Protection and Fault Management Strategy Maps for Future Electrical Propulsion Aircraft

Marie-Claire Flynn, Michal Sztykiel, Catherine Jones, Patrick Norman, Graeme Burt, Paul Miller, and Mark Husband

Abstract

Electrical propulsion has been identified as a key enabler of greener, quieter, more efficient aircraft. However, electrical propulsion aircraft (EPA) will need to demonstrate a level of safety and fault management at least equal to current aircraft. This will rely heavily on the capability and design of the electrical fault management (FM) system. Given the functional limitations and current lack of availability of FM technologies suitable for a future EPA application, strategic development of FM devices is required. Whilst there are a variety of roadmaps for EPA concepts and some of the key electrical components, the necessary strategic development of FM solutions targeted towards EPA has yet to be established. This paper proposes FM strategy maps which go beyond projections of expected development in various FM technologies to scope the feasibility of key FM solutions. This method can then be used to present FM technology projections, electrical oversizing and wider system redundancy alongside the various aircraft concepts in development. This results in strategy maps which capture the impact of any FM technology barrier on the viability of a given aircraft concept, enabling critical FM solutions to be integrated into the wider electrical system development.

Index Terms

Fault management strategy map, electrical propulsion aircraft, electrical power systems, protection technology development.

I. INTRODUCTION

Electrical propulsion has been identified as a key enabler of greener, quieter, more efficient aircraft. Novel electrical propulsion aircraft (EPA) will depend on the development of a range of electrical technologies, many of which are currently at low TRL (Technology Readiness Level). Given the risk that an EPA concept may rely on key technologies which may not be sufficiently developed as desired at the aircraft's point of entry into service, it is important to develop understanding of the particular challenges which must be addressed in bringing technologies to maturity. One of the most challenging set of technologies for EPA are the fault management (FM) devices,

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M.-C. Flynn, M. Sztykiel, C. Jones, P. Norman and G. Burt are with the Electronic and Electrical Engineering Department at the University of Strathclyde, Glasgow.

P. Miller is with Central Technologies - Future Platforms at Rolls-Royce plc, Derby. M. Husband is with Rolls-Royce Electrical, at Rolls-Royce plc, Derby.

especially since confidence in the safety of the aircraft is critically important and will rely heavily on the capability and design of the FM system.

Numerous power density targets and technology roadmaps (such as [1], [2]) exist for electrical machines, power electronic converters and energy storage, 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. Thus in the first instance, a systems-level, FM strategy map is required to outline a vision of the future development of FM solutions and identify key FM goals. In order to achieve this, 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.

Robust, effective FM solutions for complex EPA electrical systems require the integration of a number of FM 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 knowledge of both the TRL and projected future development of existing FM technologies.

FM strategy maps provide a mechanism 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 remainder of this paper is structured as follows: Section II defines requirements for effective FM strategy maps, Section III presents a literature review of the current status of the development of FM technologies. Section IV describes the proposed strategy mapping approach, then Section V describes the current landscape of state-of-the-art (SOA) FM devices and projections on required developmental time frame. Thereafter, in Section VI strategy maps for key FM solutions are presented and discussed in Section VII and finally in Section VIII conclusions are drawn and areas of future work are identified.

II. DEFINITION OF FM STRATEGY MAP

In [3] technology roadmapping is defined as a technique used to support technology management and long-range planning. By contrast, a *strategy map* lays the groundwork for specific technology roadmapping by giving an overview of the future development of a wide range of interdependent technologies and the critical stages of progression that are expected.

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. 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.

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 [4]. 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.

III. Overview of Current Fault Management Technology Strategy Maps in the Literature

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

A recent report published by the ATI [2] 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 [5] 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 [2], 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 [6], 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 lagging development of FM in relation to other aspects of the electrical system design is shown once again by the fact that FM is a identified as a sub-category of power electronics development.

Developers of future EPA [1], [7] 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 [8]–[10], 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 [11] 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 [11] 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], [9], [12].

In [13] 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 modeling and fault tolerance analysis as part of the development of future hybrid electric aircraft, yet it did not describe how this might be achieved.

IV. 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 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. 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 1.

Although fault detection will be required as part of any FM solution, FM enabler technologies (such as sensors, metrology and communications) are out of scope of this paper, and so fault detection has not been selected as a “Key FM Function”.

Since electrical FM technologies specific to EPA are at an early development stage or do not yet exist, 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 [14]. The technologies from each sector are then assigned to the corresponding voltage and current FM classes that represent four ranges of ratings, as shown in Figure 1. This classification is used to allow comparison between technologies, especially where they are not yet published at particular voltage or current classes.

The “Core Activities” (as shown in Table I) required to adapt a given technology for an aircraft electrical propulsion system are then identified, and are then compared against the current TRL status (as defined in [15]) 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 IRL (Integration Readiness Level) [16] of each technology in the electrical architecture, and relate that to the anticipated level of redundancy in the wider aircraft system.

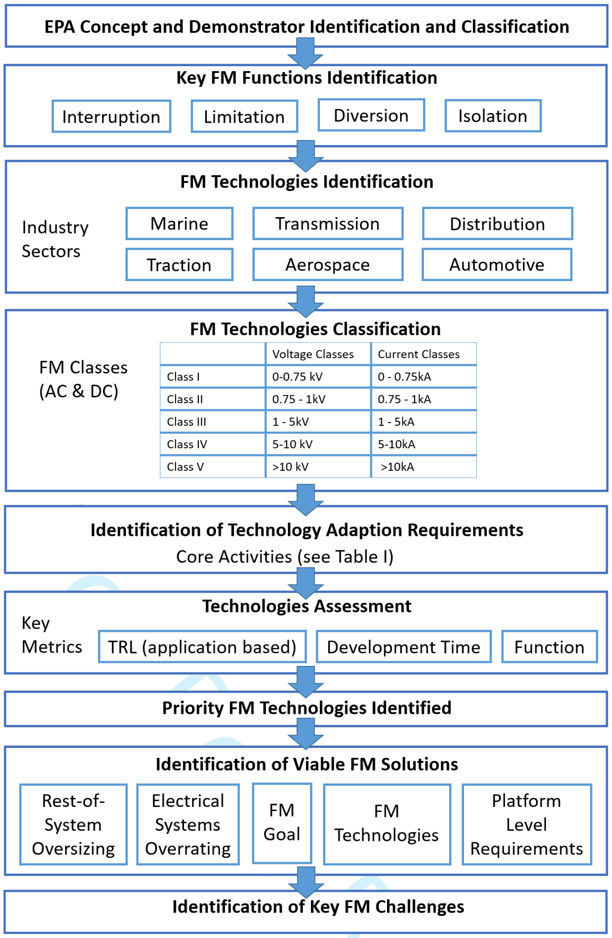


Fig. 1. Proposed approach to FM strategy map development

V. KEY FM TECHNOLOGY AND PROJECTIONS

Underpinning the proposed FM strategy map is the determination of the current status of key FM technologies and projections for the time required to adapt each technology for a future EPA application. The following sections describe the status of the various classes of FM technologies, the adaptations requirements for EPA and consequently, in Table II the highest TRL currently available for each technology across the different applications is identified.

A. *Fault Interrupters and Isolators*

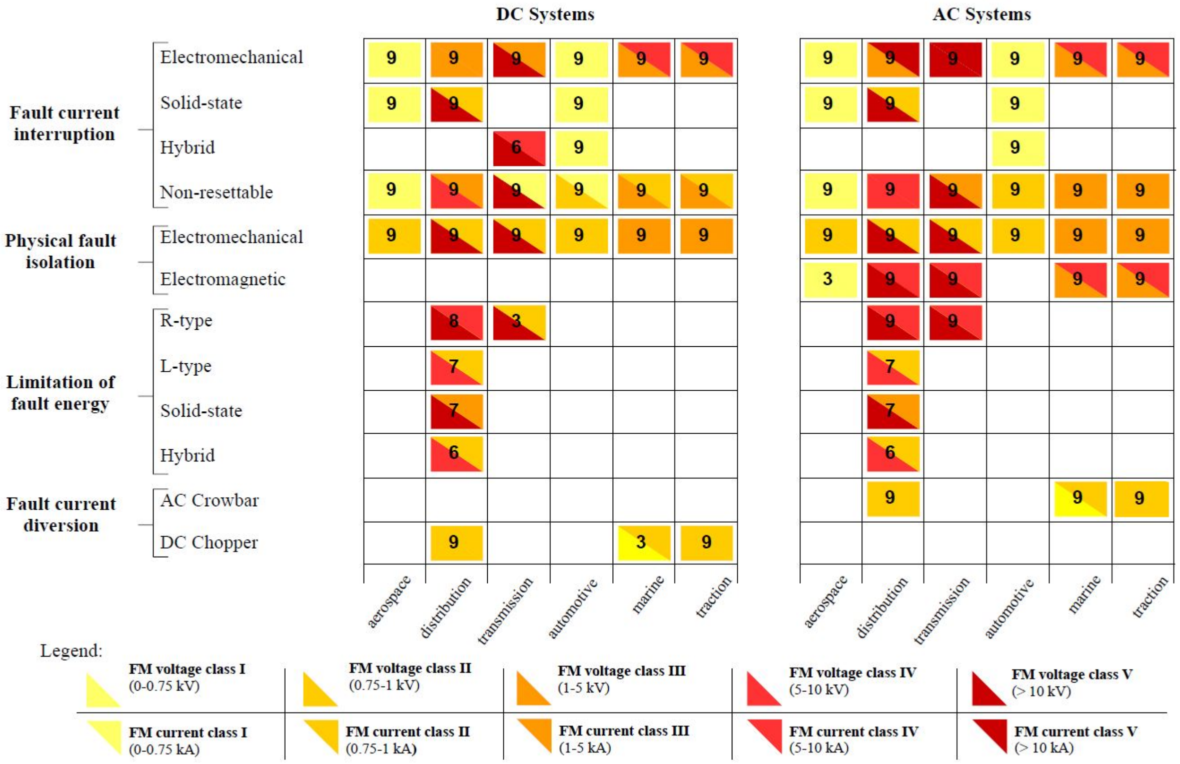
In order to eliminate fault condition and maintain safe operation, the fault needs to be interrupted and subsequently isolated by dedicated protection devices.

1) Electromechanical Fault Interruption: Electromechanical circuit breakers (EMCBs) are a highly mature technology. They are resettable and can be used multiple times to interrupt the same fault current by the mechanical movement of contacts [17]. Identified technologies for electromechanical interruption include usage of air arc chute [18], gas [19] or vacuum chambers [20]. Existing electromechanical breaker designs are relatively large and

TABLE I

CORE ACTIVITIES FOR TECHNOLOGY ADAPTATION

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.



		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)

Fig. 2. Identification of best available TRL and developmental projections for key FM technologies

sensitive to vibrations [21], but combine fault interruption with isolation functions and maintain low power losses when conducting currents [22].

2) Solid-State Fault Interruption: Solid-state interruption technology is based on using controllable MOSFETs [23] or IGBTs [24] in order to rapidly interrupt the fault current. Solid-state switches can be used multiple times without a need for replacement but they do not provide galvanic fault isolation and generate much higher conduction losses under normal conditions [22] than electromechanical breakers. The highest maturity solid-state interrupters are in applications for aerospace [23], such as Solid State Power Controllers (SSPCs), and terrestrial grid distribution systems [24]. The primary purpose of SSPCs is general load switching, control and some protection capability. However, SSPCs are not currently rated high enough for future EPA concepts (limited to FM voltage and current classes I). Solid State Circuit Breakers (SSCBs) exist for other non-aerospace applications at higher ratings and can be coupled with a mechanical contactors to provide isolation capability.

3) Hybrid Circuit Breakers: Hybrid interruption technology combines the benefits of electromechanical and solid-state technologies in order to achieve rapid interruption, low conduction losses and fault isolation. Due to the relative complexity of the hybrid breaking mechanism and low TRL, this technology has been considered as an extension to electromechanical and solid-state technologies for FM classes III-IV. Superconducting hybrid circuit breakers have been identified for transmission power system applications [25].

4) Non-Resettable Circuit Breakers: Non-resettable circuit breaking technologies include fuses [26] or pyrotechnic fuses with remote tripping control [27]. Both devices are compact and combine fault interruption with isolation, but can only be used once before a replacement is required. Fuses are widely used across all industry sectors. Pyrotechnic fuses that also employ a pyroswitch can be found in automotive sector and terrestrial grid systems.

5) Electromechanical Fault Isolation (disconnectors): Dedicated electromechanical no-load disconnect switches can enable physical fault isolation once the current has been interrupted [28]. This technology is used in combination with an interrupting device. Disconnectors are widely available across different industry sectors and can be rated for all FM classes.

6) Electromagnetic Fault Isolation (transformers): Power transformers in a EPA network can provide the dual function of power conversion and galvanic isolation [29]. Power transformers are widely available across different industry sectors and can be rated for all AC FM classes.

B. Fault Current Limiters

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.

1) R-type Limiters (Superconducting): This type of the fault current limiting technology increases resistivity of the material in response to high fault currents [30]. This technology has been successfully applied to many commercial terrestrial grid distribution systems [31]. However, it needs to be adapted for an aircraft application before it can be readily applied to FM voltage classes of I-IV and to FM current classes of I-II.

2) L-type Limiters (Saturated Core): The inductive-type fault current limiting technology injects additional magnetizing inductance once the core of the fault limiter becomes saturated with fault current [32]. These devices have been successfully deployed on a few distribution network demonstrators [33] and is therefore characterized in this paper with TRL of 7. According to available technology ratings, it can be considered in FM voltage classes I-III and current classes I -II.

3) Solid-State Limiters: A wide variety of solid-state semiconductor devices have been identified and can be grouped into series [34], bridge [35] and resonant [36] devices. The most advanced development of a series solid-state limiter for distribution systems has reached TRL 7 [37], applicable to FM voltage classes I-IV and current classes I-II.

4) Hybrid Limiters: Hybrid current limiters combine the advantages of previously described resistive, inductive and solid-state limiters to achieve rapid interruption, low conduction losses and fault isolation [38]. These devices are at TRL 6.

C. Fault Current Diverters

Fault current diversion changes the current direction to protect sensitive electrical loads and vulnerable electrical and non-electrical systems. The AC crow bar circuit and DC chopper circuit are two types of fault diverting circuits, both of which are highly mature technologies enabled by the voltage ratings of existing solid-state devices.

VI. PROPOSED FM STRATEGY MAP

Building on the FM technology status appraisal outlined in Section V, Table II 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 requirements for an effective strategy map established in Section II and goes beyond existing EPA technology roadmaps (as discussed in Section III). The confidence level (defined in [4]) in the availability and suitability of key individual FM technologies under development (grouped by FM function), are mapped against the expected developmental timeframe. 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 timeframe 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.

A. Classifications in Strategy Map

A tabular strategy map format [3] 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 II, 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 timeframe 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 is taken to mean “not part of system design”, amber is “possibly part of the design” where there is uncertainty and green is “feature is included in concept design”.

B. *Inclusion of Systems Oversizing*

The “Rest of System Oversizing” section of Table II 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.

C. *Inclusion of Electrical Systems Oversizing*

The electrical system oversizing section of Table II 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 [4].

The rationale for attributing different levels of priority to various aspects of oversizing is noted in each cell 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.

D. *Importance of FM Goal in FM Strategy Map*

In [4] 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 [7]–[9], [12], [39], [40], the FM goal is identified and mapped in Table II. For example, in [10] 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 timeframe 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 system must decide 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 II), 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.

VII. Discussion of Proposed FM Strategy Map

A. *Availability of FM Technologies*

Table II demonstrated that most FM technologies require development before use in a future EPA application. In Table II, the lack of available 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+3 concepts as there is a significant scaling up of the electrical system rating 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+2 and N+3, as well as the lack of suitable FM devices providing high-priority functionalities for an N+3 concept.

From the strategy map in Table II 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.

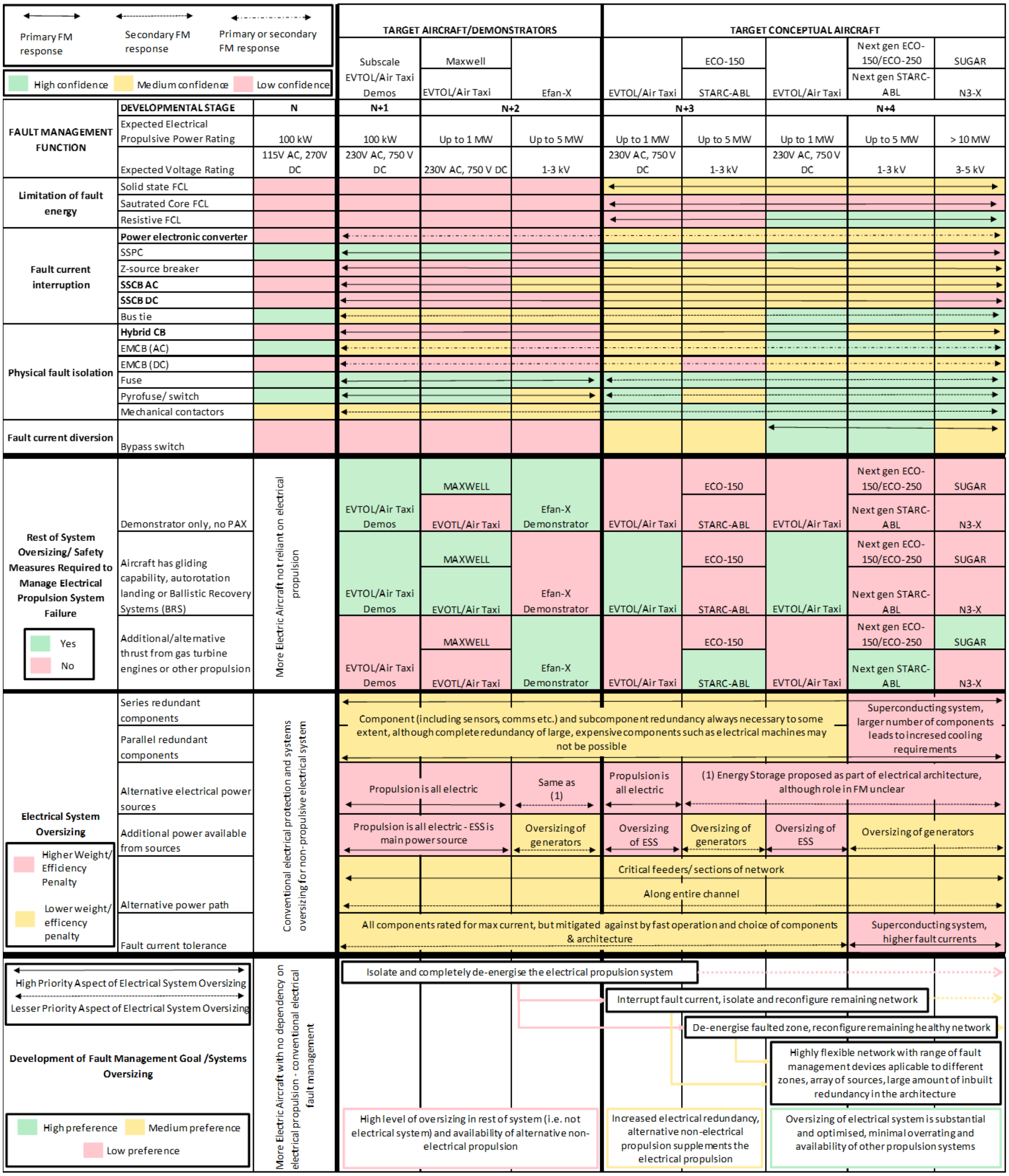
The FM devices which are the most desired in terms of capability (e.g. speed of operation) and function (e.g. ability to provide galvanic isolation) are highlighted in bold in Table II. SSCBs (both AC and DC) and hybrid circuit breakers are primary fault response devices which do not yet exist for the aircraft market. Challenges remain around thermal management, EMI, fail-safe mechanisms and power density which need to be overcome before these preferred devices can be incorporated into a robust FM strategy. The availability of power electronic converters is also limited for future EPA applications. 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.

B. *Aspects of Electrical and Wider System Oversizing*

From Table II, 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 [40]) and larger passenger concepts (such as the ECO-150 aircraft [10]). There is also a notable change when the electrical

TABLE II

FM STRATEGY MAP



⟷ Primary FM response ⇠⇢ Secondary FM response ←·-·→ Primary or secondary FM response

🟩 High confidence 🟨 Medium confidence 🟥 Low confidence

			TARGET AIRCRAFT/DEMONSTRATORS			TARGET CONCEPTUAL AIRCRAFT				
			Subscale EVTOL/Air Taxi Demos	Maxwell EVTOL/Air Taxi	Efan-X	EVTOL/Air Taxi	ECO-150 STARC-ABL	EVTOL/Air Taxi	Next gen ECO-150/ECO-250 Next gen STARC-ABL	SUGAR N3-X
FAULT MANAGEMENT FUNCTION	**DEVELOPMENTAL STAGE**	**N**	**N+1**	**N+2**		**N+3**		**N+4**		
	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/ efficiency penalty	Series redundant components	Conventional electrical protection and systems oversizing for non-propulsive electrical system	🟨 ← 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 →	
	Parallel redundant components		←						→	
	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, higher fault currents →	
Development of Fault Management Goal /Systems Oversizing ⟷ High Priority Aspect of Electrical System Oversizing ⇠⇢ Lesser Priority Aspect of Electrical System 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		

propulsion is not merely supplementing the available thrust (such as in the Efan-X demonstrator aircraft), but provides a critical proportion of total aircraft propulsion. This is shown in Table II where the ECO-150 turboelectric aircraft has the same limited range of FM technologies at high confidence level as the STARC-ABL concept, yet unlike STARC-ABL, 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 N+2 concepts remains largely unknown. 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.

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. For these, the FM goal during critical faults requires sequential or coordinated operation of devices and strategic deployment of available oversizing in the architecture design.

C. *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. Therefore, key developments in FM which will be required are not only related to the available developmental timeframe for an aircraft but will also be driven by any increase in the criticality of the electrical propulsion system. Hence 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 described in [4] and the progression of EPA concepts shown in Table II, the step change developments in PLRs with a significant impact on the criticality of the electrical propulsion 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.

D. Validation and Verification of Strategy Map

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 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.

VIII. FUTURE WORK AND CONCLUSIONS

The proposed FM strategy map 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 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 VII-C, and hence the FM system requirements.

The FM strategy map which has been presented enables the limitations of future EPA FM systems to be identified 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 classification thresholds and capture the requirements of the FM system. Furthermore, the chosen presentation of the strategy map highlights points where the FM technology development lags the requirements of the proposed EPA concepts. 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 constraints 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 data on emerging FM technologies becomes available this will be used to populate the strategy map and will also enable further detailed FM technology specific roadmaps.

This paper has also highlighted the importance of FM enablers such as communications, sensors and metrology for 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 FM to be included in the development of EPA test rigs and flying demonstrators. This would enable FM devices to be integrated into these electrical architectures and to be tested in an aircraft environment - both of which are key core activities which are necessary if FM technologies and clusters are to reach higher confidence levels.

ACKNOWLEDGMENT

This work was undertaken as part of the Rolls-Royce University Technology Centre program at the University of Strathclyde.

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