL/Air Taxi 🟩	ECO-150 🟥 STARC-ABL 🟥	EVTOL/Air Taxi 🟩	Next gen ECO-150/ECO-250 🟥 Next gen STARC-ABL 🟥	SUGAR 🟥 N3-X 🟥
Additional/alternative thrust from gas turbine engines or other propulsion		EVTOL/Air Taxi Demos 🟥	MAXWELL 🟥 EVOTL/Air Taxi 🟥	Efan-X Demonstrator 🟩	EVTOL/Air Taxi 🟥	ECO-150 🟥 STARC-ABL 🟩	EVTOL/Air Taxi 🟥	Next gen ECO-150/ECO-250 🟥 Next gen STARC-ABL 🟩	SUGAR 🟩 N3-X 🟥

Electrical System Oversizing

🟥 Higher Weight/ Efficiency Penalty

🟨 Lower weight/ efficency penalty

Conventional electrical protection and systems oversizing for non-propulsive electrical system

Series redundant components; Parallel redundant components: Component (including sensors, comms etc.) and subcomponent redundancy always necessary to some extent, although complete redundancy of large, expensive components such as electrical machines may not be possible | Superconducting system, larger number of components leads to incresed cooling requirements

Alternative electrical power sources: Propulsion is all electric | Same as (1) | Propulsion is all electric | (1) Energy Storage proposed as part of electrical architecture, although role in FM unclear

Additional power available from sources: Propulsion is all electric - ESS is main power source | Oversizing of generators | Oversizing of ESS | Oversizing of generators | Oversizing of ESS | Oversizing of generators

Alternative power path: Critical feeders/ sections of network; Along entire channel

Fault current tolerance: All components rated for max current, but mitigated against by fast operation and choice of components & architecture | Superconducting system

High Priority Aspect of Electrical System Oversizing

Lesser Priority Aspect of Electrical System Oversizing

Development of Fault Management Goal /Systems Oversizing

🟩 High preference 🟨 Medium preference 🟥 Low preference

More Electric Aircraft with no dependency on electrical propulsion - conventional electrical fault management

Isolate and completely de-energise the electrical propulsion system

Interrupt fault current, isolate and reconfigure remaining network

De-energise faulted zone, reconfigure remaining healthy network

Highly flexible network with range of fault management devices aplicable to different zones, array of sources, large amount of inbuilt redundancy in the architecture

High level of oversizing in rest of system (i.e. not electrical system) and availability of alternative non-electrical propulsion

Increased electrical redundancy, alternative non-electrical propulsion supplements the electrical propulsion

Oversizing of electrical system is substantial and optimised, minimal overrating and availability of other propulsion systems

4.6 Discussion of Proposed FM Strategy Map

4.6.1 Availability of FM Technologies

Chapter 3 highlights that most FM technologies require development before use in a future EPA application if key requirements are to be met. In Table 4.3, the lack of available high priority FM devices in the near term is shown, as well as the uncertainty (amber coloured cells) that future devices will be able to meet the electrical system constraints, even with an extended developmental time period. One of the most challenging stages is the development of the larger N+4 concepts as there is a significant scaling up of the electrical system rating (expected power ratings of greater than 10 MW) and a notable increase in the level of dependency on the electrical propulsion system, yet this is not supported with guaranteed development in the appropriate FM technologies. This highlights the gap in current SOA concept and electrical system development between N+3 and N+4, as well as the lack of suitable FM devices providing high-priority functionalities for an N+4 concept.

From the strategy map in Table 4.3 it is clear that there is no obvious, preferred technology which can perform physical fault isolation for larger scale EPA. Therefore from the strategy map it is clear that this is a priority area of technology development for future EPA.

The FM devices which are the most desired in terms of capability (e.g. speed of operation) and function (e.g. ability to provide galvanic isolation) are highlighted in bold in Table 4.3. SSCBs (both AC and DC) and hybrid circuit breakers are primary fault response devices which do not yet exist for the aircraft market. Challenges remain around thermal management (see Section 5.4.1), EMI, fail-safe mechanisms and power density (see Section 3.3.3) which need to be overcome before these preferred devices can be incorporated into a robust FM strategy. Where a solid state switching module fails, the device is left in a permanently open or short circuit state depending on the topology and type of fault [92]. Therefore, additional FM devices may be need to provide fail-safe capability of critical SSCBs. Solid state devices are also susceptible to EMI which can cause unintentional switching, and so adequate shielding of solid state devices is necessary on an EPA, which will incur additional weight [92].

The availability of power electronic converters is also limited for future EPA applications (as discussed in Section 3.5.2). However, these can be used as either a primary or secondary fault response, depending on the chosen FM solution, as long as electrical protection functionality is given a higher priority than converter self-protection.

The specific technologies that should be developed for a given aircraft concept depend on the aircraft requirements, and so cannot be determined in isolation or at the overview level presented in Table 4.3. The general review of the discrepancies which exist between the projected FM technology availability and the expected FM requirements highlights the range of directions that future FM development could take. Not all technology developments may be required, since it is not yet clear which concepts will in fact progress to maturity. For example, superconducting FM technologies are not proven in an aircraft environment, but it is also not yet known if superconducting EPA are ever to be a reality. Therefore, the recommendations in this section on the areas of FM technology which may be significant must be considered alongside the development of EPA concepts more generally.

4.6.2 Aspects of Electrical and Wider System Oversizing

From Table 4.3, it is clear that there is a significant difference in the FM technology specifications and level of oversizing which is required between small demonstrator aircraft (such as the NASA Maxwell concept [3]) and larger passenger concepts (such as the ECO-150 aircraft [4]). There is also a notable change when the electrical propulsion is not merely supplementing the available thrust (such as in the E-Fan X demonstrator aircraft), but provides a critical proportion of total aircraft propulsion. This is shown in Table 4.3 where the ECO-150 turboelectric aircraft has the same limited range of FM technologies at high confidence level as the STARC-ABL concept.However, unlike STARC-ABL, the ECO-150 cannot rely on a given level of thrust from gas turbine engines if there is a critical failure in the electrical propulsion system.

From an FM perspective, the feasibility of medium to large scale EPA beyond current proposed N+2 concepts remains largely unknown, due to the lack of high confidence in FM technologies coupled with rest-of-system oversizing mechanism for smaller aircraft such as PRS being unsuitable for these large aircraft. The PLRs for this developmental time-frame dictate greater electrical oversizing versus other systems oversizing in order to realize fuel savings and noise reductions, in combination with a scaling up of the electrical system ratings. However, these requirements are not matched by current projected developments in FM technologies. The weight penalty associated with significant levels of electrical oversizing is also not expected to be acceptable given the current status of electrical component technology development, such as energy storage capacity, and electrical machine power density and efficiency. Whilst systems level (electrical and wider aircraft systems) trades are needed to optimize system performance, the weight penalty of system oversizing as a response to the lack of alternative, mature FM solutions is detrimental to the overall aircraft performance.

Clearly, the use of oversizing in the electrical architecture would be most effective as a supplementary FM capability which would allow a more flexible fault response (for example, more reconfiguration options). However, as current concept designs stand, the use of oversizing is due to the lack of key FM technologies and not in support of them. As already mentioned, there is a weight cost to oversizing but the impact of such strategies goes further. By proposing or even accepting electrical architecture designs with a high reliance on oversizing, the challenges of integrating crucial electrical FM devices are not addressed. The trades between the time taken for such components to reach high TRL, the developmental time available to a concept, the level of investment required and the potential detrimental impact of an EPA with reduced safety capability need to be highlighted to the industry. Oversizing in the design of EPA should enhance its safety rather than be used as a means of enabling electrical propulsion flight before the key technologies are fully mature.

Further Aspects of FM Capability Requiring Development

Therefore, to enable development of future EPA which meet performance targets, appropriate FM technologies are required. This challenge is particularly acute for medium term (N+2) EPA concepts larger than air taxi in size and where electrical propulsion provides any critical operation, such as a proportion of total aircraft thrust, and so there is an increased requirement for a highly robust, multifunctional FM system. For these, the FM goal (as shown in Table 4.3) during critical faults requires sequential or coordinated operation of devices and strategic deployment of available oversizing in the architecture design. Thus it is clear that it is not only the technologies with preferred capability and functionality (as discussed in detail in Section 4.6.1) which need to be developed, since the control and co-ordination of devices within an FM system is also unproven for EPA. It is strongly recommended then that the FM algorithms, tripping mechanisms and communications between devices is a focus area for future EPA electrical architecture development (this is further discussed in Chapter 6 in the proposed future FM test rig capabilities).

4.6.3 Impact of Development of Platform Level Requirements

In the presented strategy map, it evident that two aircraft with the same EIS may have very different FM requirements (e.g. a N+3 EVTOL all electric aircraft compared to ECO-150 turboelectric single aisle EPA). Therefore, key developments in FM which will be required are not only related to the available developmental time frame for an aircraft but will also be driven by any increase in the criticality of the electrical propulsion system. Hence analysis of this strategy map enables identification of the step changes in the aircraft PLRs which will have a significant impact on the FM design. From the baseline PLRs [52] discussed in detail in Section 5.4.1 and the progression of EPA concepts shown in Table 4.3, the step-change developments or design choices related to the PLRs with a significant impact on the criticality of the electrical propulsion system, and hence FM system, are outlined below:

- Demonstrator aircraft to production aircraft.
- Increase in electrical propulsion power rating - up to 1MW, up to 5MW, up to 50 MW.
- Percentage of electrical propulsion increasing such that the other available mechanical propulsion cannot substitute for the electrical thrust should the system

fail.

- Location of propulsion from single propulsive fan to many distributed fans.
- Conventional electrical system to superconducting system.
- Tube and wing configurations to concepts including one or more than one BLI fan.
- Configurations where the electrical system controls the yaw and stability of the aircraft, or supplements the mechanical control.

4.6.4 Verification and Validation of Strategy Map

Verification and validation of novel research methodologies is performed by assessing whether the presented methodology satisfies its stated purpose (see further discussion in Section 5.12). The specified purpose of the proposed strategy map in Section 4.1 and Section 4.2 is to:

- visualise clear future goals and strategic aims for EPA-specific FM
- determine FM technology confidence levels
- provide a mechanism by which to identify points where the desired FM system goal and aircraft level requirements do not align with high confidence in the availability of the required FM technology functions

The strategy map in Table 4.3 is a valid tool to describe a future vision of FM for EPA as the table visualises by a combination of developmental stages and colour-coding overlaid with an assessment of FM system functionalities and goals. Confidence levels are clearly shown and the process of confidence level determination is described in detail. The tabular format enables the FM technologies, oversizing and FM goals for a given developmental time frame to be easily identified. Therefore, the strategy map fulfils the stated purpose.

However, as this is a first-of-a-kind systems-level strategy map, comparison with existing FM technology projections cannot sufficiently support verification and validation of this novel strategy map. Hence verification of the current technology projections will come from future publication of component manufacturers' FM technology targets and aircraft developers application of safety and redundancy measures. Expert review of the status of FM solutions and their future potential in EPA will validate the confidence levels stated in the strategy map and the capability of various technologies as part of a multi-faceted fault response. Future EPA trade studies and test bed demonstrators will enable validation of the weight and efficiency penalties identified in the strategy map, as well as the combinations and priority assigned to various aspects of electrical architecture additional capacity.

4.7 Summary

The FM strategy map which has been presented enables the limitations of future EPA FM systems to be identified (including the dependency on non-electrical oversizing and safety mechanisms) and informs decisions on the choice of electrical architecture and wider aircraft design. This is made possible by the methodical approach used to develop the strategy map, identify confidence levels and capture the feasibility of FM technologies for use in an EPA. Furthermore, the chosen presentation of the strategy map highlights points where the FM technology development lags the requirements of the proposed EPA concepts. The development of FM technologies which can form effective FMSs is a priority and must be conducted in parallel with the development of the other systems and components for EPA. Thus at an early stage, this strategy map supports the development of viable electrical propulsion systems for future EPA.

However, there is a need to further develop this strategy map to include targets for power density, efficiency, speed of operation and any other critical requirements impacting the design of FM devices. As more data on emerging FM technologies are published this will be used to validate or update the confidence levels of technologies included the strategy map. This strategy map provides the foundation for further detailed FM technology-specific roadmaps, which will support the targeted development of solutions to address the key technology bottlenecks which have been identified.

The novel methodology which is proposed allows an FM strategy map to be determined which identifies key transitions in the progressive development of future EPA. These step-changes in PLRs and the EPA configuration lead to significant changes to the FM goal and, consequently, the FM system requirements. At this stage in the development of EPA, understanding of the interdependency between the aircraft conceptual development and the FM system is critical, if robust FM solutions are to be available for all the proposed EPA concepts in the literature. It is clear that there is not a one-size-fits-all FM solution for future EPA concepts, even when the power size and time frame of the aircraft are similar. The acceptable FM solutions for research-led demonstrator aircraft (such as NASA's Maxwell) which aim to establish proof-of-concept should not be confused with the augmented FM approach which is expected to be necessary for a commercial EPA design where a reliance on gliding capability or PRS systems is less acceptable. This is captured in the increased complexity of the FM goal as EPA become larger in terms of PAX, derive a greater proportion of thrust from the electrical propulsion system and adopt more complex electrical architectures (such as superconducting configurations). Therefore, a method of determining feasible electrical architectures for EPA capable of strategic electrical FM driven by the specified FM goal is needed. On this basis, a novel method of FM oriented electrical architecture design for EPA is presented in Chapter 5.

Chapter 5

Early Stage FM Design Framework

5.1 Introduction

From reviewing the proposed architectures for future EPA in the literature (see Chapter 4.3), it is clear that there is a close interdependency between the FM system and the electrical architecture. The choice of FM solution and the deployment of FM devices on the network will strongly influence the configuration of the electrical system. Therefore, it is clear that the electrical architecture cannot be designed in isolation from the airframe and other aspects of the conceptual design. This then presents an opportunity to innovate in the approach taken to the electrical architecture design and to develop an effective methodology for to integrate FM into the design of electrical architectures for future EPA.

As discussed later in Section 5.2, there is evidence in the literature that research into strategic application of electrical FM has still to be considered in detail [6]. In cases where electrical FM is considered as part of electrical power architecture design and proof of concept studies, this is done to better estimate system weight and losses, with demonstrations of the feasibility of the approaches or estimates of availability of underpinning technology deferred to further study [8, 91]. Additionally, in these examples the selection of very low TRL technologies indicates a low confidence in existing FM methods for electrical power system architectures for EPA applications.

Electrical architecture designs which do not effectively incorporate FM risk being proven infeasible in the future, especially where protection devices, redundancy or fault tolerance capability are required to be added to the electrical architecture retrospectively in order to meet certification standards. Thus if FM is to be convincingly incorporated into the development of EPA, then a methodology for the design of FM orientated electrical architectures is required. To date, no such methodology has been presented in the literature (as discussed in Section 5.2).

Therefore a comprehensive design framework to determine feasible electrical propulsion architectures is presented in this chapter. This chapter presents an overview of the proposed framework in Section 5.3. The framework is then demonstrated through a case study in Section 5.4, and verification and validation of the framework is addressed in Section 5.12. Further detail on the stages of development through which the current FM framework was derived can be found in the Appendix in Section A.

5.2 Literature Review of FM Orientated Frameworks

The electrical architectures proposed for NASA's N-3X aircraft by Rolls-Royce [8] and GE [30] include electrical protection functionality, and highlight the significant impact that a protection system may have on the overall weight budget for an EPA. It is not clear however, whether the proposed N-3X solution is feasible or if the optimal number of protection components have been deployed [18]. This is evidenced by the pragmatic rationale behind the location and choices of devices, especially those which are at low TRL for an aircraft application.

Authors in [3] identify that the electrical system Strategic Fault Response (SFR) can often be counter-intuitive when influenced by the whole aircraft design. For example, on NASAs X-57 Maxwell aircraft, if one of the wing tip thrusters were to fail, the rudder cannot correct the imbalance. As a result, either the aircraft has to be powered down to glider mode or healthy propulsors on the opposite wing need to be turned off. In this case, the EPA system may sacrifice conventional functionality during a fault (such as maintaining power flow) to ensure that key system requirements are fulfilled.

Additional evidence of wider aircraft design influencing the electrical fault response is given in [13]. This article describes how for NASA's STARC-ABL aircraft, the contribution of the electrical system to overall thrust required varies over the flight cycle. It is conceivable that this will also result in variation of the SFR, impacting the designed-in FMS, which will need to accommodate changing operability requirements.

Furthermore, in [2] and [93], the authors describe how the electrical power system for the HYPSTAIR series hybrid propulsion system was designed using a systems approach to ensure adherence of redundancy requirements to expected certification standards. In doing so, the redundancy aspect of the FMS was factored into the design process at an early stage. However, a more detailed approach adopting the same principles is necessary for larger, more complex aircraft.

A proposed methodology of electrical system design presented in [94] determines the power requirements and the topology before assessing the impact of faults and performing fault studies. Whilst this may be a means to derive an electrical power system from first principles, the delay in considering the impact of the FM within the design overlooks the interdependency between availability and capability of different protection devices and the choice of a feasible electrical power system.

A framework for the conceptual design of aircraft to minimize environmental impact is described in [95], yet the impact of FM on the design process is not within the scope of this tool. Published work in assessing the impact of high bandwidth energy storage integration into compact DC networks highlighted the need for a comprehensive protection framework [96], which determines the protection requirements, applies relevant constraints and then selects an appropriate protection strategy. However, the means by which such a framework should implement these stages was not described, neither was an existing framework identified which adequately satisfies these requirements.

5.2.1 Unique challenge of EPA electrical architectures

The literature review focused on EPA FM approaches but there may be other future application areas for which the architectures and FM technologies do not exist, and so an approach similar to the one presented later in this chapter would be relevant. However, the specific challenges of FM for EPA are distinct from those of existing electrical propulsion applications in terms of safety-critical electrical loads, mass production of highly reliable aircraft systems and stringent weight constraints. For example, whilst the Electric Vehicle (EV) industry has given much focus to the development of fault tolerant electrical propulsion systems [97–99] and maintaining safety-critical functions, no architecture design methodology was identified in the literature which was equivalent in terms of addressing the level of uncertainty surrounding the design of future EPA, and the lack of suitable FM technologies which drives the need for a novel approach to a fault tolerant design.

5.2.2 Summary of literature review and specification of required framework

Whilst no comparable early-stage design framework exists within the literature, the articles reviewed do highlight a number of key aspects of FM design, which require appropriate representation within any new proposed design framework. Crucially, there are a number of requirements relevant to the electrical architecture design which flow down from the whole aircraft design. These requirements form the fundamental basis of down selection of electrical system design solutions and are defined in this thesis as the Platform Level Requirements (PLRs).

Additionally, it is already clear that the design of electrical architectures for EPA cannot follow a conventional approach, as thus far this has led to solutions which are sub-optimal, infeasible or overly simplistic (see Section 5.12.5) and do not reflect the novel interfaces between the aircraft conceptual and electrical design. Therefore, a new FM oriented design framework for early-stage architecture down selection should meet the following requirements:

- incorporate FM from the outset
- map the interdependencies between the aircraft concept and the electrical system design (PLRs), particularly in relation to the FMS and SFR
- define the system goal during fault conditions so that priority FM functions can

be determined

- identify the level of confidence or likely feasibility in particular FM technologies being employed within a specific developmental time frame
- manage the large amount of uncertainty present in the design of future EPA, which is due to many design constraints being ill-defined or design decisions being based on technology projections
- offer a methodical means of reducing down the very extensive initial solution space, eliminate infeasible solutions and give some indication of priority where a number of competing requirements or outcomes exist

5.2.3 Value of an FM Driven Early Design Approach

Although integrating FM into the design process from the outset signifies a significant deviation from established methods of aircraft electrical system design (as demonstrated in Section 5.2), there are, however, a number of advantages in prioritizing FM.

System Integration

The integration of components and subsystems must be understood and tested early in the design process. Since design faults and unexpected/ unplanned system interactions are known to surface at the integration stage [37], there is a need to anticipate this by initiating a systems-level design and mapping of subsystem interfaces, so that the impact (especially under faulted conditions) of each subsystem at the aircraft platform level is assessed. In software development, the cost of discovering a defect at integration testing is ten times greater than if the fault is found at the earlier design and architecture phase [100]. Similarly for aircraft design, faults in either the components or the design of the wider system can be costly [101], which implies that early interception of any vulnerability to faults prevents unnecessary costs.

Incorporating FM as a key functional requirement in the design of future EPA, also offers an opportunity to develop promising solutions that otherwise could have been overlooked and to consider electrical architectures which are optimal from an FM perspective. In this way, the critical role of FM as part of a robust design methodology realizing the potential benefits of EPA is established.

Better Informed Technology and Concept Design

Since many of these aircraft concepts are at the early design phase, the actual electrical architecture is not yet defined and the constraints on the system are subject to change as technology develops. Therefore, this presents an opportunity to explore the fault management design space more thoroughly, and seek the optimal electrical architecture from a FM perspective. This allows key technology bottlenecks to be identified or anticipated, and protection devices specific to aircraft applications to be specified and developed in tandem with the ongoing electric aircraft research. If FM is only applied as an aircraft reaches higher levels of maturity, then there may be a lag in development of required technology and the full complexity of applying robust fault management may be overlooked. Further benefits of an FM orientated approach include elimination of components within the system which will not actually be suitable for use within an aircraft system due to aero-specific constraints (such as weight), as well as the ability to chart the impact of aircraft level design decisions on both the FMS and electrical architecture over the development of the aircraft concept.

5.3 Overview of Proposed FM Orientated Framework

In this section, a novel FM oriented early-stage design framework is proposed which addresses the requirements listed above. A high-level logic flow depiction of this framework is presented in Figure 5.2, the core details and assumptions of which are then provided later, in Figure 5.3.

The framework describes a comprehensive method to identify the FM requirements for a given basic aircraft concept, and hence match suitable FM technologies to desired FM actions in order to derive feasible FMSs. At each stage of the framework, the solution space is reduced until the process converges on the final down-selected electrical architectures. In this way, the identification of feasible electrical architectures is dependent on the capture of PLRs and defined FM system goal.

The FM definitions given in Section 2.2 are the foundation of this framework. The goal of the FM system is defined early in the process (as indicated by *Phase 2* in Figure 5.3) and then feeds into the choice of both FM actions to respond to the fault and FM technologies to implement the desired SFR. At each subsequent stage of the framework, only options which support the chosen FM goal are taken forward. In this manner, any architecture which is infeasible from an FM perspective is eliminated, providing down-selection of candidate architectures. Although it is possible that there may be growth in the number of possible solutions during the process where technologies or functions are combined together or novel solutions are identified, thus expanding the solution space, the down-selection and weighting mechanisms in the framework ensures that only feasible solutions are taken forward.

The inputs to the framework (such as the PLRs) are derived from early stage EPA concepts which have been designed by experts. The database gathering and determining of system goals would also require expertise in the interpretation of the aircraft standards and in assessing the validity of any FM device. However, later in the down-selection process a level of automation may be possible whereby a tool is employed to perform trade studies or generate arrays of electrical architecture combinations. Yet at this early point in the design process, a large amount of expert input is required for the framework as the solutions which would automatically be created are not likely to be feasible nor will they capture the complexity of the interdependent aspects of the design.

5.3.1 Scope of the Proposed FM Framework

At this stage the scope of the framework is to direct the future design and development of FM to bring FM in line with the improvements in electrical technologies such as energy storage. The framework is intended to support early stage development of EPA electrical architectures, at the point in the design process where there is still a large amount of uncertainty in the choice of technologies and many of the fundamental FM studies have not yet been performed. However, for a near-term EPA design (such as a small scale demonstrator aircarft as discussed in Section 6.3) the inclusion of FM from the outset and the systems-level approach to FM would remain relevant. The framework can be applied to both superconducting and non-superconducting electrical architecture design as this requirement would be defined at the outset (see Section 5.4.1).

Furthermore, detailed FM system design is also out of scope of this framework. This is due to the fact that design tasks, e.g. determining trip thresholds and specifying the maximum ratings of FM devices, requires knowledge of the complete electrical system architecture. Safety standards will also have a significant impact on the FM detailed design and these are not yet fully specified for EPA.

It is possible that existing aircraft may be retrofitted to enable electric powered taxi on the airport runway. This mode of electrical propulsion would be a subsystem of the turbofan powered aircraft, and would not be used during a critical phase of flight (see Section 5.5). Hence electrical propulsion which is not critical to the aircraft maintaining safe flight is not considered here as part of the electrical architecture system in focus.

As with conventional aircraft, there will be electrical loads on EPA in support of auxiliary aspects of the electrical system such as hospitality or entertainment systems. This zone of the electrical architecture will also require FM, yet as these systems exist and are at a much reduced power level in comparison to the electrical propulsion architecture, the framework does not consider this section of the network.

5.3.2 Case Study Overview

To demonstrate this design framework, a case study is presented throughout Section 5.4, together with the framework description. In this, an example concept aircraft electrical architecture is derived to illustrate the use of the framework. A quantitative design and analysis is not within the scope of this thesis due to lack of published data to perform such studies, although this process is an important one which will be required later in the development of any EPA. The benefit of using the framework is not at this point a quantifiable improvement in the physical design of the system, but rather early identification of the aspects of the FM design which are critical to the wider aircraft feasibility, and demonstration of the fact that FM cannot be overlooked in any future sizing or configuration analysis. The chosen concept is a tube and wing aircraft with a rear-mounted cone thruster, similar to both the NASA STARC-ABL aircraft [13] and the Bauhaus Luftfahrt [102] propulsive fuselage aircraft, as shown in Figure 5.1. The input requirements to the case study, including the data in Table 5.1 are based on published technical data from early feasibility studies for the STARC-ABL aircraft [13]. Given that the data in [13] is the extent of the published electrical system quantitative data for this early EPA concept means that numerical sizing of the electrical architecture solutions derived in the framework would be ineffectual and, most likely, invalid.

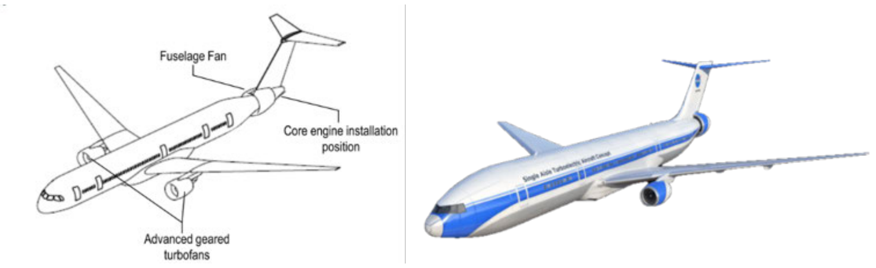


Figure 5.1: Illustration of Bauhaus DisPURSAL [12] and NASA Concepts [13]

The safety regulations (as discussed in Section 2.9) would inform the platform level and FM system requirements (e.g. length of time the electrical propulsion system must be able to safely operate after a fault to enable the aircraft to land at an airport). Any safety regulations in the operation of the FM system would be taken account in the choice of FM actions (see Section 5.6) and requirements for FM capable components would be incorporated in the choice of FM technologies (see Section 5.7).

5.4 Demonstration of Proposed FM Orientated Design Framework

A detailed illustration of the design framework is presented in Figure 5.3, expanding the key stages outlined in Figure 5.2 and showing the way in which assumptions have been captured. The following sections describe and discuss each major stage of the framework, drawing direct reference to the appropriate part of Figure 5.3 for convenience.

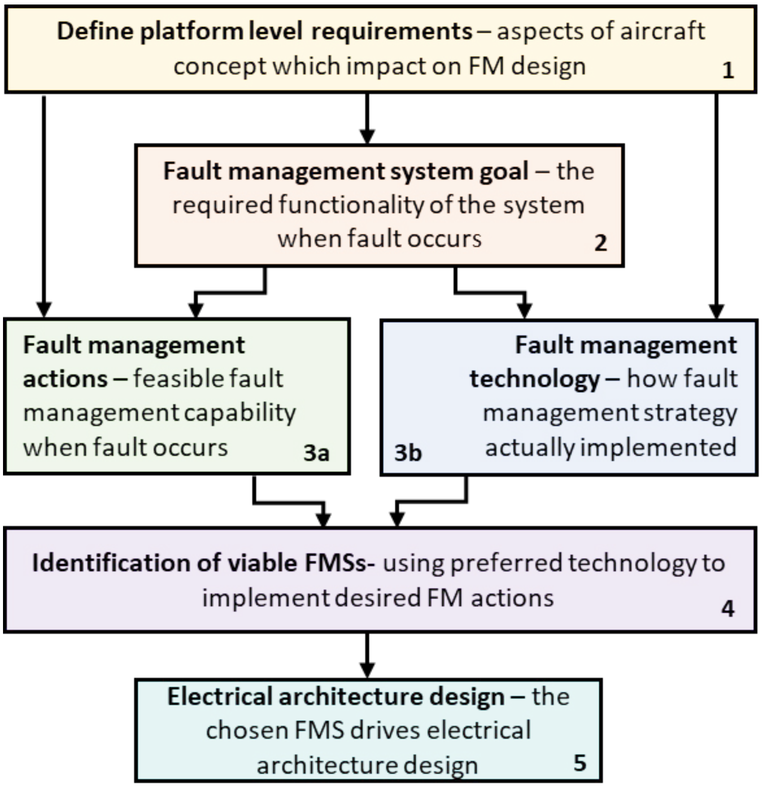


Figure 5.2: FM Orientated Framework Overview

5.4.1 Platform level requirements (*Phase 1*, Figure 5.3)

By reviewing the aircraft concept, the key PLRs which have an impact on the electrical system can be defined. This mapping of the dependencies between these two facets of the system design is a key contribution of this framework. The process of weighting the PLRs relative to each other at this early point in the design process identifies the most challenging aspects of the FM design from the outset.

For the case study presented, the PLRs were based on available data for the STARC-ABL aircraft [13]. These are shown in Table 5.1 in the same order as in Figure 5.3 and are discussed in the following subsections. Where data does not exist in the literature an appropriate estimation has been made, as indicated in Table 5.1 by an asterisk.

Table 5.1: Identification of Aircraft Platform Level Requirements (PLRs), Initial Assumptions and Risks for Case Study (high priority PLRs in **bold**)

PLR	**Case Study Data**	**Initial Weighting**	**Assumptions for FM Design**	**Risk**
External Factors	Proof of concept aircraft, immature technology*	Medium	In the absence of data, the “External Factors” are defined as the fact that the aircraft is a novel concept and therefore there is a lot of uncertainty in its design	Unknown external factors could have a large impact on design and may not yet be anticipated
Developmental Time frame	**Estimated EIS 2035**	**High**	**The complete FM system will be certified for flight within the available time**	**FM system components do not reach high TRL, the FM system does not have high IRL (Integration Readiness Level) in time for complete electrical system tests**
Airframe & BLI	Single BLI fan at rear	Medium	The use of BLI is required, loss of power to the fan is detrimental causing drag and dependence on mechanical compensation measures should be avoided	Mechanical/ airframe design variations may change the size of the fan and thus the power demand, mechanical responses to electrical failure at the fan may be preferred
Weight Budget	**Expected weight budget of total electrical system (not including any energy storage) is approx. 1400 kg**	**High**	**The additional weight of the electrical drive train must be minimized and is assumed to be offset by the fuel, emissions and noise savings for this EPA concept to be viable**	**FM system may not be viable within the given weight budget, FM options may be considerably limited, innovative FM measures may be needed**

Table 5.1: Identification of Aircraft Platform Level Requirements (PLRs), Initial Assumptions and Risks for Case Study (high priority PLRs in **bold**)

PLR	**Case Study Data**	**Initial Weighting**	**Assumptions for FM Design**	**Risk**
Percentage Hybridization and Location of Propulsion	**Up to 50% of total thrust at top of climb electrical, power delivered to rear fan**	**High**	**The maximum power demand must be maintained, the 50% mix is assumed optimal and feasible, power must be distributed to different parts of the aircraft, single large fan at rear is preferred to wing mounted fans**	**The electrical drive system cannot reliably supply the max power requirement, fitting the large components of the electrical FM system within the airframe at the required locations is not possible or carries risks**
Thermal Management	Non-superconducting system, must minimize thermal loads	Low	Heat generated by components needs to be easily dissipated and components have to be operated in a temperature controlled environment to enable optimal performance	The thermal loads will reduce the overall efficiency & power will be required to dissipate the heat. Uncontrolled variation in temperature of devices causes failure or constrains the location of devices within the aircraft
Typical Flight Plan & PAX	150 PAX, single aisle passenger aircraft	Low	The electrical propulsion system can meet certification standards for single aisle civil aircraft	The certification and safety requirements will significantly constrain or direct the choice of FM solutions
Propulsion Power Rating	2.5 MW max propulsive power required	Medium	FM devices can be rated to deliver the maximum power demand and withstand maximum fault current	FM devices may not be available at the required power rating or may be limited in quantity or location

Table 5.1: Identification of Aircraft Platform Level Requirements (PLRs), Initial Assumptions and Risks for Case Study (high priority PLRs in **bold**)

PLR	**Case Study Data**	**Initial Weighting**	**Assumptions for FM Design**	**Risk**
Pre-defined Architecture Preference	DC distribution network*	Low	It is assumed that this is the design preference for the first iteration of the design framework	Any bias towards this particular solution may risk alternatives being overlooked
Customer Operational and Safety Requirements	Assumed comparable to ETOPS requirements for a similar sized passenger aircraft*	Low	The customer requirements for the electrical system design have to be specified and in the absence of data, the requirement has been based on existing safety requirements for similar aircraft	These requirements might not be defined and may vary largely over the development of the aircraft

External factors

There may also be PLRs due to external factors that impact on FM design, e.g. cost or intellectual property restraints. Even if these aspects are not significant in the initial electrical design, they may result in reiterations of the framework or impact the down selection processes within the framework.

Developmental time frame

Identifying the available developmental time frame at the outset guides the selection of FM functions and technologies. The developmental time frame for the aircraft platform determines the time period available for the maturation of relevant technologies to the required TRL for demonstration/production depending on the platform aims. This is distinct from the point of Entry into Service (EIS), since the detailed specification of the electrical system must occur well ahead of the initial aircraft becoming available on the market.

Airframe propulsion integration

The aerodynamics of the airframe structure are linked to the FM requirements for the aircraft. A key driver for electrical propulsion is that it enables novel airframe configurations and the use of improved aerodynamics to bring efficiency improvements to overall aircraft operation [103]. In particular, Boundary Layer Ingestion (BLI) is expected to reduce aircraft drag, enabling the aircraft to achieve the same amount of thrust with less propulsive power. However, the use of an electrical motor to power a propulsor fan as part of an integrated BLI fan design creates a new interface between the aerodynamics of the aircraft and the electrical system. If a fault were to occur causing loss of power to the fan, this could create drag and the windmilling effect of the faulted fan may impact on the flow of air through neighbouring fans where there is an array [104].

Weight budget

It is essential to establish during the first stage of the framework the available weight budget for the aircraft. The weight budget for the aircraft will also have an impact on the FM design -such as eliminating particular technologies which are too heavy. A number of aircraft concepts have been proposed where the weight of the FM system is not explicitly included in the total electrical weight budget, e.g. [6, 56]. However, FM specific devices and components with an FM capability will form a non-negligible proportion of the available weight budget.

Percentage hybridization and distribution of propulsion

The degree of hybridization for the aircraft and the location within the airframe of the electrical propulsors will also influence FM design, because these influence aspects of the electrical architecture such the maximum power rating of the system and the required length of cables between components. Distributed propulsion leads to more power channels to feed the propulsive loads, which requires a more complex electrical architecture and greater co-ordination between FM devices during a SFR. This PLR is also linked to the required level of *Rest-of-Sytem* oversizing discussed in Section 4.5.3. The greater proportion of total electrical thrust at critical points in flight which is required, the more critical the FM system will be since the possible level of mechanical thrust compensation will be limited.

Thermal management

Thermal management is a key aspect of system design for both superconducting and conventional aircraft systems. Any losses in electrical components, including FM devices, will create a thermal load which will need to be safely and effectively dissipated.

Aircraft type and PAX

The size of an aircraft will influence the design of FM solutions. Indeed, the segment of the market for which the aircraft is intended is often linked to the developmental time frame. This can be seen in the strategy map presented in Table 4.3.

Propulsion power rating

The choice of FM technology must match the power (and by implication, voltage) requirements of the electrical architecture which will be determined by the required power output of the propulsor motors. These electrical power requirements also have implications for the number of power channels required, as the total required power flow could be split into multiple channels to accommodate limitations in the rating of devices and realize system redundancy, in turn forming part of the FM approach.

Pre-defined architecture preference

If there is a legacy preferred solution (resulting from IP protection or from a wider commercial motive), then identifying the scope of this PLR in the initial stages of the process means that it is possible to record its effect on the downstream design decisions. This is particularly evident in the choice between AC and DC systems, and possibly in the physical locations of the electrical propulsion where there is a need to differentiate an EPA concept from competitors.

A key aspect of novelty in this framework is that the architecture is not known at the beginning of the FM system development. The approach where the FM system is applied to a defined electrical architecture has been identified as a pitfall of the EPA FM systems in the literature (see Section 2.4), which leads to a scenario where the chosen electrical architecture is not FM capable within the expected FM requirements (such as weight, altitude, power density). Therefore this proposed framework is configured such that any key architecture features which are known at the outset of the design are identified in the PLRs. If a later iteration of the framework had derived an electrical architecture or a range of possible architecture solutions these would be fed into the design at this point (see Section 5.11).

Customer operational and safety requirements

The customer requirements related to airport logistics (such as length of time the aircraft batteries could be charged while on stand) and government and international safety regulations (such as [45, 105]), help formulate the PLRs for the FM system.

There may also be various customer requirements which will directly impact on the electrical system design, for example where the safety or required training for maintenance personnel working on the aircraft would dictate that particular voltage levels are undesirable or require special safety measures, as is the case in marine vessels [106]. Operational requirements will need to be considered throughout the entire flight cycle since different points in the cycle will correspond to different failure modes and requirements. This will impact on the detailed FM design (*Phase 5* in Figure 5.3) and on the critical corner points in the design.

5.4.2 Weighting of platform level requirements

Classification of the impact rating of PLRs captures the sensitivity of the electrical design to changes in the aircraft conceptual design. Hence, once all PLRs have been identified, they are weighted according to the level of direct impact each requirement will have on the selection of the FM system goal. A similar process of requirements mapping to that described in Section B.3 could be used, with higher priority being given to PLRs which have more *strong* interdependencies and are relevant to the key design challenges facing the chosen EPA concept. In performing this weighting of PLRs, the ensuing down selection process of key systems level requirements is simplified. The weighting of the PLRs is also used later in the framework to determine priority technology constraints (see Section 5.7).

The initial weighting of the PLRs is based on engineering judgment, but this would be standardized through repeated runs of multiple concepts through the framework. This is because at this early stage in the concept design, there is not enough confidence in the available data to definitively determine the PLRs that will be the most challenging for a given EPA design. Thus, the weighting process is used to further facilitate down selection of the solution space and to show the relative risk of each PLR for a given concept. Therefore, tuning the weighting of the PLRs by multiple runs enables the relative impact of different PLRs on the available feasible options to be better understood. The intention is not that individual runs of this FM-orientated design process are fused together as this would require some form of optimization to be applied. The aim of this framework is to illustrate the FM solutions that exist and are feasible at an early stage, and not to perform optimisation at this point.

For the case study described in Section 5.3.2, a greater weighting is arbitrarily assigned to the location and degree of hybridization, weight budget and the developmental time frame. These are highlighted in bold in Table 5.1.

5.4.3 Assumptions and risks

The risks associated with asserting any particular assumption and the restriction this may place on the options presented further down the design process must be recognized. For the case study presented in Section 5.3.2, the risks associated with the PLRs are listed in Table 5.1. There is also a risk that the PLRs will be incorrectly weighted or the impact of a PLR may be under estimated. However, most assumptions are likely to relate to unknowns in the concept or electrical design which require some extrapolation of available knowledge or data. This leads to the key risk that the chosen FM option is a solution which is infeasible or uncompetitive. Thus, after defining the PLR, and then after later stages in the framework (*Phase 2, 3a, 3b* in Figure 5.3), sensitivity studies are proposed in order to identify and assess the assumptions and risks associated with any design decisions that have been made.

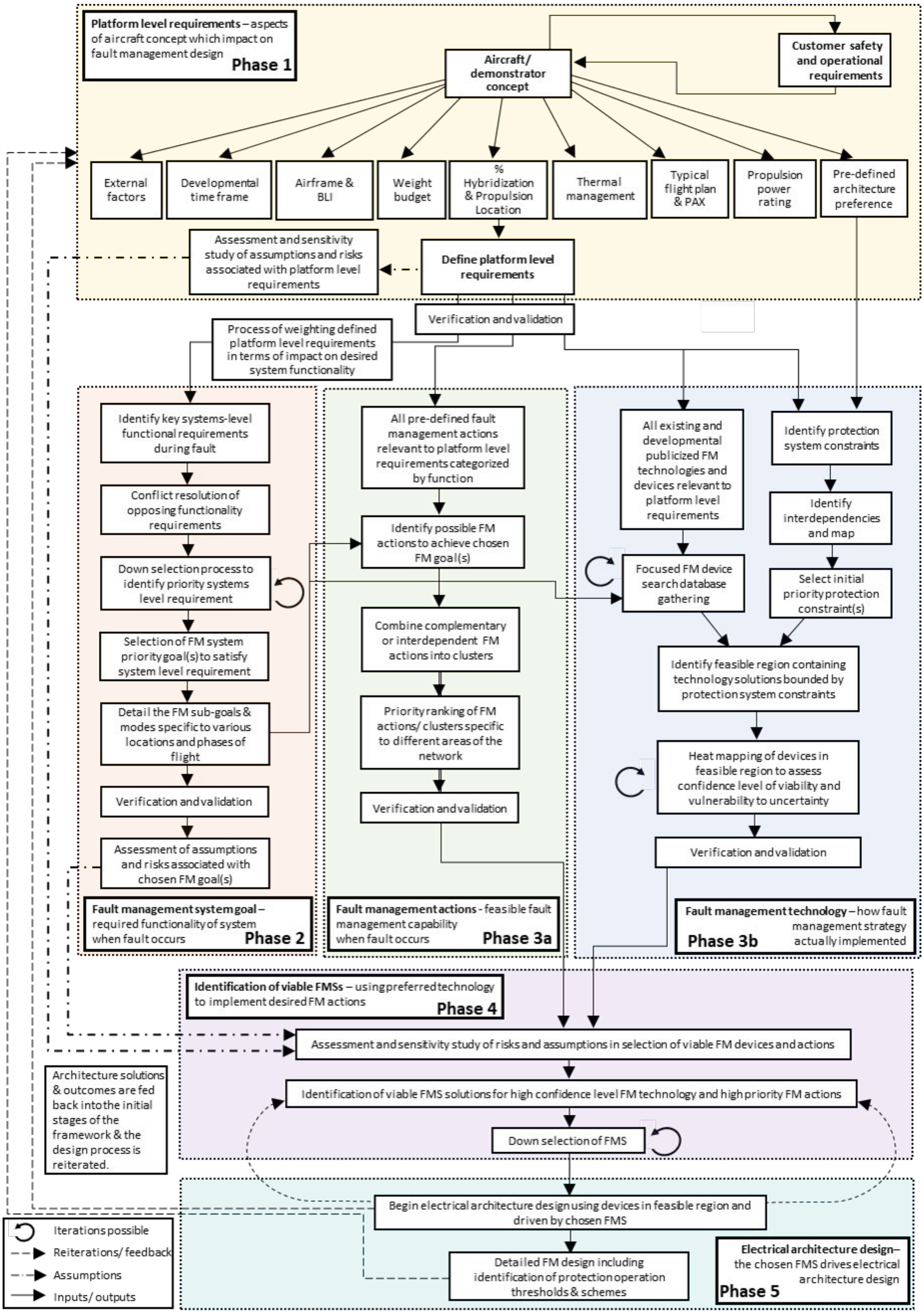


Figure 5.3: FM Design Framework

5.5 Fault management system goal (*Phase 2*, Figure 5.3)

In any aircraft electrical power system, there are many possible responses to the detection of a fault (see Section 5.6). A strategic FM response is needed to ensure safety of flight and to satisfy the PLRs.

The determination of FM goals and the process of utilising the FM goal to drive the operational aims of the whole system under faulted conditions is aligned with safety engineering best practice (as defined in [36]). This approach moves away from implementing a defined set of responses to the detection of a fault towards a systems-level identification of the functionality that needs to be maintained to ensure flight safety.

5.5.1 System level functional requirements

To ultimately determine the strategic FM response for a given aircraft, the desired system functionalities first have to be identified. Since there may be conflicting system functionalities which cannot be fulfilled simultaneously, the system functionalities are ranked in terms of priority. The most important system functionality can then be down selected.

By using the desired response of the electrical system during a fault to determine the FM goal, only the necessary FM functions are included in the design. This leads to a solution which is directly driven by the critical FM requirements. Hence the proposed framework presents an important improvement on existing methodologies.

For the case study presented in Section 5.3.2, the functional requirements are driven by the need to deliver power to the BLI fan reliably with the technology and architectures which are actually viable for a pre-2035 time frame. These are listed below, ranked in terms of priority:

1. **Ensure sufficient power is supplied to key electrical loads, maintaining flight stability**

2. Ensure the integrity and continued capability of the electrical system
3. Ensure that BLI propulsion is maintained
4. Minimize the thermal loads and excessive mechanical loading of the BLI fan

5.5.2 Selection of FM system priority goal

After determining the priority functional requirement (number 1 in list in Section 5.5.1), the FM-specific priority goal required to satisfy this requirement can then be derived.

For the case study presented, the priority goal for the FM system is *maintain minimum power flow to the rear fan when an electrical fault occurs upstream from the fan.*

5.5.3 FM sub-goals

The criticality of the electrical propulsion system may alter over flight (especially where the percentage of total thrust coming from the electrical system varies). Hence, within the FM system goal there are operating modes and sub-goals which can be defined for both critical (such as take-off) and non-critical stages of flight (such as taxi). An example list of FM modes and sub-goals are described in Table 5.2. For the case study presented, the selected FM sub-goals are shown later as a function of flight phase, in Table 6 (complemented by subsequent framework outputs).

5.5.4 Assumptions and risks

The final stage of FM goal setting is to undertake a final check of the validity of assumptions made, and evaluate the risk of incorrect assumptions. For particularly high-risk assumptions which do not reach the validity threshold is not possible due to lack of data at this early stage in the design process, further investigative work is required to progress through the framework.

For the case study presented, a number of requirements are implicit in the realization of the FM system goal (such as the requirement that the FM response should not cause fault propagation or cascaded faults). However, both limitations on the FM system goal

Table 5.2: Possible FM modes, goals and the associated risks and assumptions

Possible FM Modes	Possible FM Sub-goals
Pre-empt fault	Reconfigure/ increase power availability Reconfigure power flow De-energize complete network or zone
No change & monitor fault	Maintain power flow and architecture
React to fault	Reconfigure power flow Reconfigure/ increase power availability Maintain electrical power flow architecture Remove faulted section from network De-energize complete network or zone Maintain power availability

and sub-goals specific to locations on the network will be determined in later iterations of the framework for this particular case, as the FMS and architecture is not yet known.

5.6 Fault management actions (*Phase 3a*, Figure 5.3)

Following the establishment of the desired FM priority and sub goals, FM actions, which are the potential means of realizing these FM goals, can then be defined. FM actions include both conventional electrical protection mechanisms (*conventional FM actions*) and architecture choices *system overrating*), examples of which are shown in Table 5.3.

For the case study presented, the example list in Table 5.3 is further expanded in Figure 5.4, which also captures candidate technologies as part of "conventional FM actions" and their confidence levels aligned with the heaviest weighted PLRs. The clustering approach illustrated is utilized to facilitate the process of matching actions and technologies to form a viable FMS. This adds value to the framework as it succinctly identifies components capable of implementing multiple FM actions as well as combi-

Table 5.3: FM Actions

System Overrating	Conventional FM Actions
Redundant components	Fault current interruption/ diversion
Fault tolerant components	Limitation of impact of fault current energy
Multiple power flow channels	Physical isolation of faulted network
Additional or alternative power sources	Fault detection, diagnosis and locating
Additional or alternative propulsion sources	

nations of FM actions for which no solution currently exists. Although the means of "system overrating" identified are obvious, the framework captures the ways in which these would be used effectively in combination with other FM actions to formulate a strategic fault response, rather than simply including an element of redundancy in the electrical architecture.

Additionally, the use of alternative electrical or engine propulsion has not been included in the list of possible FM actions since the PLRs for this case study state that there is only one single propulsor fan and an assumption has been made that the engines cannot compensate for loss of electrical propulsion.

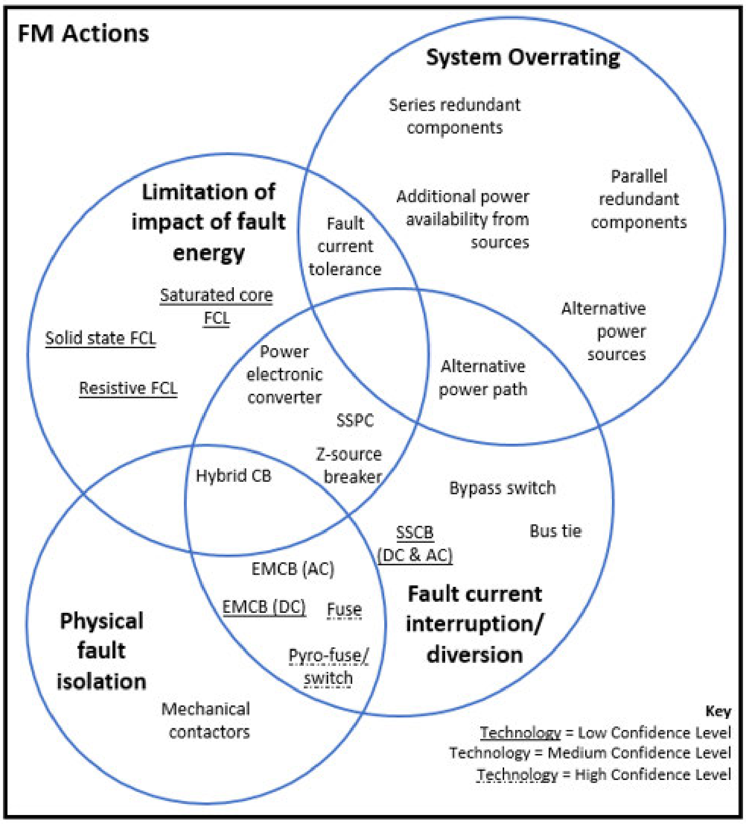


Figure 5.4: FM Actions Venn diagram showing clustering of technologies with corresponding FM Actions

5.7 Fault management technology (***Phase 3b***, Figure 5.3)

The next stage of the FM framework is the identification of the available and preferred FM technologies. Before scoping the landscape of various protection devices, target FM technologies are identified. This is because outputs from earlier stages in the framework, e.g. aircraft PLRs, can identify specific aspects of design, e.g. preference for a DC system, which are relevant to the choice of protection technologies. A targeted approach to selecting protection technologies is valuable as it reduces the solution space early in the design process.

5.7.1 Feasible Region Identification

The process of establishing a baseline database, selecting target technologies, identifying and quantifying (as far as possible) the constraints on the choice of technology, mapping the interdependency of constraints, prioritizing the constraints on the design process has been established in [51] and is described in detail in Section C and B. By considering the key constraints, devices which are not within the feasible region can be eliminated and only viable FM technologies can then be used to form FMS in the next stage of the framework.

5.7.2 Determination of Confidence Levels for FM Devices

To determine if devices which do not yet exist for an aircraft application may develop sufficiently to enter the feasible region in the future, or for where the EIS date is very far in the future, the confidence level of the different technologies needs to be assessed. This aspect of the framework involves determining a confidence level (*Low, Medium or High*) for individual technologies based on their current TRL [107] and IRL [10] and then extrapolating to the point of EIS to estimate the level of development that will have been achieved in regards to the key EPA requirements (discussed in Section 3.3). This rating can then be updated as requirements shift over the developmental time frame. This determination of confidence level is defined and is discussed in detail in Section 4.5.2.

The same process can also be applied to the down-selected FMS options later in the FM framework to determine the confidence level of combinations of different FM technologies. The confidence level of a number of different components or architecture features is limited by the lowest individual confidence level in the cluster. The maturity of a particular combination of devices for use in an aircraft application will also impact the combined confidence rating (as discussed in Section 4.5.2), as will the dependency the components on each other for future development of technologies or subsystems. It is possible that the combined effect of a number of components leads to a better confidence level overall, where a particular solution is more robust due to increased redundancy or if components compensate for each other in the case of failed operation.

Since this process is based on estimating future development and trends from the current status of the FM devices, it is imperative that the best available publicized data is constantly added to the FM database (and FM strategy map in Chapter 4), so that understanding of the current FM technology landscape is maintained and an appropriate basis for determining technology confidence levels is achieved. This also would enable identification of technology gaps and their development priority.

For the case study presented, the FM technologies which are relevant to the PLRs defined in Table 5.1 are shown in Table 5.4, based on data presented in [51]. It is assumed that from the range of constraints discussed in [51], the most important constraints are weight, speed of SFR, efficiency and certification, and these are identified and mapped in Figure 5.5.

Table 5.4: Confidence Levels of Key FM Technologies for Case Study EPA Concept

From Database of Current FM Devices			**For Given EIS**
Device	**TRL of Available Devices for Case Study**	**Current Development Application Area(s)**	**Confidence Level for Case Study Aircraft**
SSPC	Medium/ High	Aircraft	Medium
SSCB (AC)	Low	Naval, Traction systems	Low
SSCB (DC)	Low	Naval, HVDC, Traction systems	Low
EMCB (AC)	High	Terrestrial Grid, traction,	Medium
EMCB (DC)	High	Terrestrial Grid, traction, HVDC	Low
Hybrid Circuit Breaker	Low	Terrestrial Grid, traction, being developed at low TRL for aircraft	Medium
Pyrofuse/ switch	High	Aircraft	High
Power Electronic Converter	Low	HVDC, Naval Marine, Traction	Medium
Mechanical Contactors	High	Aircraft, Naval, HVDC	Medium
Z-source breaker (DC)	Medium	Naval DC	Medium
Bypass Switch	Low	Aircraft	Medium
Bus Tie	Medium/ High	Aircraft	Medium
Resistive SFCL	High	Terrestrial grid, naval	Low
Saturated SFCL Core	High	Terrestrial grid	Low
Solid State FCL	High	Terrestrial grid	Low

From Figure 5.5, it is clear that the weight of the FM system is linked to both the speed of the FM response, and efficiency, and is in itself a significant aircraft design constraint. Therefore, FM system weight is chosen as the priority constraint or Most Important Constraint (MIC) for the initial iteration of the framework case study. The confidence level for each device considered in the case study is given in Table 5.4, and the criteria which were used to determine the confidence level of devices are defined in Section 4.5.2. Confidence levels for future aircraft switchgear technologies are particularly difficult to ascertain as there is a limited range of publicized research targets for these devices within an EPA [27]. Furthermore, it is expected that there are some technologies (such as circuit breakers) which may simply be necessary even if they are bulky, heavy, slow to operate or inefficient because they perform critical FM functionalities and are available at an appropriate TRL compared to other technologies. For this reason, some technologies which are Low confidence in Table 5.4 (such as SSCBs) have been included for consideration in the FMS selection, so that the FM system sub-goals can be achieved.

Furthermore, integrating FM devices into an aircraft system may be significantly more difficult than deploying these within a terrestrial grid network. This is the reasoning behind the *Low* confidence rating of the superconducting fault current limiting devices, as the cryogenic cooling system has to be considered in the weight budget. As fuses are a mature technology for aircraft electrical systems it is assumed that these devices could be easily integrated into future EPA systems, and so these devices are the only technology with a *High* confidence level as they have a simple function and may be necessary as a last resort physical fault isolation mechanism, if switchgear on the faulted zone should fail.

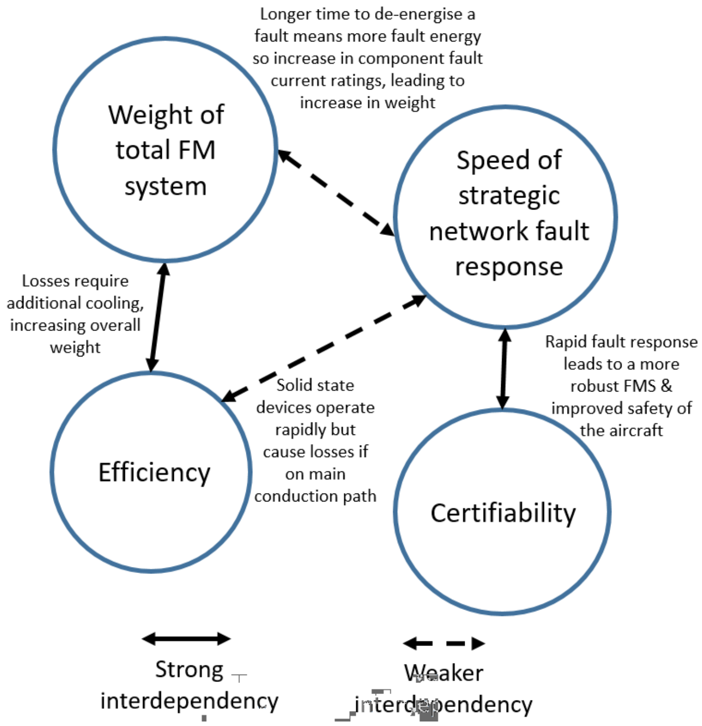


Figure 5.5: Mapping of priority constraints for case study

5.8 Identification of viable FM solutions (*Phase 4*, Figure 5.3)

In order to implement the desired FM goals for a specific case, FM technologies combined with other enabling aspects of system overrating can be compiled into a selection of feasible, comprehensive FMSs. Down selection of a preferred FMS solution is then performed through qualitative judgement and quantitative assessment (for example, through modelling and simulation-based studies). This evaluation process would also take into account any sensitivity of the viable FM solutions (and hence electrical architectures) to the FM technology confidence levels (as discussed in detail in Section 5.7.2). It would be preferable to reduce the risk to the design of variations in confidence levels of FM technology, and regression of confidence level in particular. Therefore, the down selection of FM solutions needs to be cognisant of both the current and possible future confidence levels attributed to each relevant FM-capable technology.

For the case study data presented in Table 5.1, technologies which can implement the desired FM goals were selected, with reference to the FM actions shown in Figure 5.4. A description of the selected FMSs and associated technologies for the case study is given in Table 5.5. There are also a number of assumptions underlying each FMS and these are noted, although the most common assumption at this stage is that the devices in the FMS are available within the developmental time frame.

Table 5.5: Possible FMS Options for Case Study

FMS Choice	**FMS solution to MIC**	**Key Electrical Architecture Features and Configuration of Possible FMS**	**Selected FM Technologies**	**Assumptions Associated with FMS**
A	No DC circuit breakers	1. Ability to de-energize the entire DC network 2. Availability of ESS located towards the propulsive motor to provide short term power supply to motor 3. Separate power channels for redundancy 4. Dual feed (2 converters) to motor 5. AC breakers included to provide physical isolation of faulted DC network and isolation of machines 6. Overrating of channels, so single channel can provide maximum power to load	1. AC EM breakers 2. Power electronic converters 3. High bandwidth ESS 4. Non-current interrupting DC switches	1. The downtime of the affected network does not have a noticeably detrimental impact on the propulsive power 2. ESS with sufficient energy density can supply power sufficiently fast through the converter to maintain security of supply 3. Overrating of devices does not cause excessive weight penalty 4. The converters have a power density acceptable for an aircraft application 5. ESS can be stored within the airframe in the vicinity of the DC busbar
B	Number of DC circuit breakers limited on the network	1. AC and DC SSCBs included on network to rapidly isolate the faulted network 2. AC and DC bus-tie switches to reroute power between channels 3. DC switches available in architecture to reconfigure and to isolate the specific fault on cables 4. Converters switching capability used for back-up 5. Fault current tolerance for inverter increased as on single power channel	1. SSCBs (AC and DC) 2. Non-current interrupting DC switches 3. Power electronic converters 4. AC and DC bus tie switches	1. The SSCBs for the DC network are of a sufficient power density 2. Lack of current interruption capability on each of the DC cables is acceptable for certification standards 3. ESS is not available or unsuitable for this configuration
C	Choice of an alternative technology to SSCB with reduced weight	1. Architecture providing parallel redundancy on all DC power paths 2. Components rated to single channel limited maximum fault current rating 3. Z-source breakers capable of fast fault isolation 4. AC EMCB breakers included at machines on the AC side for physical fault isolation	Multiple z-source breakers	1. Double redundancy of components does not lead to an excessive weight penalty 2. Z-source breakers can be certified for aircraft and can be developed with sufficient power density and efficiency 3. ESS with sufficient energy density can supply power sufficiently fast through the converter to maintain security of supply 4. ESS can be stored within the airframe in the vicinity of the DC busbar

The case study is intended as an illustration of how the process of defining a range of possible FMSs and then performing down-selection operates, and the way in which both availability of FM technology and the FM technology requirements need to be matched. There may be many more FMS options, especially if location-specific FM strategies are considered. However, this is where expertise is necessary in the application of the framework in that the three FMS options presented here would generally be considered to be three examples which effectively demonstrate the value of the early stage design framework.

This method of compiling an FMS based on different solutions to meet the most challenging constraints marks a novel approach to the application of FM to EPA systems. This framework also offers a model for designing a robust FM where the complete system and interactions are considered, together with the rationale behind the selection and location of each individual FM device.

For the case study presented, the candidate FMSs were subjected to a down selection process, the findings of which are shown in Table 5.6. The ideal FMS is robust and is achievable within the selected priority constraints. Where an FMS is *Better* or *Worse* in regards to a particular constraint, reference is made to Table 5.6, to ascertain the impact of that constraint on the other constraints important to the FM system design.

Since the case study aircraft utilizes a single propulsive load, the FMS at the load end of the electrical network is relatively straightforward, compared to an aircraft with highly distributed propulsion (the choice of case study is further discussed in Section 5.12). A single propulsive load reduces the number of power channels likely to be necessary and limits the level of co-ordination needed between various electrical propulsion sources during a fault. The only difference in protection for this zone between the proposed options is the use of *System Overrating*, with option A utilizing parallel redundancy and option B using increased fault current tolerance of the inverter. As the AC fault isolation mechanism across the three FMSs is largely the same (based on the assumption that suitable AC breakers are available), with the exception of AC side bus-ties in option B, the DC FM operation is the basis on which to differentiate the FMS options. The weights and efficiencies of different DC current interruption devices were compared in [51], which provides a basis to evaluate the relative weights, speed of response and efficiency of the candidate DC FM strategies, as shown in Table 5.6.

Certification may require there to be physical isolation possible at key points on the network (including the DC network), which is why option A is considered less ideal. Also protection settings may have to be adjusted if the network configuration changes, so isolating channels reduces the amount of adaptive control required in the short time period available to implement an SFR [108].

Any SFR that depends on sequential operation is more vulnerable to failures of the FM system itself, where functional FM devices are unable to operate due to the failure of some other FM device or network component. Whilst such options allow a weight reduction where there are a reduced number of DC breakers required, it is assumed that this will be unacceptable for certification purposes due to an extended time period before the system is completely re-energized or reconfigured.

For the case study aircraft, it is preferable to maximize efficiency, and as such, solid-state protection devices with their typically higher conduction losses are undesirable. Therefore, the lack of solid-state devices in option A is preferential, whereas the large number of Z-source breakers (which utilize a solid-state device on the normal current path) in option C would be problematic. The chosen FMS for this case study initial iteration is therefore option B as it satisfies the MIC whilst also not jeopardizing the FM being viable within the bounds of the other priority constraints.

In future iterations, aspects of option A and C could be combined with the original embodiment of FMS B in order to make the fault response even more robust. In particular, an Energy Storage System (ESS) could be added on the DC bus bar and included in the FMS or a parallel inverter/motor combination could be included.

Table 5.6: Down selection of FMS Options

Priority Ranking	**Chosen High Priority Constraints**	**Comparison of Possible FMS Solutions**		
		Option A	**Option B**	**Option C**
1	Weight of Total FM system	Better	-	Worse
2	Speed of SFR	Worse	Better	Better
3	Efficiency	Better	-	Worse
4	Certifiability	Worse	-	Better
Critical	Reconfiguration to maintain power flow	Cross feeder DC cables ESS on both DC bus bars Dual motor feeder cables Components rated for single channel power delivery	Bus ties on AC and DC bus bars Redundant DC cables with DC bypass switches	Z-source hybrid breakers on DC network & AC breakers
	Redundant Power Rapidly Available	ESS located at DC bus bar for short term supply to motor via converter	Generators oversized to supply load from single generator Inverter and motor fault current tolerance overrated	ESS on ring bus bar for short term supply to motor via converter
Non-critical	De-energise Faulted Network	AC breakers and converter switching capability	AC & DC SSCBs	Co-ordinated operation of AC breakers and/ or Z-source breakers
	Physically Isolate Faulted Network to Prevent Fault Propagation	AC breakers at machine side DC switches isolate after operation of AC switches	Open DC switches after SSCBs have operated	Open mechanical contactor in Z-source breaker AC EMCBs

5.9 Architecture design (***Phase 5***, Fig. 5.3)

At this stage of the process, the FMS options have been identified for the case study, viable electrical architectures for the aircraft can now be determined by using expert knowledge to identify possible, valid electrical architectures which include all the required architecture features and FM technologies.

From the range of possible architectures for the case study presented, one possible example architecture relating to FMS option B is shown in Figure 5.6. It should be noted that there is often more than one means of implementing an FMS on an architecture, especially in the first iteration of the framework where location specific goals may not yet be defined. There are not a pre-defined set of architectures which are simply updated at this point, but there may be architectures features which have been defined in earlier stages of the framework. This is captured in the section of the framework labelled *Pre-defined architecture preference* (in Section 5.4.1) where a preference for a particular architecture type or feature (such as DC distribution) can be specified.

The process by which an FMS is developed into an electrical architecture is based on reviewing the available FM technologies and the PLRs for the concept and then determining the architectural features which would allow a particular FM action to be implemented such that the high priority PLRs are met. Since this is an early stage FM design framework, there is not a decision tree to determine viable features, nor is there a validated database of architecture features to choose from. This is why expert knowledge is required to determine architecture features which satisfy the PLRs, FM goal, FM actions and available FM technology and form combinations and variations of architectural features into a baseline electrical architecture. It is acknowledged that not all possible electrical architectures may be sensible. Therefore, the evidence that supports the electrical architectures derived at this point in the design process is based on the rigour applied in the previous stages of the framework whereby infeasible solutions are eliminated.

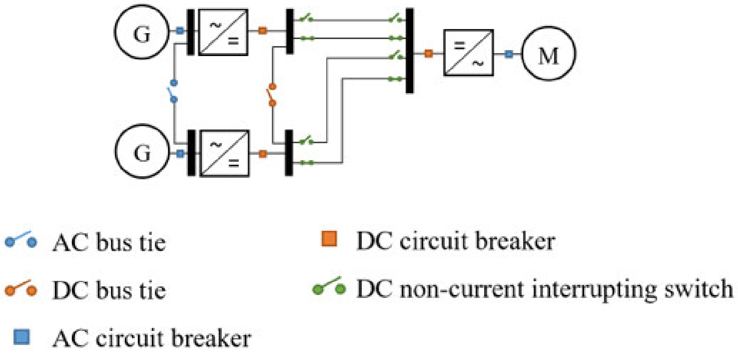


Figure 5.6: Possible Architecture for FMS option B

5.10 Detailed fault management design

Once the baseline architectures have been established for the down selected FMSs, detailed design of FM operation, including setting trip thresholds for the protection devices would be completed. This would require detailed knowledge of technology availability and specification, and also well defined requirements, neither of which are available at an early stage in the design process. This stage is, therefore, identified here for completeness and as an indicator of future work, but is not the focus of the framework which has been clearly defined as a methodology for early stage electrical architecture design.

5.11 Reiteration process

As new technologies emerge or standards become better defined, the design process can be repeated. Design decisions and outcomes from defining the FMS, architecture and detailed FM design can be fed back and the PLRs can then be adjusted to widen or narrow the selection of feasible solutions. The solution space as defined by the PLRs would be widened where no feasible or acceptable solutions exist in the final stages of the framework for a given aircraft concept. Equally where there are an excessive number of solutions the solution space would need to be better defined to enable a meaningful down selection process. Numerous iterations would also establish the impact of a bias towards a particular architecture, particularly if this may cause other potential solutions to be overlooked [109]. Acknowledging the assumptions for each design iteration is also useful in terms of planning and optimizing future design cycles. This would allow alternative assumptions to be chosen and the process repeated.

5.12 Verification and Validation of Design Framework

To evaluate the correctness and effectiveness of the early stage design framework presented in Section 5.4, a process of verification and validation (V&V) is necessary. *Verification* is defined as “a set of actions used to check the correctness of any element” [110] and *validation* is defined as “a set of actions used to check the compliance of any element...with its purpose and functions” [111]. In [112], the authors state that “validating a design method is a contextual process of demonstrating usefulness with respect to a purpose” and make the case that engineering design research requires both quantitative and qualitative validation, given that there are both objective and subjective aspects.

5.12.1 Verification and Validation Plan

Therefore, the verification and validation of this research method requires a wider approach than would normally be employed for an experimental procedure or a model of a particular system. In these cases the verification comes from comparing the behaviour of the novel model with the expected system behaviour to determine the model does reliably replicate that of the system under test. A novel experimental procedure can be verified by comparison of the results with existing data to assess whether the outputs are correct and if the procedure is in some way an improvement on existing methods. Therefore validation by comparison of the output of the framework needs to be made on the basis of whether the architectures produced are in fact feasible and if the results are more feasible, or more justifiably feasible than those proposed for a similar concept in the literature. Then the validity of the framework needs to be considered beyond the case study, as the method should be applicable to any EPA design not only STARC-ABL. These generalised stages of V&V are shown in Figure 5.7.

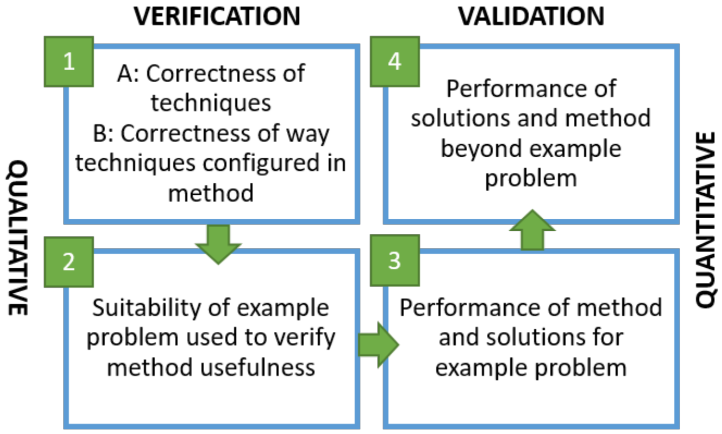


Figure 5.7: Design method validation square based on [112]

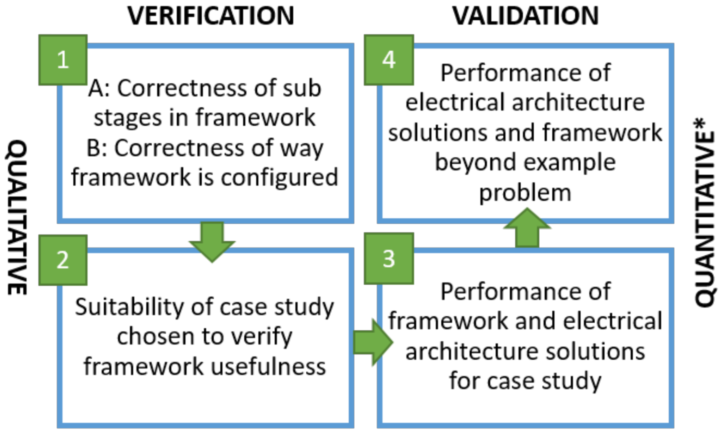


Figure 5.8: FM orientated early stage design framework specific validation square (*quantitative V&V is considered as future work)

Stages 1A and 1B verify the techniques and method used, and stage 2 verifies the choice of problem used to demonstrate the method. Stage 3 validates the output solutions of the chosen example problem. Then in Stage 4 the wider performance of the methodology beyond the chosen case study and in reference to other problem applications is validated.

This method combines both qualitative and quantitative phases of V&V. However, given the lack of data for FM technologies and fully defined FM requirements, there is insufficient confidence in a quantitative validation of the framework down selection effectiveness. The down selection of electrical architecture solutions performed by the framework is not quantitative at this stage, and so a numerical validation is not yet possible. Therefore for Stages 3 and 4, a qualitative validation of the framework is demonstrated. A detailed quantitative validation is thus proposed as an area of future work (see Section 7.3.1).

The generalised stages shown in Figure 5.7 have been applied to the framework and a specific V&V plan is summarised in Figure 5.8. This firstly considers the sub stages in the proposed methodology to verify if the techniques used are correct. Then the combination of these techniques into a method is verified. In stage 2, the case study which is chosen to demonstrate the framework is verified. Next the outputs (down selected FMSs and architectures) of the case study are compared to existing FM approaches and architectures in the literature to validate the results from the framework. Lastly in stage 4, the performance of the framework beyond the chosen case study is considered to determine the wider validity and usefulness of this methodology.

5.12.2 Verification of the Sub Stages in the Framework (Stage 1A in Figure 5.8)

The techniques used within the framework to identify requirements, compile FM solutions and perform down selection of a range of options are all widely used in existing design methods. A list of the component techniques used in the various sub stages of the framework are given in Table 5.7.

This demonstrates that the inclusion of these techniques within the framework is

Table 5.7: Examples of existing use of design techniques in the FM framework

Technique Common to Engineering Design Processes	**Examples of Current Use**
Interdependency Mapping	[50, 113]
Trade space mapping	[6, 13, 48]
Weighting/ ranking/ confidence level categorising/ prioritising	[114, 115]
Identification of constraints	[116]
Clustering of compatible options	[113]
Gathering of assumptions	[117]
Gathering of input data	[118]
Identification of ranking criteria	[114]
Identification of risks	[119]
Down selecting options based on criteria	[120]
Conflict resolution of conflicting requirements	[115]
Reiteration of process to converge on solution	[121]

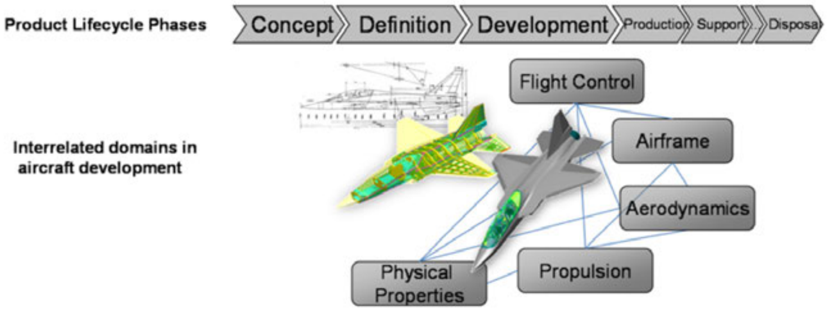
valid given that there is evidence of similar applications in the literature and hence they are widely accepted. In particular, the techniques used to prioritise or rank options are based on logic and can be readily applied to any similar problem. Thus the novelty of the proposed methodology in Section 5.4 is in the way that these validated sub-stages are compiled into a detailed and robust design methodology.

As a further demonstration of the validity of the techniques used within the framework, a visual comparison of the graphical methods is shown in Figures 5.9a and 5.10b and Figures 5.10a and 5.10b.

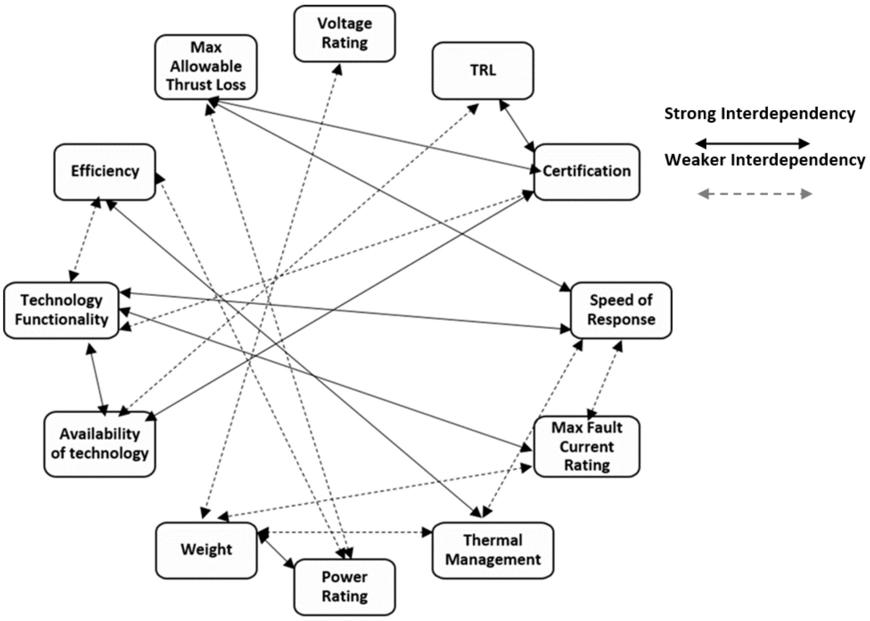
5.12.3 Verification of Method Employed in Framework (Stage 1B in Figure 5.8)

Verification of the method requires assessing the confidence in the way the various techniques are compiled and used within the framework. Any method that is inconsistent would exhibit [112]:

- generation of inadequate information
- generation of unnecessary info
- invalid assumptions



(a) Example of interdependency mapping in literature [50]

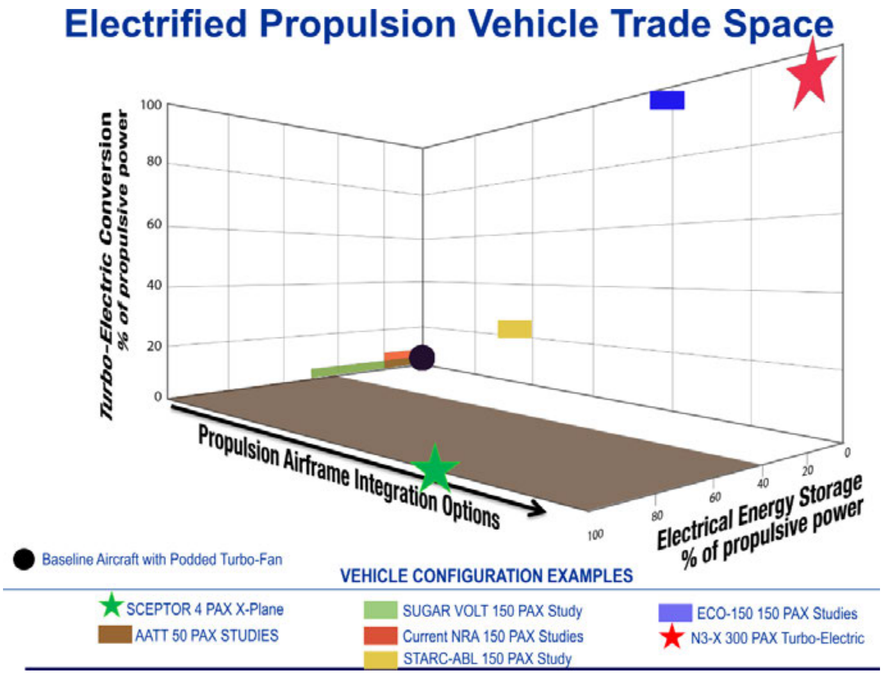


(b) Example of interdependency mapping in FM framework [51]

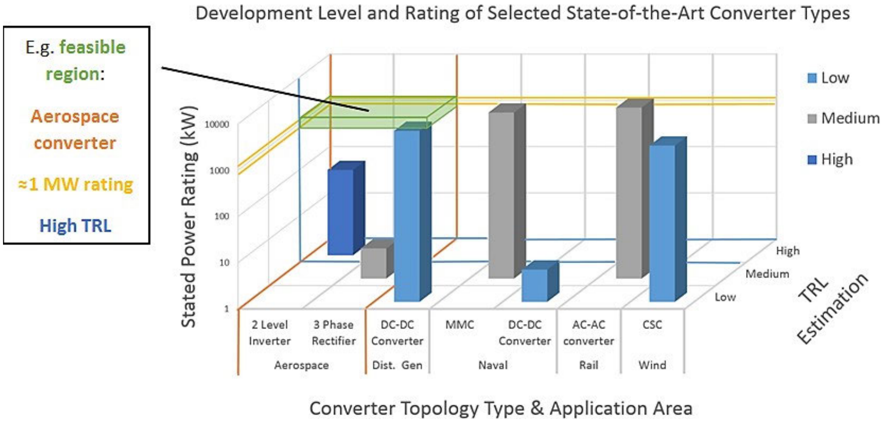
Figure 5.9: Comparison of interdependency mapping

- inadequate inputs at each step
- unlikely outputs from each step

In the presented framework, infeasible solutions are eliminated leaving only viable solutions remaining in the design process. This removes any excess or unnecessary FM considerations or solutions. Assumptions are gathered and assessed in terms of impact on the design at a number of points in the method, which demonstrates traceability of the assumptions and ensures that any assumption that is considered is valid. The data included is sufficient for the current developmental stage, however, and a greater range



(a) Example of trade space mapping in literature [50]



(b) Example of trade space mapping in FM framework [51]

Figure 5.10: Comparison of trade space mapping

of data on EPA concepts, FM devices and FM goals would be expected for later stages of the design. In areas such as the *"Customer operational requirements"* (see Figure 5.3)) that are currently undefined, these requirements are identified and are used as placeholders within the framework which can then be populated as the data becomes available.

The output of every stage of the framework better defines the viable FM solutions. The only cases where each stage of the framework would not contribute to a better defined solution space is where there are no remaining solutions, or solutions do not exist for the input criteria weighted according to specific requirements. The lack of detailed FM design in this framework is also valid since the purpose of the framework is to determine feasible electrical architectures capable of FM. At a systems level this satisfies the purpose of the framework whilst acknowledging the need for future detailed design.

5.12.4 Verification of Choice Case Study (Stage 2 in Figure 5.8)

Verification of the framework can be supported by analysis of the suitability of the case study used to demonstrate the framework (stage 2 in Figure 5.8). The chosen aircraft concept is representative of the types of aircraft configuration that may be the target aircraft type for an N+3 development time frame. This is evidenced by the fact that two independent, industry recognised research collaborations have both conducted initial studies on a tail cone BLI thruster tube-and-wing EPA concept. The choice of case study is useful as the electrical concept is comparatively simple and therefore can effectively highlight the challenges of developing FM solutions for nearer term scaled aircraft. Data is also available (to an extent) as NASA have published their studies on this concept, making a STARC-ABL style case study viable. Since the concept is at an early stage the benchmark architecture is still minimally defined, and so there is scope for innovation in the design approach which is adopted.

5.12.5 Validation of Framework Performance of Case Study (Stage 3 in Figure 5.8)

A key means of validation of the proposed design methodology is to compare the solutions already existing in the literature, and those which are the output of the framework (see stage 3 in Figure 5.8). Therefore, the architecture solution which is one particular example embodiment of the chosen FMS can be compared to the relevant benchmark electrical architectures for STARC-ABL in the literature (see Figure 5.11). It should be noted that the purpose of the case study was not to select a final ideal electrical architecture for the chosen aircraft concept, but rather to demonstrate the use of the framework in down selecting viable electrical architectures for a chosen set of aircraft requirements.

Whilst there is only one electrical architecture presented in the literature specifically for the STARC-ABL aircraft, there is another architecture of a similar scale that is being developed on a reduced scale test bed at NASA Glenn Research Centre [109] (see Figure 5.12). Both the existing electrical architectures for this aircraft concept have not been developed as part of an FM orientated design process and so it is expected that there would be differences of FM approach. However, in comparison, the level of confidence in the FM solutions identified by the framework is greater as a comprehensive scoping of the feasibility of the FM strategy has been performed. There are a number of risks and assumptions that can be identified for these alternative architectures. These are outlined below in order to highlight that the feasibility of the initial designs in the literature has not been proven, and there may be risks that are unknown.

STARC-ABL Initial Architecture

Clearly, the architecture presented by the authors in [13] is not intended to be a comprehensive analysis of FM compatible architectures, however, the minimal FM applied to this relatively critical electrical propulsion system implies that there is a risk that FM may not have been considered in detail in the development of early stage concepts. One of the most significant risks associated with this proposed architecture (and highlighted in Section 3.5) is the current lack of aircraft suitable rated DC circuit breakers (not shown in Figure 5.11). Furthermore, the availability of rectifiers and inverters rated and proven in the harsh aircraft environment is another area of uncertainty.

The architecture features and the possible embodiment of the chosen FMS resulting from the proposed framework mitigates against these risks by scoping the FM requirements in detail. There is greater redundancy incorporated into the presented solution as a result of the PLRs and the differing challenges between the AC and DC systems are also acknowledged. Thus the framework better maps the way in which specific

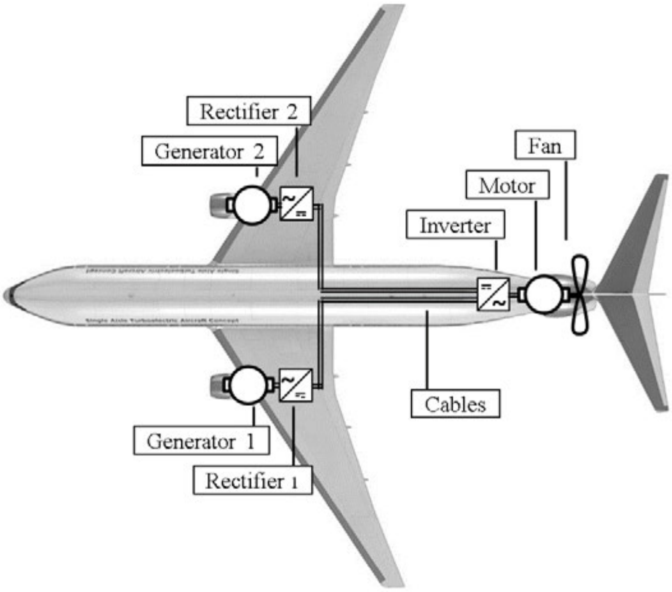


Figure 5.11: Notional STARC-ABL Electrical Architecture [13]

requirements (such as the weight budget, as identified in Section 3.3.2) correspond to the inclusion or elimination of specific architecture features.

AC Architecture

The proposed alternative architecture configuration in [14] is itself a response to the risk that DC distribution may not be feasible or preferred for the main aircraft electrical propulsion architecture. However, this configuration is also unproven and relies on the availability of appropriately fast DC and AC circuit breakers. Furthermore, there is a risk that high energy density Energy Storage System (ESS) may not be available within the given time frame and co-ordination of multiple ESS devices supporting a network may not be possible (one proposed configuration). Whilst Doubly Fed Induction Generators (DFIGs) are widely used in the wind energy industry [122], this technology is not proven in an EPA environment and so there is a risk this configuration may not meet certification standards or would require a significant amount of testing before reaching high confidence level.

The proposed solution in Figure 5.6 was derived from different PLRs to the AC architecture described in Figure 5.12. This shows that the framework does eliminate

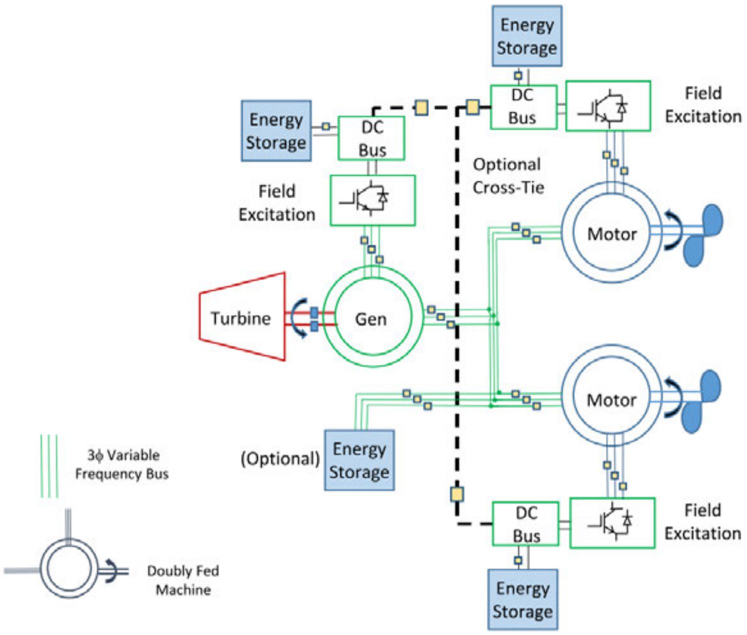


Figure 5.12: AC Electrical Architecture [14]

architecture features which do not support the critical PLRs, the MIC and the FM system goal, since if had there been a *Pre-defined architecture preference* for an AC system, the resulting architecture could have had similarities with this configuration.

5.12.6 Validity of the Framework Performance Beyond Case Study (Stage 4 in Figure 5.8)

The validity of the framework is further demonstrated by the fact that the same logical method is used to determine viable and useful electrical architectures for EPA demonstrators (see Section 6). A detailed discussion of the demonstrator specific version of the framework is given in Section 6.3.1. From this further development of the stages in the framework proposed in Chapter 5 it is clear that the methodology is widely applicable, especially in determining the FM goal which is necessary for any FM capable electrical architecture.

5.13 Summary

This chapter has presented a novel methodology for early-stage design of FM compatible architectures for future EPA. A number of key FM definitions have been outlined in order to highlight the ways in which comprehensive FM is more complex than conventional protection. The framework is then demonstrated by means of a case study to illustrate the way in which required architectural features can be identified for a given set of aircraft requirements and technology constraints. This method has traceability of the rationale driving the design which is a distinct improvement on the architectures described in the literature. Further quantitative studies could further verify the method which has been developed.

Chapter 6

A Novel Framework for Strategic Integration of FM into EPA Demonstrators

6.1 Introduction

The presented FM orientated design framework (Chapter 5) establishes the relevance of FM in the development of feasible, reliable electrical architectures for future EPA systems. However, any FM-capable EPA architecture will require some form of testing in hardware. It is also clear from the proposed FM strategy map (Chapter 4) that FM needs to be integrated into the ground-based test beds and flying demonstrators that will test, prove and build public confidence in the key FM technologies for future EPA.

However, effective FM testing is challenging due to the possibility of applied faults or faulted test scenarios causing damage to equipment and posing danger to personnel, and the increased cost and risk compared to simulation studies. In order to de-risk FM testing for EPA demonstrators, an FM testing strategy is required which incrementally builds confidence in key FM solutions. Therefore, thorough testing of FM solutions from early-stage design to pre-EIS certification will require a range of demonstrators and test rigs. This novel approach to demonstrator design which is proposed describes the different levels of FM testing, from individual components to complete flying demonstrators, which are required to increase FM readiness. In capturing the FM test aims for each level of EPA system testing a strong case is made for early integration of strategic FM development into future EPA demonstrators. The importance of a range of FM-capable demonstrators and the progression from concept agonistic technology development to testing of specific FM solutions for a given aircraft have not been identified in the existing literature or reflected in the configuration of current FM demonstrators.

Furthermore, the proposal and definition of a range of DLRs (Demonstrator Level Requirements) which have a critical impact on the feasible system and FM test goals is an important contribution and an aspect of EPA demonstrator design that has not been well understood in the literature. Where key DLRs have been underestimated or overlooked in the early design phases of a demonstrator, there is a significant risk that the demonstrator tests the wrong FM technology, the wrong topology of a required FM technology or does not have the capacity to perform the types of test that would be necessary to effectively test required FM solutions. In order to demonstrate these key aspects of FM in hardware-based electrical architectures, a novel framework for the design of FM-capable electric architectures for EPA demonstrators is proposed.

By building on the strategy map presented in Chapter 4, and presenting a methodology of EPA demonstrator design driven by the need to increase FM confidence levels a number of pitfalls in EPA test rig and demonstrator design are avoided, such as:

- Demonstrator incapable of testing FM without significant redesign
- Demonstrator designed to test a poorly designed FM solution e.g. one which is unnecessary, over-complex or infeasible
- Developmental FM technologies are not integrated into demonstrator design, leading to a possible use of existing FM solutions
- Limitations of FM solutions developed for nearer term EPA are not identified
- Innovative FM solutions are not developed, tested or ultimately available for future EPA concepts as the FM requirements and therefore testing of FM solutions

are not well understood

- FM solution not adequately tested leading to possible unidentified issues and/or overconfidence in an FM solution

In order to highlight the lack of comprehensive FM development for existing published EPA demonstrators, this chapter firstly scopes the current range of EPA test-rigs and demonstrator aircraft in Section 6.2. Then, a new method for integration of FM into the EPA demonstrator design is proposed in Section 6.3. A number of key Demonstrator Level Requirements (DLRs) are defined in Section 6.3.1 and the importance of the FM goal of the demonstrator is highlighted in Section 6.4.5. A systems-level view of the progression and variety of FM orientated demonstrators which are likely to be required is then proposed in Section 6.4. The chapter culminates in a case study featuring NASA's NEAT demonstrator [17] in Section 6.5 which demonstrates the value of the proposed DLRs and framework for effective FM testing.

6.2 EPA Demonstrator Literature Review

This literature review captures publicly available data (such as EIS, power rating, configuration) for EPA demonstrators, although it is noted that there may be other demonstrators with FM compatibility or functionality which exist. There is a limited range of existing EPA demonstrators and test beds which can be classified into:

- Small scale EVTOL demonstrators (flying)
- Reduced scale EPA used by the aircraft industry to demonstrate commercial capability and to show proof-of-concept (flying)
- Full scale EPA demonstrators (flying)
- Laboratory based larger scale electrical architecture test beds which aim to capture different design trades or aspects of performance, together with an analysis of environmental effects (ground-based)

- EPA related demonstrators testing non-electrical aspects of EPA design such as BLI (flying or ground-based)

These are discussed in greater detail in Sections 6.2.1 to 6.2.5. Existing and planned flying demonstrators are typically small scale aircraft where a complete EPA concept is under test, or where a subsection of a wider configuration is tested in flight. Test beds for EPA are lab-based rigs which allow testing of technologies, electrical architectures or environmental effects related the electrical system design. Flying demonstrators and test rigs may be specifically designed to test FM or may be testing other aspects of the electrical system design but have demonstrable FM capability.

No EPA demonstrators in the public domain have so far been designed for the prime purpose of FM demonstration or testing. A likely reason for this is the fact that fault throwing on any rig comes with the risk of severe damage to the equipment and the technologies under test if the FM system fails. There is always a need to minimize the risk to personnel and to ensure the *safe failure* of any test case, especially for a flying demonstrator, where a critical failure could pose a tangible threat to life.

Current FAA regulations for electrical testing in aircraft require that aircraft manufacturers *"verify proper operation of system during simulated power failures by* ***flight test functional demonstrations****. The applicant must show by* ***design analysis or laboratory demonstration****, that no failure or malfunction of any power source, including the battery can create a hazard or impair the ability of remaining sources to supply essential loads"* [123]. Therefore, MEA test rigs such as [124–126] and certification testing facilities such as [127] are required to perform protection testing capability, but do not feature large propulsive loads or novel architecture configurations such as TeDP that are proposed for future EPA and which demand more complex FM testing. For fault testing for terrestrial power networks, facilities such as those in [128] can throw faults on an 11 kV network. Furthermore, development and testing of naval electrical systems can be performed on the 5 MW Center for Advanced Power Systems (CAPS) test facility at Florida State University (although the hard fault throwing capability of CAPS is unclear) [129]. There is little evidence of hardware testing of effective FM for future EPA. This of course will change as EPA concepts and electrical architectures become more mature and are required for public confidence to demonstrate fail-safe operation to pass key design stage-gates.

6.2.1 EVTOL Demonstrators and First-of-Kind Electric Taxi Aircraft

There has been significant focus in the aircraft industry and in the media given to new air taxi concepts and early test flights of EVTOL aircraft (such as [130–132]). For example, tethered testing of the CityAirbus EVTOL aircraft was successfully performed [133], whilst Boeing/ Aurora Flight Sciences EVTOL prototype recently crashed on its fifth test flight [134]. Other notable EVTOL development aircraft include Ehang [135, 136], Lilium Aviation [137], A3 Vahana [138] (shown in Figure 6.1) and Skycar [139]. Whilst the technology development required to successfully test such aircraft is a key stage in the development of reliable EPA, there will still be a large amount of testing and proving needed to scale these systems up to larger single or double aisle commercial EPA.

Figure 6.1: A^3 Vahana EVTOL during test flight [15]

Although the first commercial EVTOL aircraft are expected to enter the market in the near future, in this FM-focused thesis they are considered as demonstrators of electrical propulsion and a stepping stone to larger concepts where the electrical propulsion system is also highly critical but other non-electrical oversizing measures will not be suitable. It should be noted that there are no FM test EVTOL aircraft or test beds in the literature. Yet, the inclusion of FM testing is as necessary for these aircraft as much as for larger N+2 onwards aircraft, especially if the risk-adverse aircraft industry is to adopt these novel aircraft. However, the lower operating altitudes of these EVTOL aircraft compared to current commercial MEA may enable higher confidence testing with ground-based rigs.

6.2.2 Small Scale EPA Flying Demonstrators

To date, EPA flying demonstrators have been small scale and so have not had to contend with the challenges of scaling current FM solutions for higher power rated EPA. Demonstrators currently under development are largely aimed towards proof of the aircraft concept, and are constrained by the very limited availability of FM technologies. Recent demonstrator aircraft with electrical propulsion capability include Diamond E-Star, Green CriCri and eGenius [140]. However, the power ratings of these early aircraft have been superseded by HYPSTAIR and eFAN 1.0, as described below.

Siemen's HYPSTAIR aircraft [2] is rated for 200 kW MTOP and was designed from a systems perspective with considerations of redundancy and fault tolerance. However, details of real or emulated faults being actively applied to the system in the flight testing phase are not given, nor is it known whether the aircraft did in fact encounter any failures in flight. This demonstrator was aimed at flight testing of an electrical architecture and the developing subsystems and components. This aircraft was not intended as an FM specific demonstrator, despite exhibiting FM capability, as would be expected with any developmental aircraft.

The Airbus eFAN 1.0 aircraft is a 64 kW maximum rated proof-of-concept EPA which completed test flights in 2015 [141]. This aircraft incorporated safety and reliability requirements and this was stressed in the design [142]. Yet this aircraft was not an FM demonstrator nor was it intended to test the resilience of the electrical system. For a small, pilot only aircraft it is unlikely that the system would be tested to failure as there is limited inbuilt rest-of-system oversizing. There were plans to develop the eFAN range into a commercial training aircraft, however this was abandoned in 2017 an favour of the larger E-Fan X demonstrator [143].

6.2.3 Proof-of-Concept Flying Demonstrators

The E-Fan X is a flying EPA demonstrator being developed as part of a collaboration between Airbus, Rolls-Royce and Siemens (Siemens eAircraft business was recently acquired by Rolls-Royce [144]). An overview of the aircraft configuration is shown in Figure 6.2. The aim of the project is to develop a flying demonstrator where one of the four engines on a British Aerospace 146 aircraft is replaced by a 2 MW electric motor [145]. Initial flight testing is planned for 2020 with further public test flights in 2021. E-Fan X is a proof-of-concept aircraft as key desired outcomes are testing of aircraft environmental effects and prove the feasibility of *"high-power propulsion"* for EPA [145].

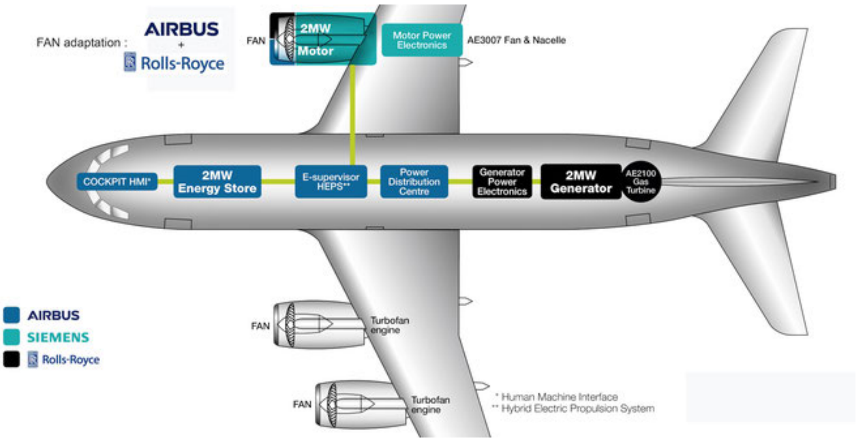


Figure 6.2: E-Fan X electrical system configuration [16]

6.2.4 Larger Scale Electrical Architecture Test Bed Demonstrators

The NEAT facility [17] represents a major development in the design and testing of electrical architectures for EPA. This facility has the capability to test electrical propulsion architectures for a STARC-ABL sized aircraft in a full scale physical layout and to simulate environmental effects on electrical components in the altitude chamber. Whilst this project seeks to incorporate novel electrical technologies as part of the series of planned tests, NEAT is not an FM specific demonstrator, and would require a significant amount of adaptation before being suitable for effective FM testing.

Another electrical architecture test bed in development by NASA is the AC DFIG test bed at NASA's Glenn Research Centre [14]. This alternative architecture configuration featuring AC distribution enables a variety of testing but is not intended as an FM specific test bench and is smaller in scale than the NEAT facility. It is not specified whether faults have been applied to this rig, but as the main aim of the demonstrator is to test the feasibility of an AC distribution and DFIG for EPA, it may not be within scope to perform such tests with this rig in its current configuration.

6.2.5 EPA Related Demonstrators

A number of EPA related demonstrators are also in development, and although these systems may not directly test aspects of FM, the resulting increase in technology maturity and confidence in novel EPA concepts will support FM-specific testing.

NASA's LEAPTech demonstrator [146] aims to assess the viability of an array of fans on the aircraft wing, and testing of the electrical motors required to reliably power the fans. Although there is an array of electrical propulsion motors under test, it is not specified whether the electrical system has been subjected to electrical faults. FM testing in this rig seems unlikely as it forms part of an initial feasibility study.

Similarly, there are two BLI test facilities in the literature [147, 148] which will supplement the development of electrical architecture FM demonstrators although studies undertaken at these facilities will scope the aero-dynamic, and not the electrical, impact of various losses of propulsion.

6.2.6 Best Practice in FM in Testing and Systems Development

In the aircraft industry there is a wealth of experience in developing highly reliable systems, and specifically electrical systems [149]. However, no industry recognized established practice exists for the design of EPA electrical architectures which, as already discussed in Section 2.4, pose novel challenges. Therefore, it is beneficial to the design of future EPA demonstrators to capture FM best practice in the early stage design, prototype testing, test bed studies and finally flying demonstrator aircraft.

NASA's *Fault Management Handbook* [37] is a log of best practice in the application of FM within the various aerospace and space programs under its administration.

Although not specific to the design of future EPA, this handbook advocates the integration of FM practices from the outset of the project. This has implications for the design of future electrical propulsion test facilities, especially those that aim to demonstrate whole system integration as FM requirements need to be considered early in EPA demonstrator design if FM capable demonstrators are to be realised.

6.2.7 Conclusions of Literature Review

Current test beds described in the literature were not intended to demonstrate integrated FM (unless simplified to component self-protection or equipment turn-off) and would require adaptation if electrical faults are to be safely tested. Flying demonstrators to-date have been small scale aircraft usually with no passenger capacity. The real step changes in the electrical architecture which will be come apparent as EPA demonstrator aircraft are scaled up have not yet been adequately addressed, and testing of novel FM solutions has not been undertaken. In order to realize effective FM in future EPA systems, FM needs to be incorporated into the design and planned test cases of future demonstrator test rigs and aircraft. A strategic approach to developing all the necessary FM technologies and enablers is required, and best practice in the application of FM to EPA aircraft will be beneficial.

6.3 Overview of Demonstrator Electrical Architecture Design Framework

FM-capable test rigs can test a variety of developmental devices, find integration issues and test impact of environment on performance or operation. Test rigs can be FM dedicated or have a wider testing purpose but incorporate some level of FM-capability. There are a number of aspects of FM testing which are more suitable for test beds than flying demonstrators, as there is reduced risk testing a test bed to failure. The suitability of different demonstrators for FM testing has not been addressed in the literature on EPA development, and so a contribution of this thesis is the identification and reasoning associated with the decision to test different aspects of FM on different demonstrators, assuming there is no ideal demonstrator capable of all required testing exists. The most significant aspects are:

- Verification of FM device operation
    - Variation of speed of FM devices operation (including metrology and communications latency) as this is difficult to do to a high confidence level in simulation
    - Interaction and integration of devices and control, especially where a fault leads to potentially conflicting control commands
    - Impact of aircraft environment on device operation and reliability
- Verification of FM system operation
    - Failure of the FM system itself
    - Effective reconfiguration or choice of response for flexible architectures
    - Primary or Secondary FM response failure or limitations of a particular FM response
        - FM specific component failure
        - Communications failure
        - Control failure
        - Reconfiguration failure or limitations

These FM testing scenarios are crucial to the development of future EPA, since comprehensive, successful FM testing increases the confidence level associated with key electrical architectures. Therefore there is a need to bridge this developmental gap with FM capable electrical architecture test bed demonstrators. Furthermore, these electrical architecture requirements are crucial to the overall design of some of the proposed future EPA concepts, yet there remains a large amount of uncertainty as to whether such FM architecture features are in fact feasible. Therefore, early elimination and verification through demonstrator testing of these aspects of the FM operation will inform and support viable electrical architecture design.

In order to demonstrate these key aspects of FM in hardware-based electrical architectures, a novel framework for the design of FM-capable electric architectures for EPA demonstrators is proposed. An overview of this proposed FM orientated demonstrator design process is shown in Figure 6.3 and described in subsequent subsections. This framework describes key stages in the determination of the physical electrical architecture that will enable desired FM tests to be performed. In the literature, incorporation of FM into hardware-based electrical architectures for EPA demonstrators has not been prioritised from the outset. Therefore, this novel approach is an important contribution which facilitates improved integration of FM into EPA demonstrators.

This framework closely reflects the EPA framework (see Chapter 5) and emphasizes that the FM functionality cannot be retrospectively applied to an electrical propulsion architecture. The goal of the FM testing, the technology and the fault response must all be taken into account to determine viable test architecture(s). This is reflected in the sequential progression of the framework showing that the design decisions at each stage will down select and shape the effective FM solution testing that will be possible.

6.3.1 Demonstrator Level Requirements (Stage 1 in Figure 6.3)

Any demonstrator which will be utilized to test and validate FM functions will need to take into account a range of requirements which will drive the design and purpose of the facility, much in the same way that the PLRs in Section 5.4.1 drive the design of FM orientated electrical architectures. The identified DLRs are described in Table 6.1 and the impact of each requirement on the design of demonstrators is discussed. The DLRs listed in Table 6.1 come from reviewing the FM requirements for various flying demonstrators and test-rigs. Identification of these requirements is a significant contribution which has not been performed in the literature. The key value of specifying these DLRs in relation to down selecting electrical architectures for hardware demonstrators is that it allows factors that define the feasible FM testing capability of a demonstrator (such as physical constraints on the demonstrator housing) to be highlighted in the early stages of the demonstrator design. This enables better understanding of the interdependency between the desired FM capability of a demonstrator

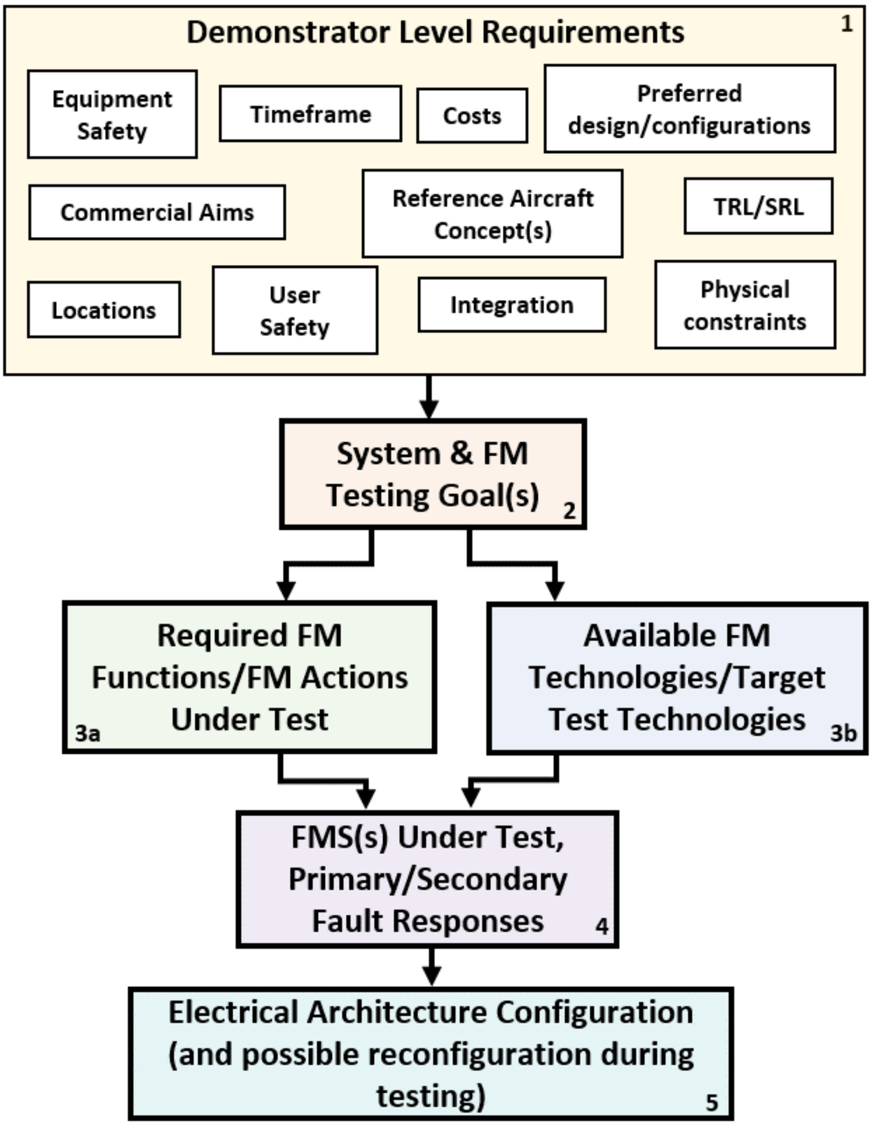


Figure 6.3: Framework for design of FM capable demonstrators

and the physical electrical architecture configuration.

There is no particular order to the DLRs listed in Table 6.1 as for any given demonstrator design a weighting process will be applied to determine the relative priority where requirements are conflicting (a similar process is described for PLRs in Section 5.4.1). The difference here between the PLRs and the DLRs is that the electrical architecture under test in a demonstrator may be concept agnostic, especially where testing is focused on initial technology viability. Therefore, the wider factors in the design

Table 6.1: EPA Demonstrator Level Requirements and Impact

Demonstrator Level Requirement	**Impact of Requirement on Demonstrator Design**
Equipment Safety	This is a major concern where there are developmental technologies under test and higher power experimental test rigs.
Time Frame	This may be critical where there is a need to protect IP or to be the first to show proof of concept. This will also impact on the available technologies and possibly the range of tests that can be carried out.
Cost	Costs must be minimized especially as any failure which leads to a loss of key equipment will incur a cost implication.
Preferred design/ configurations	Due to IP or commercial aims there may be a preferred configuration of the electrical architecture or FMS under test.
Commercial aims	There will be commercial aims which need to be considered, especially where the electrical architecture is novel or there is a significant amount of risk in the adopted design.
Reference Aircraft Concept(s)	The demonstrator may not reflect the complete electrical system for a target aircraft concept, or a specific aircraft. Where a reference concept does exist, this will strongly determine the architecture of the test demonstrator.
TRL/SRL	The TRL/SRL of the technologies, subsystems and the FMS are significant in determining the FMS options which are possible or desirable to test.
Locations	The requirements related to the location of the test facility or the test location of a flying demonstrator (such as availability of space, power input from the grid where relevant, coolants, impact on the environment etc.) will determine feasible FM testing
User Safety	User safety must be ensured in the design and operation of any demonstrator, especially where personnel are in proximity to high voltage equipment.
Integration	The integration of the different technologies into an existing rig or integration of a novel cluster of technologies may be a challenge to the overall success of a demonstrator rig.
Physical Constraints	The test bed will have to fit inside the physical housing, which may make scaled electrical architecture testing challenging or limited to a specific architecture configuration. As the EPA scale up, this will increasingly become an important factor in determining the system goal and configuration.

which were classified as *External Factors* in Figure 5.3 in Section 5.4.1, may have a more significant role. Current demonstrators have been used to prove out concepts and establish a technology track record (such as the E-Fan X) and so identification of the technology TRL and Systems Readiness Level (SRL) which are under test is critical.

Demonstrators differ from the final, commercial EPA in that the physical constraints of the airframe may not exist where a demonstrator is ground-based, yet there will be other key aspects of the physical design in terms of locations where the required power levels can be supplied and safely tested.

A key factor causing current EPA demonstrators to fall into the pitfalls listed in Section 6.1 is that the impact of these DLRs on the feasibility of effective testing of FM solutions has not been well understood. As a result, the electrical FM testing capability (for demonstrators such as Efan-X, X-57 Maxwell and NEAT) is limited as a result. Alternatively, where demonstrators have been very effective in achieving some of the DLRs (such as *Commercial Aims and User Safety*), there has been little evidence of any significant gain in electrical FM development. Therefore, this strategic method to consider the key FM-related demonstrator requirements enables an effective choice of FM solution under test.

6.3.2 System and FM Test Goals (Stage 2 in 6.3)

The DLRs described in Table 6.1 will then feed into the determination of a suitable system goal during faults (where the demonstrator is flying or incorporates other systems besides the electrical system), and then also the FM goal which will be crucial in the selection of appropriate FM functions. The key value of this approach is that it is possible to include FM in the design from the outset and to record the rationale for the choice of FM that is ultimately applied, especially where the demonstrator *System Testing Goals* are not FM-specific. Depending on the scale of the demonstrator, a complete FMS, range of FMSs or particular fault response may be tested. In defining the system testing goals, and subsequently the FM test goals, the priority test cases can be identified. This will enable developers of demonstrators to maximise the FM testing capability, even where this is a lower priority than other required testing, and will grow confidence and expertise in the application of FM as it will have been considered to some extent for every EPA demonstrator project.

6.3.3 FM Functions (Stage 3a in 6.3)

The DLRs will also impact on the FM functions under test, e.g. fault current interruption. There may be a range of discrete functions which need to be demonstrated for an aircraft application, or a combination of FM functions and supporting FM enablers to be tested (see Section 2.2.1). Where particular requirements exist around *User safety*, *Equipment safety* and *Physical constraints*, the ability of the demonstrator to be used to perform FM functions with greater risk (e.g. DC short circuit fault throwing) may be limited.

6.3.4 FM Test Technologies (Stage 3b in 6.3)

Furthermore, the technologies included in the FMS are determined by the FM technologies which are available or which form a critical part of the developmental targets for the demonstrator. This could be technologies which have not yet reached high TRL, or which are unproven in an EPA electrical architecture. This step of the framework is also significant where a demonstrator is required to have future compatibility with developing technologies which are not available at the initial point of specification, but which will be required to be integrated into the testing at a later point. This further highlights the importance of fully scoping the *Integration* requirement at the outset of the demonstrator design, if FM is to be successfully implemented at all stages in the design cycle.

6.3.5 FMS Options Under Test (Stage 4 in 6.3)

The selection of FMS option(s) under test is a critical stage in the down selection of electrical architectures for a demonstrator. FMS require the strategic use of both FM devices and aspects of the electrical architecture which support a fault response (such as redundant cables). Therefore, there must be sufficient confidence in the choice of FM functions and FM technologies (as determined by the DLRs) to proceed to this stage of demonstrator design.

6.3.6 Test Electrical Architecture (Stage 5 in 6.3)

The electrical architecture configuration for a demonstrator, particularly a ground-based test rig, may be reconfigurable as part of the FM response or as a feature of the demonstrator which can be employed in the set-up of various test runs. This will be determined by the *Preferred design/ configurations*, reference aircraft concepts and the level of FM testing (FM enablers, technologies, complete FMS, electrical architecture FM response or whole aircraft response). The DLRs will also impact on whether the architecture is reconfigurable and the amount or scale of network that needs to be included to fully demonstrate the desired fault response.

6.4 FM Demonstrator Development Strategy

An overview of the proposed progression of FM capable demonstrators is shown in Figure 6.4 and is described in later subsections 6.4.1 to 6.4.5. The proposed strategic development of FM demonstrators is mapped by the logical progression and scale of demonstrators described in the diagonal flow chart in the left hand side of Figure 6.4. The vertical flow chart in the centre of Figure 6.4 describes the proposed level to which FM-capable demonstrators should incorporate the *Reference aircraft concept(s)* DLR (see Table 6.1). The pyramid on the right of Figure 6.4 reflects the different levels of FM testing, from systems-level testing at the top, down to FM enablers and individual component testing at the bottom. Critical testing goals for each stage of the pyramid are identified and the bottom-up flow of testing aims indicates the dependency of large scale testing on the earlier stages of FM development.

The immaturity of FM solutions for EPA presents an opportunity to propose the progression and development of demonstrator test rigs and aircraft which will build confidence in appropriate FM solutions and prove the feasibility of novel technologies and systems. The key value in proposing a range of demonstrator aircraft and test beds is that FM solutions can be tested against a variety of electrical faults and failures, as well as failures of the FM system itself. Crucially, the presented FM demonstrator development strategy provides two paths (vertical and horizontal axes of Figure 6.4) which feed high confidence solutions into the next stage of FM development. This double pronged approach to FM development ensures that the technology and strategic aspects of an FMS are jointly developed, and that the electrical system integration and the aircraft integration are performed in tandem. Therefore, this FM development strategy goes beyond simply applying TRL progression to FM by considering the confidence level of a electrical FM solution, comprising FM technologies, oversizing and FM enablers and mapping a methodical means to prevent further development of FM solutions which are not at the required level of maturity to be taken forward. This incremental approach to FM development allows any issues of integration of FM technologies into strategic FMSs, then electrical architectures and then airframe to be identified. This overview of FM development does not exist in the literature for EPA yet is necessary if there is to be high confidence in the operation of complex the FM systems which are expected to be required for future EPA.

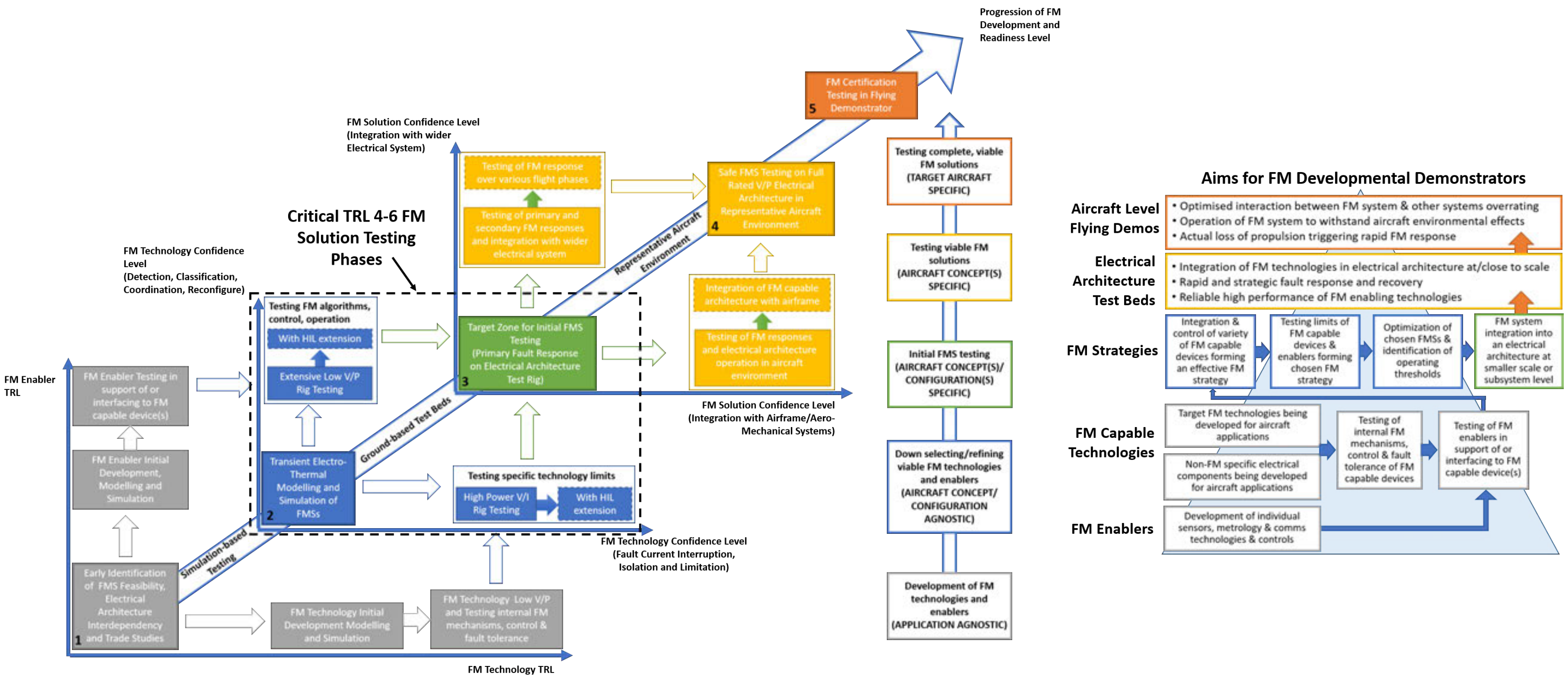


Figure 6.4: Framework describing the progression and range of required FM capable demonstrators

6.4.1 Initial FM Technology and Enabler Testing

Initially, the focus of FM demonstrator is on increasing TRL and functionality of FM technologies and FM enablers (see progression of grey boxes in FM stage 1 in bottom left hand corner of Figure 6.4). Whilst some of this can be done in simulation, there is greater confidence in the FM technologies if they can operate effectively in hardware. In transferring from simulation based studies to hardware testing, the FM solution confidence level can be increased by either testing the technology limitations or testing the algorithms, control and operation of devices. A test rig may combine these two facets depending on the rating of components.

As well as FM-specific technologies, the need for development and integration of FM enablers is highlighted in the grey boxes on the vertical axis on the lower left hand side of Figure 6.4. Metrology and sensors deployed on a future electrical propulsion architecture may introduce a non-negligible latency in the system fault response. Furthermore the ability of the system to differentiate between false trips and faults on the system will depend on the effective use of FM enablers. As the propulsion systems become more complex and with a greater amount of distributed propulsion at increased power levels, more FM enablers will need to be deployed and coordinated. An integrated approach is therefore needed which captures the systems level interaction of the FM enablers and the wider electrical system.

A key supplement to the range of test bed options is the use of Hardware-in-the-Loop (HIL) (see blue dashed boxes in FM stage 2 of Figure 6.4). This could be used for both the high voltage/current or low voltage/power test beds to simulate the wider system or to emulate the effects of a fault on an architecture which is not configured to be able withstand the effects of a hard fault (such as a short circuit applied across two cables). This also allows fault studies on a much larger network where the DLRs dictate that there is a physical or other constraint on the scale of the electrical architecture that can be tested.

Individual FM technologies and enablers need to be developed at component level before being integrated into the wider system. De-risking the component technologies and their interactions with relevant FM enablers is a key early FM testing stage, but it does not de-risk the complete FM solution or wider aspects of FM system interactions. Whilst testing individual technologies to the limit, particularly where the FM capabilities are unproven or the device exhibits dual functionality is very important, this does not prove that a given device will be able to operate effectively as part of a complex FMS. However, testing at rated voltage or current ensures that the sub-components can be specified at high confidence for the required power levels.

6.4.2 FMS Testing

FMS testing on an electrical architecture combines the previous stages of FM control/algorithm testing with the technology verification and is a critical stage in increasing the FMS confidence level. Testing of an initial range of FMS options (green box in FM stage 3 in Figure 6.4) is dependent on the FM technologies and non-FM specific technologies being at sufficiently high confidence level to be combined into an FMS. This would be determined by the TRL of the technologies, the IRL of the technology within a a FM strategy and any technically immature aspects of the FM cluster (including FM enablers) that would undermine confidence in testing the complete FMS.

After initial FMS options have been tested and are down selected, testing of high confidence or key FMS options at a larger scale is possible. Furthermore, testing the layers of FM that is designed into a system is critical (see vertical left hand yellow boxes in Figure 6.4). This includes wider electrical system response such as bringing on redundant energy storage to supplement available power. Given that the FM goal may vary over different phases of flight (see Section 5.5) the variation in the FM system response needs to be adequately tested.

In parallel to this wider electrical system testing, further integration with non-electrical systems on the aircraft is necessary (see right hand yellow boxes in Figure 6.4). Testing an FM solution in a representative aircraft environment enables aspects of the FM operation which are sensitive to vibration, temperature fluctuation, altitude effects to be assessed. This is particularly useful when transferring FM solutions from other applications where these environmental effects may not be present to the same extent (see discussion of *Core Activities* in Section 4.4).

As FM development moves towards demonstrators to test the operation and optimization of detailed FMSs, testing of sequential FM operations is key. A demonstrator test bed may, depending on the DLRs, test fault capability of the primary, primary and secondary or primary, secondary and wider system fault response.

It should be noted that the specific FM devices which will operate as part of each phase will depend on the severity of the fault, the location of the fault and the FM test goal. Therefore, it is overly simplistic to designate FM technologies as purely as part of a primary or secondary fault response. For example fast-acting circuit breakers will be included in the FM design for the primary fault response, but could be part of a slower secondary reconfiguration response for a fault on another zone of the network.

Representative Aircraft Environment

FMS testing will also need to assess the operation of various fault responses in the aircraft environment to ensure that devices can withstand environmental effects such as altitude, vibration, temperature variation over flight. These effects could be real or emulated, depending on prior technology and system confidence levels. This phase of testing which is critical to adapting technologies from other application areas will increase the confidence in the integration of the FM solution with the airframe (one of the key challenges of FM identified in [18]).

Given that some form of variable FM response will be required where the FM goal varies over the course of flight, this is an important aspect of demonstrator testing. This will require knowledge of the location(s) where FM actions can be implemented and so the electrical architecture needs to be sufficiently defined to test location specific and time of flight specific goals (see Figure 5.3).

The ultimate goal of any test bed or demonstrator is to de-risk the chosen concept, and so the greater scale of testing, the range of functions and FMSs that can be verified, the greater the level of confidence in the FM solution and hence, the more robust the FM system is expected to be. However, it is not necessary to test all FM functions at full scale, nor do all functions require to be tested on a full systems test bed, or flying demonstrators. A number of smaller scale test beds may be the proving ground for specific technologies that form part of a larger system. For example, the studies performed on the BLI wind tunnel demonstrator [104] will support the development of the STARC-ABL aircraft concept which includes a BLI fan.

6.4.3 Later Stages of FM Testing

Extensive testing of FMSs culminates with FM testing on a full rated electrical architecture in a representative aircraft environment, as shown in stage 4 of Figure 6.4. Where feasible, this could be in a flying demonstrator, but to reduce risk and cost such testing could also be performed in a simulated aircraft environment, such as the McKinley Climatic Lab in Florida [150]. Although it may not be possible or advisable to test real faults in flying demonstrators, some form of reconfiguration or fault tolerance testing is expected to be required to gain public confidence and to satisfy the customer safety requirements. Existing flying EPA demonstrators (such eFAN, HYPSTAIR) have demonstrated increased confidence in the chosen technologies and electrical architecture but, from the available literature, there is no evidence of FM testing being performed. The value of the proposed approach described in Figure 6.4 is that the earlier stages in FM capable demonstrator testing methodically build capability and confidence in FM testing. Then, in the final stages of testing where there is a much greater cost if the FM system fails, there is reduced risk and ultimately the final FM solution is one in which there can reasonably be high confidence.

The final stage of FM testing in Figure 6.4 (stage 5) is certification testing which would occur for an aircraft type prior to first delivery of the aircraft. The reliable operation of the FM system would certainly need to be tested in this context but more likely with the purpose to gain public confidence in these novel aircraft types, as opposed to prove the FM technologies.

6.4.4 Relevance of Target Aircraft or Concept

As indicated in the vertical flow chart in the centre of Figure 6.4, developing the FM technologies will be aircraft agnostic since the target electrical architectures may not yet be known and a wide range of FM functions will be required. Demonstrator test beds which aim to increase FM technology or enabler confidence level will not necessarily reflect a defined aircraft concept or form part of the development of a specific type of aircraft electrical architecture. If all demonstrators for early FM development are designed in support of specific concepts then any designs which do not fit this mould would not be considered for testing. Since there are many new entrants to the EPA market, especially in electric air taxis, it would be detrimental to lose the ability to test a range of possible solutions, particularly whilst the technologies are still at low TRL. This would mean that the availability or configuration of the available demonstrators would strongly influence the *Pre-defined architecture preference*, which would be undesirable that this point in the developmental time frame. Therefore, reconfigurability of demonstrators after completion of a test program to allow iterative FM testing or comparison of competing configurations is highly desirable.

However, in the later stages of testing where the focus is on increasing confidence in the FM solution (green, yellow and orange boxes in Figure 6.4), the *Reference Aircraft Concept* DLR will become more significant, as the electrical architecture under test may need to reflect key aspects of a preferred EPA configuration (e.g. turboelectric), specified concept (single aisle TeDP aircraft for N+3 EIS) or target aircraft (e.g. ECO-150).

6.4.5 FM Test Goals for Demonstrators

The identification of key aims of each stage of FM testing is an important contribution and supports the mapped progression and scale of demonstrators described in the left hand side of Figure 6.4. The pyramid on the right of Figure 6.4 reflects the systems-level testing at the top down to FM enablers and individual component testing, with key testing goals for each stage of the pyramid identified. The bottom-up flow of aims shows the dependency of large scale testing on sufficient confidence in testing performed at the earlier stages of FM development. The different levels of testing are identified in Figure 6.4 as follows:

- Aircraft Level Flying Demos
- Electrical Architecture Test Beds
- FM Strategies
- FM Capable Technologies
- FM Enablers

The logical progression of FM goals which is proposed highlights the fact that the electrical design and FM test capability of a demonstrator will be determined by stage of testing. This links to the role of the FM goal of the electrical architecture (see Chapter 5) and the choice of FM goal in Figure 6.3.

The required FM testing applicable at each of these stages reinforces the fact that FM cannot be added to an electrical architecture design, and neither can FM testing be retrospectively added to a test rig. It must be integrated into the FM demonstrator development strategy from the outset. It is also clear that the challenge of effective FM demonstration must be addressed by means of a number of different testing facilities, targeted to each level of testing. There is a significant amount of verification and validation of FM actions and technologies which need to occur ahead of integration into a viable electrical architecture configuration. This stage should not be overlooked as it allows high confidence in the technologies to be achieved and innovation in FM capability to be identified, irrespective of the final aircraft concept.

6.5 NASA NEAT Case Study

In order to demonstrate the value of the FM demonstrator development strategy proposed in this chapter, a case study is presented on the NASA NEAT facility. This validates the need for a new approach to FM-capable EPA demonstrator design and, and by suggestion of complementary testing capability, confirms the value of the strategy presented in Section 6.4. The FM capability of the current NEAT design is first critically appraised before the novel demonstrator strategy (see in Section 6.4) is applied to NEAT, allowing key FM demonstrator design recommendations to be made.

6.5.1 Overview of Key NEAT Data in the Literature

In the literature on this demonstrator [17], the purpose of this rig is *"to enable the high-power ambient and cryogenic flight-weight power system testing that is required for the development of the following components to Technology Readiness Level (TRL) 6:"*

- *High-voltage bus architecture — Insulation and geometry; 600 to 4500 V*
- *High-power megawatt inverters and rectifiers - Commercial, in-house, and NASA Research Announcement (NRA)) development*
- *High-power megawatt motors and generators — Commercial, in-house, and NRA development*
- *System communication — Aircraft Controller Area Network (CAN)), Ethernet, and fiber optics*
- *System electromagnetic interference (EMI) mitigation and standards — Shielding; DOD–160 and MIL–STD–461*
- ***System fault protection — Fuse, circuit breaker, and current limiter***
- *System thermal management — Active/passive, ambient/cryogenic, and distributed/ mixed*

TRL 6 can be described as: *technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)* [107]. The system testing goal for the test bed is for components under test to meet NASA's defined technology development goals [151]. This facility is intended as a stepping-stone to full-scale power train testing in an operational environment. The FM test goals are highlighted in bold.

An overview of the main electrical architecture under test is given in Figure 6.5.

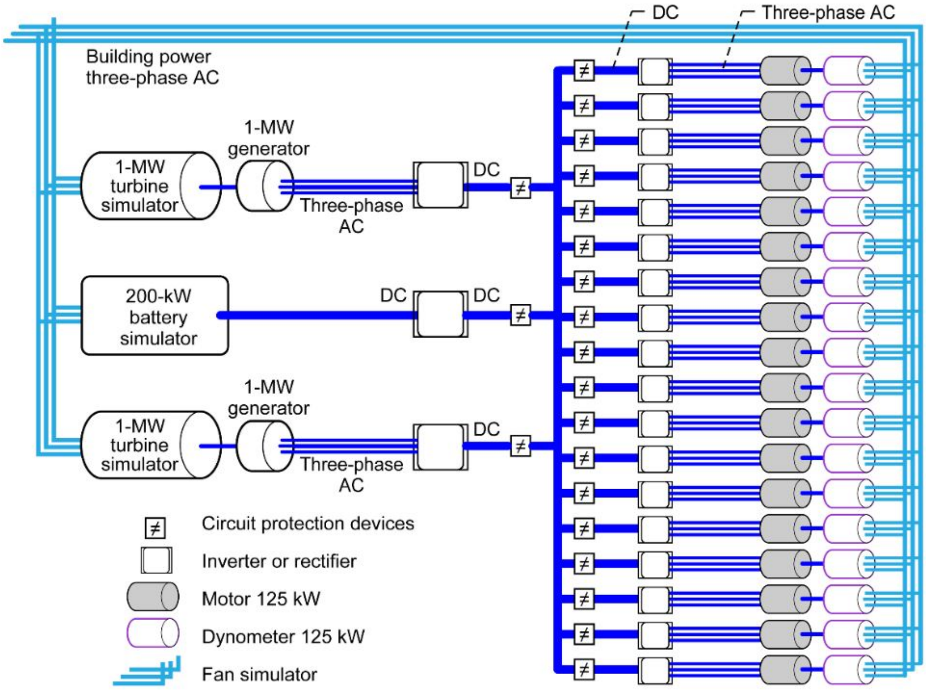


Figure 6.5: NEAT Electrical Architecture Overview [17]

6.5.2 FM Testing Capability with Current Proposed Electrical Architecture

NEAT is an electrical architecture test bed aiming to test an EPA power train in hardware so would correspond to the category of testing aiming to increase confidence in a chosen FM solution (green box which is stage 3 in Figure 6.4). In reference to Figure 6.4 testing of FM components would come under the *high power V/I rig* testing phase which feeds into FM stage 3. However, here there is no FM solution explicitly identified. This may be due to the rig seeking to demonstrate FM functions but not primarily being designed as an FM-specific demonstrator. Yet this leads to a configuration where there are protection devices included in the electrical architecture, but there is no clearly defined rationale as to why these specific protection devices have been chosen. For example, there are no AC circuit breakers included in the design shown in Figure 6.5, but the ability to interrupt the power flow to the motors and from the generators is a key FM function. To ensure rig safety there may be AC supply over-current trip protection yet this is not specified. Furthermore, it is also possible that in this regenerative electrical design these sections of the architecture are not under test, and so are not active in any fault response.

The availability of rated DC circuit breakers suitable for an aircraft application that can act within a defined FMS needs to be established before this technology can be integrated into a larger electrical architecture demonstrator, such as the one proposed for NEAT. Fuses are not a novel technology but are likely to be a last line of FM response in demonstrators (see Section 2.2.1), and so need to be tested as a secondary or tertiary function of an FM response, to avoid fault testing on the rig simply triggering protective fuses instead of the strategic protection devices on the network.

Reference is made in [17] to developmental components being integrated into NEAT as they become available. However, since there is little detail given on the current protection devices (topology, ratings, manufacturers), it is unclear what the next stage of FM testing would involve. The fuses have been shown on the single-string, initial schematic of NEAT on the DC cables. The location of fuses on later stage iterations of NEAT is unclear. The rating of the fuses is 5 A 700 V in one configuration of the test bed (the 2016 test plan [17]), and so any primary fault response testing would have to operate within this range to prevent the fuses being tripped. This is to be avoided to prevent the fuses from having to be replaced, which would increase operating costs.

The algorithms to detect and isolate across multiple channels and perform co-ordination are not tested, and is a necessary step before a high confidence level FMS can be applied to a test-rig and operate as expected, since the main focus of the testing is to integrate the technologies on that kind of scale and not to find weaknesses in the FM solution which is under test. It is difficult to perform testing of these FM components whilst ensuring the safety of the surrounding components – for example, if a DC short circuit is applied to NEAT (current configuration does not appear to have this function included) then there would have to be high confidence that the protection devices could interrupt the fault before the fault current level exceeded the maximum current ratings of the components on the fault current path.

The NEAT facility is designed to be able to supply large amounts of power to the rig to reflect the MW scale electrical architectures which have been proposed for future EPA concepts. The power output from the motors (driving the fans) is used to power generators, creating a regenerative electrical architecture. Whilst this reduces the total power consumption for the rig, it does create unwanted side-effects from FM testing. A downstream fault could impact the power input into the system (a fault at the feeder to the motors affecting the power obtained from the generators) which would not happen on a flying demonstrator or operational aircraft.

Given the scale of the NEAT rig, the FM testing challenge is to effectively test components without damaging other equipment, tripping internal component protection schemes (such as in the converters) or blow the safety fuses (unless part of the FM strategy under test). The design of the rig to test distributed propulsion and to incorporate DC transmission, leads to a comparatively complex electrical architecture, which (as discussed in Chapter 5 in turn demands a complex FM solution). However, there is a significant amount of FM component and solution testing that has not been done (as far as can be ascertained from the literature) and so the value of the FM testing in NEAT is constrained as it is not supported by previous high confidence tests of the interactions between FM components and their limitations. The risk then (see Figure 6.4) is that the NEAT facility tests the wrong FM technology, the wrong topology of a required FM technology or does not have the capacity to perform the types of test that would be necessary to effectively test required FM technologies.

6.5.3 NEAT DLRs

The general DLRs which are proposed in Section 6.3.1 and shown in the first stage of Figure 6.3 are then applied to NEAT. Considering the available data for NEAT, DLRs with reference to NEAT are defined and described in Table 6.2.

The key value and contribution that these specified DLRs bring is that the final configuration of a demonstrator (in this case an existing one) can be traced back to a bank of key requirements. Knowledge of key DLRs not only allows the possible FM test goals of a demonstrator to be retrospectively determined, but from an early stage in the design of PLRs the factors that shape the range of testing which is feasible are known. This allows the requirements to shape the FM test goals, rather than the FM testing capability to be selected by reviewing an established electrical architecture design for a demonstrator. Any electrical test facility will require factors such as safety, costs and location to be taken into account. These apply here also, but the impact that such requirements have on FM testing for EPA has not been well understood. Fundamentally, testing of FM is not straight forward as faults have to be emulated or applied to a system. To avoid failures, the required level of safety around testing of failures is complex. Faults need to be applied in a way that replicates real, expected fault behaviour (in terms of fault energy and where fault occurs) and ideally some level of manufactured unpredictability (the system should be able to identify a fault and act appropriately where the fault type and location are not explicitly known by the system).

It is evident from reviewing the stated aims for NEAT that FM testing is only one of a number of simultaneous developmental areas. When this systems test goal is combined with the DLRs defined in Table 6.2, the scope of FM testing and development at TRL 6 (NEAT target [17]) is clearly limited.

From reviewing the data in Table 6.2, the requirements that define this test bed make integration of FM capability difficult. This demonstrator is not FM-specific, and so is not optimally configured to test FM components. DC ground faults can be applied as shown on the single-string schematic in [17], but the rationale is unclear as is the value to the development of strategic FM by the testing of Commercial Off-

Table 6.2: DLRs with reference to NEAT demonstrator

DLR	**NEAT Requirements**
Equipment Safety	The safety and continued operation of the surrounding equipment is important, especially where high voltage (kV range) cables and, in future configurations, superconducting components are concerned.
Physical constraints	The test bed is ground-based and must fit within the physical constraints of the existing facility at NASA's Plum Brook Centre. The scaled layout of cables and components which is desired to make the testing of the power train more realistic is constrained by the location of the altitude chamber at one end of the facility.
Costs	The physical constraint requirement is linked to the requirement to minimise costs in that the test bed is planned to fit within an existing facility and not a custom-built structure to prevent increased costs.
Commercial aim	The "Commercial" aim of this facility, or more accurately, the research aim is to meet NASA technology testing goals [151].
Location	NEAT is housed at a single location chosen for the capacity of the electrical grid to supply the required power levels and as it is the site of an existing facility.
Time frame	The build began in 2016 with testing planned until 2022, with interim phased development of the configuration under test at NEAT.
Reference Aircraft	From the sizing of the facility and the use of distributed propulsor fans, the reference aircraft would resemble the ECO-150 concept.
Preferred configurations	The test rig features distributed electrical propulsion, DC transmission, and although not initially including cryogenic components, this is planned for later configurations of NEAT.
User safety	The safety of the operators of the facility is paramount and so the control room is required to be situated separate from the live rig.
Integration	The test bed will demonstrate successful electrical component integration into a EPA test rig.
TRL/SRL	Components will be tested to TRL 6 as defined in [107], although the required target SRL of the FM system is not identified.

the-Shelf (COTS) circuit breakers operating at 600 V_{dc} without evidence of planned reconfiguration or manipulation of the battery simulators during the fault and recovery. The type of circuit breaker that is used is not specified so the time taken for the fault to be cleared is not stated. The speed of operation is one aspect of testing that is useful to conduct in hardware (as discussed in Section 2.2.1), yet there is no evidence that there is capability to accurately conduct FM responses and identify the minimal time taken. Again, this is a possible contribution to testing of DC system FM solutions that would be of great benefit to scope at this point in the development of EPA demonstrators but the DLRs, system testing aim and the resulting configuration severely limit the range of useful FM tests that can be performed.

6.5.4 NEAT System and FM Test Goals

Assuming the same input requirements as those described in [17] and collated in Table 6.2 and a systems testing aim of component-level technology development and integration, the FM test goals are re-evaluated in this section.

The FM test goal for NEAT should, ideally, be to test the integrated FM solution(s) which are viable and preferred for an aircraft with a similar size and EIS to the ECO-150 (as identified in Section 4). Therefore, in the first instance, the FMSs which are being considered for this aircraft configuration and hence are relevant to testing on this rig need to be identified and the corresponding FM technologies and enablers tested.

In Figure 6.6 the current NEAT FM test goal (TRL 6 testing and integration) is highlighted by a dashed box. In comparison, the current NEAT testing proposed capability is indicated by perforated boxes labelled *"Current NEAT FM Capability"*. On the right hand side of Figure 6.6 the general TRL 6 FMS testing goal is shown by a dashed box, and as discussed in Section 6.5.1, the NEAT test aim as applied to FM is shown by a perforated box.

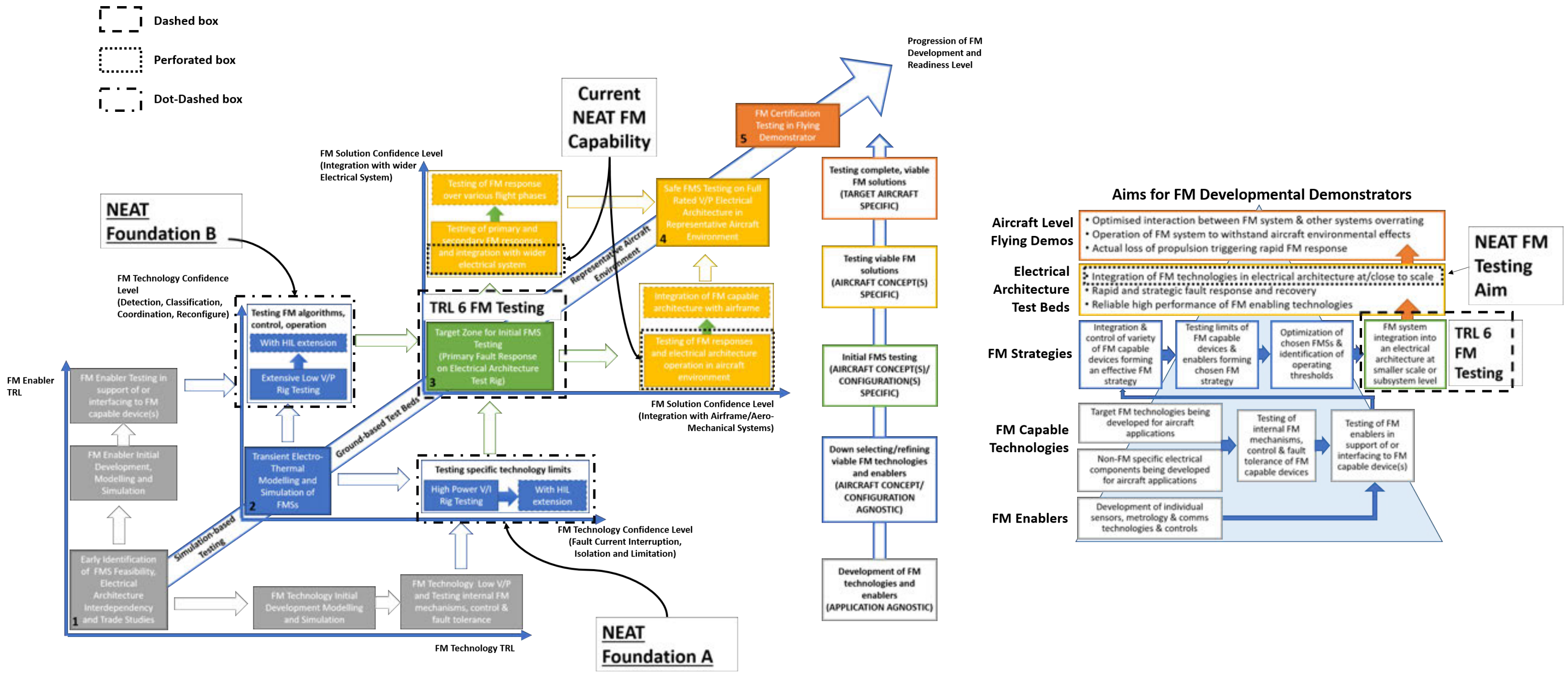


Figure 6.6: Overview of NEAT current FM capability, TRL 6 FM testing and proposed NEAT foundation test beds (A and B) applied to progression of required FM development

The scale of testing as proposed for NEAT dictates that the FM goal is targeted towards testing of FM strategies, combinations of FM technologies and other components and enablers in which there is already high confidence. If a demonstrator is to be effectively configured to enable testing of FM then the system goal (TRL 6 testing of components and integration into electrical architecture) needs to match to the FM test goal (*FM system integration into an electrical architecture at smaller scale or subsystem level*). This stage of building confidence in the FMS option(s) is shown in Figure 6.6 by the central green box. This stage focuses on selecting a FMS under test, applying to an electrical architecture and performing initial tests, the scale of the test bed depending on the existing level of confidence in the FMS under test.

In regards to NEAT there is a disparity between the wider system goal and the FM testing that this should correspond to - the dashed and perforated line boxes should overlap. The reason for this is that the FM system readiness lags the development of other aspects of the electrical system. The preceding stages of FM testing in both the FM technology side and the FM enablers have not been done to the extent that would be necessary to ensure a range of high confidence solutions exist to feed into the initial FM testing phase. Without these critical stages of development, there cannot be high confidence in applying FMS testing to a rig such as NEAT. The DLRs regarding safety of personnel and equipment would inhibit the integration of technologies which were not deemed sufficiently proven. The ability to test environmental effects and a complex distributed propulsion system are critical in the path of FM testing (see yellow boxes in Figure 6.6), yet are currently too far in the future for effective FM testing.

6.5.5 Proposed NEAT Foundation Test Beds

It follows from this critical appraisal of NEAT that a test rig that is not FM dedicated cannot feasibly implement innovative FM approaches or FM solutions which have not been already verified on a suitably rated voltage and current rig. There are preceding stages of testing and identification of critical FM solutions which must be completed for any FM testing on NEAT not to pose a large risk to key DLRs, namely *User safety* and *Equipment safety*. Therefore, two pre-cursor demonstrator test beds are proposed.

The first of which, (labelled *NEAT Foundation A* in Figure 6.6), which will perform testing of critical FM technologies, such as the DC breakers shown in Figure 6.5. Methodical testing of target FM technologies for NEAT will increase the confidence level in the available FM devices. Once there is high confidence in the availability of the required FM technologies suitable for an aircraft application that can act within specified FMSs under test, then these technologies can later be integrated into a larger electrical architecture demonstrator, such as the one proposed for NEAT. Thereafter, the FM capability of the DC-DC converter interface to the battery simulators, the rectifiers and inverters could also be tested where components could provide fault current interruption for the wider network, and not just converter self-protection.

Another test bed is proposed in parallel to NEAT Foundation A, named NEAT Foundation B in Figure 6.6. This would enable testing of FM enabler integration and control in hardware, with any added complexities that are introduced by test rig studies such as latency in control of FM system. Testing of *FM enablers in support of or interfacing to FM capable devices* is a key aim of fault testing at the lower levels of the pyramid of aims presented in the right hand side of Figure 6.4. NEAT Foundation B would perform this role and ensure *High confidence* in the operation of strategic fault responses across a complex electrical architecture.

Both NEAT Foundation A and B could be tested with Hardware-in-the-Loop (HIL) extensions (as shown by dot-dashed boxes in Figure 6.6). This would allow to emulation of the wider electrical architecture or range of possible electrical architectures being considered for initial FMS testing. HIL FM testing would be useful for increasing the confidence levels in novel FM solutions being applied to NEAT as the impact of FM responses on critical components is de-risked (addressing the key *"Equipment Safety"* DLR).

The scale of the investment (linked to the *Cost* DLR) in NEAT is considerable and forces the need to derive as much useful testing as possible with the available equipment. The configuration of NEAT would have greater FM capability if there was no power regeneration, or at least a configuration setting which would decouple the motor and generators during FM testing. There would also be added value in the design of NEAT if the electrical architecture could be reconfigured in future testing phases or if the rig can be later retrofitted as an AC system to allow comparison of the fault responses for contrasting electrical architecture configurations.

Aside from the benefits which would come from developing the recommended foundational test-beds for NEAT, there is a cost associated with such FM development not being performed. Firstly, the FM approach which is proposed, adopted and integrated into the design is shown to be infeasible when the scaled-up testing phase commences, leading to cost and delay in the development of the EPA. The risk to

6.5.6 Case Study Summary

In summary, a number of modifications to NEAT are proposed:

- Two parallel test beds to be developed as pre-cursors to NEAT, to de-risk FMS testing on higher power electrical architecture
  - *NEAT Foundation A* to develop and increase confidence levels in the operational limits of key FM technologies (such as the DC circuit breakers specified in [17]) for use in NEAT
  - *NEAT Foundation B* to develop and increase confidence levels in key FM enablers for NEAT, thus enabling appropriate FM responses for a multi-channel, complex electrical architecture

  - HIL extensions to both NEAT Foundation A and B to emulate the wider electrical architecture, and de-risk the impact of FM real time FM responses on critical components

- The ability to reconfigure and/or retrofit the electrical architecture to enable comparison of different FM solutions, and enable down selection of feasible FMS options under test

This case study successfully highlights the impact of the lagging development of FM for current demonstrator electrical architectures. The fact that an electrical architecture can feasibly be configured for integrated testing of developmental electrical machines and power converters, yet the chosen FM solution is not available at high confidence for the same application is evidence of the lack of high TRL FM technologies for suitable EPA demonstrators. As demonstrated in Chapter 5 and again underlined in this chapter, this shows that FM cannot be considered as an addition to an established architecture design. FM must be considered form the outset and integrated into the development of EPA demonstrators. The value and FM testing capability of complete electrical architecture demonstrators such as NEAT will be limited if there is insufficient confidence in the individual FM technologies, if the possible range of FMSs for the demonstrator are not tested to high confidence and if the FM system cannot be integrated into the wider electrical architecture configuration.

6.6 Recommendations for Strategic EPA Development

The case study presented in this chapter has demonstrated the lack of FM integration into EPA development in what is arguably the most advanced EPA ground demonstrator in the literature. If then, the best available testing facilities are lacking FM capability this has implications for the wider development of FM across the industry. Therefore, a number of key recommendations are put forward on the basis of the breadth of work in this thesis to achieve an ideal set of demonstrators:

- FM needs to be considered in the early conceptual design stages of the development of any future EPA as this will direct the selection of FM demonstrators which are most suitable for the particular EPA concept.

- The progress of the FM design and the maturity of the FM technologies and wider electrical system is key indicator of the readiness of the EPA concept as a whole, and so metrics for accurately measuring the maturity of FM technologies and FM testing achieved need to be developed and applied appropriately to any EPA design.
- Safety standards for electrical systems and specifically FM operations urgently need to be developed and agreed across the industry to enable cohesive development of FM solutions which could be utilised in a range of application areas, thus decreasing the costs of development and ensuring that FM can feasibly operate within these key limits. This would prevent demonstrators being designed and built which were not fit for purpose or which were incapable of performing required certification testing.
- Electrical FM knowledge and expertise needs to be better disseminated in the aviation industry and given increased visibility if this critical area of future EPA design is to be given the level of focus that it requires.

6.7 Summary

The literature review presented in this chapter of various demonstrators for which data is publicly available highlighted the lack of methodical, targeted FM testing for future EPA concepts. Yet, a critical part of the developmental roadmap for FM orientated architectures is the need for FM-capable demonstrator aircraft and test rigs. By considering FM from the outset of EPA demonstrator design and identifying both the systems testing (general) and FM-specific test goals for the demonstrator, effective FM test cases can be identified. Understanding the FM test aims for different levels of demonstrator will ensure that no stage of FM testing is overlooked and assumptions on the viability or suitability of an FM solution will be supported by appropriate testing. This will ultimately lead to high confidence in the FM solutions which later in the development process are selected for future EPA concepts.

The DLRs identified in this chapter formed the basis of a proposed methodology of demonstrator electrical architecture design. This has not previously been established in the literature, and enables early integration of target aspects of FM which are viable to test on a given EPA demonstrator.

It has been shown that a range of demonstrators is required to fully test FM solutions, from reduced scale ground-based testing of FM algorithms to flying demonstrators with FM capability. In particular, the testing of FMSs in hardware at TRL 6 is identified as a key stage in ensuring high confidence in an FM solution. However, as indicated in the presented case study, this demands high confidence in the FM technologies and FM enablers which form the complete FMS, and due to the increased risk of applying fault testing to a wider electrical architecture, these two feeder stages must be successfully completed if such FMS testing is to be feasible.

The case study on the NASA NEAT facility further emphasises the importance of early integration of FM into the design of EPA demonstrators. The DLRs identified for this demonstrator highlighted the challenge of testing FM on larger scale electrical architecture test beds, where high confidence in the operation of the FM system is critical if key DLRs (*Safety*, *Cost*, *Time frame* and *Commercial aims*) are to be met. Furthermore, the case study also demonstrates that effective testing of FMS options at TRL 6 is limited by the fact that the FM system readiness lags the development of other aspects of the electrical system. Therefore, the presented case study validates the need for a novel approach to FM-capable EPA demonstrator design. The proposal of two complementary demonstrators as pre-cursors to NEAT ensures that increased confidence in key FM technology and enablers is achieved. This confirms the value of the strategy presented in Section 6.4 and the importance of strategic FM development in hardware demonstrators.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The work contained in this thesis has demonstrated the importance of FM in the design of future EPA electrical architectures. A number of key conclusions are evident:

1. **A novel FM approach is required which goes beyond selection of individual protection devices towards identification of systems-level, strategic FM solutions.** The review and analysis of key FM requirements in Chapter 3 has highlighted the range and complexity of the technology challenges facing the design of robust FM systems for future EPA. A number of key technology bottlenecks have been identified which have implications for the design of viable FM for EPA electrical architectures and further targeted development of FM devices is required to address these technology challenges. The uncertainty underlying the capability of current protection technologies in an aircraft environment and the required adaptation of current technologies that will be necessary dictates that a novel methodology of electrical FM design is adopted.

2. **The availability, TRL and range of capability of protection devices at an aircraft's point of final electrical design will have a significant impact on the feasible FMSs, and hence the available electrical architectures.** The requirements surrounding the design of an electrical propulsion FM system

are demanding (as discussed in Section 3.7), particularly in regard to those which are critical in aero-electrical systems (such as weight).

3. **A novel approach to electrical protection of EPA requires the definition of new terminology.** The scope of FM is wider than simply specifying and deploying conventional electrical protection technologies on a given electrical architecture. The electrical architecture and the FMS are interdependent, and an effective FM solution for a future EPA must consider the wider system overrating (non-electrical) as well as non-FM specific components (such as redundant cables) which could form part of a strategic, layered FM solution (as described in the presented strategy map in Chapter 4.

4. **Critical architectural features and FM functionalities can be identified for a given set of aircraft PLRs without the electrical architecture being fully defined.** This is evident in the novel methodology for early-stage design of FM compatible architectures for future EPA presented in Chapter 5. A significant benefit of this method is the explicit specification of the chosen FMS for the system, a key aspect of design which is not evident in the architectures described in the literature.

5. **While electrical FM solutions remain limited by the availability and capability of technologies, significant levels of rest-of-system (non-electrical) oversizing will continue to be required (see discussion in Section 4.5.3).** This is not ideal as some aspects of rest-of-system oversizing may not scale up for future EPA concepts, and a reliance on alternative safety measures detracts focus from the much needed developments in EPA specific FM solutions.

6. **The importance of FM in the wider testing and development of EPA has been highlighted and a system-level approach is necessary to capture the complexity of integrating FM into the design of EPA demonstrator aircraft and test beds.** The lack of in-depth FM integration in EPA flying demonstrators and test beds is identified in Chapter 6. On this basis, key

demonstrator design requirements that impact on the scale and variety of FM strategies that can be tested are discussed. Given the importance of the FM goal in any demonstrator configuration, an overview of the types of FM function which need to be developed at scale, and those which can be performed on reduced power or voltage rigs is outlined. This scoping of FM testing requirements has not been conducted in the existing literature and supports the effective integration of FM into a range of testing configurations.

7. **Targeted development of FM technologies is required where the current status of technology lags the projected requirements for future EPA FM design (as discussed in Chapter 4).** Any limitation of confidence level in particular FM solutions (such as SSCBs for a N+2 single aisle EPA) informs decisions on the choice of electrical architecture and wider aircraft design. This is made possible by the methodical approach used to develop the strategy map, identify classification thresholds and capture the requirements of the FM system.

8. **A portfolio of EPA demonstrators and test beds across a range of scales and functions will be necessary to test the integration of FM into EPA electrical architectures and prove key FM technologies.** Identification of the DLRs and FM test goals for a future EPA concept is crucial if an EPA demonstrator or test bed (especially a non-FM specific demonstrator) is to effectively integrate essential FM functionality and safely demonstrate real time FM system responses in hardware (as discussed in Section 6.5.6 and Section 6.7).

7.2 Wider Discussion of Conclusions

The value of effective FM has been shown to go beyond improved fault tolerance in the electrical architecture. By considering the system design from an FM point of view, it is possible to identify solutions which under other metrics would not have been considered. This resets the trade space for EPA design and emphasises that FM is an intrinsic and critical aspect of robust electrical architecture design. FM orientated electrical architecture down-selection not only incorporates comprehensive FM into the design, but can in fact improve the wider reliability of the system. This idea is put forward in [36], and is highly pertinent to the design of EPA: *Fault protection, done right, greatly improves the safety and reliability of a system, whether or not a fault ever occurs.* The importance of FM *done right* has been demonstrated through the design framework, as the outcome of this method was a rational, logical and feasible electrical architecture capable of robust FM. It is also clear that FM can only be *done right* if strategic FM solutions are available at a high confidence of safety certification and at sufficient in-flight maturity, and the presented strategy map provides a basis to progress towards this aim.

It is evident from the work in this thesis that *fault protection done right* improves the complete electrical system design. By adopting an FM orientated design of EPA, and in deviating from the FM approaches where FM is applied to an established design, it is possible to identify innovative electrical architecture configurations which may not otherwise have been considered. Although a key function of any design methodology is the down-selection of solutions, at this early developmental stage there is good reason to widen the solution space to include disruptive or alternative solutions (such as an AC synchronous distributed propulsion system), which may provide desirable FM functionality. With the lack of fully defined the electrical design requirements and safety standards, there is a rare opportunity to shape not only the future of critical FM design, but of best practice in complete systems-level EPA design. Thus effective FM integration into the conceptual, electrical architecture and demonstrator design for EPA could inform other critical electrical propulsion applications.

It should also be noted that a key condition that underpins the value of the FM framework and strategy map presented in this thesis is the lack of existing safety standards. If the safety standards for electrical architectures operating in future EPA were defined and applied in the design, then the uncertainty around FM requirements would be reduced. The safety standards would support down selection of technologies and identification of FM goals, since the necessary capability of the FM system would be stipulated directly or indirectly in the standards. Therefore, given the lack of safety standards which have been published, a novel approach to determining the FM system requirements has been proposed in order to strategically develop key aspects of FM.

In Section 2.4 it was demonstrated that FM in existing EPA electrical architectures has been done at a first-pass, minimal level or simply not at all. This thesis has shown that in order for FM to be done well, it must be integrated into the design at an early stage. This is also true for EPA demonstrators and test beds, as it was shown in Chapter 6 that it is difficult to add FM to a test configuration retrospectively. EPA mark a departure from conventional aircraft design and so it is logical that a novel approach to safety is required which does not depend on analysis and feedback from decades of flight hours. Therefore, it is critical that FM development is prioritised now in order that the significant technology challenges which have been identified can be addressed and industry-wide best practice can be established. In doing so, engineers designing future aircraft concepts will be much better placed to make a strong case for the safety of EPA to the wider industry, customers, safety regulators, governments and the public when, much further ahead, these aircraft eventually enter into service.

7.3 Future Work

Based on the findings of this research four areas of future work are recommended and are outlined in the following sections. Future work directly related to integrating FM into the design and development of future EPA is discussed in Section 7.3.1 and wider areas relevant to FM for EPA are then discussed in Section 7.3.2.

7.3.1 Further Integration of FM into Design and Development of EPA

Availability of Quantitative Data

The down selection process that is demonstrated in Chapter 5 could be repeated once quantitative data is available. Where PLRs can be quantitatively stated then this enables a more thorough down selection, as the feasible region (Appendix Section B) in which technologies must exist will be more definitively bounded. Trade studies between different electrical architecture configurations applying preferred FMSs can be performed to determine the relative weight and performance characteristics. It would also be interesting to consider the quantitative threshold values of the different PLRs which lead to the greatest impact in the number of feasible solutions. For example, if there is a threshold level of percentage hybridisation which, if exceeded, leads to a significant change in the FM goal or required level of electrical system oversizing.

A quantitative down selection would reveal the stages of the framework which cause the greatest reduction in the solution space, and also whether the weighting of PLRs or FM goals has greater impact on the range of possible solutions. This would further inform the design process as increased emphasis would be placed on fully defining and scoping the weighting criteria. The down selection of similar FM technologies from various manufacturers could be demonstrated based on detailed specifications.

Another advantage of this phase of later electrical architecture down selection would be the quantitative evaluation of different configurations beyond conventional weight and performance metrics to consider the range of FM functionalities on a given electrical architecture, and to determine if increased FM capability is worth any increase in weight. Furthermore, the availability of quantitative FM technology data and fully specified FM requirements would also enable a quantitative validation of the effectiveness of the framework down selection mechanisms and its performance as applied to the design of further electrical architectures for EPA. Quantitative validation of the framework would increase confidence in this novel method and the impact of FM requirements on the range of feasible FM electrical architectures.

There is also a need to further develop the strategy map presented in Chapter 4 to include quantitative targets for power density, efficiency, speed of operation and any other critical requirements impacting the design of FM devices. These targets are related to the safety standards for EPA, which are also under development, and so any future FM strategy map should be guided by input from appropriate standards. As more quantitative data on the specifications and TRLs of emerging FM technologies becomes available this will be used to populate the strategy map and adjust classifications of devices (such as confidence level or FM class) accordingly. Augmenting the quantitative data in the strategy map will also support the development of a range of detailed FM technology roadmaps for specific FM devices or FM functions.

The focus of this work has been on the systems level design of FM and the future development of FM solutions. As the component technologies develop, further work will be required to perform detailed FM component design and specification. This includes the setting of relevant trip thresholds, choice of protection scheme and specification of exact locations of devices, cable lengths and control mechanisms. The low TRL of technologies and the lack of a range of detailed electrical architectures in the public domain make this task impossible at present.

FM Enablers

This thesis has also highlighted the importance of integrating testing of FM enablers such as communications, sensors and metrology into the strategic development of robust FM systems. Hence there is further work required to integrate FM enabler technology into that of the wider FM system. It would also be timely for strategic FM enabler development to be included in the FM test goals for EPA test beds and flying demonstrators. This would allow increased confidence in the integration and coordination of FM enablers in EPA electrical architectures. As sensors for FM systems may be deployed in physical locations throughout the EPA (e.g. in proximity to the aircraft engine) which are exposed to vibration, temperature changes and pressure variation, it is critical that these FM supporting devices are tested in a representative or live aircraft environment. These key *core activities* [11] are necessary if individual FM enablers and FM clusters which include FM enablers are to reach higher confidence levels.

7.3.2 Wider Development of FM Technologies and Solutions

FM Technology Development

It is notable from the framework case study that none of the FMS solutions for a 2035 EIS are *High* confidence, and there is only a single FM device which is considered to be *High* confidence. Therefore, there is a need to develop the relevant FM technologies so that there is an array of technologies at high confidence level from which to compile a robust FMS. The process of determining technology confidence levels has also demonstrated the difficulty in monitoring and estimating technology development, particularly where there is a lack of published data. A wider discussion will enable verification of which technologies could be classified as high confidence. Hence, FM technology appraisal would benefit from greater collaboration within the industry and publication of any SOA developments in FM devices and system overrating concepts.

Throughout this thesis it has been argued that FM needs to be considered from a systems level perspective, and must consider the electrical FM devices together in a strategy and not as individual technologies. Therefore, developmental roadmaps and targets for potential FMSs (incorporating aspects of systems overrating and the capability of the individual devices) are required. This will focus research efforts and identify any FMSs which may be challenging to implement within a given developmental time frame.

The proposed FM strategy map has highlighted the range and complexity of the technology challenges (such as availability of suitable FM technologies at high confidence level) facing the design of robust FM systems for future EPA. A number of key technology bottlenecks have been identified in Section 3.5 which at worst threaten the viability of certain EPA concepts, and at best will severely limit the choice of FM solutions available. In particular, there is currently no obvious technology solution which can perform physical fault isolation for larger scale EPA. Further targeted development of FM devices is required to meet the projected step changes in the criticality of the electrical propulsion system described in Section 4.6.3, and hence the FM system requirements.

Role of ESS in EPA FMSs

It has been shown in the review of technology challenges facing EPA in Section 3.5 that ESS require development before becoming a primary power source for larger aircraft concepts. However, the role of ESS in an EPA remains to be established - whether ESS can be feasibly used as part of a primary fault response, whether power converters can feasibly integrate such devices into the electrical architecture, if ESS can feasibly be located at desired locations or if the volume or weight will pre-determine limits on their location. The design of effective FM relies on confidence in all the FM components and their capabilities. Therefore, confidence in the final chosen FM solution will be undermined where there is insufficient confidence in the maturity and capacity of any of the contributing technologies. Similarly, future development is necessary to verify the capability of power converters as part of a FMS and whether this is firstly feasible, and secondly, a preferred fault response action.

Increased Confidence in EPA Electrical Architectures

FM design methodologies will benefit from the in-flight testing and design experience gained by the continuing progress in EVTOLs. These aircraft are currently at the highly competitive design stages with a large number of players entering the market, creating an environment that catalyses innovation. The importance of considering novel FM approaches has been highlighted in this thesis, and so future development in EVOTLs where developers aim to differentiate concepts will support the analysis and inclusion of unconventional solutions with high potential. As EVOTLs grow in maturity and the flight hours for EVTOLs increases, this will increase the technical and wider public confidence in the reliability of EPA. Increased flight experience will enable unknown failure modes and faults in the electrical architecture designs to be identified. Better understanding of EPA electrical architecture FM requirements will then impact on the choice of future technologies, FMSs and topologies of components. This informs the design of future EPA and will validate the choice of MIC and other aspects of weighting/ prioritisation in the electrical architecture design. This will surely enhance the industry understanding of FM best practice, and as more data is published, a more collaborative approach to certain aspects of safety will better define the challenges and the FM technology solutions which are possible in the near term.

Alignment of Thesis Recommendations with Wider Industry EPA Areas for Development

The key areas of recommended future work (FM technology development,ESS for FM and leveraging EVTOL testing to increase confidence in EPA) are aligned with the strategic development programs of both the ATI (Aerospace Technology Institute [31] and NASA [1]. The ATI and NASA have identified the need to test small scale EPA initially and then gradually scale up as the concepts are de-risked. ESS and the power converter interface of any ESS to the electrical architecture is also highlighted in [31] as key enabling technologies. In [8], [96] and [34] the impact of ESS in an electrical architecture in terms of FM is underlined and highlighted as an area requiring increased focus. Airbus have acknowledged the importance of demonstrator testing to perform trade studies and de-risk design with the build of the E-Aircraft Systems Test House near Munich [152]. This facility will focus on integration of subsystems, which is a key aspect of EPA demonstrator design discussed in 6. Therefore, the areas of future work proposed in this thesis are aligned with the wider industry research and development aims, which emphasises the importance of integrating electrical FM into EPA designs from the outset.

Appendix A

FM Framework Development

A.1 Initial Framework

From initial studies simulating the effects of a fault on an electrical architecture it is made clear that the FM system and the electrical architecture in an EPA are interdependent. This is particularly the case where aspects of the electrical architecture are intrinsic to the fault response of the network, such as bus bar interconnects or if cables are allowed to quench to limit fault current. Therefore, FM is not merely to do with the application of FM devices in an electrical system, since the electrical system, including control mechanisms, are part of the electrical FM response. Figure A.1 summarizes this approach FM, and indicates that effective FM includes protection, redundancy, FM technologies and reconfiguration. Here *External Factors* are taken to include factors in the wider aircraft design which impact on the FM design, such as changes to the airframe shape in which FM technologies must fit, or cost constraints.

This initial FM framework provided the basis for the definition of FM which is presented in Section 2.2 and describes the fundamental understanding of FM which is proposed and further developed in later iterations of the FM framework.

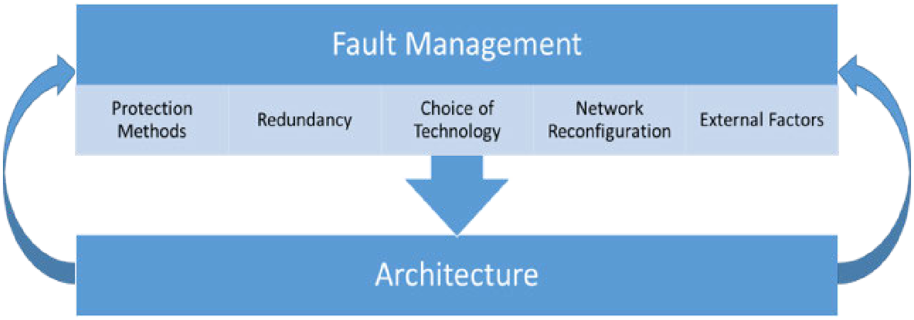


Figure A.1: FM framework initial version, as described in [18]

A.2 Inclusion of Constraints and Aircraft Configuration

The initial framework was expanded to include aspects of the system design that would determine the *Fault Management Concept* as shown in Figure A.2. The aircraft configuration (such as scale and conventional/superconducting) will dictate the types of FM strategies which are appropriate and available, and so the framework was developed such that this input to the FM system, and subsequently the electrical architecture, was captured. Another important development was the inclusion of the *Point of Entry Into Service*. This is due to the fact that the time available for the technologies to mature and for the aircraft concept to develop will have a significant impact on the electrical FM design. It should be noted that this time period is distinct from the developmental time frame (a later development of this important input to the framework) as there will be an offset in time between when FM technologies are required at high TRL and an aircraft reaches a commercially available.

This framework also identified the iterative nature of the design process and the need for a range of design options to be selected and then be subject to some down selection mechanism - the *Concept 1, Concept 2...* part of Figure A.2 indicates this.

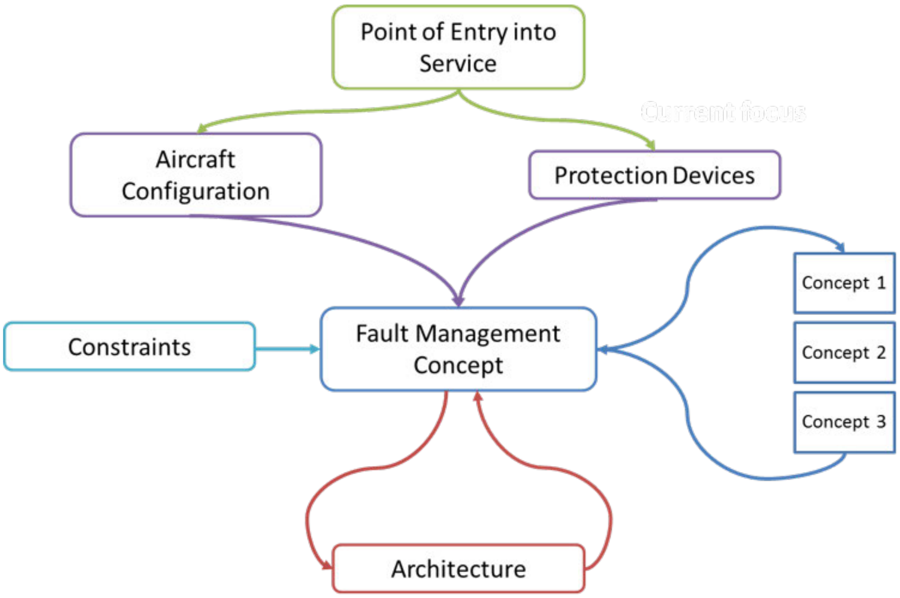


Figure A.2: FM framework development May 2016

A.3 Expansion of Constraints and Technologies

Work undertaken to determine the availability of FM devices C highlighted that there is a limited range of FM devices currently suitable for an aircraft application and that it is difficult to accurately predict the point at which any such device becomes commercially available. Hence the updated framework (as shown in Figure A.3) aimed to tackle this technology development uncertainty by identifying the target feasible region for any future devices. Furthermore, the constraints that are likely to shape the choice of FM strategy can be identified ahead of the EIS and mapped in terms of their interdependency. This allows the constraints to be weighted such that the FM design is driven by the most critical constraints. There are also further feedback loops included in the framework to show the way that design decisions must be fed back and can cause reconsideration of the constraints of the electrical system design.

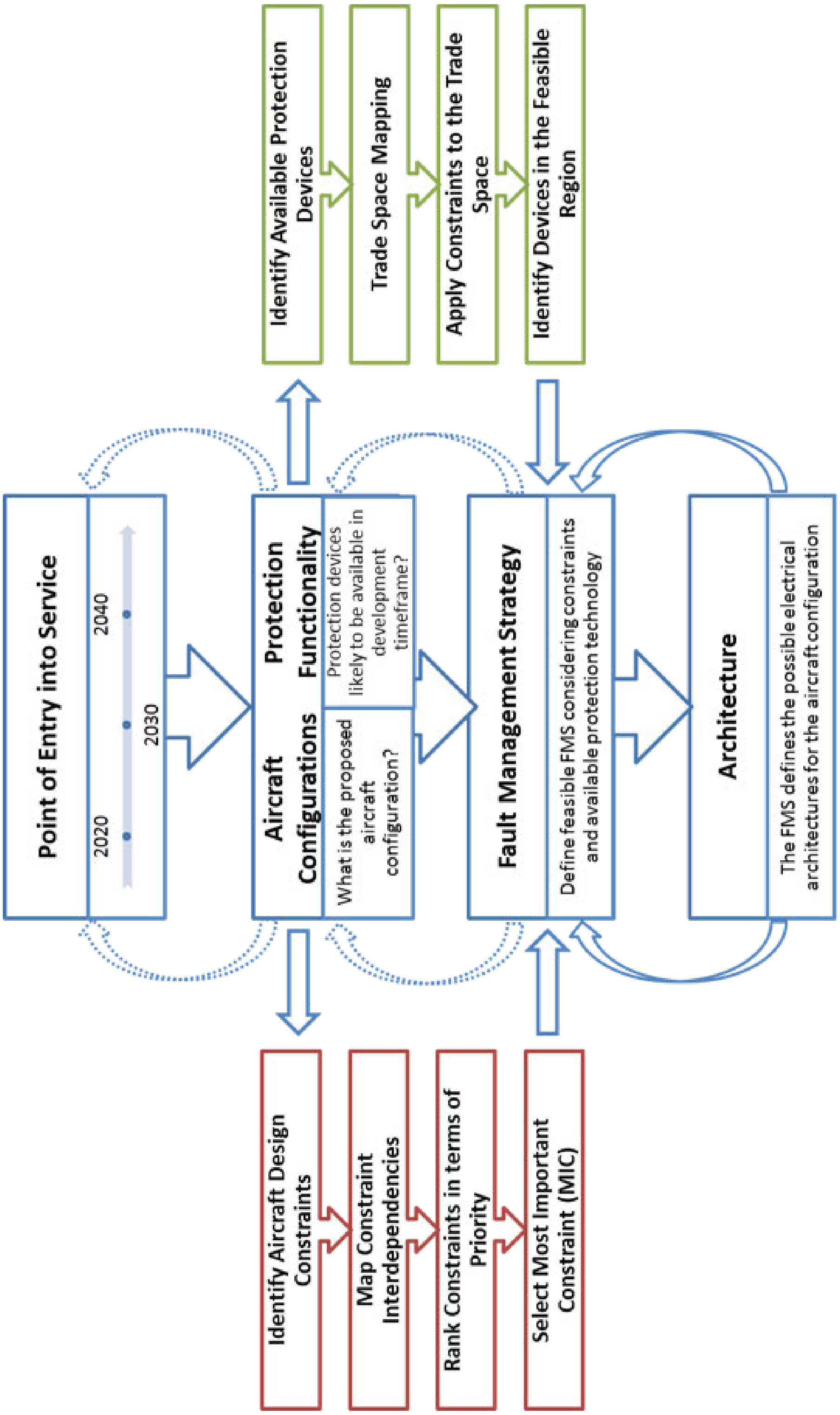


Figure A.3: FM framework redraft, as described in [19]

A.4 Inclusion of PLRs and FM Goal

After obtaining feedback on the framework from industry experts, it became clear that there needed to be a defined input or case study to the framework for the framework down selection process to have any relevance. As a result the PLRs which result from the aircraft design were incorporated into the framework. The choice of PLRs was the result of detailed literature review as well as feedback from both internal (research team and supervisors) and external reviews (industrial sponsor and international conference presentations). This updated framework is shown in Figure A.4. The importance of the FM goal is discussed in detail in Section 5.5 and is included in this iteration of the framework as it informs the down selection of technologies and functions and directs the choice of FM strategy, and is particularly required where the FM response would seem counter intuitive (such as de-energizing the electrical propulsion system and relying on the gliding capability of the aircraft).

These earlier iterations of the FM framework are included to show the development of the concept of FM for EPA. This demonstrates the way in which the proposed method of design of FM is the result of a deep understanding of the electrical system design for such an application. As this is the first of a kind framework, the developmental stages also show the novelty of the work and the way in which it draws on conventional protection design and yet is driven by the specific challenges associated with future EPA.

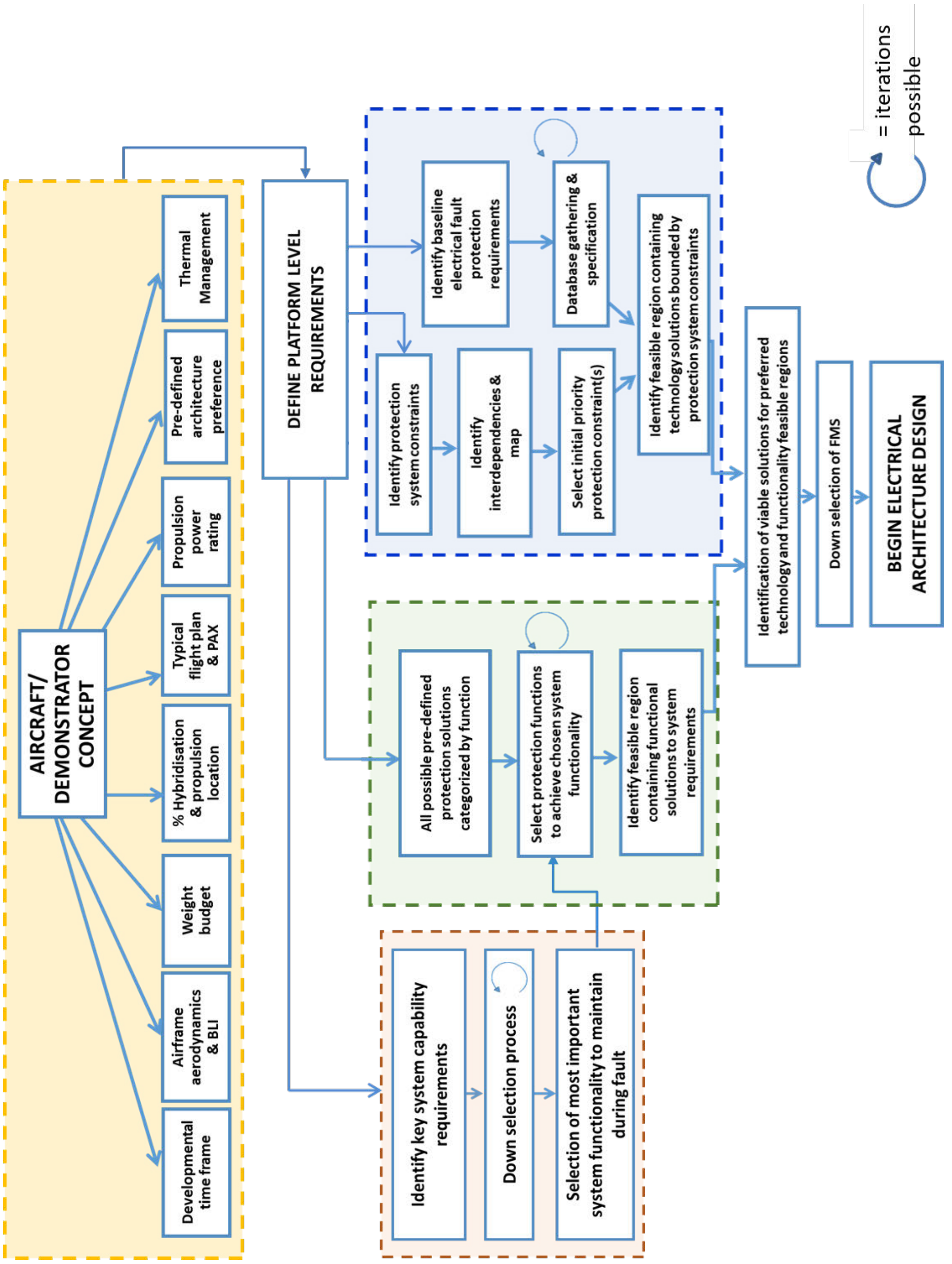


Figure A.4: FM framework redraft, Nov 2017

Appendix B

Trade Space Mapping

This section (based on work in [51]) describes the way in which key constraints can be applied to the down selection of future FM technologies for a given EPA concept and the way in which they determine the feasible region of the trade space. This role of this stage of the EPA design framework (Chapter 5) is discussed in Section 5.7.1.

B.1 Technology Constraints

From reviewing the relevant protection system constraints (see Section 3.3), it is clear that there are a range of important constraints which determine the feasibility of a given technology. Many of these constraints are interdependent and so cannot be considered in isolation if an effective FM solution is to be found. This process presents a means to assess the interdependencies between constraints even before the architecture is decided, which allows the impact of variations in the range or rating of a particular constraint to be understood. Although the devices do not yet exist, it is possible to determine the preferred functionality of devices and to specify the likely constraints which would apply to these technologies. This would then further highlight the need to develop FM solutions which address the lack of FM technologies currently feasible for use as part of an electrical architecture for EPA.

In order to better demonstrate the stringent constraints which apply to technologies for future EPA, a process of trade space mapping with key constraints is demonstrated.

The critical constraints for EPA electrical architecture design are also identified and the interdependency between these constraints is then mapped.

The data on available protection devices can be visually analysed to determine feasible protection devices, and hence possible FMSs. Trade space mapping involves plotting multiple aspects of system design in 3D space. The trade space can then illustrate the status or capability of certain protection devices within that 3D plot. Trends in the data (such as low TRL of a particular converter topology) can be identified. An example of trade space mapping of selected fault current limiter devices based on the data in Table 1 is shown in Figure B.1.

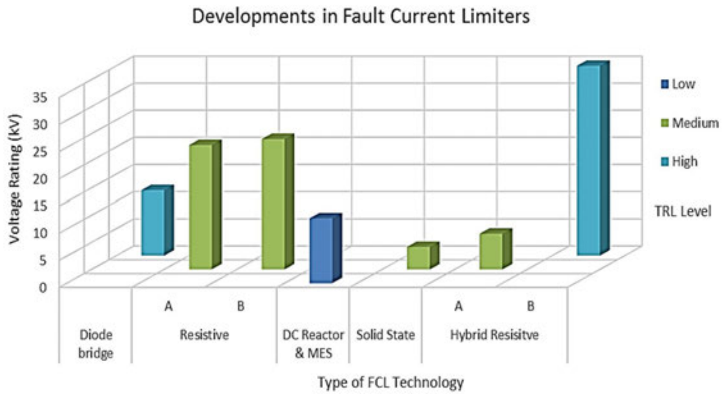


Figure B.1: Example of 3D trade space showing voltage rating, technology and TRL level for various fault current limiters

B.2 Mapping of Constraints onto Trade Space

In the first instance, it is important to identify the main constraints on the design of the FMS for a given system. Mapping of the constraints must also consider the fact that some constraints are variable between a small number discrete values (such as defined technology types), and some are variable across a wide range of values (such as operating time of DC breakers). Furthermore, as part of a process of performing trades between different FMS constraints it is possible to set some constraints to be constant and then others to vary. For example, this could involve defining TRL as high and selecting power converters as the technology type, and then varying the allowable power density and efficiencies. A graphical example of this application of constraints within the protection device trade space is shown in Figure B.2.

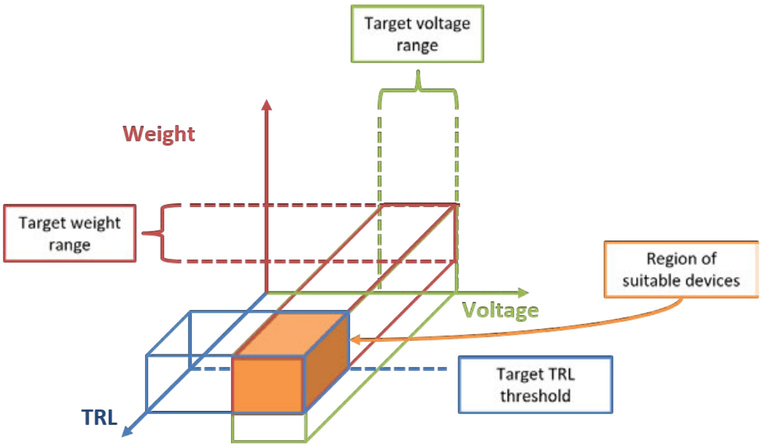


Figure B.2: Example of 3D trade space showing power rating, topology/ application and TRL level for state-of-the-art power converters

After each iteration of the design process as technology evolves and the constraints become better defined, the trade space can be updated until there are devices which exist in the feasible region. The feasible region can also be paralleled to the technology roadmap to define the feasible region for protection devices across a spectrum of potential aircraft technology selection dates.

B.3 Mapping of Constraints Interdependency

However, as each constraint impacts on other constraints and design considerations it is necessary to understand the interdependencies between constraints. By mapping out the connections between different constraints the relative criticality of each can be weighted. This enables constraints to be ranked according to which are the most critical for a given system. In this way the FMS is shaped by the most challenging constraints and the effect of any changes in constraints over time can be anticipated.

In order to demonstrate how this method of constraint mapping can be applied to the design of a future aircraft FMS, the following example is given using a selection of constraints. A number of likely constraints for an aircraft system are shown in Figure B.3. There are many more constraints not included in this example that would be considered for a complete FMS, however the constraints identified here are all of the *first order*. Future work would involve classifying constraints as first or second order. It could also be argued that almost every constraint impacts on the others in some way, so it should be emphasized that at this point in the process the focus is to clarify the most crucial connections between constraints in order to simplify and direct the choice of FMS for a given system. Furthermore, choosing the most relevant constraints at this point is not necessarily straight forward, particularly due to the number of unknowns at this stage and the relatively low TRL of some of the protection technologies. However, these initial constraints have been identified from reviewing the aircraft and protection system requirements.

B.4 Constraint Dependency Example

If the constraint *Maximum Allowable Thrust Loss* is taken as an example, then it can be seen that there are a number of possible interdependencies between this constraint and the other selected constraints shown in the diagram. This can be explained as follows:

- Maximum allowable thrust loss for the aircraft is likely to be defined by safety standards, but also linked to the certification of the aircraft [105].
- The impact of loss of power to the motors (leading to loss of thrust) will also depend on how quickly the protection system can respond to a fault and reconfigure power flow. This in turn is subject to redundant power being installed on the system and whether or not the network architecture enables this power to be delivered to any remaining motors.
- The power rating of the motors is also dependent on the allowable loss of thrust as if motors are overrated then loss of thrust due to fault at a single motor may be reduced, if the remaining generation capacity is sufficient.

In this way it is possible to identify key relationships between protection constraints as well as any sensitivities to changes to the design criteria.

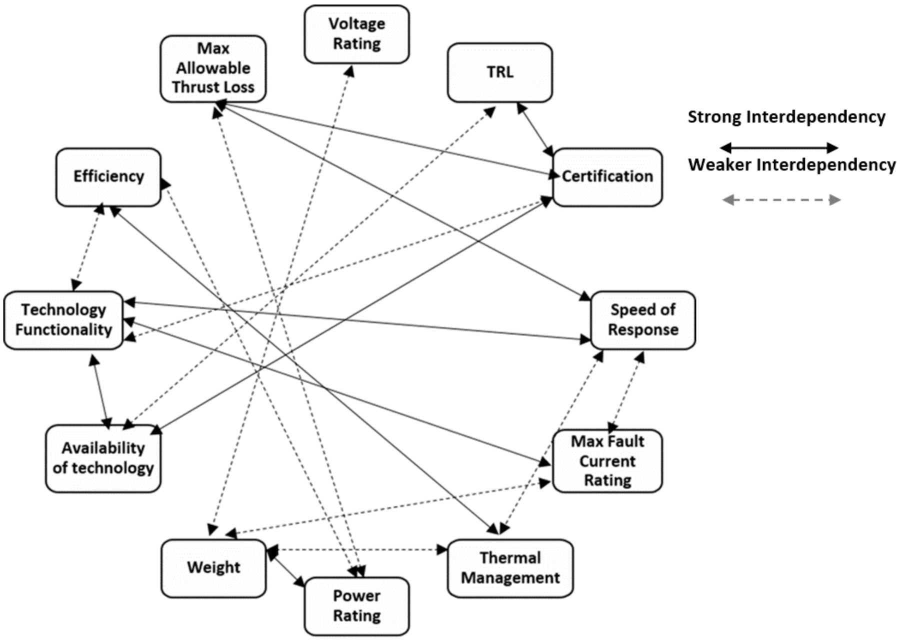


Figure B.3: Most Important Constraint Mapping

B.5 Selection of Most Important Constraint

Once the key constraints have been identified from reviewing the aircraft requirements and the interdependencies have been mapped, the next stage is to ascertain the most important constraint (MIC). A constraint may be selected as the MIC based on a variety of factors such as technology limitations/progress, number of interlinked constraints and commercial innovation opportunities.

Since the design of the FMS for a future electrical propulsion aircraft is subject to many complex constraints, ranking the constraints in terms of criticality enables the selection of a single, important constraint. Thereafter, the choice of protection devices, FMS and ultimately network architecture will be defined in the first instance by the need to meet this constraint. By iterating this process, it is possible that an alternative MIC may be adopted, or that the MIC will vary depending on the aircraft developmental timeline.

Appendix C

Protection Technology Database

This section presents the initial version of the technology database, as presented in [51] in response to some of the key technology challenges identified for the N-3X aircraft. Some of the technologies in the database are discussed in Chapter 3. This landscaping of FM technologies has informed the down selection of FM technologies in the FM design framework (see Section 5.7).

C.1 Database Criteria

Conventional electrical protection in electrical propulsion systems relies on the use of protection technologies strategically deployed on the network. Therefore, a logical starting point in the design of reliable electrical propulsion systems is to scope the available protection technologies for future EPA. This enables the current status of protection devices for aircraft applications to be established and areas for further technology development to be identified.

It is acknowledged that only data and devices which are in the public domain have been reviewed, and so therefore there is a possibility that a significant SOA FM technology exists which has not been identified here. However, this method of scoping FM capable technologies gives a broad perspective of the current status of devices suitable for a future EPA application and would be periodically repeated as FM technologies develop.

To this end, a knowledge database has been compiled to illustrate the current level of development of a variety of circuit breakers, SFCLs and power electronics converters (which can offer a range of FM functions) potentially suitable for distributed propulsion aircraft applications. Since the rate of improvement of various technologies is unknown, devices have been considered across a range of TRLs, from patented technologies to commercial products.

C.1.1 TRL Selection

The TRL for each device or project in the database was categorized based on the TRL stages developed by NASA [10]. As discussed in Section 3.3.5, the exact TRL level (0-9) for some projects is difficult to ascertain based on the published data, so the TRL rating has been simplified into three broad stages as follows:

- Low TRL (1 to 3) – evidence of patents, computational modelling and simulations or conceptual description
- Medium TRL (4 to 6)– evidence of lab based prototype, hardware testing or scaling up of initial testing
- High TRL (7 to 9)– evidence of extensive in-field testing or commercially available

The TRL listed in the database is based on the latest evidenced in the literature. A more generic assessment of maturity allows comparison between technologies for which there is differing levels of data available.

C.1.2 Relevance of Date of Publication

The date of publication is included in the FM database so that the progress of a particular device can be monitored over time and over iterations of the database. This supports the later determination of confidence level of the technology (See Section 5.4). For example, a recent publication at high TRL leads to higher confidence than a lower TRL technology published a number of years ago for which there is no updated status in the literature.

C.1.3 Cross-discipline Technologies

The database presented in this chapter enables identification of complexities introduced when applying devices ordinarily used within HVDC (High Voltage Direct Current) systems, traction applications, terrestrial grids, naval and marine systems, solar systems and electric vehicles to EPA. In reviewing the literature and compiling the database to this point it is clear that there are no off-the-shelf protection devices which are currently suitable for future aircraft concepts. Therefore, in the first instance, devices which have been developed for other applications must be considered. In order to demonstrate this, a number of application areas with particular relevance to EPA electrical architectures are discussed below.

HVDC

HVDC electrical systems are advancing DC power technologies such as high voltage DC converters [153]. This may be beneficial where the aircraft electrical architectures are DC, since the TRL level and availability of devices should increase. This area of the industry has also identified the need for standardisation of technologies and operating points, such as a common DC voltage level [154]. As the standards for novel aircraft electrical architectures are still under development and remain largely undefined, this will prove useful as an indicator of the level of standards that future electrical aircraft protection devices will have to comply with.

Terrestrial Grid

Micro-grids and smart grids are another application area with relevance to future aircraft. The type of protection devices deployed on the national grid are normally large, robust, well established technologies, which dictates that there would need to be a reduction in scale to make them suitable for EPA. However, the pressure on the network to maintain ever-increasing levels of supply and manage distributed generation mean that greater flexibility of network management and protection is needed. This has led to the development and installation of novel SFCLs on congested networks [155, 156] in the UK. If SFCLs can be proven in the field as a cost-effective and reliable means of reducing maximum fault current, then there is a possibility that SFCLs might transfer to other applications where fault current limitation may provide significant benefits. The increased level of monitoring and measurement that is being applied to smart grids [157] is also interesting for EPA as the critical electrical propulsion architecture is likely to include a large number of FM enablers (see Chaper 6) to ensure power quality and delivery is maintained.

Naval and Marine

Naval protection devices are of particular interest as there is a similar need for high reliability, high power density and high speed of response, while the fact that naval electrical propulsion systems have reached a higher maturity provides a testing ground for new technologies. Whilst naval systems are subject to weight and volume constraints, these are not as stringent as for aircraft applications, and so it is not clear if and how devices and architecture configurations will scale down. The naval circuit breaker devices and fault current limiters listed in the database are much too sizable for aircraft at present, and so reduction in weight and volume remains a key developmental goal. Furthermore, electrical standards for the US Navy electric warship program are already under development [158], and this is seen as a key part of integrating electrical power technologies into future vessels. This provides a good basis for the development of standards for future EPA electrical architectures as these specifications can be used as a reference for standardizing aspects of aircraft specific DC distribution and novel protection mechanisms.

Electric Vehicle (EV)

Electric and hybrid electric vehicles are becoming increasingly common across the automotive sector, from Formula 1 [66] to leisure buggies to taxis [159]. Whilst the power levels are not comparable to EPA, the focus on improving power density implies that protection devices for electric vehicles are likely to become more compact. Automotive electrical power systems also require high level of passenger safety, similar to aircraft electrical systems. Electric vehicles are also changing the public perception of electric transport and are demonstrating the feasibility of electric systems replacing fossil fuel combustion engines.

Since it is highly likely that energy storage (possibly in the form of batteries, super capacitors, or magnetic energy storage) will play a role in either the normal or faulted operation of the electrical architecture, the increasing energy density of batteries for EVs is of interest. This is shown by the number of air-taxi concepts using SOA energy storage devices (see Section 6). However, an increase in the capacity of energy storage would be necessary for these devices to be feasible for larger scale concepts (as discussed in Section 4.6.3).

Furthermore, there is a difference in how the energy storage may be applied to the network in an EPA. The energy storage on an aircraft may need to be distributed throughout the network (depending on the architecture), requiring multiple small, high power converters instead of a single larger converter. This highlights that it may be challenging to integrate energy storage within an EPA electrical architecture, as it may not be possible to achieve similar levels of power density and high efficiency.

Traction Vehicles

Electric propulsion in traction vehicles is a well-established technology and so offers a useful comparison point for protection technology development. Although the weight of the system is much less of a constraint in traction applications compared to aircraft, there is extensive use of DC power transmission which may inform the use of DC networks in future EPA. Furthermore, electrified railways allow a noise reduction in the vicinity of the track, particularly where rails pass through residential areas. The potential to reduce noise is also a key driver for electrical propulsion aircraft, especially given the aggressive noise reduction targets that have been identified by both NASA and the EU [160].

Validity of Database Content

The database was compiled from recent protection device publications. It will require regular updates to reflect developments in the technology and has been updated since it was initially presented in [51]. However, the date of publication may not in fact reflect the actual status of a current project and so there is a degree of uncertainty in interpreting the availability of different devices. An additional challenge is that data on some of the most pertinent and promising protection devices being commercially developed may not be available in the public domain. The purpose of this database is not to attempt to scope all possible protection devices, but rather to provide a landscape of the current situation as far as possible, and to use that as a basis of developing a novel electrical architecture design methodology to mitigate for the lack of FM devices. Once a first pass through the design framework is complete, the next iteration of the protection device data gathering include any relevant technologies or devices which may have not have been identified in the first wide review of technologies.

C.1.4 Categories of Protection Device

The various protection devices have been categorised in the database in terms of the main purpose of that device as part of the SNR (defined as the FM action in Section 5). Technologies can be classified in terms of their specifications, the topology subtype and TRL.

C.2 Protection Device Database

The following sections describe the status of the various classes of protection devices related to the technology bottlenecks identified in Section 3.5 and the adaptations required to meet the key FM requirements for EPA (see Section 3.3).

C.2.1 Fault Interrupters and Isolators

In order to eliminate the fault condition and maintain safe operation, the fault needs to be interrupted within an appropriate time frame at an appropriate location on the network, and subsequently isolated by dedicated protection devices. Circuit breakers perform the key function of isolating a faulted section of the power system from the remainder of the network, often under high current conditions. This functionality is essential in the realisation of safety critical systems. Whilst the developed database (as discussed in Section contains information on both AC and DC circuit breaking technologies, the initial version presented here focused primarily on the DC breakers. DC transmission and distribution on an EPA is considered as a possible future electrical configuration which offers a number of benefits, including:

- Electrical decoupling of the generators and motors, increasing efficiency of the machines
- Greater flexibility of control of individual propulsor motors where propulsion is distributed across an array of motors
- Simpler integration of DC energy storage devices such as batteries, with less complex power electronics

The difference between fault interrupters and isolators refers to whether or not the topology of a given protection device enables physical isolation of a fault or not. Solid state circuit breakers are fault current interrupters but do not have the capability to physically isolate a fault without being used in a hybrid configuration. A review of state-of-the-art DC circuit breakers was undertaken, with summary data stored in the protection device database as shown in Table C.1.

Table C.1: Fault current interrupter database excerpt

Developer	**Technology Type**	**Application**	**Voltage Rating (kV)**	**TRL**	**Date of Publication**
Eaton AVD [161]	Solid State DC Breaker	Naval	2	High	2007
Helmut Schmidt University, Airbus Group Innovation [71]	HVDC SSPC	MEA/ Future DC aircraft grids	0.54	Medium	2000
Virginia Polytech. Inst. & State Univ [162]	Emitter Turn-off Thyristor-based DC Circuit Breaker	High power systems	2.5	Medium	2002

Table C.1: Fault current interrupter database excerpt

Developer	**Technology Type**	**Application**	**Voltage Rating (kV)**	**TRL**	**Date of Publication**
ABB Schweiz, Ecole Polytechnique Fédérale de Lausanne [163]	Hybrid CB IGCTs	Rail	1.5	Medium	2006
Industrial Education College, Cairo, Northumbria University, University of Durham [164]	Solid-State Fault-Current Limiting and Interrupting Device	LV Distribution networks	0.23	Medium	2006
ABB [165]	HVDC Breaker	Grid	320	Medium	2012
Eidgenössischen Technischen Hochschule Zürich [73]	Hybrid DC breaker	MVDC	12	Medium	2001
Diversified Technologies, Inc. [72]	MVDC IGBT Converter	Naval	10-20	Low	2011
Creative Energy Solutions [81]	Z source breaker DC	Naval	6	Low	2010
MIT Sea Grant College Program [54] 8	Improved z source breaker	Naval	6	Low	2011

C.2.2 Power Electronic Converters

Power electronics converters enable electrical decoupling of the motors from the generators and integration of energy storage. The output of the FM framework will determine whether a DC or AC architecture is preferable, and hence the converter topologies which are required.

By control of the solid state switches (manipulating firing angle [166] pulse width modulation control [167]) or current blocking diodes [168] within some topologies of power converters it is possible to limit fault current or de-energize the downstream network when a fault occurs. The converters in Table C.2 are able to perform FM functions by manipulating the solid state switches to interrupt or limit fault current. The technology type (AC-AC, CSC, DC-DC or MMC) describes the physical and electrical configuration of the switches which varies between converters, and details of the specific converter topologies can be found in the corresponding references listed in the table.

If converters are included in an architecture for power conditioning purposes, exploiting this potential dual functionality may provide a weight and efficiency benefit. The type of switches and the chosen semi-conductor material is also an area for consideration, since this impacts on voltage ratings, switching frequency, packaging etc., and is therefore relevant to the final weight and efficiency of the converter. A review of devices which are currently in development across a range of application areas was undertaken to assess the viability of these technologies for use in an FMS. The data contained in the original database on power converter topologies is shown in Table C.2.

It is important to note that the applicability of developmental devices to a future aircraft, especially those for use in other industries, has not yet been demonstrated. Technology functions and specifications may alter as devices reach higher TRL and there is no guarantee that a specific protection system capability from another application could be feasibly implemented on an EPA.

Table C.2: Power converter technologies

Developer	Technology	Year of Publication	TRL level	Power Rating	Application
Universität der Bundeswehr, Siemens [169]	AC-AC converter	2005	Medium	5 MW	AC driven traction vehicles
Pusan National University, Pusan, Republic of Korea [170]	CSI	2007	Medium	1.2 kVA	Solar PV connection to grid
Ruhr-University Bochum [171]	MMC	2013	Medium	3.9 MW	Shipboard systems
Florida State University, ABB [167]	MMC AC-DC	2015	Medium	1.25 MVA	Shipboard systems

University of Aberdeen [172]	DC-DC converter	2009	Low	5 MW	DC source to grid interface
Southeast University, China and Hong Kong University [173]	CSC	2010	Low	2.4 MW	Wind turbine connection

C.2.3 Fault Current Limiters

When a fault occurs on a compact, low impedance network, a large fault current can be seen in the system. The maximum fault current which the system will experience will depend on the location of the fault, the fault path impedance and the power sources (such as DC link capacitances) which will feed current into the fault. Thus the fault current, if large or sustained, can cause significant damage to components on the network. A fault current limiter (FCL) reduces the fault current, to aid interruption and limit energy at the point of fault. This function can be selectively applied by a FM system to reduce the required interruption ratings and withstand ratings of the electrical components. This can be performed in a variety of ways, including:

1. Fast acting differential protection which measures the di/dt of the current and manipulates circuit breakers to isolate the fault when the di/dt rating is at fault level (interruption prior to current peak)
2. Control of power electronic switches in converters to switch off at a threshold current value (interruption prior to current peak)
3. Solid state and Superconducting Fault Current Limiters (SFCLs) for active current limiting (peak prevention)

SFCLs are advantageous in that the fault detection is inherent and does not require a complex trigger mechanism. However, the recovery time of different SFCL technologies varies, and so the limitations on their use for successive faults must be assessed. In future EPA concepts that have superconducting electrical architectures SFCLs may prove highly useful in reducing the maximum fault current rating of the other components so that the overall weight is reduced.

The data gathered on current SFCL projects is given in Table C.3. The technical description of each technology type listed in C.3 is described in detail in [89].

Table C.3: SFCL Database

Developer	**Technology**	**Phases**	**Voltage (kV)**	**TRL level**	**Weight (kg)**	**Application**	**Year of Publication**
SuperPower [174]	Resistive	1-phase	8.6	High	approx. 3000	Grid	2006
CAS [175]	Rectifier Type	3-phase	10.5	High	Unknown	Grid	2006
Innovative Technomics USA LLC [176]	Dynamic ambient temperature magnetic core	3-phase	12	High	Unknown	Naval	2011
Innopower [177]	Saturable Core	3-phase	35	High	27000	Grid	2009
Zenergy [177]	Saturable Core	3-phase	15	High	20000	Grid	2009
Nexans [67]	Hybrid	3-phase	24	High	Unknown	Grid	2012
Nexans [67]	Resistive	3-phase	12	High	2500	Grid	2012
DAPAS Korea, KEPRI/LSIS [67]	Hybrid	3-phase	22.9	High	907	Grid	2012
Applied Superconductor Limited, Northern Powergrid [156]	Saturated Core	3-phase	33	High	Unknown	Grid	2013
Hyundai [178]	Resistive	1-phase	13.2	Medium	Unknown	Grid	2008
Siemens/AMSC [179]	Resistive	1-phase	7.5	Medium	Unknown	Grid	2008
Arkansas Power Electronics International, Inc. [69]	Solid state	1-phase	4.16	Medium	Unknown	Naval	2009

Table C.3: SFCL Database

Developer	**Technology**	**Phases**	**Voltage (kV)**	**TRL level**	**Weight (kg)**	**Application**	**Year of Publication**
University of Wollongong/ Zenergy [180]	Saturated Core	3-phase	0.4 (line-line)	Medium	Unknown	Grid	2009
Toshiba, Fujikura Ltd [181]	Magnetic coil	3-phase	6.6	Medium	Unknown	Grid	2009
ERSE Spa [67]	Resistive	3-phase	9	Medium	3800	Grid	2012
AMSC, Siemens, and Nexans [67]	Hybrid	1-phase	138	Medium/ High	40000	Grid	2012

Bibliography

[1] N. Madavan, J. Heidmann, C. Bowman, P. Kascak, A. Jankovsky, and R. Jansen, "A NASA Perspective on Electric Propulsion Technologies for Commercial Aviation: Advanced Air Transport Technology Project NASA Advanced Air Vehicles Program," 2016. [Online]. Available: https://machineroadmap.ece.illinois.edu/files/2016/04/Madavan.pdf

[2] F. Anton, "HYPSTAIR - System Architecture, Certifiability and Safety Aspects," in *E2 Fliegen Symposium*, 2017. [Online]. Available: http://www.lvbayern.de/fileadmin/content/allgemein/dokumente/Fliegertag/2017_Frank_Anton_electric_prop_syst_aircraft.pdf

[3] S. Clarke, M. Redifer, K. Papathakis, A. Samuel, and T. Foster, "X-57 power and command system design," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*. IEEE, jun 2017, pp. 393–400. [Online]. Available: http://ieeexplore.ieee.org/document/7993303/

[4] D. C. Loder, A. Bollman, and M. J. Armstrong, "Turbo-electric Distributed Aircraft Propulsion: Microgrid Architecture and Evaluation for ECO-150," in *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*. IEEE, jun 2018, pp. 550–557. [Online]. Available: https://ieeexplore.ieee.org/document/8450180/

[5] C. Pornet and A. Isikveren, "Conceptual design of hybrid-electric transport aircraft," *Progress in Aerospace Sciences*, vol. 79, pp. 114–135, 2015.

[6] M. K. Bradley and C. K. Droney, "Subsonic Ultra Green Aircraft Research: Phase II – Volume II – Hybrid Electric Design Exploration," Boeing Research and Technology, California, Tech. Rep., 2015. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150017039.pdf

[7] F. Berg, J. Palmer, P. Miller, M. Husband, and G. Dodds, "HTS Electrical System for a Distributed Propulsion Aircraft," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1–5, 2015.

[8] M. J. Armstrong, M. Blackwelder, A. Bollman, C. Ross, A. Campbell, C. Jones, and P. Norman, "Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)," 2015. [Online]. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150014237.pdf.

[9] M. Claessens, D. Dujic, F. Canales, J.-G. K. Steinke, P. Stefanutti, and C. Vetterli, "Traction transformation A power-electronic traction transformer (PETT)," Zurich, 2013. [Online]. Available: https://library.e.abb.com/public/fc192d38056fa3b3c12579f20055483b/11-17/1m211_EN_72dpi.pdf

[10] B. Sauser, D. Verma, J. Ramirez-Marquez, and R. Gove, "From TRL to SRL: The concept of systems readiness levels," *Conference on Systems Engineering Research, Los Angeles, CA*, pp. 1–10, 2006. [Online]. Available: https://pdfs.semanticscholar.org/ba46/9d142a535b5ad54b56afbcc5a09d09b4f2ac.pdfhttp://www.boardmansauser.com/downloads/2005SauserRamirezVermaGoveCSER.pdf

[11] M.-C. Flynn, M. Sztykiel, C. E. Jones, P. J. Norman, G. M. Burt, P. Miller, and M. Husband, "Protection and Fault Management Strategy Maps for Future Electrical Propulsion Aircraft," *IEEE Transactions on Transportation Electrification*, p. Accepted 27th Aug 2019, 2019.

[12] S. Stückl, A. Mirzoyan, and A. T. Isikveren, "DisPURSAL D1.2 – Report on the Technology Roadmap for 2035," Bauhaus Luftfahrt e.V, Tech. Rep., 2015.

[Online]. Available: http://www.dispursal.eu/doc/DisPURSAL_D1.2_FINAL.pdf

[13] C. Bowman, R. Jansen, D. G. Brown, K. Duffy, and J. Trudell, "Key Performance Parameter Driven Technology Goals for Electric Machines and Power Systems," Tech. Rep. [Online]. Available: www.nasa.gov

[14] D. J. Sadey, L. M. Taylor, and R. F. Beach, "Proposal and Development of a High Voltage Variable Frequency Alternating Current Power System for Hybrid Electric Aircraft," in *AIAA/ASME/SAE/ASEE Joint Propulsion Conference; 25-27 Jul. 2016; Salt Lake City, UT; United States.* Salt Lake City: NASA Glenn Research Center; Cleveland, OH United States, jul 2016. [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=20170000886

[15] Airbus, "Vahana, the Self-Piloted, eVTOL aircraft from A3 by Airbus, Successfully Completes First Full-Scale Test Flight," 2018. [Online]. Available: https://www.airbus.com/newsroom/press-releases/en/2018/02/vahana--the-self-piloted--evtol-aircraft-from-a--by-airbus--succ.html

[16] Sami Grover, "New hybrid plane will add second electric engine as battery costs drop — TreeHugger," 2017. [Online]. Available: https://www.treehugger.com/aviation/new-hybrid-plane-will-gradually-go-all-electric-battery-costs-drop.html

[17] R. W. Dyson, "NASA Electric Aircraft Test bed (NEAT) Development Plan—Design, Fabrication, Installation," NASA Glenn Research Centre, Tech. Rep., 2016. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010440.pdf

[18] M.-C. Flynn, C. Jones, P. Norman, and S. Galloway, "Fault Management Strategies and Architecture Design for Turboelectric Distributed Propulsion," in *Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles.* Toulouse: IEEE, 2016.

[19] M.-C. Flynn, C. E. Jones, P. J. Norman, and S. J. Galloway, "Establishing viable fault management strategies for distributed electrical propulsion

aircraft," in *International Society of Air Breathing Engines*, Manchester, sep 2017. [Online]. Available: https://pureportal.strath.ac.uk/en/publications/establishing-viable-fault-management-strategies-for-distributed-e

[20] N. Leveson, "White paper on approaches to safety engineering," pp. 1–10, 2003. [Online]. Available: http://sunnyday.mit.edu/caib/concepts.pdfhttp://www.idc-online.com/technical_references/pdfs/mechanical_engineering/concepts.pdf

[21] New York Times, "In 12 Minutes, Everything Went Wrong - The New York Times," 2018. [Online]. Available: https://www.nytimes.com/interactive/2018/12/26/world/asia/lion-air-crash-12-minutes.html

[22] BBC News, "Ethiopian Airlines: 'No survivors' on crashed Boeing 737 - BBC News," 2019. [Online]. Available: https://www.bbc.co.uk/news/world-africa-47513508

[23] Aerospace Engineering Blog, "The DeHavilland Comet Crash – Aerospace Engineering BlogAerospace Engineering Blog," 2012. [Online]. Available: https://aerospaceengineeringblog.com/dehavilland-comet-crash/

[24] W. G. W. G. Johnson, *MORT safety assurance systems.* M. Dekker, 1980. [Online]. Available: https://books.google.co.uk/books?redir_esc=y&id=h7shAQAAIAAJ&focus=searchwithinvolume&q=design+decisions

[25] Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions, "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions," Washington DC, pp. 51–71, 2016. [Online]. Available: https://www.nap.edu/read/23490/chapter/4

[26] European Commission, *Flightpath 2050, Europe's Vision for Aviation*, Luxembourg, 2011.

[27] S. Fletcher, M.-C. Flynn, C. E. Jones, and P. J. Norman, "Hybrid Electric Aircraft : State of the Art and Key Electrical System

Challenges," *The Transportation Electrification eNewsletter*, no. September, 2016. [Online]. Available: https://tec.ieee.org/newsletter/september-2016/hybrid-electric-aircraft-state-of-the-art-and-key-electrical-system-challenges

[28] D. Schlabe and J. Lienig, "Energy management of aircraft electrical systems - state of the art and further directions," in *2012 Electrical Systems for Aircraft, Railway and Ship Propulsion*. IEEE, oct 2012, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/document/6387387/

[29] R. H. Jansen, C. Bowman, and A. Jankovsky, "Sizing Power Components of an Electrically Driven Tail Cone Thruster and a Range Extender," in *16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum*. AIAA, 2016, pp. 2016–3766.

[30] P. Gemin, T. Kupiszewski, A. Radun, Y. Pan, and R. Lai, "Architecture , Voltage and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)," Cleveland, Ohio, 2015. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150014583.pdf

[31] Aerospace Technology Institute, "Electrical Power Systems," pp. 1–16, 2018. [Online]. Available: https://www.ati.org.uk/resource/insight_07-electrical-power-systems/

[32] K. S. Haran, S. Kalsi, T. Arndt, H. Karmaker, R. Badcock, B. Buckley, T. Haugan, M. Izumi, D. Loder, J. W. Bray, P. Masson, and E. W. Stautner, "High power density superconducting rotating machines - Development status and technology roadmap," *Superconductor Science and Technology*, vol. 30, no. 12, p. 123002, 2017. [Online]. Available: https://doi.org/10.1088/1361-6668/aa833e

[33] C. Ross, M. Armstrong, M. Blackwelder, C. Jones, P. Norman, and S. Fletcher, "Turboelectric Distributed Propulsion Protection System Design Trades," in *SAE 2014 Aerospace Systems and Technology Conference*, 2014, pp. 2014–01–2141. [Online]. Available: http://papers.sae.org/2014-01-2141/

[34] C. E. Jones, K. Davies, P. Norman, S. Galloway, G. Burt, M. Armstrong, and A. Bollman, "Protection System Considerations for DC Distributed Electrical Propulsion Systems," sep 2015. [Online]. Available: http://papers.sae.org/2015-01-2404/

[35] D. Dvorak, "Goal-Based Fault Management 2012 NASA Spacecraft Fault Management Workshop New Orleans, LA," Tech. Rep., 2012. [Online]. Available: https://www.nasa.gov/pdf/636743main_day_1-dan_dvorak.pdf

[36] R. D. Rasmussen, "GN&C Fault Protection Fundamentals," in *31st ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE*. Breckenridge, Colorado: American Astronautical Society, 2008. [Online]. Available: https://trs.jpl.nasa.gov/bitstream/handle/2014/41696/08-0125.pdf?sequence=1

[37] Michael G. Ryschkewitsch, "FAULT MANAGEMENT HANDBOOK," NASA, Tech. Rep., 2012. [Online]. Available: https://www.nasa.gov/pdf/636372main_NASA-HDBK-1002_Draft.pdf

[38] Q. Deng, X. Liu, R. Soman, M. Steurer, and R. A. Dougal, "Primary and backup protection for fault current limited mvdc shipboard power systems," in *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, June 2015, pp. 40–47.

[39] Uber Elevate, "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," 2016. [Online]. Available: https://www.uber.com/elevate.pdf?state=2G2avoaZe8HDNboFkqPtpOMHQtulATTu_Ls6478WWuY%3D&_csid=Y2I5GZwFJUeISRZRWSMviw#_

[40] Active VTOL Crash Prevention Ltd, "A Complete Zero/Zero Safety System for eVTOLs and Other Applications." 2018. [Online]. Available: https://www.proactiveinvestors.co.uk/upload/SponsorFile/File/2018_03/1520590718_AVCP.Proactive.Investor.8th.March.2018.pdf

[41] European Aviation Safety Agency, "SPECIAL CONDITION Vertical Take-Off and Landing (VTOL) Aircraft Proposed Special Condition for small-

category VTOL aircraft," EASA, Tech. Rep., 2018. [Online]. Available: https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01proposed.pdf

[42] D. Gebre Egziabher, "Managing uncertainty in the design of safety-critical aviation systems: Safety-critical unmanned aerial systems," in *Proceedings of the 31st International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+ 2018*, ser. Proceedings of the 31st International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+ 2018. United States: Institute of Navigation, 1 2018, pp. 2297–2320.

[43] F. Saunders, "The management of uncertainty in large-scale safety-critical projects practitioner summary," 2016. [Online]. Available: http://fionasaunders.co.uk/wp-content/uploads/2016/07/Managing-Uncertainty-in-LargeScale-SafetyCritical-Projects.pdf

[44] Rachel Reeves MP, Vernon Coaker MP, Drew Hendry MP, Stephen Kerr MP, Peter Kyle MP, Ian Liddell-Grainger MP, Rachel Maclean MP, Albert Owen MP, Mark Pawsey MP, Antoinette Sandbach MP, and Anna Turley MP, "The impact of Brexit on the aerospace sector: Sixth Report of Session 2017-19," House of Commons Business, Energy and Industrial Strategy Committee, London, Tech. Rep., 2018. [Online]. Available: https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/380/380.pdf

[45] US Department of Defence, "MIL-STD-704F Aircraft Electric Power Characteristics," 2004. [Online]. Available: https://prod.nais.nasa.gov/eps/eps{_}data/137899-SOL-001-015.pdf

[46] SAE International, "New SAE International Committee Established for Aircraft Hybrid/Electric Propulsion," 2018. [Online]. Available: https://www.sae.org/news/press-room/2018/10/new-sae-international-committee-established-for-aircraft-hybrid-electric-propulsion

[47] ASTM International, "ASTM F3316/F3316M-18 Standard Specification for Electrical Systems for Aircraft with Electric or Hybrid-Electric Propulsion,"

ASTM Compass, vol. 15.09, p. 5, 2018. [Online]. Available: https://compass.astm.org/EDIT/html_annot.cgi?F3316+18

[48] M. Armstrong, C. Ross, D. Phillips, and M. Blackwelder, "Stability, transient response, control, and safety of a high-power electric grid for turboelectric propulsion of aircraft," Tech. Rep. June, 2013.

[49] K. Satpathi, A. Ukil, and J. Pou, "Short-Circuit Fault Management in DC Electric Ship Propulsion System: Protection Requirements, Review of Existing Technologies and Future Research Trends," *IEEE Transactions on Transportation Electrification*, vol. 4, no. 1, pp. 272–291, mar 2018. [Online]. Available: http://ieeexplore.ieee.org/document/8241807/

[50] C. Tristl and A. Karcher (EADS), "INTEGRATING SYSTEMS AND MECHANICAL/ ELECTRICAL ENGINEERING – HOW MODEL-BASED INTERFACE MANAGEMENT SUPPORTS MULTI-DOMAIN COLLABORATION," in *INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012*, Dubrovnik - Croatia, 2012, pp. 1811–1820. [Online]. Available: https://www.designsociety.org/download-publication/32150/integrating_systems_and_mechanical-electrical_engineering-how_model-based_interface_management_supports_multi-domain_collaboration

[51] M.-C. Flynn, C. Jones, P. Rakhra, P. Norman, and S. Galloway, "Impact of key design constraints on fault management strategies for distributed electrical propulsion aircraft," in *AIAA Energy and Propulsion Conference.* AIAA, 2017.

[52] M.-C. Flynn, C. E. Jones, P. J. Norman, and G. M. Burt, "A Fault Management-Oriented Early-Design Framework for Electrical Propulsion Aircraft," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 2, pp. 465–478, jun 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8698811/

[53] M. A. Kempkes, "Diversified Technologies' New PowerMod$^{\text{TM}}$ Solid-State DC Circuit Breaker Assures Safe MVDC Power Systems Operation," 2017. [Online]. Available: http://www.prweb.com/releases/2017/09/prweb14708639.htm

[54] P. Prempraneerach, G. E. Karniadakis, and C. Chryssostomidis, "DC Fault Protection in Shipboard Power Systems Using Z-Source Breakers," 2011. [Online]. Available: https://seagrant.mit.edu/ESRD_library/MITSG_11-30.pdf

[55] B. Esker, "ARMD Strategic Thrust 4: Transition to Low-Carbon Propulsion," 2016. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/armd-sip-thrust-4-508.pdf

[56] B. Schiltgen, M. Green, D. Hall, A. Gibson, T. Foster, and M. Waters, "Split-wing propulsor design and analysis for electric distributed propulsion," in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2011-224

[57] C. E. Jones, K. Davies, P. Norman, S. Galloway, G. Burt, M. Armstrong, and A. Bollman, "Protection System Considerations for DC Distributed Electrical Propulsion Systems Protection for TeDP Network," *SAE Technical Paper*, pp. 2015–01–2404, 2015.

[58] R. W. De Doncker, "Fast Charging (350 kW) for Electric Vehicles-Possibilities and Issues Integration of e-Mobility into a SE Supply Introduction." [Online]. Available: https://www.futureofcharging.com/presentations/6-dedoncker-rwth-aachen.pdf

[59] A. R. Gibson, D. Hall, M. Waters, B. Schiltgen, T. Foster, J. Keith, and P. Masson, "The Potential and Challenge of TurboElectric Propulsion for Subsonic Transport Aircraft," in *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida, 2010, pp. 2010–276.

[60] R. H. Jansen, G. V. Brown, J. L. Felder, and K. P. Duffy, "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements," NASA Glenn Research Centre, Tech. Rep., 2016. [Online]. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006295.pdf

[61] Raytheon, “Meeting the More Electric Aircraft Challenge,” 2013. [Online]. Available: http://www.raytheon.com/news/rtnwcm/groups/gallery/documents/content/rtn_164022.pdf

[62] P. Thalin, “Overview of challenges in active power conversion for the More Electric Aircraft,” in *Electrical Technologies for the Aviation of the Future, Europe-Japan Symposium.* Tokyo: SUNJET Project, 2015. [Online]. Available: www.thalesgroup.com

[63] M. Hartmann, “Ultra-Compact and Ultra-Efficient Three-Phase PWM Rectifier Systems for More Electric Aircraft,” Ph.D. dissertation, ETH Zurich, 2011. [Online]. Available: http://e-collection.library.ethz.ch/eserv/eth:5020/eth-5020-02.pdf

[64] M. Olszewski, “Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System,” Oak Ridge National Laboratory, Tech. Rep., 2011. [Online]. Available: https://info.ornl.gov/sites/publications/files/Pub26762.pdf

[65] McLaren Applied Technologies, “Motor Control Unit MCU-500 / MCU-510,” 2017. [Online]. Available: http://www.mclaren.com/appliedtechnologies/products/item/motor-control-unit-mcu-500mcu-510/

[66] ——, “High Performance Electric Motors and Drives,” 2016. [Online]. Available: http://www.mclaren.com/appliedtechnologies/case-study/relentless-drive-power-density-and-efficiency

[67] EPRI, “Superconducting Power Equipment: Technology Watch 2012,” Electric Power Research Institute, California, Tech. Rep., 2012. [Online]. Available: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001024190&Mode=download

[68] S. M. Blair, C. D. Booth, and G. M. Burt, “Current-Time Characteristics of Resistive Superconducting Fault Current Limiters,” *IEEE Trans Appl Supercond*, vol. 22, no. 2, p. 5600205, 2012.

[69] J. Bourne, M. Schupbach, J. Carr, H. A. Mantooth, and J. Balda, “Initial development of a solid-state fault current limiter for naval power systems protection,” pp. 491–498, 2009.

[70] D. Izquierdo, A. Barrado, C. Raga, M. Sanz, and A. Lazaro, “Protection Devices for Aircraft Electrical Power Distribution Systems: State of the Art,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 47, no. 3, pp. 1538–1550, 2011. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5937248

[71] M. Terörde, F. Grumm, D. Schulz, H. Wattar, and J. Lemke, “Implementation of a Solid-State Power Controller for High-Voltage DC Grids in Aircraft.” [Online]. Available: https://eldorado.tu-dortmund.de/bitstream/2003/33985/1/P02.8.pdf

[72] M. Kempkes, I. Roth, and M. Gaudreau, “Solid-state circuit breakers for Medium Voltage DC power,” in *2011 IEEE Electric Ship Technologies Symposium.* Alexandria, VA: IEEE, 2011, pp. 254–257. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5770877&tag=1

[73] Michael Steurer, “Ein hybrides Schaltsystem für Mittelspannung zur strombegrenzenden Kurzschlussunterbrechung,” 2001. [Online]. Available: http://e-collection.library.ethz.ch/eserv/eth:23871/eth-23871-02.pdf

[74] ABB, “Medium voltage vacuum circuit-breakers,” 2010. [Online]. Available: https://library.e.abb.com/public/aed7a9f817002bac4825776900265388/VmaxSpecificationENRev.B.pdf

[75] D. Rothmund, G. Ortiz, T. Guillod, and J. W. Kolar, “10kV SiC-Based Isolated DC-DC Converter for Medium Voltage-Connected Solid-State Transformers,” in *IEEE Applied Power Electronics Conference and Exposition (APEC).* IEEE, 2015. [Online]. Available: http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=7104485&tag=1

[76] D. Bosche, E.-D. Wilkening, H. Kopf, and M. Kurrat, “Hybrid DC Circuit Breaker Feasibility Study,” *IEEE Transactions on Components,*

Packaging and Manufacturing Technology, pp. 1–9, 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7605456/

[77] S. A. Pandya, "Preliminary Assessment of the Boundary Layer Inges7on Benefit for the D8 Aircra< Applied Modeling and Simula7on Seminar Series," 2014. [Online]. Available: https://www.nas.nasa.gov/assets/pdf/ams/2014/AMS_20140403_Pandya.pdf

[78] I. Moir and A. Seabridge, *Aircraft Systems: Mechanical, Electrical and Avionics Subsystems Integration*, ser. Aerospace Series. Wiley, 2008. [Online]. Available: https://books.google.co.uk/books?id=2PBa68zWggEC

[79] Electric Ship Research and Development Consortium and for the Office of Naval Research, "DC Protection," Electric Ship Research and Development Consortium, Tech. Rep., 2011. [Online]. Available: https://www.esrdc.com/library/?q=system/files/DCPROTECTIONFORSHIPS-FINAL.pdf

[80] S. Settemsdal, E. Haugan, B. Zahedi, and K. Aagesen, "New Enhanced Safety Power Plant Solutions for DP Vessels Operating in Closed Ring Configuration," in *Dynamic Positioning Conference: Marine Technology Society*. Marine Technology Society, 2014.

[81] K. A. Corzine and R. W. Ashton, "A new z-source dc circuit breaker," in *2010 IEEE International Symposium on Industrial Electronics*. Bari: IEEE, 2010, pp. 585–590. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5637261&tag=1

[82] T. P. Dever, K. P. Duffy, A. J. Provenza, P. L. Loyselle, B. B. Choi, C. R. Morrison, and A. M. Lowe, "Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion," Tech. Rep., 2015. [Online]. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150000747.pdf

[83] D. L. Schweickart, D. F. Grosjean, I. Cotton, R. Gardner, D. G. Kasten, and S. A. Sebo, "Considerations for Failure Prevention in

Aerospace Electrical Power Systems Utilizing Higher Voltages," AIR FORCE RESEARCH LABORATORY, Tech. Rep., 2017. [Online]. Available: https://apps.dtic.mil/dtic/tr/fulltext/u2/1039413.pdf

[84] C. E. Jones, P. J. Norman, S. J. Galloway, M. J. Armstrong, and A. M. Bollman, "Comparison of Candidate Architectures for Future Distributed Propulsion Aircraft," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 6, pp. 1–9, sep 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7407568/

[85] R. Phaal, C. J. Farrukh, and D. R. Probert, "Technology roadmapping—A planning framework for evolution and revolution," *Technological Forecasting and Social Change*, vol. 71, no. 1-2, pp. 5–26, jan 2004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0040162503000726?via%3Dihub

[86] CGMA, "Strategy Mapping," 2013. [Online]. Available: https://www.cgma.org/resources/tools/essential-tools/strategy-mapping.html

[87] Robert Thomson (Roland Berger), Maxim Nazukin, Nikhil Sachdeva, Nicolas Martinez, "Aircraft Electrical Propulsion - The Next Chapter of Aviation?" Roland Berger, Tech. Rep., 2017. [Online]. Available: https://www.rolandberger.com/publications/publication_pdf/roland_berger_aircraft_electrical_propulsion.pdf

[88] G. Kopasakis and C. Bowman, "NASA Aero-Propulsion Control Technology Roadmap Development Workshop," Tech. Rep., 2016. [Online]. Available: https://www.grc.nasa.gov/www/cdtb/aboutus/workshop2016/HybridElectricPropulsionReportOut-LCCPCDRoadmapWorkshop.pdf

[89] M. Noe and M. Steurer, "High-temperature superconductor fault current limiters: concepts, applications, and development status," *Superconductor Science and Technology*, vol. 20, no. 3, p. R15, 2007.

[90] Y. Zhang and R. A. Dougal, "State of the art of Fault Current Limiters and their applications in smart grid," in *2012 IEEE Power and Energy Society General Meeting*. San diego, CA: IEEE, 2012, pp. 1–6.

[91] A. R. Gibson, “Company Overview,” 2015. [Online]. Available: http://esaero.com/ESAeroCompanyOverview.pdf

[92] W. Y. Kong, “Review of DC Circuit Breakers for Submarine Applications,” *Australian Defence Scienece and Technology Organisation, Maritime Platforms Division*, no. dc, 2012. [Online]. Available: https://www.dst.defence.gov.au/sites/default/files/publications/documents/DSTO-TN-1074PR.pdf

[93] Heintje Wyczisk and Claus Zeumer, “HYPSTAIR – System Architecture, Certifiability and Safety Aspects Symposium E2-Fliegen 2016, Stuttgart,” in *Symposium E2-Fliegen 2016*, Stuttgart, 2016. [Online]. Available: http://www.hypstair.eu/wp-content/uploads/2013/10/E2-Fliegen-Symposium-Stuttgart_SAG.pdf

[94] P. Malkin, “Electric Power Systems for MEA and the Link to Hybrid Electric,” in *More Electric Aircraft Conference - Hybrid-Electric Aircraft Technology.* Hamburg: Newcastle University, 2016.

[95] N. E. Antoine and I. M. Kroo, “Framework for Aircraft Conceptual Design and Environmental Performance Studies,” *AIAA Journal*, vol. 43, no. 10, pp. 2100–2109, 2005. [Online]. Available: https://pdfs.semanticscholar.org/ae91/a72f1ffd903d8c1ca072cfb5deabd67f35f6.pdfhttp://arc.aiaa.org/doi/10.2514/1.13017

[96] P. Rakhra, P. J. Norman, S. D. A. Fletcher, S. J. Galloway, and G. M. Burt, “Evaluation of the Impact of High-Bandwidth Energy-Storage Systems on DC Protection,” *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 586–595, 2016.

[97] D. Wanner, A. Trigell, L. Drugge, J. Jerrelind, D. Wanner, A. S. Trigell, L. Drugge, and J. Jerrelind, “Survey on Fault-Tolerant Vehicle Design,” *World Electric Vehicle Journal*, vol. 5, no. 2, pp. 598–609, jun 2012. [Online]. Available: http://www.mdpi.com/2032-6653/5/2/598

[98] B. Tabbache, A. Kheloui, M. Benbouzid, A. Mamoune, and D. Diallo, “Research on Fault Analysis and Fault-Tolerant Control of EV/HEV Powertrain,” Tech. Rep., 2014. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01023503

[99] Y. Song and B. Wang, *A Hybrid Electric Vehicle Powertrain with Fault-Tolerant Capability*, 2012. [Online]. Available: https://www.egr.msu.edu/~bingsen/files_publications/C-12_APEC.pdf

[100] Kari Ann Briski, Poonam Chitale, Valerie Hamilton, Allan Pratt, Brian Starr, Jim Veroulis, and Bruce Villard, “Minimizing code defects to improve software quality and lower development costs.” 2008. [Online]. Available: ftp://ftp.software.ibm.com/software/rational/info/do-more/RAW14109USEN.pdf

[101] Gregory Travis, “How the Boeing 737 Max Disaster Looks to a Software Developer - IEEE Spectrum,” 2019. [Online]. Available: https://spectrum.ieee.org/aerospace/aviation/how-the-boeing-737-max-disaster-looks-to-a-software-developer

[102] A. T. Isikveren, A. Seitz, P. C. Vratny, C. Pornet, K. O. Plötner, and M. Hornung, “CONCEPTUAL STUDIES OF UNIVERSALLY - ELECTRIC SYSTEMS ARCHITECTURES SUITABLE FOR TRANSPORT AIRCRAFT,” 2012.

[103] J. L. Felder, G. V. Brown, H. D. Kim, and J. Chu, “Turboelectric Distributed Propulsion in a Hybrid Wing Body Aircraft,” in *20th International Society for Airbreathing Engines (ISABE 2011) International Society of Air Breathing Engines*, 2011. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120000856.pdf

[104] M. Kerho and B. Kramer, “NASA Aeronautics Research Mission Directorate FY12 LEARN Phase I Technical Seminar ROLLING HILLS RESEARCH,” 2013. [Online]. Available: https://nari.arc.nasa.gov/sites/default/files/KERHO_LEARN.pdf

[105] EASA, "AMC-20 Amendment 7 - Annex II AMC 20-6 rev. 2," pp. 1–65, 2010. [Online]. Available: https://www.easa.europa.eu/system/files/dfu/AnnexII-AMC20-6.pdf

[106] S. Fletcher, P. Norman, S. Galloway, and G. Burt, "Fault detection and location in DC systems from initial di/dt measurement," in *Paper presented at Euro Tech Con Conference, Manchester, United Kingdom.*, nov 2012. [Online]. Available: http://www.techcon.info/index.php/euro-techcon-2013

[107] NASA, "TRL Definition Hardware Description Software Description Exit Criteria," 2015. [Online]. Available: https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-522-space-propulsion-spring-2015/assignments/MIT16_522S15_TRLDefinition.pdf

[108] P. Rakhra, "On the protection of compact DC power systems with high-power energy storage," Ph.D. dissertation, University of Strathclyde, 2017. [Online]. Available: http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.723028

[109] R. F. Beach, "Overview of NASA Power Technologies for Space and Aero Applications," in *IEEE Cleveland Power and Energy Society Met*, oct 2014. [Online]. Available: http://ntrs.nasa.gov/search.jsp?R=20150002080

[110] Systems Engineering Body of Knowledge, "System Verification - SEBoK," 2019. [Online]. Available: https://www.sebokwiki.org/wiki/System_Verification

[111] ——, "System Validation - SEBoK," 2019. [Online]. Available: https://www.sebokwiki.org/wiki/System_Validation

[112] Kjartan Pedersen, Jan Emblemsvåg, Reid Bailey, Janet K. Allen, and Farrokh Mistree, "Validating Design Methods & Research: The Validation Square," in *Proceedings of DETC '00 2000 ASME Design Engineering Technical Conferences*. Baltimore: ASME, 2000. [Online]. Available: https://www.researchgate.net/publication/236735347_Validating_Design_Methods_Research_The_Validation_Square

[113] S. Buzuku, J. Farfan, K. Harmaa, A. Kraslawski, and T. Kässi, "A Case Study of Complex Policy Design: The Systems Engineering Approach," *Complexity*, vol. 2019, pp. 1–23, jan 2019. [Online]. Available: https://www.hindawi.com/journals/complexity/2019/7643685/

[114] N. Dechev, "Lecture 7: Decision Making CONSIDERING MULTIPLE DESIGN OBJECTIVES BASIC RANKING TABLES AND SCALES FOR DESIGN OBJECTIVES WEIGHTING FACTORS THE DECISION TABLE," University of Victoria, Tech. Rep. [Online]. Available: https://www.engr.uvic.ca/~mech350/Lectures/MECH350-Lecture-7.pdf

[115] A. Salado and R. Nilchiani, "The Concept of Order of Conflict in Requirements Engineering," *IEEE Systems Journal*, vol. 10, no. 1, pp. 25–35, mar 2016. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6807513

[116] A. S. Gohardani, G. Doulgeris, and R. Singh, "Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all electric commercial aircraft," *Progress in Aerospace Sciences*, vol. 47, no. 5, pp. 369–391, jul 2011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0376042110000497

[117] D. Mody and D. S. Strong, "AN OVERVIEW OF CHEMICAL PROCESS DESIGN ENGINEERING," *Proceedings of the Canadian Engineering Education Association*, aug 2017. [Online]. Available: http://ojs.library.queensu.ca/index.php/PCEEA/article/view/3824

[118] D. University of Florida and M. Laboratory), "Introduction to the Design Process." [Online]. Available: http://mae.ufl.edu/designlab/labassignments/eml2322l-designprocess.pdf

[119] J. Goral, "Risk Management in the Conceptual Design Phase of Building Projects Choice of Solution Risk Management Information Information

Information," Ph.D. dissertation, Chalmers, 2007. [Online]. Available: http://documents.vsect.chalmers.se/CPL/exjobb2007/ex2007-124.pdf

[120] R. W. Saaty, "THE ANALYTIC HIERARCHY PROCESS-WHAT IT IS AND HOW IT IS USED," *Mathematical Modelling*, vol. 9, no. 5, pp. 161–176, 1987. [Online]. Available: https://core.ac.uk/download/pdf/82000104.pdf

[121] D. C. Wynn and P. J. Clarkson, "Process models in design and development," *Research in Engineering Design*, vol. 29, no. 2, pp. 161–202, 2018. [Online]. Available: https://www.repository.cam.ac.uk/bitstream/handle/1810/274492/Processmodelsindesignanddevelopment.pdf?sequence=1

[122] S. MÜLLER, M. DEICKE, and RIK W. DE DONCKER, "A viable alternative to adjust speed over a wide range at minimal cost," 2002. [Online]. Available: http://web.mit.edu/kirtley/binlustuff/literature/windturbinesys/DFIGinWindTurbine.pdf

[123] FAA, "Advisory circular - flight test guide for certification of transport category airplanes," Dec 2012. [Online]. Available: FlightTestGuideForCertificationOfTransportCategoryAirplanesAC-25

[124] Safran Electrical Power, "With COPPER Bird®, Safran Electrical & Power benefits from a unique test rig for use in research into more electric aircraft — Safran Electrical & Power," 2015. [Online]. Available: https://www.safran-electrical-power.com/media/20150504_copper-birdr-lps-benefits-unique-test-rig-use-research-more-electric-aircraft

[125] Wineman Technology Incorporated, "Iron Bird Test Systems — Aerospace — Wineman Technology," 2019. [Online]. Available: https://www.winemantech.com/campaign/iron-birds/

[126] Flight International, "Europe paves way to more-electric aircraft," *Flight International*, p. 26, 2005. [Online]. Available: https://www.flightglobal.com/news/articles/europe-paves-way-to-more-electric-aircraft-203599/

[127] Safran, “Test Benches — Safran Electrical & Power,” 2019. [Online]. Available: https://www.safran-electrical-power.com/electrical-systems/electrical-systems-integration-certification-esr/test-benches

[128] F. Coffele and R. Manager, “POWER NETWORKS DEMONSTRATION CENTRE,” Tech. Rep. [Online]. Available: https://www.ukpowernetworks.co.uk/losses/static/pdfs/power-networks-demonstration-centre.2a4745d.pdf

[129] F. S. University, “Center for Advanced Power Systems History and Background r&d Facility,” Tech. Rep. [Online]. Available: https://www.caps.fsu.edu/media/1158/caps_flyer.pdf

[130] Nancy S. Giges, “Demand for Flying Taxis Lifts Electric Aircraft Market,” 2018. [Online]. Available: https://www.asme.org/engineering-topics/articles/technology-and-society/demand-flying-taxis-lifts-electric-aircraft

[131] Elan Head, “Behind the controls of an eVTOL aircraft: A test pilot’s perspective - Vertical Magazine,” 2019. [Online]. Available: https://www.verticalmag.com/news/evtol-test-pilot-perspective/

[132] Stephen Pope, “Boeing Completes First Test of Air-Taxi Prototype — Flying Magazine,” 2019. [Online]. Available: https://www.flyingmag.com/boeing-air-taxi-prototype-test-flight

[133] Mark Huber, “CityAirbus eVTOL Makes ’Tethered Jump’ — General Aviation News: Aviation International News,” 2019. [Online]. Available: https://www.ainonline.com/aviation-news/general-aviation/2019-05-07/cityairbus-evtol-makes-tethered-jump

[134] Kate O’Connor, “Boeing eVTOL Prototype Crashes - AVweb,” 2019. [Online]. Available: https://www.avweb.com/recent-updates/evtols-urban-mobility/boeing-evtol-prototype-crashes/

[135] Jon Phillips, “The Ehang 184 is a single-passenger drone that transports people (yes, people) at 11,000 feet — PCWorld,” 2016. [Online]. Available: https://www.

pcworld.com/article/3019704/the-ehang-184-is-a-single-passenger-drone-that-/transports-people-yes-/people-at-11-000-feet.html

[136] Associated Press, "First passenger drone makes its debut at CES — Technology — The Guardian," 2016. [Online]. Available: https://www.theguardian.com/technology/2016/jan/07/first-passenger-drone-makes-world-debut

[137] Lillium, "Lilium — Technology." [Online]. Available: https://lilium.com/technology/

[138] Airbus, "A3 Vahana." [Online]. Available: https://www.airbus-sv.com/projects/1

[139] Moller International, "Skycar: Two passenger electric/ethanol hybrid VTOL aircraft," 2019. [Online]. Available: https://moller.com/moller_skycar200.html

[140] J. Delhaye and P. Rostek, "Hybrid Electric Propulsion Europe-Japan Symposium Electrical Technologies for the Aviation of the Future," in *Europe-Japan Symposium Electrical Technologies for the Aviation of the Future*, Tokyo, 2015.

[141] Peggy Hollinger, "French stunt pilot pips Airbus to fly electric plane over Channel — Financial Times," 2015. [Online]. Available: https://www.ft.com/content/57f83916-26e4-11e5-bd83-71cb60e8f08c

[142] L. Juvé, E. Joubert, B. Ferran, and N. Fouquet, "Aircraft electric propulsion versus reliability and safety, the eFAN experience," in *53rd AIAA/SAE/ASEE Joint Propulsion Conference.* Reston, Virginia: American Institute of Aeronautics and Astronautics, jul 2017. [Online]. Available: https://arc.aiaa.org/doi/10.2514/6.2017-5031

[143] Dean Sigler, "Airbus drops E-fans 2.0, 4.0, moves to E-Fan X single aisle airliner," 2017. [Online]. Available: http://sustainableskies.org/airbus-e-fans-2-0-and-4-0-dropped-in-favor-of-e-fan-x/

[144] Rolls-Royce, "Press releases - Rolls-Royce accelerates electrification strategy with acquisition of Siemens' electric and hybrid-electric aerospace propulsion business

–Rolls-Royce," 2019. [Online]. Available: https://www.rolls-royce.com/media/press-releases/2019/18-06-2019-rr-accelerates-electrification-strategy.aspx

[145] Airbus, "The future is electric," 2018. [Online]. Available: https://www.airbus.com/newsroom/news/en/2018/07/the-future-is-electric.html

[146] Starr Ginn and NASA Armstrong Flight Research Centre, "Spiral Development of Electrified Aircraft Propulsion from Ground to Flight," Cologne, 2016.

[147] Michael Kerho, "Turboelectric Distributed Propulsion Test Bed Aircraft LEARN Phase I FINAL REPORT Contract Number NNX13AB92A," 2013. [Online]. Available: https://nari.arc.nasa.gov/sites/default/files/Kerho_TeDP.PhaseI.Final_.Report.ContractNNX13AB92A.pdf

[148] J. D. Wolter, "BLI 2 DTF Testing in the 8x6' Boundary-Layer-Ingesting Inlet / Distortion-Tolerant Fan," 2018. [Online]. Available: https://evt.grc.nasa.gov/pai-tim-2018/wp-content/uploads/sites/25/2.4-BLI2DTF-Testing-in-the-8'x6'.pdf

[149] E. ZIO, M. FAN, Z. ZENG, and R. KANG, "Application of reliability technologies in civil aviation: Lessons learnt and perspectives," *Chinese Journal of Aeronautics*, vol. 32, no. 1, pp. 143–158, jan 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1000936118301948

[150] Airbus, "A350 XWB at McKinley Climatic Lab in Florida for more extreme weather tests," 2014. [Online]. Available: https://www.airbus.com/newsroom/press-releases/en/2014/05/a350-xwb-at-mckinley-climatic-lab-in-florida-for-more-extreme-weather-tests.html

[151] C. Bowman and A. Jankovsky, "NASA Hybrid Gas-Electric Propulsion (HGEP) Subproject Advanced Air Transport Technologies (AATT) Progress update for One Boeing NASA Electric Aircraft Workshop Arlington VA," 2017. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170004515.pdf

[152] P. Smith, “Airbus opens electric aircraft test facility,” Oct 2019. [Online]. Available: https://www.aerospacetestinginternational.com/news/electric-hybrid/airbus-opens-electric-aircraft-test-facility.html

[153] G. P. Adam, I. A. Gowaid, S. J. Finney, B. W. Williams, and D. Holliday, “Review of dc–dc converters for multi-terminal HVDC transmission networks,” *IET Power Electronics*, vol. 9, no. 2, pp. 281–296, feb 2016. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/iet-pel.2015.0530

[154] H. Müller, S. S. Torbaghan, M. Gibescu, M. Roggenkamp, and M. van der Meijden, “The need for a common standard for voltage levels of HVDC VSC technology,” *Energy Policy*, vol. 63, pp. 244–251, 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0301421513008823

[155] F. Moriconi, F. De La Rosa, F. Darmann, A. Nelson, and L. Masur, “Development and Deployment of Saturated-Core Fault Current Limiters in Distribution and Transmission Substations,” *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 1288–1293, jun 2011. [Online]. Available: http://ieeexplore.ieee.org/document/5712156/

[156] D. Klaus, J. Bock, C. Waller, J. Helm, D. Jones, M. Jafarnia, J. McWilliam, A. Hobl, and J. Berry, “Superconducting fault current limiters - UK network trials live and limiting,” in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*. Institution of Engineering and Technology, 2013, pp. 0285–0285. [Online]. Available: http://digital-library.theiet.org/content/conferences/10.1049/cp.2013.0650

[157] C. Muscas, M. Pau, P. Pegoraro, and S. Sulis, “Smart electric energy measurements in power distribution grids,” *IEEE Instrumentation & Measurement Magazine*, vol. 18, no. 1, pp. 17–21, feb 2015. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7016676

[158] N. Doerry and K. Moniri, “Specifications and standards for the electric warship,” in *2013 IEEE Electric Ship Technologies Symposium (ESTS)*. IEEE, apr 2013, pp. 21–28. [Online]. Available: http://ieeexplore.ieee.org/document/6523706/

[159] Jimi Beckwith, “London Taxi Company’s electrified cab to hit the road this year — Autocar,” 2017. [Online]. Available: https://www.autocar.co.uk/car-news/new-cars/london-taxi-companys-electrified-cab-hit-road-year

[160] W. Graham, C. Hall, and M. Vera Morales, “The potential of future aircraft technology for noise and pollutant emissions reduction,” *Transport Policy*, vol. 34, pp. 36–51, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0967070X14000481

[161] Eaton, “Redefining the boundaries of electric vehicle design,” 2017. [Online]. Available: http://www.cooperindustries.com/content/dam/public/bussmann/Electrical/Resources/product-literature/bus-ele-br-10569-ev-fuses.pdf

[162] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. A. Pérez, J. I. Leon, L. G. Franquelo, J. I. Leon, J. Rodriguez, and M. A. Pérez, “Recent Advances and Industrial Applications of Multilevel Converters,” *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 57, no. 8, 2010. [Online]. Available: http://ieeexplore.ieee.org.

[163] J. M. Meyer and A. Rufer, “A DC hybrid circuit breaker with ultra-fast contact opening and integrated gate-commutated thyristors (IGCTs),” *IEEE Transactions on Power Delivery*, vol. 21, no. 2, pp. 646–651, 2006. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=161067&tag=1

[164] M. Ahmed, G. Putrus, L. Ran, and R. Penlington, “Development of a Prototype Solid-State Fault-Current Limiting and Interrupting Device for Low-Voltage Distribution Networks,” *IEEE Transactions on Power Delivery*, vol. 21, no. 4, pp. 1997–2005, oct 2006. [Online]. Available: http://ieeexplore.ieee.org/document/1705560/

[165] M. Callavik, A. Blomberg, J. Häfner, and B. Jacobson, "The Hybrid HVDC Breaker An innovation breakthrough enabling reliable HVDC grids," Tech. Rep., 2012. [Online]. Available: http://new.abb.com/docs/default-source/default-document-library/hybrid-hvdc/-breaker---an-innovation-breakthrough-for-reliable-hvdc/-gridsnov2012finmc20121210_clean.pdf?sfvrsn=2

[166] R. Cuzner and A. Jeutter, "DC zonal electrical system fault isolation and reconfiguration," in *2009 IEEE Electric Ship Technologies Symposium.* IEEE, apr 2009, pp. 227–234. [Online]. Available: http://ieeexplore.ieee.org/document/4906520/

[167] M. Steurer, F. Bogdan, M. Bosworth, O. Faruque, J. Hauer, K. Schoder, M. Sloderbeck, D. Soto, K. Sun, M. Winkelnkemper, L. Schwager, and P. Blaszczyk, "Multifunctional megawatt scale medium voltage DC test bed based on modular multilevel converter (MMC) technology," in *2015 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS).* IEEE, mar 2015, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/document/7101535/

[168] S. Xue, F. Gao, W. Sun, and B. Li, "Protection Principle for a DC Distribution System with a Resistive Superconductive Fault Current Limiter," *Energies*, vol. 8, no. 6, pp. 4839–4852, 2015. [Online]. Available: http://econpapers.repec.org/article/gamjeners/v_3a8_3ay_3a2015_3ai_3a_3ap_3a4839-4852_3ad_3a50146.htmhttp://www.mdpi.com/1996-1073/8/6/4839/htm

[169] M. Glinka and R. Marquardt, "A New AC/AC Multilevel Converter Family," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 3, pp. 662–669, jun 2005. [Online]. Available: http://ieeexplore.ieee.org/document/1435677/

[170] S.-H. Lee, S.-G. Song, S.-J. Park, C.-J. Moon, and M.-H. Lee, "Grid-connected photovoltaic system using current-source inverter," *Solar Energy*, vol. 82, no. 5,

pp. 411–419, 2008.

[171] M. Spichartz, C. Heising, V. Staudt, and A. Steimel, "State control of MMC-fed ship propulsion induction machine," in *2013 IEEE Electric Ship Technologies Symposium (ESTS).* IEEE, apr 2013, pp. 173–177. [Online]. Available: http://ieeexplore.ieee.org/document/6523730/

[172] D. Jovcic, "Bidirectional, High-Power DC Transformer," *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 2276–2283, oct 2009. [Online]. Available: http://ieeexplore.ieee.org/document/5235872/

[173] Zheng Wang, Ming Cheng, and K.T. Chau, "A current source converter fed high power wind energy conversion system with superconducting magnetic storage system in DC link," in *International Conference on Electrical Machines and Systems (ICEMS).* Incheon, Korea (South): IEEE, 2010.

[174] X. Yuan, K. Tekletsadik, L. Kovalsky, J. Bock, F. Breuer, and S. Elschner, "Proof-of-Concept Prototype Test Results of a Superconducting Fault Current Limiter for Transmission-Level Applications," *IEEE Transactions on Appiled Superconductivity*, vol. 15, no. 2, pp. 1982–1985, jun 2005. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1440046

[175] D. Hui, Z. Wang, J. Zhang, D. Zhang, S. Dai, C. Zhao, Z. Zhu, H. Li, Z. Zhang, Y. Guan, L. Xiao, L. Lin, L. Li, L. Gong, X. Xu, J. Lu, Z. Fang, H. Zhang, J. Zeng, G. Li, and S. Zhou, "Development and Test of 10.5 kV/1.5 kA HTS Fault Current Limiter," *IEEE Transactions on Applied Superconductivity*, vol. 16, no. 2, pp. 687–690, jun 2006. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1642941

[176] P. R. Deo, T. P. Shah, and R. Chong, "Ambient-temperature fault current limiter for electric ship power systems," in *2011 IEEE Electric Ship Technologies Symposium, ESTS 2011.* IEEE, apr 2011, pp. 223–227. [Online]. Available: http://ieeexplore.ieee.org/document/5770871/

[177] Electric Power Research Institute;, "Superconducting Fault Current Limiters Technology Watch 2009," 2009. [Online]. Available: https://www.epri.com/#/pages/product/000000000001017793/

[178] Hyoungku Kang, Chanjoo Lee, Kwanwoo Nam, Yong Soo Yoon, Ho-Myung Chang, Tae Kuk Ko, and Bok-Yeol Seok, "Development of a 13.2 kV/630 A (8.3 MVA) High Temperature Superconducting Fault Current Limiter," *IEEE Transactions on Applied Superconductivity*, vol. 18, no. 2, pp. 628–631, jun 2008. [Online]. Available: http://ieeexplore.ieee.org/document/4497299/

[179] A. P. Malozemoff, S. Fleshler, M. Rupich, C. Thieme, X. Li, W. Zhang, A. Otto, J. Maguire, D. Folts, J. Yuan, H. P. Kraemer, W. Schmidt, M. Wohlfart, and H. W. Neumueller, "Progress in high temperature superconductor coated conductors and their applications," in *Superconductor Science and Technology*, vol. 21, no. 3. IOP Publishing, mar 2008, p. 034005. [Online]. Available: http://stacks.iop.org/0953-2048/21/i=3/a=034005?key=crossref.2fcd9439af4f4972d5450eb9e7101f25

[180] J. W. Moscrop, F. Darmann, and J. Moscrop, "Design and development of a 3-Phase saturated core high temperature superconducting fault current limiter," in *International Conference on Electric Power and Energy Conversion Systems, EPECS'09*. Sharjah, Arabia: IEEE, 2009. [Online]. Available: http://ro.uow.edu.au/engpapers/1084

[181] T. Yazawa, K. Koyanagi, M. Takahashi, M. Ono, M. Sakai, K. Toba, H. Takigami, M. Urata, Y. Iijima, T. Saitoh, N. Amemiya, and Y. Shiohara, "Design and Experimental Results of Three-Phase Superconducting Fault Current Limiter Using Highly-Resistive YBCO Tapes," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 1956–1959, jun 2009. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5067031