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ORIGINAL RESEARCH

Design rules to establish a credible More-Electric Engine baseline power architecture concept

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Abstract

The More-Electric Engine (MEE), with its electrified engine auxiliary systems and increased multi-shaft power offtake, is likely to become an increasingly central aspect of future More-Electric Aircraft. Consequently, lightweight but resilient electrical power architectures are needed for these future MEE applications. However, whilst a range of MEE architectures exist in the research literature, no effective baseline architecture or standardised feature identification has been proposed to specifically address their unique design requirements. Accordingly, any underpinning technology-focused research for critical MEE subsystems may ultimately have a reduced effectiveness without this credible baseline. Based on comprehensive design analyses, preliminary design requirements and anticipated operational modes, this article proposes key design rules for the formation of the first generic baseline MEE electrical power system architecture concept. Guidance is provided on features such as the number of power generation systems, the number and topologies of distribution channels, type of power conversion, essential load redundancy, and the location of emergency power supply. This article also provides full transparency of the design process so that key decision points can be revisited to capture application-specific requirements and updates to certification requirements.

KEYWORDS

aerospace engines, aircraft power systems, design engineering, power system reliability

1 | INTRODUCTION

The More-Electric Engine (MEE) concept is expected to become an integral feature of future generations of More-Electric Aircraft (MEA) [1], providing enhanced fuel efficiency and flight reliability [2]. The MEE concept focuses primarily around the electrification of traditionally mechanical and hydraulic engine auxiliary systems such as the fuel and oil pump systems, and guide vane actuation. The load demands of large aircraft MEE applications are expected to be significant. For example, the authors in ref. [3] estimate that the fuel pump system and lubrication oil pump combined will draw approximately 100 kW of electrical power, whilst electrical thrust reverse actuator systems (ETRAs) could require up to 35–45 kW [4]. Such load levels are not insignificant in comparison with airframe loads of modern MEA applications [5]. These high power, flight-critical electrical loads require an increased electrical power offtake from the engine (in comparison with conventional systems), and high integrity power generation and distribution systems, featuring multi-shaft electrical power offtakes. To date, this requirement has encouraged the proposal of standalone on-engine power systems, integrating the engine-driven main generators (which supply both the MEE and airframe loads) with MEE-specific loads in a dedicated local distribution system that then provides suitable interfaces to the airframe power distribution system [6], loads and sources (e.g. Auxiliary Power Unit [APU] generator and batteries). This approach brings a requirement for systems to be tolerant of the engine-proximity harsh environment but avoids the complexity of utilising remote airframe-mounted motor drive systems as an alternative. It also represents a significant deviation from conventional engine systems, whose auxiliary loads are supplied by local mechanical, pneumatic and hydraulic systems [2].

Whilst conventional aircraft and engine systems certification standards (such as CS-25/CS-E [7]) provide clear guidance on the design requirements for conventional engines and aircraft power systems, there are no established certification-driven requirements directly specific to MEE designs yet. Some preliminary design requirements for MEE systems have recently been proposed in the literature [8], but these are limited to a subset of MEE design features. In addition, the design space for the MEE electrical power system architectures is vast because of the potential for multiple power sources, expected need for redundant supplies to critical loads, and the significant range of potential technologies that could be employed. The combination of these factors, and the absence of a 'conventional' architecture from which to incrementally evolve new architectures from, means that it can be challenging to derive and down-select candidate MEE architectures.

There is a clear need for a credible MEE baseline power system architecture concept, which provides all necessary key features for later certification compliance, and focuses on solution sets which are already tailored towards weight, efficiency, and reliability goals. From this baseline, further application-specific design revisions can then be undertaken during later stages of the design and optimisation process. In addition, the process for establishing this baseline architecture should be captured such that updates to standards/application requirements or technology breakthroughs can quickly be incorporated into a revised baseline architecture.

Accordingly, this paper proposes design rules to enable the establishment of the first generic MEE Baseline Power Architecture (BPA) concept. The scope of MEE BPA concept is determined by design criteria relating to the quantity of generation sources, minimum architecture redundancy, type of power conversion and distribution, essential loads redundancy and emergency power supplies' roles. In this manner, the paper establishes a credible baseline architecture which eliminates a range of infeasible and overdesigned concepts at an early stage of the design process. The focus of this paper is on the configuration of the power network and connection of key components. Discussion of voltage and power levels is highly system and load-specific and as such, is not captured in detail here (discussions around this point are offered in the conclusions of the paper however). Instead, full transparency of the preliminary design process is provided, facilitating subsequent revisions to the candidate MEE architecture in order to capture application-specific requirements.

The structure of the paper is as follows: The Section 2 reviews and summarises the common features and differences in candidate MEE architectures proposed in the literature and patents. In Section 3, through the analysis of certification requirements of the MEE BPA concept and assumptions around operational functionality, a range of design rules and guidance are given for the derivation of a BPA concept and key systems. In Section 4, the paper summarises these design rules and recommendations and illustrates an example MEE BPA concept derived from these.

2 | REVIEW OF BASELINE ARCHITECTURE DESIGNS FOR MORE-ELECTRIC ENGINE

In this section, the various MEE power architectures proposed in the research literature and patents are reviewed, and the common features and differences in these are highlighted. It is found that most current MEE electrical power system architectures are presented in the literature as a basis from which to demonstrate novel system functions or new control methodologies rather than the architecture being the focus of the paper itself. As such, although a number of common features can be identified, no consistent baseline architecture is presented in the literature, and comprehensive design rationale/rules are also often not given. The section concludes that the establishment of preliminary-design requirements is necessary to define the key features and configuration of an MEE BPA concept, and that full transparency is required in this process in order to facilitate justifiable feature or architecture revisions at a later stage of the design process.

Y. Zhang, G. Peng et al. [6] propose a Power and Load Management system for MEE/MEA applications, which is demonstrated on a modelled MEE power system architecture [9], illustrated as Architecture A in Figure 1. This proposed architecture features a three-generator system with a three-channel power distribution network. Each generator is connected to a main channel, while a redundant channel is included in case of a failure in the main channel. A proposed single ±270 V DC distribution bus directly connects loads, supercapacitors, and batteries to all three generation channels. However, the establishment of this power system architecture has not been described in detail.

M. French, J. T. Alt et al. [10] describe an electrical system and its power controllers for gas turbine engines. The power architecture is given, but the design rationale for the architectural features is not included in the patent. Huw Edwards, R.W. Slater et al. [11] present an engine-based three-generator power system, which is illustrated as Architecture B in Figure 1, and which claims to improve the electric generating capacity and increase overall system efficiency. This patent focuses on the primarily on the mechanical specifications of multi-spool gas turbine engine where engine shafts transmit power through gearboxes. The intermediate-pressure (IP) shaft connects the main transmission gearbox to provide mechanical torque to two generators and the low-pressure shaft generates electricity through an independent gearbox. Energy storage can be used to stabilise the network by transiently removing or providing excess power to the loads. Further features of the electrical network architecture are not described in the patent.

Q. Zhang, M. Sztykiel et al. [12] propose dual and three channel MEE architectures with different busbar topologies to examine the effects of the busbar configuration on the reliability and weight of the overall architecture. Different busbar topologies such as radial bus and ring bus are reviewed. From these, a two-channel network with sectionalised radial bus topology is shown as Architecture C in Figure 1. In this power network, two stages of bus connection are illustrated. The AC

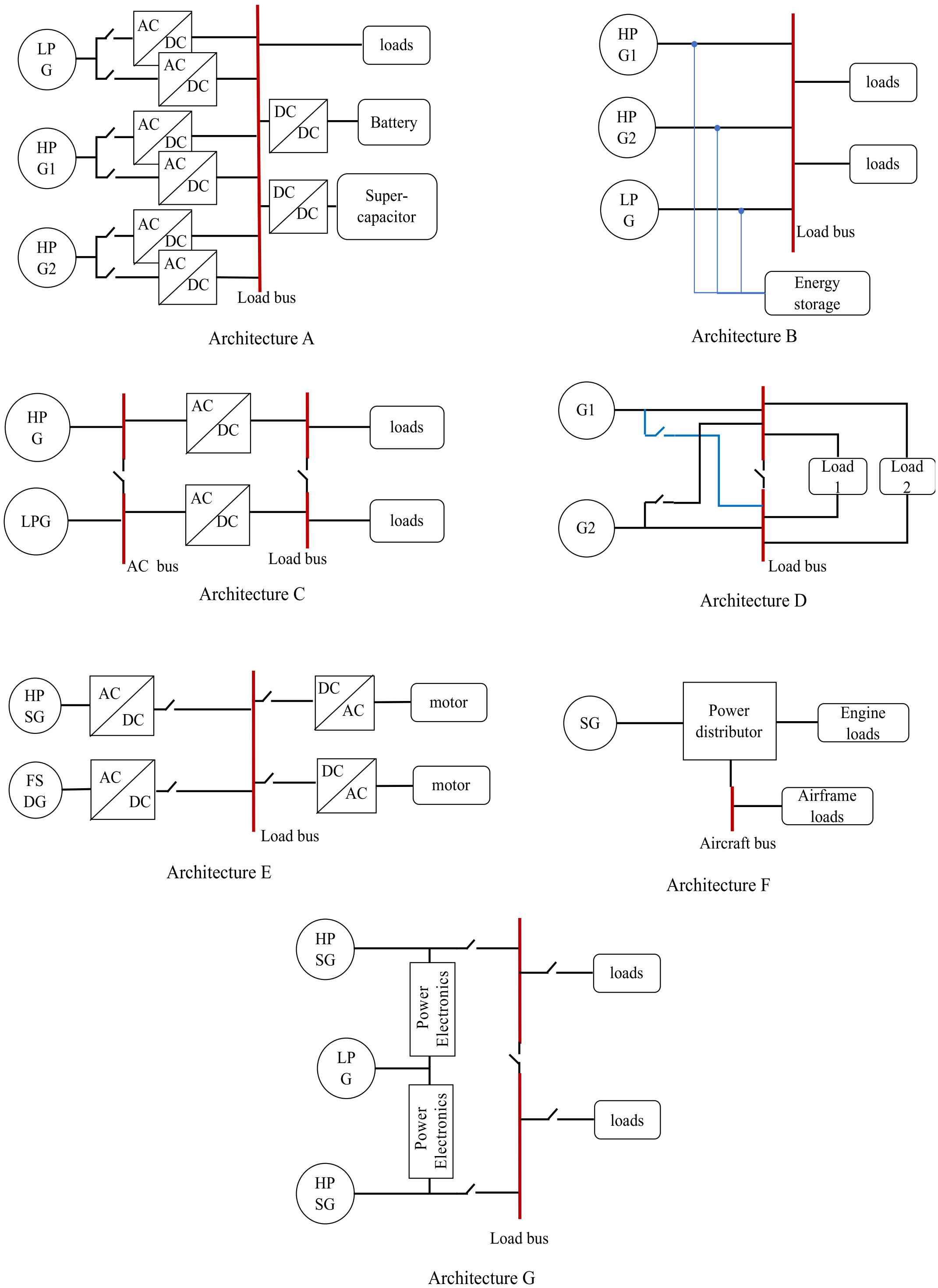

FIGURE 1 Proposed More-Electric Engine architectures.

bus is connected to the generators to supply power into the engine and fuselage loads, and the load bus is the High Voltage Direct Current (HVDC) bus connecting the engine loads. S. Fletcher, P. Norman et al. [8] describe the impact of engine certification and design requirements on a two-channel MEE power architecture, which is shown as Architecture D in Figure 1. In this, there are at least two power paths for each generator and critical load, although the rationale behind this configuration is not included in the paper. M. Hirst, A. McLoughlin et al. [13] present an MEE concept demonstrator, in which a single busbar distribution system is implemented. A simplified version of this architecture is shown as Architecture E in Figure 1. Similar to Architecture C, Architecture E features one high-pressure (HP) shaft driven generator and a Fan Shaft Driven Generator. N. Morioka, K. Daiki et al. [14] describe the actuation control technologies for a simplified

MEE power architecture, shown as Architecture F in Figure 1, which has only one starter/generator. In this architecture, a power distribution system is connected to an aircraft bus and engine loads, but little information on the architectural features is given. Lastly, J. Kern, H. Wiegman et al. [15] propose a three-generator power architecture for a multi-spool engine, shown as Architecture G in Figure 1. In this, the low-pressure generator is connected to both HP shaft generator AC channels by power electronic interfaces. A sectionalised radial busbar arrangement, connected to the HP generator channels, is utilised for the load bus.

From the MEE power architectures reviewed it can be seen that most of the proposed MEE architectures have redundancy in generation, distribution and critical loads, predominantly utilise radial bus configurations, feature HP/IP and Low-Pressure (LP) shaft offtake driven generation, and employ power electronic interfaces at the generators or busbar connections for power flow regulation. However, whilst these provide an indication as to the likely common features of an MEE baseline architecture, their use should not be assumed without the appropriate capture of existing or new design rationale. Indeed, whilst some recent articles in the research literature propose new reliability requirements for MEE systems [8] and requirements for the configuration and management of interconnected generation in MEE/MEA [16], comprehensive MEE design requirements and rationale for good practice design have not yet been comprehensively established.

It is therefore necessary to determine suitable requirements for the preliminary design of MEE power system architectures. Once the requirements established, adherence to these requirements will then illustrate the necessary features and configuration of an MEE BPA concept. However, overdesign is still a possibility when using this approach, and as such, the formation of a baseline architecture should be realised with due consideration of an overarching desire to also minimise the architecture weight and complexity, at least until later stages of the design cycle, where such elements may be more acutely justified.

The designed baseline model should reflect the reasonable use of high-Technology Readiness Level (Technology Readiness Level) technologies whilst also readily facilitating an evaluation of the function-unlock capabilities of novel breakthrough technologies. In addition, full transparency of the BPA design process is captured so that key design decisions can be later revisited if necessary to capture application-specific requirements and/or updates to certification requirements.

3 | DETERMINING KEY FEATURES OF THE MORE-ELECTRIC ENGINE BASELINE POWER ARCHITECTURE CONCEPT

The proposed key features of the MEE BPA concept are considered in the following subsections. In Section 3.1, considerations for system reliability, the number of generation systems, the number of distribution channels, and busbar topologies are presented. Section 3.2 is used to establish the power system features' requirements and design suggestions that should be considered in the MEE. Section 3.3 introduces the design considerations for nominal and off-nominal modes of operation. In Section 3.4, the required redundancy of MEE loads is addressed.

3.1 | Generators and reconfiguration considerations

System safety is the most significant design feature for any type of aircraft [17]. A summary of engine system failure rate specifications can be found in European Aviation Safety Agency (EASA) standards document CS-E [7]. According to this, the rate of a single conventional engine shutdown can be considered acceptable if it is no worse that 10^{-7} per flight hour (this level is identified as extremely remote of failure). For an MEE power system, all essential loads are powered via the electrical power system architecture. As such, the authors propose that for the baseline architecture definition (this may be revised at a later design stage), flight-critical electrical MEE loads should meet a stricter reliability classification. In other words, the loss of the functionality of these loads resulting from the loads themselves failing or as a result of a loss of electrical power supply to these loads should be extremely improbable, occurring at a rate of less than 10^{-9} failures per flight hour. This requirement will impact on the baseline power system architecture redundancy levels, and is explored further for key baseline architecture features and technologies in the following subsections.

3.1.1 | Number of power channel

A power channel is defined in this paper as an independent power flow path with at least one power supply source (i.e. a generator or energy storage system) and a distribution system, feeding one or more dedicated loads. When considering the number of power channels to utilise within an MEE electrical power system architecture, the impact on the reliability of the entire MEE power system should be considered. Informing this, the failure rate for a complete loss of electrical power supply from a power channel to its loads can be calculated using Fault Tree Analysis or other equivalent methods.

For example, the simplified power channel (with loads omitted for clarity) shown in Figure 2, featuring a Variable Speed Constant Frequency generator system, has a rate of complete power loss to the load bus of 2.5×10^{-4} failures per flight hour (using subsystem failure rate data from ref. [18]). This failure rate is calculated by summing the individual failure rates of the main system components, the failure of any of which (including the generator itself, cabling, protection/contactor, and Generator Control Unit) would cause this considered top failure event.

Employing a similar approach, the failure rate of a complete loss of supply can be calculated for configurations with 1, 2, 3, and 4 power channels. Whilst acknowledging that the use of different generation technologies may impact on the calculated failure rates, these indicative values provide useful guidance on the likely number of power channels required in the MEE BPA concept. These calculated failure rates are summarised in Table 1.

According to Table 1, the failure rate of a single power channel configuration is clearly not good enough to meet the imposed design requirements. It can also be seen the calculated failure rates for a 2-power channel system are close to meeting the imposed design requirement. Indeed, utilising different technologies or failure rate parameters may still yield acceptable failure rates. However, the authors believe that the use of at least 3 power channels in the MEE BPA is necessary to provide a sufficient design margin. Additionally, whilst from the results presented it can be seen that the 4 power channel system provides excellent failure rate characteristics, it provides no immediate useful value over the 3-channel system unless much-improved failure rates are required, but does introduce additional size and complexity to the BPA. As such, the authors recommend the implementation of a 3-power channel system for the MEE BPA concept.

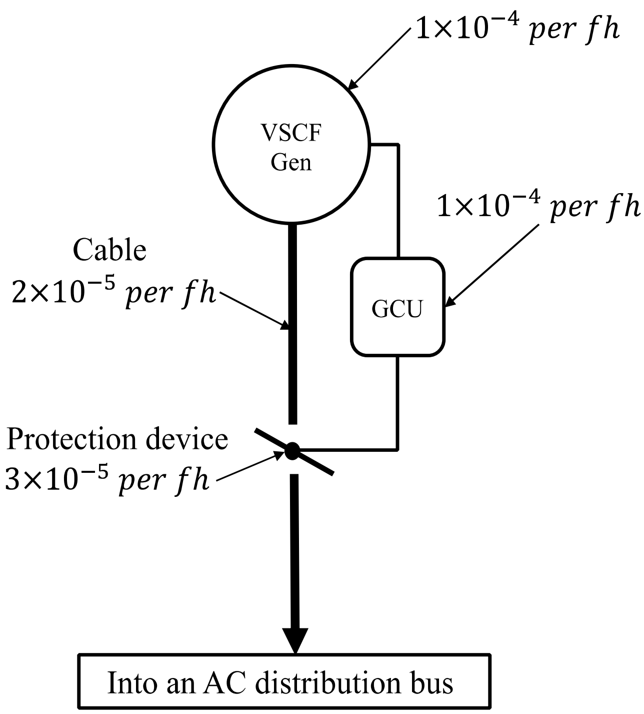

FIGURE 2 The variable speed constant frequency generation system with component failure rates.

3.1.2 | The busbar topology for More-Electric Engine baseline power architecture concept

The bus topology and the choice of the number of power channels each affect different characteristics of the distribution network. Bus topologies typically have less impact on the failure rate of total supply to the loads (where the number of power channels is the dominant factor), but they do offer different levels of flexibility in system reconfiguration and fault accommodation. Accordingly, these should be considered separately in the formation of the MEE BPA. Figure 3 illustrates the connection configurations of a selection of common bus topologies applicable to MEE systems, including the single busbar, sectionalised radial bus arrangement, ring bus arrangement, and breaker and a half (BAAH) bus arrangement. Other more complex configurations also exist, but are not considered here as they are considered by the authors to be too complex for consideration at the baselining stage. Table 2 provides a summary of the key characteristics of each of the illustrated busbar configurations. Note, that whilst the authors acknowledge their previous recommendation for the use of a 3-channel architecture, the busbar topologies illustrated here are configured 2-channel systems for simplicity.

The single busbar provides no redundancy, and is hence not recommended for the MEE BPA concept. The sectionalised radial bus arrangement has a circuit breaker system between two busbars, providing power flow reconfiguration availability, and is widely used in current aerospace applications [19–21]. Alternatively, the ring bus has flexible power paths and is often used in other transportation facilities, such as shipboard power systems [22]. BAAH arrangements are usually implemented in terrestrial power grids, featuring two busbars and two conducting bays to provide a high degree of flexibility in reconfiguring power flow between the buses and conducting bays [23].

In order to better understand the power path redundancy of each bus topology, Table 3 provides a summary of the quantity of power paths (from power sources to loads) retained

TABLE 1 Component failure rate and mission reliability according to number of power channels.

Number of generator systems	Failure rate of complete power supply loss (per fh)	Probability of complete loss of electrical power supply in a 5 h mission	Probability of complete loss of electrical power supply in a 10 h mission	Probability of complete loss of electrical power supply in a 15 h mission
1	2.50×10^{-4}	1.25×10^{-3}	2.50×10^{-3}	3.74×10^{-3}
2	6.25×10^{-8}	3.12×10^{-7}	6.25×10^{-7}	9.37×10^{-7}
3	1.56×10^{-11}	7.81×10^{-11}	1.56×10^{-10}	2.34×10^{-10}
4	3.75×10^{-15}	~0	~0	~0

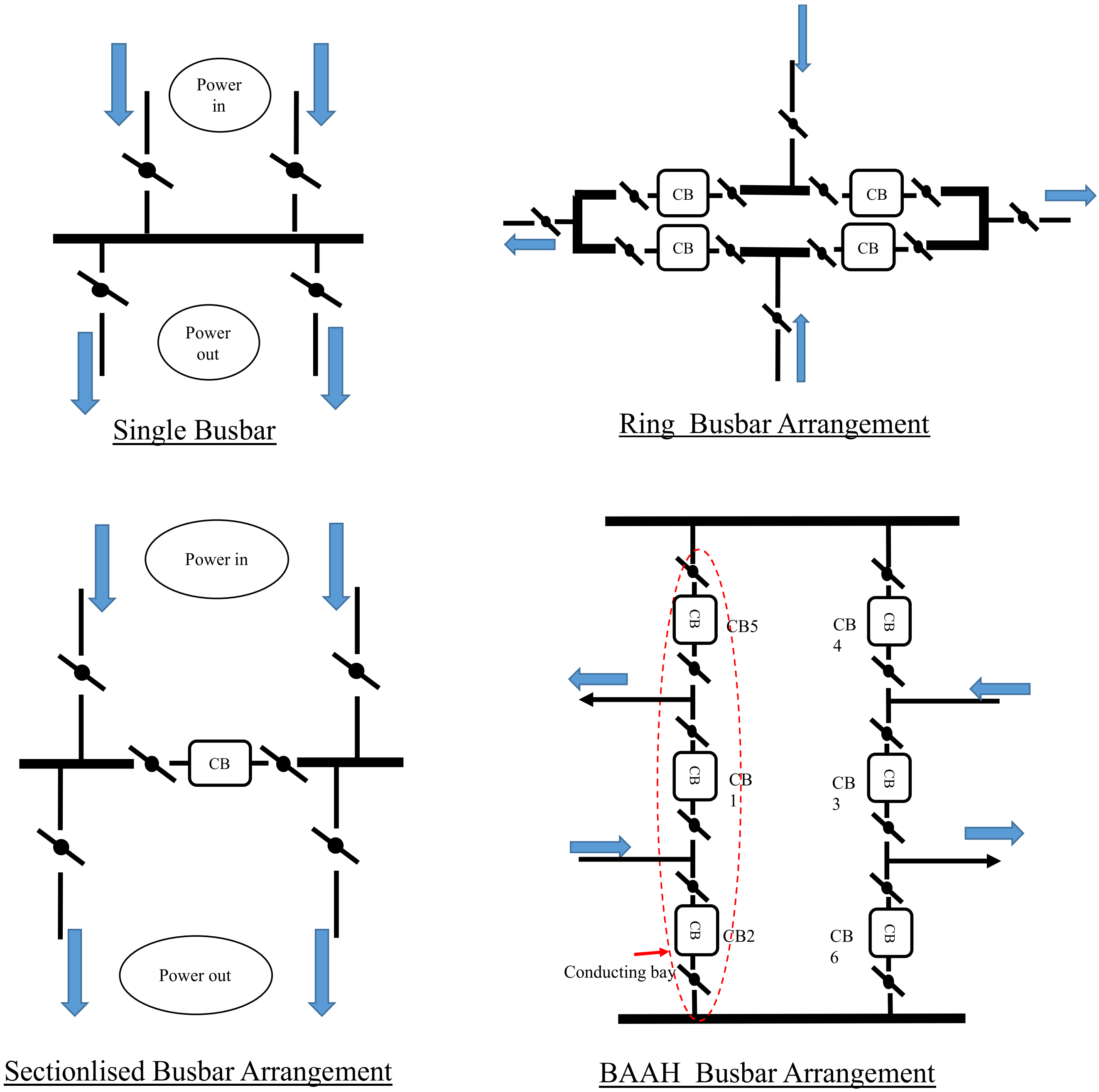

FIGURE 3 Potential busbar topologies for the More-Electric Engine baseline power architecture.

for each of the bus types described above, following a variety of different fault conditions. For some busbar topologies, where specific combinations of multiple faults lead to different quantities of power paths remaining, the minimum and maximum possible number of remaining power paths are indicated in the table.

From Table 3, it can be observed that the sectionalised radial busbar arrangement provides the minimum level of supply redundancy, while the ring bus arrangement offers an improved power reconfiguration capability and resilience. It is in the authors' opinion that the use of BAAH bus topology is unnecessary for the BPA concept, but this configuration may still be attractive at later stages of the system design when reconfiguration requirements are more specific. Overall, the authors recommend the use of either the sectionalised radial busbar or ring bus arrangements for the MEE BPA concept.

3.1.3 | DC power distribution for More-Electric Engine

HVDC distribution is consistently proposed in the literature as the preferred power distribution method for MEE systems,

TABLE 2 Potential busbar topologies for More-Electric Engine.

Type of busbar arrangement	Advantages and disadvantages
Single bus	• Simple operation. • Low initial cost. • Parallelling of sources is possible. • The entire power supply is impacted by the occurrence of a fault on or around the busbar. • No flexibility in power flow through the busbar.
Two-channel sectionalised radial busbar arrangement	• Single fault tolerant. • Increased component count and weight compared with a single busbar. • Sectionalising may cause transient interruption of the non-faulted channel.
Two-channel ring busbar arrangement	• An electrical fault in one section is localised to that section alone. The other section can continue to operate normally. • No single failure within the busbar arrangement can lead to the loss of a channel. • Further increased component count and busbar weight compared with previous configurations.
Two-channel breaker and a half (BAAH) busbar arrangement	• Features significant redundancy. • No permanent interruption of the power occurs following an electrical fault, as all power input can be transferred to another bus. • Further increased component count and busbar weight compared with previous configurations. • Complex control strategy may be required.

TABLE 3 Number of power paths remaining after the occurrence of electrical faults.

Failure case / Type of Busbar	One source failed	One busbar failed	One CB failed	Two CBs failed	One source and one CB or busbar failed
Single bus	1	0	N/A	N/A	0
Two-channel sectionalised radial bus	1	1	2	N/A	0 or 1
Two-channel ring bus	3	2	3	2	2
Two-channel (BAAH) bus	3	4	4	2 or 4	2

owing to favourable characteristics such as reduced end-end conversion losses (in systems with a prevalence of naturally DC-output or -input technologies), easier control of parallel power sources and a reduction in the size of current carrying conductors [4, 24].

In addition, with the emergence of converter-interfaced permanent magnet synchronous machines (and to a lesser extent, switched reluctance machines) as the most power dense generator technologies available for the aerospace sector (as discussed in ref. [25]), the use of DC distribution provides a natural interface. As such, DC distribution is recommended for the MEE BPA concept.

3.2 | Technical functionalities of the More-Electric Engine architecture

In addition to the number of the power generation and distribution channels, the required functionality, redundancy and configurations of key electrical technologies should be considered for the MEE BPA concept. The following subsections consider aspects such as starter/generators, mixed HP-IP/LP offtake, and power converter functionality.

3.2.1 | Starter/generator functionalities for More-Electric Engine

In current and proposed MEA designs featuring an electric engine start capability, two electrical HP/IP spool-driven starter/generators are employed so that aircraft dispatch is still possible with one of these machines failed. Electric engine starting affords a number of advantages including system volume and weight reduction through the application of dual-use subsystems (i.e. no separate air starter and electrical generator), and supports the wider reduction of engine bleed-air use and the potential complementary elimination of pneumatic secondary power systems around the aircraft [26]. As such, it seems reasonable to recommend that the MEE BPA concept also features, as a minimum, two electrical starter/generators mounted on the HP/IP spool, per engine, although additional generators may also be required (as discussed in subsequent sections). As discussed earlier, permanent magnet synchronous machines [27, 28] and switched reluctance technologies [29] appear to offer favourable characteristics for future aero-electrical applications.

3.2.2 | HP/IP and LP shaft offtake

Whilst current state of the art MEA feature HP- or IP-only driven generation (for example the B787 features 2 HP/IP driven starter/generators per engine [27]), the anticipated increase electrical power offtake required for the MEE electrical engine auxiliary systems and the required third generation channel per engine may necessitate a change in approach. The use of additional LP spool-driven generation to supplement existing HP offtake power has been shown to potentially improve engine stability and fuel consumption [16, 27]. In addition, LP shaft-driven generation also has the potential to provide a limited supply of emergency electrical power offtake in some off-nominal engine operating conditions, such as wind-milling (discussed later in Section 3.3). However, the LP shaft does have a wider operational speed range, impacting on the driven-generator size and associated downstream power conversion systems, which require careful consideration in the design stage.

For the MEE BPA concept, it is hence recommended that at least one LP spool-driven generator is utilised in addition to the previously recommended two HP/IP spool-driven starter/generators per engine.

This recommendation is consistent with the earlier recommendation on the minimum number of BPA channels, which raises an interesting issue. Even if the failure rate requirement for the MEE electrical loads could be justifiably and safely relaxed, the number of BPA power channels is more likely to be shaped by redundancy requirements in the starter/generator systems, improving engine operability and optimisation of generator sizing. Only if fault-tolerant multiphase machines were employed (thereby enabling the use of a single starter/generator), would the safety requirements shape the boundaries of BPA design space.

3.2.3 | Nature, functionality and directionality of power converters

There are various types of converters that could potentially be utilised within an MEE system. Therefore, early consideration of the characteristics (the type, functionality, and directionality) of the power converters can minimise uncertainty in subsequent design phases.

For the MEE BPA concept, the authors recommend the initial working assumption of a bidirectional capability in all power converters, which implies that the power converters should also be assumed to be actively controlled (i.e. no passive converter topologies are utilised). Whilst these assumptions may be later revised once specific power converter operating requirements and topologies are considered, the assumption of bi-directionality enables the identification of all possible configurations/operating states of the BPA at this preliminary design stage.

In addition, the authors recommend the initial working assumption that all power converters are non-isolated in nature. Whilst a range of common aerospace rectifier and DC-DC converter topologies do provide galvanic isolation between input and output, the consideration of this level of detail, and indeed the grounding/bonding configuration of the power system are out of scope of the BPA concept definition.

With the emergence of wide band gap devices, such as SiC and GaN, facilitating improved efficiencies and weight reductions in new power converter designs [30, 31], there is the potential for a shift in 'convention' in high-performance power converter topologies. This may potentially require assumptions around bi-directionality, galvanic isolation and DC distribution to be revisited on a case-by-case basis.

3.3 | Nominal and off-nominal mode considerations for More-Electric Engine power architecture

This section describes power supply and distribution functions in nominal and off-nominal modes of operation, addressing the potential impact on the MEE BPA concept configuration.

3.3.1 | Power source independence

The definition of an independent source can be found in amendment 5 of CS-23 [32]. In CS-23.2430 section a), it is stated that the power-plant installation, energy storage and electrical power distribution system must 'be designed to provide independence between multiple energy storage and supply systems so that a failure in any one component in one system will not result in the loss of energy storage or supply of another system'. Reflecting this to the MEE BPA concept, separate electrical generators or battery systems can hence be considered as independent sources unless they are parallelled within the BPA. It is recognised that parallelled generation may be required to maximise the benefits of mixed HP/IP-LP power offtakes, and that the implementation of fast isolation switches or similar devices may still realise independence between parallelled sources following an electrical failure or fault. However, the authors recommend the use of non-parallelled sources at the outset of the formation of the BPA concept in order to enable the definition of power channels and load connections before potential additional complexities associated with the parallelling of sources, and protection against fault and failure conditions are introduced.

3.3.2 | Energy storage systems use in nominal and off-nominal modes of baseline power architecture operation

In proposed MEA applications, Energy Storage Systems (ESS) are typically battery-based systems, with the capability to temporarily provide or absorb electric energy from the electrical power system. Functionally, they are often proposed either for use in normal operation (to meet peak loads and enable the reduction of main generator ratings and load step stresses) and/or to provide a secondary emergency supply in case of a loss of the primary generation source (increasing the availability of power to flight critical loads). Given the transient and flight-critical nature of typical MEE electrical loads, the use of ESS in both roles is likely for future MEE platforms. Indeed, with the increasing energy-densities of modern battery technologies, an increased use of battery-ESS systems for normal-operation generator support can be expected.

In addition to its functional role, it is also necessary to consider both the location and complementarity of the ESS to other generation sources within the MEE BPA concept. Detailed specification of power rating and capacity are not required during the definition of the MEE BPA concept though.

In terms of location, if the ESS main function is to provide supplementary power during transient peak loading conditions, connection to a generator bus will be most effective. In contrast, if the ESS main function is to provide an emergency supply of power to essential engine loads during transient or sustained periods of supply loss from the main generation, connection to a dedicated load bus is likely to be required.

In terms of complementing or providing an alternative to other generation sources, it is apparent that ESS cannot replace either of the two recommended HP/IP generators because of the aforementioned electrical engine starting and dispatch requirements. Theoretically, the use of a suitably rated ESS could alleviate the requirement for a dedicated LP generator in some applications. However, the authors recommend against this approach at the MEE BPA concept definition stage until more specific load profiles and criticalities are established.

In summary, when establishing the MEE BPA concept, the authors recommend the inclusion of at least one ESS system at either a generator busbar or load busbar location within the MEE BPA concept, operating in both generator support and emergency power supply roles. This ESS should be considered in addition to the already established primary generation. Whilst it is likely that the ESS specification and requirements will be revised at later stages of the system design, its inclusion in this manner in the BPA concept encourages definition of key power architecture features required for its incorporation.

3.3.3 | Wind-milling of LP/fan-shaft driven generator

Wind-milling describes the action of rotating the engine shafts using natural air intake whilst the aircraft is in flight. This process can be utilised to restart a stalled engine in mid-air (if the APU is unavailable to restart the engine). It also represents an opportunity for continuous but reduced-scale electrical power offtake from the rotating LP/Fan-shaft engine shaft (if it is undamaged) [33]. Indeed, the authors in ref. [34] indicate that 10% of the normal rated power output can be generated from a wind-milling LP generator. With this additional power supply, if the LP generator is connected to the essential loads within the BPA concept, it could add more power supply flexibility to the architecture.

However, it is worth noting that some engine-electrical loads may require continued supply even during wind-milling conditions, reducing the effective power available from the LP shaft generation to other flight critical loads. For example, continued operation of fuel and oil pumps may be required to provide continued cooling and lubrication benefits for the LP shaft [35]. As such, during the BPA concept definition, the authors recommend that the LP wind-milling generation is not considered as a valid alternative to ESS for an emergency power supply role, as a significant surplus of electrical energy is not guaranteed.

3.3.4 | Alternative use of auxiliary power unit generation

An APU is an independent source of electrical, hydraulic and pneumatic power on board an aircraft, and is typically utilised whilst the main aircraft engines are not operational (for example to power cockpit and cabin systems when the aircraft is stationary at the terminal gate, and for engine starting). However, the APU can also be utilised to provide electrical power to the airframe during flight, if for example, the aircraft has been dispatched with a main generator faulty [36]. Indeed, research is ongoing exploring the more regular use of APU generation systems throughout the entire flight envelope in order to reduce the impact of increased electrical offtake required for more-electric loads on the operating efficiency of the main engines [37].

Using the in-flight APU generation may enable reductions in the size/weight of the main engine-driven power generation systems (although these rating are not considered in detail during the BPA concept definition), but it cannot replace a HP generator because of the starting requirements of the engine. The APU could be considered as an alternative to LP-driven generation if the designers are specifically targeting a concept with blended APU and on-engine generation. Otherwise, the availability of the APU generation for normal operation should not be assumed, although this choice can be revisited at a later stage of the design process. Furthermore, in-flight APU generation cannot be considered as an ESS alternative if the ESS is performing the recommended dual roles, as the previously established emergency power role requires a close location of the ESS to the flight-critical loads.

As such, in the BPA concept definition stage, the authors suggest that the use of APU as a supply for MEE loads purely the choice of designers.

3.4 | Redundancy within More-Electric Engine essential loads

Essential auxiliary MEE loads may include; fuel pump systems, oil lubrication systems, and electric thrust reverser actuation systems [38]. For the MEE BPA concept definition, the authors recommend that the preliminary design requirement for these essential load systems is the provision of single-fault tolerance [39]. As such, it is recommended that each essential load has both a primary and redundant power supply path, and that these two paths are supplied from upstream buses which are in turn, supplied by separate generators. Given the potential uncertainties in equipment failure rates and the impact of the engine compartment operating environment, this decision can be revisited later in the design process, where a greater level of redundancy may be deemed to be required.

The previous recommendations regarding recommended busbar configurations are consistent with the provision of single-fault tolerance. Furthermore, Figure 4 illustrates an example configuration of MEE essential loads supplied from a dual split-bus. The illustrated MEE auxiliary systems could for example, be driven by double stator-winding motors [40, 41] or two single-stator motors powered by main and redundant local power electronic drives. As with the starter/generator machines, the use of fault-tolerant multiphase machines and drives may potentially enable the deployment of just a single motor drive for each MEE load.

4 | FORMING AN MORE-ELECTRIC ENGINE BASELINE POWER ARCHITECTURE CONCEPT WITH THE SUMMARISED RECOMMENDATIONS

This section summaries the baseline architecture design recommendations given in detail in Section 3 and illustrates a potential MEE BPA concept configuration, which is established based on the prior recommendations given.

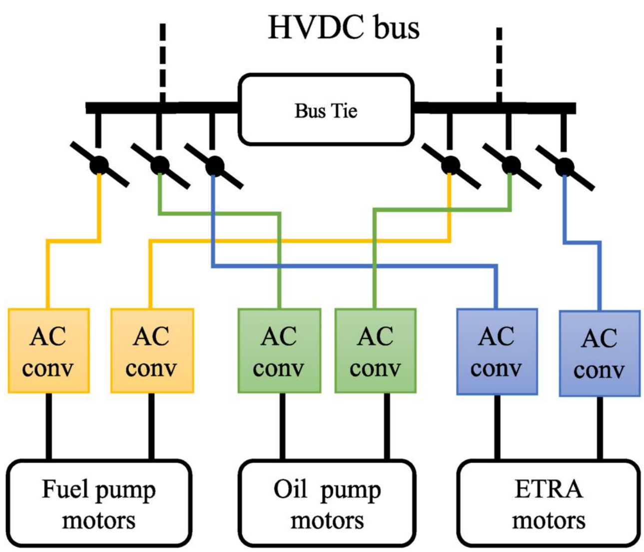

FIGURE 4 Proposed More-Electric Engine essential loads with system redundancy.

4.1 | Summary of baseline power architecture concept design recommendations

After considering the system reliability, equipment choices and the technical functionality of the MEE BPA, the summary of design recommendations is given as follows:

1) The probability of power supply failure to the essential loads for the MEE BPA should be in the level of extremely improbable condition, which is below 10^{-9} per flight hour.
2) The MEE BPA concept should be a three-channel network combined with a three-generator system.
3) In terms of bus connection, the BPA concept should at least consider the three-channel sectionalised radial bus to provide minimum power reconfiguration ability. For additional dispatch flexibility, the three-channel ring bus can be considered.
4) A DC distribution system is recommended for the MEE BPA concept.
5) The use of one LP spool-driven generator and two HP/IP spool-driven starter/generators is recommended.
6) At least one ESS should feature in the BPA concept to support off-nominal conditions and temporary peak loading on the MEE. In terms of location, if the main function of the ESS is to provide supplementary power during transient peak loading conditions, the ESS should be connected to a generator bus. If instead, the main function of the ESS is to provide an emergency supply of power to essential engine loads during transient or sustained periods of supply loss from the main generation, the ESS should be connected to a dedicated load bus.
7) In the BPA concept stage, all converters can be assumed to be active, bidirectional, and non-isolated.
8) In the BPA concept, APU-driven generation should not considered be an alternative for HP-driven generation nor for the dual-role ESS. It can perhaps be considered as an alternative LP-driven generation but is dependent on the design concept of the MEE system.
9) LP wind-milling generation should not be considered as a valid alternative to ESS for an emergency power supply role in the BPA concept.
10) Flight-critical loads and corresponding power paths must meet the single-fault-tolerance requirement, whereby each flight-critical load needs at least one redundant power supply from a different upstream bus to the main supply.

4.2 | An example More-Electric Engine baseline power architecture concept

Figure 5 shows an illustration of the three-generator, three-channel MEE BPA concept, derived from the design recommendations provided earlier.

In this MEE baseline architecture, multi-shaft power generation is utilised. Two HP starter/generators and a single LP shaft-driven generator are configured as a three-channel system

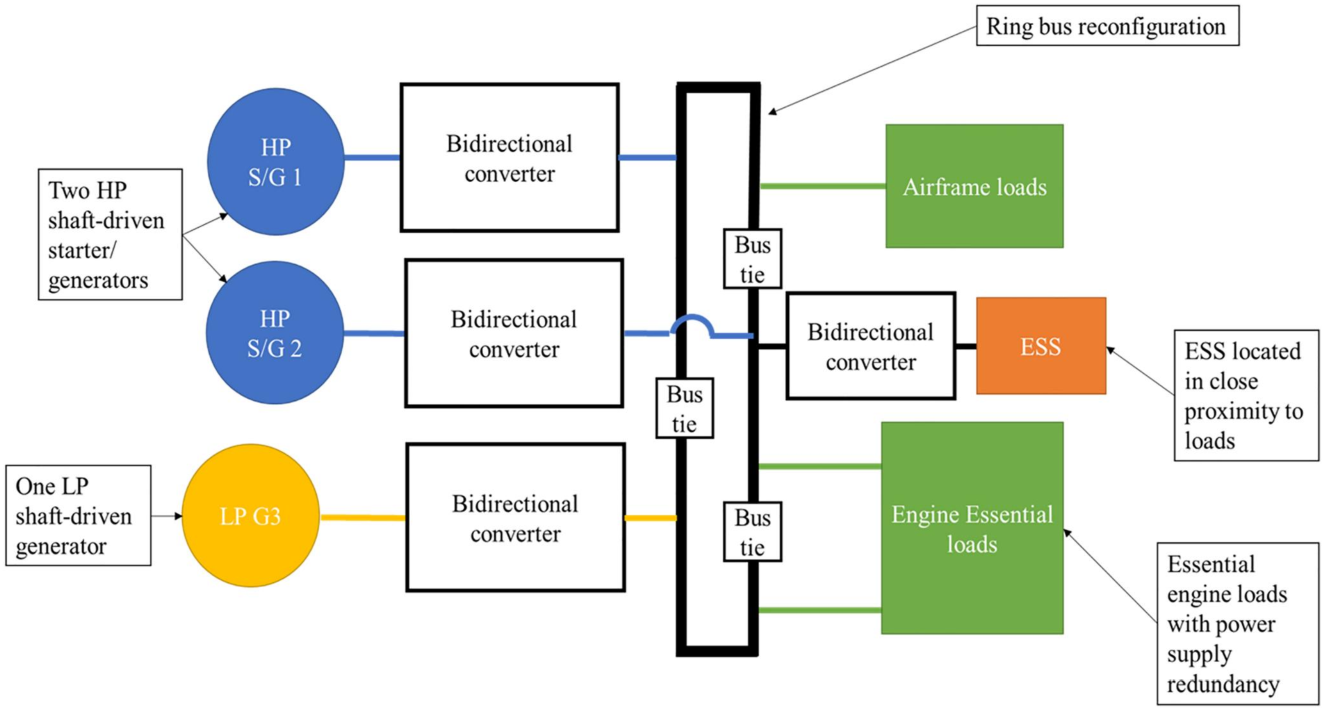

FIGURE 5 The example of baseline power architecture for More Electric Engine.

with dedicated bidirectional power electronic converters to interface the generators to the DC network. A three-channel ring bus topology has been implemented to provide a significant degree of power reconfiguration capability, and all engine-essential loads feature power supplies from different upstream buses. A single busbar feed is assumed to be sufficient for the airframe loads, although this design decision can be easily revisited. The assumed primary role of the ESS in this example is that of an emergency supply, and as such, it is connected to a load bus for proximity to the loads themselves. Finally, APU and wind-milling generation are not featured in this BPA concept based on the previous design recommendations.

As discussed in earlier sections of the paper, a number of sensitivities exist which may result in potential changes to the presented example BPA concept. In particular, the use of multiphase/fault tolerant drives and generators, or parallelled generators could instigate a required increase or the option to decrease the number of generators and/or power channels featured, impacting also on number and configuration of downstream busbars. Improvements in battery ESS energy densities may further encourage their use for normal operation, dictating a change in location in the BPA (as well as possible change in the busbar configuration to facilitate greater levels of availability of supply to MEE loads).

5 | CONCLUSION

Whilst significant research has been undertaken on MEE electrical systems and technologies to date, this paper has identified that there is still the need for a credible, consistent, baseline power system architecture to be established. Accordingly, comprehensive design recommendations are presented in this paper to facilitate this. These are derived using a combination of anticipated safety requirements, failure rates analysis, and logical functional system needs.

Whilst at the outset of this study, it was noted that there was the potential for a significant design space and scope of variation in the formation of the MEE BPA concept, the establishment of the design recommendations has been shown to reduce this uncertainty to manageable levels, providing a platform for rapid design evolution thereafter. Capturing the rationale of these recommendations also enables key decision points and even design recommendations themselves to be revisited as necessary in order to capture application-specific requirements, updates to certification requirements and/or the utilisation of game-changing technologies (for example fault tolerant electrical machines or power electronics which may enable the use of fewer power supply channels or greater periods between maintenance). Indeed, further research is required in this particular aspect, assessing the potential impact of a wide range of breakthrough technologies on the BPA concept, allowing potential updates to be mapped.

This paper has not directly considered aspects such as; fault management, where the requirements for protection systems will be shaped by a need to minimise disruption to the continued operation of MEE loads as well as preventing propagating fault effects to nearby engine systems; power quality and EMI requirements, where new power quality standards may need to be derived to reflect the unique environment and potential robustness of motor loads; and operating voltage/insulation requirements, which look to optimise system mass but account for power transmission routes through harsh environments. Further work into these aspects could yield additional useful insight in the shaping of an MEE BPA.

From previous research conducted into the feasibility of MEE systems, the true benefits of these new platforms, beyond the immediate fuel burn reduction which could be provided by electric fuel pump systems, are unlocked synergistically through the electrification of all engine auxiliary loads. As such, the electrical power system architecture becomes the final underpinning system for transition to the higher TRLs (and associated system-level testing) required for the realisation of MEE systems on in-service aircraft. In this manner, the definition of a credible BPA becomes a key step for the future of the MEE.

AUTHOR CONTRIBUTIONS

Qiyang Zhang: Conceptualisation; Formal analysis; Investigation; Methodology; Writing – original draft. **Patrick Norman**: Methodology; Supervision; Writing – review & editing. **Graeme Burt**: Supervision.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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