The Design of More-Electric Engine Power Systems

Qiyang Zhang

Submitted for the Degree
of
Doctor of Philosophy

Rolls-Royce University Technology Centre
Department of Electronic and Electrical Engineering
University of Strathclyde
Glasgow

16 February 2024

Abstract

The More-Electric Aircraft (MEA) concept is now a well-established concept, following its introduction and development over the previous couple of decades. MEA systems are underpinned by state-of-the-art technologies to realise the reduction of CO2 emissions and increased the effectiveness of on-board power transmission. The More-Electric Engine (MEE) concept is increasingly being seen as a complementary solution for MEA applications. Within this concept, the engine auxiliary systems such as fuel pumps, oil pumps and actuation systems will be replaced by electrically driven equivalents and power will be extracted from multiple different engine shafts for electrical generation, with the potential to achieve significant fuel savings. However, with these changes, a dedicated high-integrity and flexibly reconfigurable MEE multiple-channel power architecture is required.

When designing a multiple-channel power architecture for MEE， it should comply with relevant power system design certification standards, requiring the application of a multi-disciplinary design methodology. In this thesis, key design certification and airworthiness standards are reviewed in order to identify those applicable to MEE design. Combining these with traceable qualitative and quantitative design logic, the first power system design rule set for MEE power system architecture baselining is established. Building on this foundational knowledge base, candidate novel multiple-channel power architectures are proposed and evaluated. These studies determine that a high degree of controllability and redundancy is key to achieving high system reliability and resilience in MEE power system architectures.

In addition, a review of the research literature in this thesis is shown to reveal a shortage of proposed design and optimisation processes for flexible and redundant MEE-type power systems, making it difficult to maximise the design value of a feasible solution. As interdisciplinary and multi-system design processes can be time-consuming and laborious, this thesis instead presents a concurrent design (Co-design) methodology, addressing both MEE power architecture concepts and power management functions. This novel design

process includes an initial coarse optimisation to determine the design space boundaries and exclude unsuitable and over-designed solutions for further detailed design, reducing design iterations. A subsequent collaborative synthesis stage for the concurrent design process is then proposed, in which fault scenario case studies and load shedding factor are used to verify the robustness of the combined MEE architecture and power management solutions to off-nominal operating conditions. This enables the refinement of the solution-space by using the simulated results to highlight the areas of the MEE power architecture that can be further optimised, demonstrating the benefits of knowledge-based collaborative design as a process for multi-criteria design.

The contributions to the design of MEE power systems architectures presented in this thesis hence provide end-to-end value to the academic and industrial research community in the formation and design of new MEE concepts, with wider application to technologically-adjacent applications (such as hybrid electric aircraft, or high-integrity dc microgrids) also possible.

Contents

List of Figures

List of Tables

Abbreviations

AEA	All-Electric Aircraft
APM	Architecture and Power Management
APU	Auxiliary Power Unit
ATAG	Air Transport Action Group
ATRU	Auto-Transformer Rectifier Unit
ATU	Auto-Transformer Unit
BAAH	Break and A Half bus arrangement
BPA	Baseline Power Architecture
CB	Circuit Breaker
CF	Constant Frequency
CO2	Carbon dioxide
CPU	Central Processing Units
CSD	Constant Speed Drive
CSCF	Constant Speed Constant Frequency
EASA	European Union Aviation Safety Agency
EMA	Electronic Mechanical Actuator
EMI	Electromagnetic interference

EPS	Electrical Power System
ESS	Energy Storage System
ETRAS	Electrical Thrust Reverse Actuation System
FAA	Federal Aviation Administration
FHA	Functional Hazard Assessment
FSDG	Fan Shaft Driven Generator
FTA	Fault Tree Analysis
GCU	Generator Control Unit
HP	High-Pressure
HVDC	High-Voltage Direct Current
IC	Integrated Circuit
IDG	Integrated Drive Generator
IP	Intermediate Pressure
IGBT	Insulated-Gate Bipolar Transistor
LP	Low-Pressure
MEA	More Electric Aircraft
MEE	More Electric Engine
MILP	Mixed-Integer Linear Programme
NPC	Neutral Point Clamped
PLM	Power and Load Management

PM	Permanent Magnet
POA	Power Optimised Aircraft
PSSA	Preliminary System Safety Assessment
RAT	Ram Air Turbine
SAE	Society of Automotive Engineers
SAF	Sustainable Aviation Fuel
SF	Load Shedding Factor
SR	Switched Reluctance
SVPWM	Space Vector Pulse-Width Modulation
TRL	Technology Readiness Levels
TRU	Transformer Rectifier Unit
VF	Variable Frequency
VFSG	Variable Frequency Starter Generator
VSCF	Variable Speed Constant Frequency
VSVF	Variable Speed Variable Frequency
WF	Wound Field

Acknowledgements

First of all, I would like to thank my supervisors, Dr. Patrick Norman and Professor Graeme Burt, for their truly valuable technical guidance on my PhD in the field of electrical power system engineering and thank them for being given me the opportunity, encouragement and support to pursue my doctoral degree. It is my honour that I have such knowledgeable, approachable, and dedicated supervisors.

I would also like to thank Dr. Kenny Fong and Dr. Michal Sztykiel for their invaluable spiritual and technical support. I am also grateful to all members of the Strathclyde Aero-team and long-standing members of the AES group, for given me such a memorable and enjoyable PhD experience. As a team member, I have been experienced a first-class research environment and organisational culture.

I am grateful to my grandparents who are located far from me have been alongside and encouraged me throughout the PhD. I would like to express my heartfelt gratitude towards my parents, Bofeng and Yuhua, for their many years of nurturing and selfless dedication to me. I would like to express my wife, Katie, a special thanks for being with me all the time whatever the difficulties had been came. Finally, I would like to thank my daughter, Claire, for giving me the motivation to complete my doctoral degree and thesis.

Chapter 1.
Introduction

By 2050, in order to minimise the impact to global warming, 75 % of CO2 mission reduction per passenger kilometres is targeted by aviation sector of European Commission[1] to support the ATAG goals. One option to help achieving this target is in the development of more energy efficient aircraft system design with the advanced technologies.

As part of this, one way is to disruptively change the entire propulsion and auxiliary system layout on the aircraft through replacing the full electrically propulsion and electrically auxiliary equivalent. In literature [2][3], the CO2 emission can potentially be completely/mostly removed by the use of All-Electric Aircraft (AEA) and Hydrogen-Powered Aircraft. However, based on the current power density of electronic components and the energy storage technologies, the AEA concept would be a more applicable on the small-scaled aircraft [4]. The narrow/wide-body AEA can be considered as a long-term goal on the aviation industry and engineering philosophy. In line with realistic development and current technology progression, narrow/wide-body aircraft also take up a certain percentage of the CO2 emissions, and the AEA concept with electric propulsion has limited application for narrow/wide-body models in near future[5]. Although the concepts of using Sustainable Aviation Fuel (SAF) and hydrogen fuel cell are proposed for aircraft applications to achieve the CO2 emission reduction, the infrastructure, storage, distribution, and associated systems is still in initial stage developments. With all the uncertainties of development on hydrogen-based fuel, the concept is also expected as a long-term development[6]. How the large-scaled aircraft can transitionally improve their energy conversion systems to satisfy the CO2 emission goals then becomes a challenge.

Another option to solving the CO2 emission issue in large civil aviation is to replace the conventional aircraft systems incrementally with More Electric technologies[7]. In the concept of MEA, conventionally, mechanical or bleed air secondary systems are replaced by electrically powered equivalents (excluded the propulsion). In the past two decades, the MEA has been developed and applied in the aerospace industry. The power distribution efficiency has been initially improved, and the CO2 emission has been reduced significantly. As one of the first generation MEAs, the Boeing 787 has achieved 20% CO2 emission reduction compared to the other similar sized conventional aircraft. On Boeing 787, the amount of bleed air from the combustion chamber is reduced, with fuel savings of 3% and 35% less power has extracted from engine; along with component weight reductions [8].

Although the first generation of MEA have achieved significant reductions, there are still other auxiliary systems that can be converted to ‘More Electric’. The next generation of MEA can potentially further reduce the hydraulic systems and hydraulic architecture to their complete electrically driven equivalent or locally closed-loop hydraulic system that's driven by an electrical system, in order to further reduce the fuel burn [5]. With such increases in electrification this will further increase electrical power off-take from the engine as well as the electrical demand and associated electrical system size. The concept of More Electric Engine (MEE) is also part of the solution to further improve efficiency performance using electrical engine loads and the increase of electrical power generation, using different engine shafts for more effective power off-take. Therefore, MEE can improve the energy conversion efficiency. However, the aerospace sectors such as EASA [9]and FAA[10] tend to be cautious in adopting innovation.

As a new system on the MEA, MEE power network needs to be compatible with certification requirements in terms of system failure and system redundancy, which may require long development processes and strict testing. In term of the system design, the MEE power system should adhere to required level of reliability and fail-safety to cope with failures and faults. Currently, in the aerospace sector, EASA has published a special condition standard for EVTOL, but this cannot directly be referenced for MEE power systems due to conceptual differences. Although the existing industry standards (such as ARP4754/4761, CS-25 and CS-E) already provide a design boundaries and development guidelines for the aircraft system-level requirements, supplementary design approaches to optimise the design of MEE power systems are still required. Once the safety performance of the designed MEE power system is matched with the industry standards, it still needs to ensure the compatibility and integration of MEE power architecture and power management, which would be a challenge. According to all of that, it is necessary for this thesis to investigate these issues when MEE is playing an increasingly important role in the aviation industry.

1.1. Research Justification and Objectives

For decades, the high reliability design specifications for aero turbine engines have been focused on traditional configurations that are not optimised for MEE applications. For MEEs that require more electrical power supply and electrical distribution flexibility, it is important to re-evaluate the MEE's design guidelines and rules. Unlike conventional aircraft gas turbines, the MEE concepts increase the total electrical off take from the engine shafts. However, many of the critical sub-systems are still in development and have not been fully deployed in the aerospace environment. Therefore, the utilisation of the component configuration and technology and how they can integrate into the MEE power architecture prototypes is an urgent task.

1.1.1. The Scope of research

In term of system engineering study, the scope of this research is mainly focus on the power system reliability, component weight, operational flexibility of the system and the availability of power architecture reconfigurations for MEE. The cost of different technologies would be varied in the market and difficult obtain from public domain data, which is not in the scope this thesis. Furthermore, details of power electronics and battery design/sizing and the aircraft grounding technologies are not considered in scope of research. Regarding the Power and Load management (PLM) strategy, the thesis is offering high level of description of PLM. The design process of PLM strategy is also not included in scope of research.

1.1.2. The Necessity of a Baseline Architecture

Most literature focuses on either intelligent electrical management algorithms[11][12][13] or specific technologies development such as energy storage[14][15], power converters[16][17][18], generators[19][20][21] rather than systems integration. The information available in the public domain in this area is relatively limited. Thus, this thesis proposes to address this research gap by firstly **establishing an electrical architecture baseline** for the MEE concept to capture key system requirements of the MEE design. In particular, the baseline targets the multi-criteria design rules of the MEE power system design, which contains the electrical architecture requiring the redundancy of equipment, stringent weight, and the resilience of the power distribution. To design the power system of the MEE, it must be considering the reliability and redundancy of power supply[22], and stringent weight. Therefore, simply transferring the technologies and power architectural layout from other transportation application such as marine and electric vehicle are not feasible.

1.1.3. The Requirements of a Suitable Design Approach for MEE Power System Integration

Even after the MEE baseline model is determined, there is space for design refinement. The existing literature is focused on the design and optimisation of MEE sub-systems such as optimal power management scheme [23] and power system reliability analysis [24], but no studies have been done on the framework/design approach of overall system level and the integrated process of MEE power systems.

Hence, a further significant challenge is that the configuration of the electrical architecture and the choice of electrical management strategy has a strong impact on the overall performance of the MEE. Considering that the complementary nature and compatibility aspects of the electrical management and power architecture are key elements to the operational safety and power distribution flexibility of MEE power system, **it is necessary to utilise a suitable design approach to optimise the overall performance of power system coarsely at the early stage of design for MEE**. Furthermore, the thesis also proposes a potential solution to address this challenge completely **via a refining design procedure in the detail design that can reduce the uncertainty when the power architecture and the power management scheme are synthesised into an MEE system**. With the cooperation of the preliminary optimisation and refining design procedure, the design of power architecture and power management strategies can be incorporated and achieve the compatibility of both in nature of the design flow. The novelty of this entire design approach is enabling the integration of the subsystem-level characteristics at beginning of the design to reduce the design space, and a detailed integration of power management and architecture at the same time for system-level refinement. To date, there are no such detailed systematic developments in the published MEE system design [25].

Since most of accessory systems of contemporary engines are still driven by full hydraulically or electric-hydraulically[26], it can be argued that the MEE concept is currently still at low Technology Readiness Levels (TRL); and its design approach has also not yet been determined. There is now the opportunity to conduct an overall investigation on the design influences of developing a future 'more electric' jet engine. Because the power architecture design has a more visual manner in displaying the changes of the design demonstration, the thesis proposes that the use of the design of electrical architecture as a breakthrough point to investigate the overall development of MEE power network.

1.2. Research Contributions

The thesis provides the following contributions to knowledge (a diagram of the relationship between contributions is shown as Figure 1):

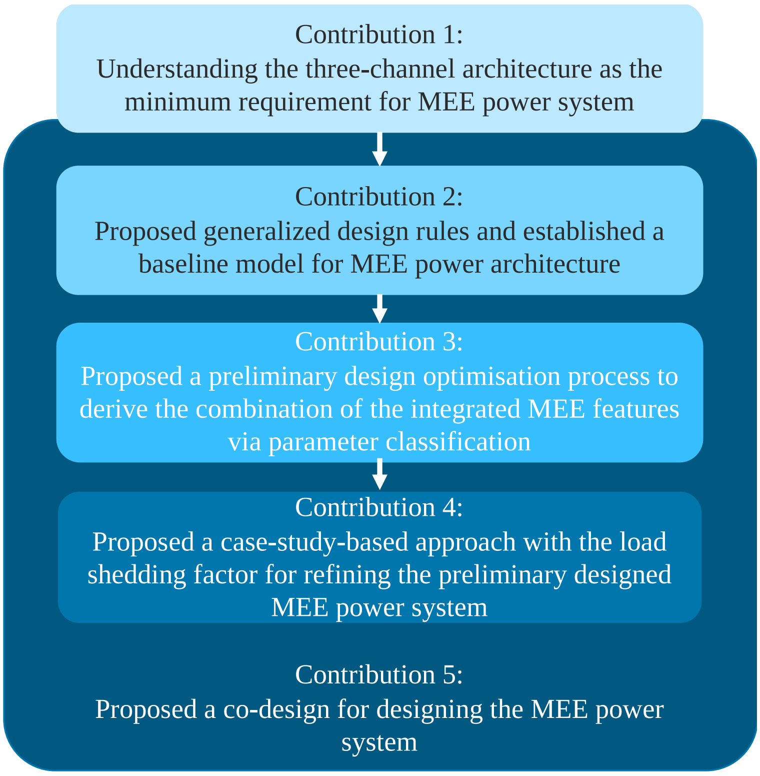


Figure 1.Relationship between academic contributions

1. To date, single or dual channel power generation and distribution systems have been used in jet engines. However, with the improvement of the electrification of key engine auxiliary equipment for flight; and the requirement for greater load transfer flexibility has placed greater emphasis on the criticality of the electrical supply, the three-channel architecture should be considered. This thesis first considers the issues such as architecture layout and key technologies that may impact on the reliability consideration of MEE design. A detailed fault tree analysis is used to further quantify these requirements by using the extensive database of component failure rates of MEA/MEE power systems in the public domain. This provides a quantitative comparison of dual-channel and three-channel architecture candidates under relevant failure modes and shows the impact of common architecture features on system reliability and robustness. **The acquisition of these results points to the three-channel architecture as the minimum requirement for a MEE power system.**

2. Specific design rules for addressing the rationale of MEE have not yet been defined in literature. As such, another contribution of thesis is in **the definition of key functional requirements for the MEE architecture**, **and the establishment of a certification-compliant MEE Baseline Power Architecture (BPA). The multi-criteria design rules of power architecture are presented for the corresponding MEE electrical system.** This builds on top of contribution 1 which identified the minimum three-channel system requirement. With recognising that the MEE having a significant design space, the established BPA provides a platform for eliminating the uncertainties of design to a manageable level. This certifiable baseline provides key decision points for the design, also updates the requirements on the certification and/or the utilisation of game-changing technologies.

3. Following on from contribution 2, in order to address the significant design space on operational compatibility of the power management and the additional design features (bus tie, bi-directional converters, power source types,) of the BPA, **a preliminary characteristic-capture-based optimisation is proposed**

(called Parameter Classification Optimisation) to initially down select integrated MEE power system concepts. Feasible MEE EPS solutions from this process that meet the overall design requirements are determined by parameter classification ranking. The proposed optimisation approach navigates the designer to determining the functional similarities and differences between high ranked concepts and lower ranked concept, which maximise the ability of searching optimal solutions. When designing the MEE power system in a design space with large degrees of freedom, this contribution accelerates the selection of MEE subsystems. The optimisation approach also addresses the drawbacks of incorrectly selecting a dominating but non-system-optimised subsystem to begin with.

4. Following on from contribution 3, to identify and to improve the availability of power supply in the integrated MEE power system, **a refinement procedure that is influenced by load shedding management is proposed. This procedure firstly utilises a proposed parameter (Load Shedding Factor, LSF) that can divide the power balance state of MEE system into several levels, which is used to evaluate the essential power demand of MEE with each flight phase in different failure modes.** The compared results of LSF reflects that the connection and location of power resource are vital to the power reconfiguration. A small alternation on the EPS architecture can improves the capability of MEE power supply and results significant effect in power dispatch operation. Hence, this procedure provides a platform to fine-tuning the systematic operation of MEE power system.

5. **In respect of contributions 2,3 and 4, a more comprehensive version of the co-design process is established for the MEE power system design. This so called APM co-design process oriented to MEE electric power system particularly fills in the gap in literature, by co-currently deriving feasible electrical architectures and power management schemes**. The utilisation of this co-design process ensures MEE power system have intersystem compatibility, operational flexibility, and system redundancy. The uncertainties

in the multi-criteria design for MEE power system can be largely reduced with using this proposed design process.

1.3. Related Publications

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

1.3.1. Article Journal

- Q. Zhang, P. Norman and G. Burt, "Design Rules to establish a Credible MEE baseline Power Architecture Concept" 2022 IET Electrical System in Transportation (published on 21/April/2023)

1.3.2. Conference Paper

- Q. Zhang, M. Sztykiel, P. Norman, and G. Burt, "Towards Two and Three-Channel Electrical Architecture Design for More-Electric Engines," in the Society of Automotive Engineers (SAE) International, London, United Kingdom, November 2018.

1.4. Thesis Outline

A thesis layout diagram is illustrated in Figure 2. Chapter 2 contains the relevant literature review, introduces the concepts of MEA and MEE, important systems of the potential power system of MEE. The power architecture characteristics of MEE and power load management (PLM) are reviewed. Chapter 2 also includes a review of the pros and cons of the available engineering design processes for the development of MEE power systems. At the end of Chapter 2, the design approach for designing MEE power architecture is preliminarily hypothesised.

Chapter 3 conducts a preliminary multi-criteria analysis of the dual- and three-channel power architecture of MEE. The result defines a clear design direction for the baseline architecture of the MEE power system. However, there is no literature explaining why those multi-channel architectures are chosen. Therefore, Chapter 4 presents an understanding of the unique design features and requirements of MEE power systems, gives overall design considerations on the baseline model of MEE power architecture, and gives a series of effective and credible design rules. This chapter also provides a sample of the baseline model for MEE power architecture.

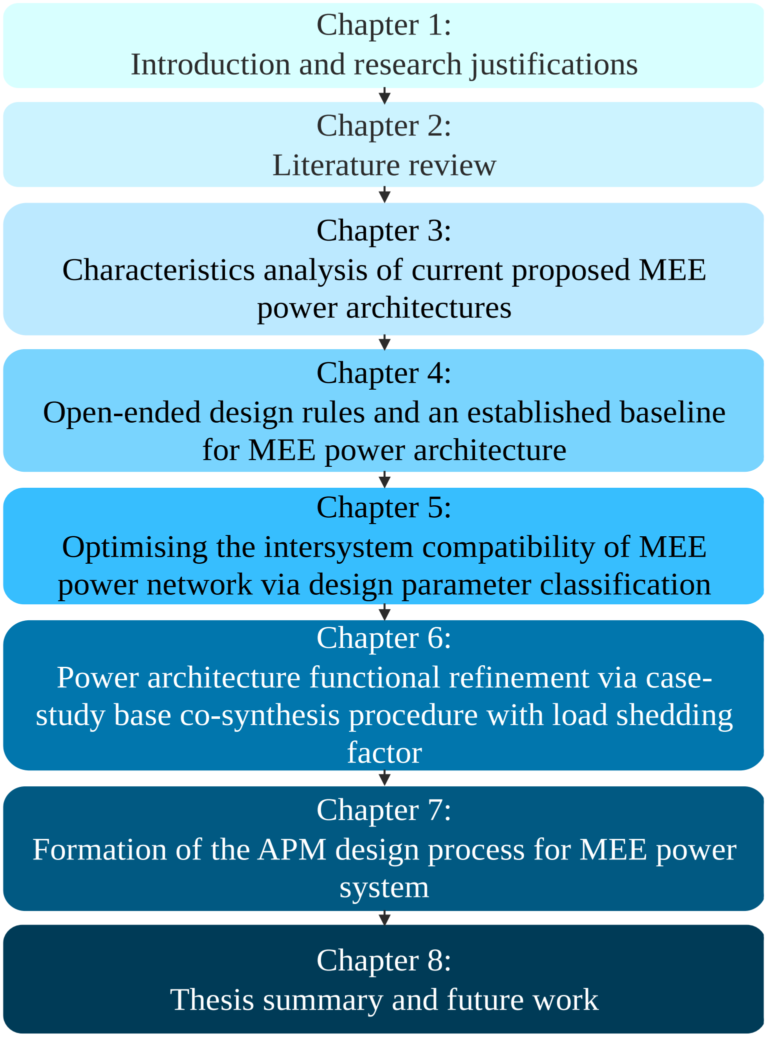


Figure 2.Thesis chapter layout

Chapter 5 mainly describes a preliminary optimisation process that utilises parameter classification to rank and compare the integrated MEE power system. This process leads to the design of MEE power system to be a ‘coarsely’ optimal stage, which can reduce the design iterations. In addition to proposing a novel approach for designing MEE power system, this chapter also carries out the preliminary matching and feasibility analysis for the MEE power network solutions.

Chapter 6 describes a further refinement procedure for MEE power system design, in which the final solution is determined by validation and inference of MEE power network candidates under various abnormal conditions. At this stage of design, the candidates for MEE system are enhanced via the Load Shedding Factor. Furthermore, Chapter 7 presents a complete version of the co-design framework for MEE power systems (including the contents of Chapters 3, 4 ,5 and 6). And lastly, Chapter 8 concludes the thesis conclusions and the further development of the co-design process.

Chapter 2.
Existing MEA and MEE Power Architectures and Engineering Design Processes

2.1. Chapter Overview

In recent years, the aerospace industry has ushered in major technological advancement changes [27] as More Electric concepts are applied to system design. The More Electric concept replaces the conventional mechanical, hydraulic, and pneumatic systems with their electrical equivalent systems, resulting in significant space and weight savings. These equivalent high electric density advanced distribution systems should also provide greater system capability, operation efficiency, and greater design flexibility than conventional aerospace applications.

This chapter provides an overview of the concepts and systems of electrification applied in the aerospace industry in recent years, will focus on describing the layout and evolution of the electrical architectures of the MEA and MEE, and in turn discusses the potential benefits and challenges posed by these electrical architectures. In addition, as the design process is critical to the success of the MEE power system design, this chapter will also discuss and review the role of the MEE architecture for different design processes. Furthermore, this chapter concludes with an emphasis on some of the key research challenges that have been undertaken using a MEE as the research object.

2.1.1. Existing More-Electric Aircraft

The first generation of MEA includes Boeing 787, Airbus 380 and F35, their total on-board electrical power production are 1460kVA, 910kVA and 250kVA respectively[28][29], which is a significant power generation capability compared to the conventional aircraft. As one of the large commercial aircraft, the twin-engine, wide-body jet Boeing 787 is a milestone of the more-electric aircraft evolution, as it has implement two starter/generators of 250kW per engine and two 225kW Auxiliary Power Unit (APU) starter/generators [28]. Similarly, as the largest passenger airliner, Airbus 380 has four 370-770Hz variable-frequency (VF) generators that can produce in total 600kW, and two 120kW APU generators[28]. In the defence industry, the F35 has a single generator that can produce 250kW, which is much higher than F15 and F22[28].

The reason for significantly increasing the electrical power generation is the conventional auxiliary systems are replaced by the electrical driven systems. The Boeing 787 has substituted the pneumatic system of environment control system, pressurisation system and wing anti-icing system with their electrical equivalents. This evolution largely improves the fuel burn efficiency, as it has significantly reduced the hot air extracted from the combustion chamber. The weight reduction of the no-bleed air system of 787 is shown in Figure 3, and compared with the conventional jet engine[8].

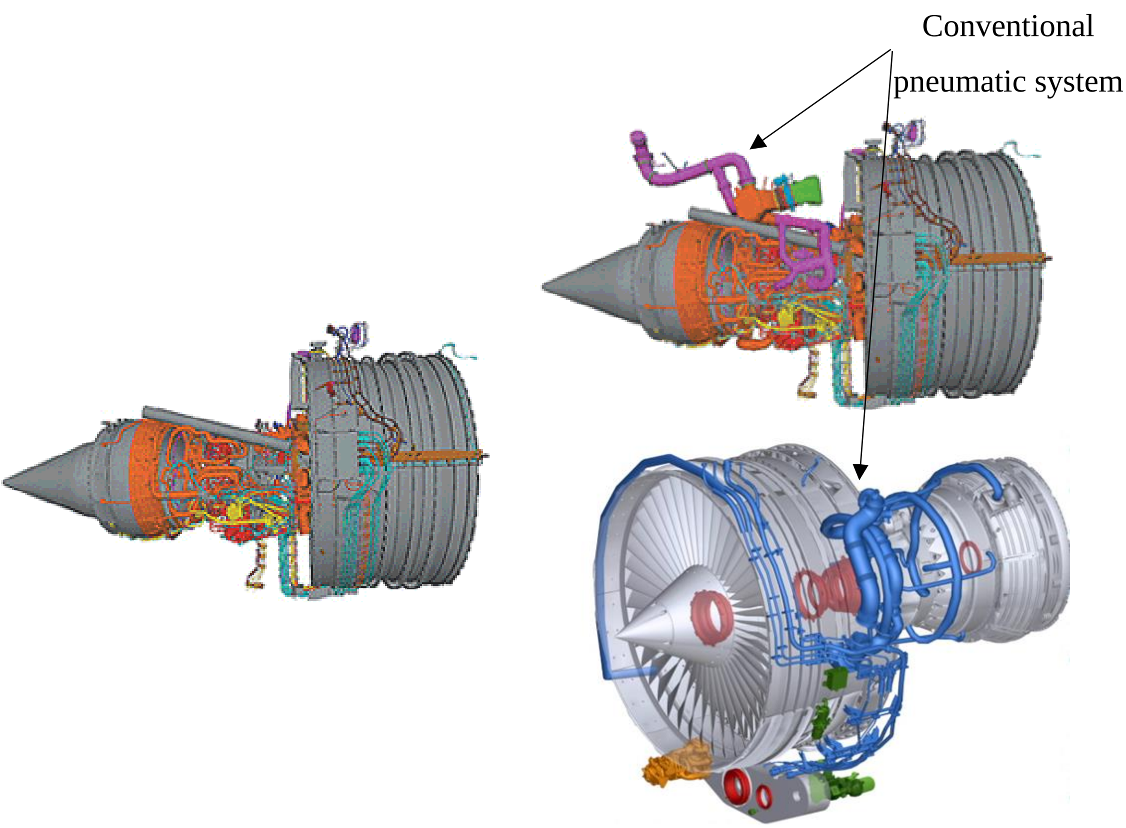


Figure 3. Boeing 787 engine (left) vs conventional jet engines (right) [8]

Due to the increased quantity of electrical loads the electrical power architecture of the Boeing 787 has been developed to satisfy the demands. The electrical power architecture of Boeing 787 is shown in Figure 4 [30], which is a hybrid distribution network with four different voltage types in the AC and DC electrical systems. The starter/generators powered by engine shaft and output $230V_{AC}$ power with variable frequency between 360Hz to 800Hz, which depend on the rotational speed of the engine shaft. With the starter/Generator, the MEA B787 can save space and system weight in the engine. The starter/generator can achieve both starting mode and generating mode in one unit which can operate as a motor and rotating the engine shaft. It can also swap to a generator to supply electrical load[21].

The AC power is distributed to the demands of anti-icing system, environment control system and galley ovens; it also converts to other different voltage levels and types. The $\pm 270V_{DC}$ distribution is converted by the Auto-Transformer Rectifier Units (ATRUs) and used to power the adjustable speed motors, electrical motor pump, etc (shown in appendix A). By using ATRUs in high-power level of MEA, the power system can benefit of lightweight and higher reliability from it compared to

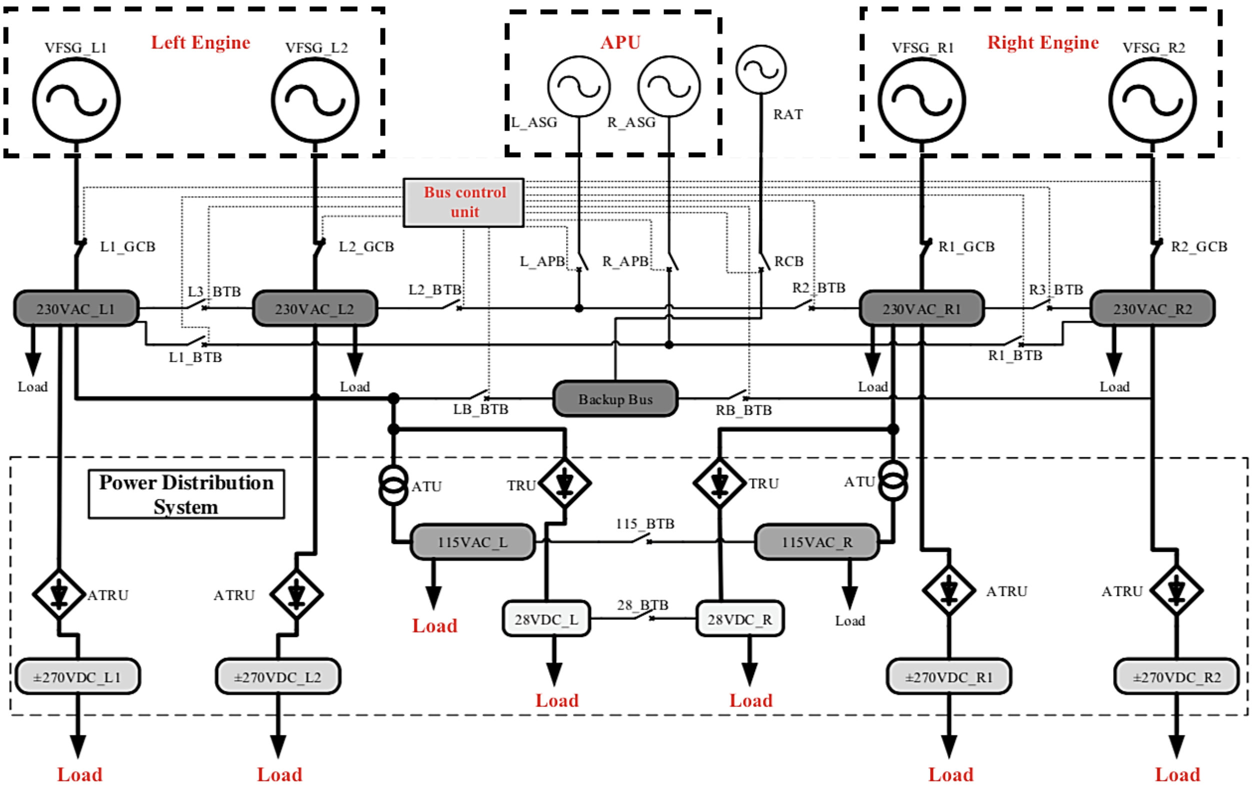


Figure 4. B787 power architecture [30]

conventional Transformer Rectifier Units (TRU). The electrical cooling fans and window heaters are obtained from the $115V_{AC}$ bus via Auto Transformer Units (ATU) for. The $28V_{DC}$ power is taken from the main AC bus by the TRU for igniters, fuel pump, Bus Power Control Unit, Generator Control Units (GCU). The power of APU generators is also connected to the $230V_{AC}$ bus, which is to power the demands on the fuselage. Lastly, the Ram Air Turbine (RAT) would be connected to the backup bus, which is able to supply power in emergency. Throughout the characteristics of the MEA, it can be concluded that there are three aspects different to the conventional aircraft. Firstly, the most of pneumatic systems are replaced by electrical equivalents in the MEA, and its pneumatic architecture is much simpler, saved large space and weight. Secondly, MEA has implemented starter/generators to self-starting the engine system, which has simplified the mechanical interface (a much straightforward gearbox) to reduce the weight and improve operation efficiency. Lastly, replacing large part of pneumatic and mechanical architecture to their electrical driven equivalents, the MEA electrical power architecture is developed to a hybrid AC and DC power distribution system with novel technologies and distribution topologies.

2.1.2. **The Existing Demonstration of More-Electric Engine**

The MEE concept was proposed to promote the electrification of engine auxiliary systems, advocating the use of equivalent electrical systems, such as the mechanical/hydraulic thrust reverser actuation, engine lubrication and fuel pump systems. A significant consideration of MEE design is the flexibility of obtaining power from different engine shafts, to ensure the reliability during component failures. As shown in Figure 5 [31], the More Electric Engine RR Trent 500 typically employs a Low-Pressure (LP) shaft-driven generator in addition to the conventional High-Pressure (HP) generator, to provide a more flexible power source to the novel electrical components.

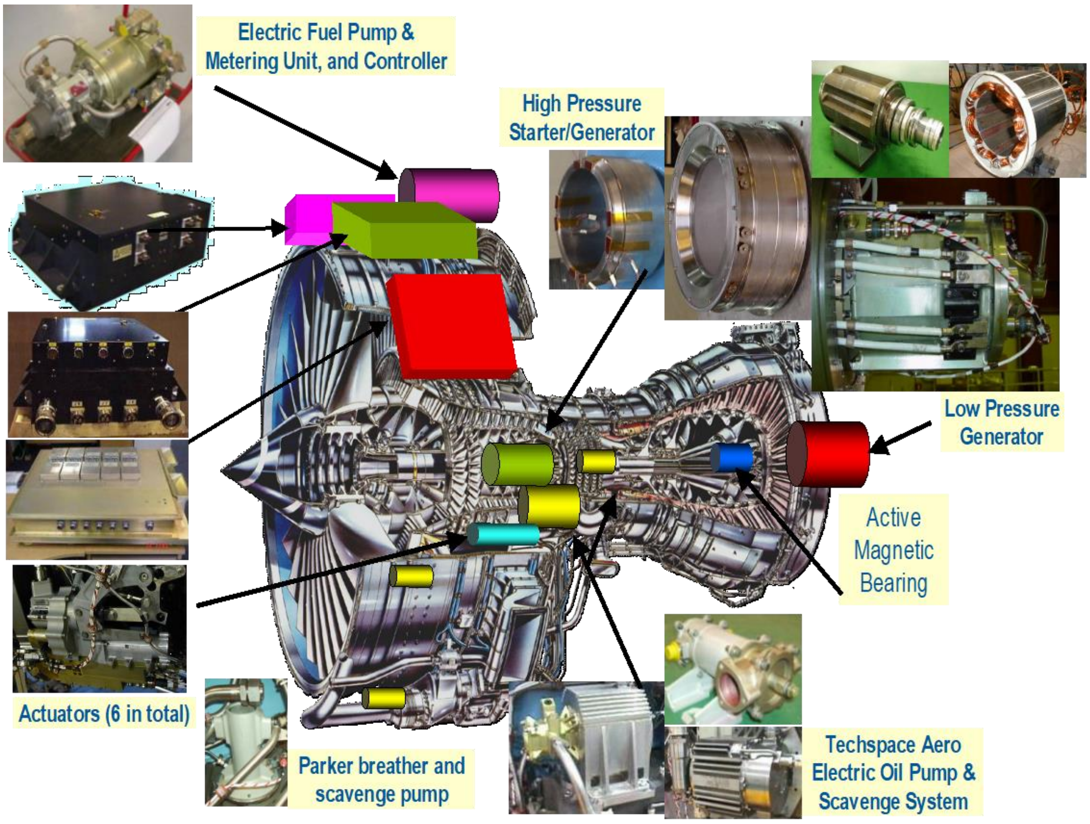


Figure 5. Concept of MEE form ESVR demonstrator [31]

This MEE has been demonstrated in 2006, in a programme called Power Optimised Aircraft (POA) by the European Consortium [28]. This MEE demo has a permanent magnet HP starter/generator providing 150kVA and a LP fan shaft drive generator providing 150kVA. The load demands of large aircraft (such as wide-body aircraft B787/A350) MEE applications are expected to be significant. For example, authors in [32] estimate that the fuel pump system and lubrication oil pump combined will draw approximately 100kW of electrical power, whilst electrical thrust reverse actuator systems (ETRAs) could require up to 35-45kW [28]. Additionally, a range of electrical actuators for engine vanes and electric de-icing function should also be considered into the concept. Such load levels are not insignificant in comparison with airframe loads of modern MEA applications[33]. The Trent 500 has been given a preliminary and small scaled electrical power architecture with a 350VDC bus as the MEE demonstration in the POA. Reflect it to the realistic commercial airline conditions, the power ratings, demands and densities of components need to be reasonably estimated.

RR Trent 1000[34] is one of the optional propulsion engines to implement on the Boeing 787. To accommodate the concept of fuel efficiency improvement in the MEA, the RR Trent 1000 offtakes the power from Intermediate Pressure (IP) shaft instead the HP shaft and retains the hydraulic architecture and hydraulic actuators for fan blade actuation, nozzle actuation. With the hydraulic architecture, the Trent 1000 can only be called a more efficient engine[34] but not an MEE. Moreover, the data and features of More-Electric Trent 500 cannot be directly used into the RR Trent 1000 or any of the larger sized jet engines. These high power, flight-critical electrical loads require an increased electrical power offtake from the engine (in comparison to 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[23], loads and sources (e.g., 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

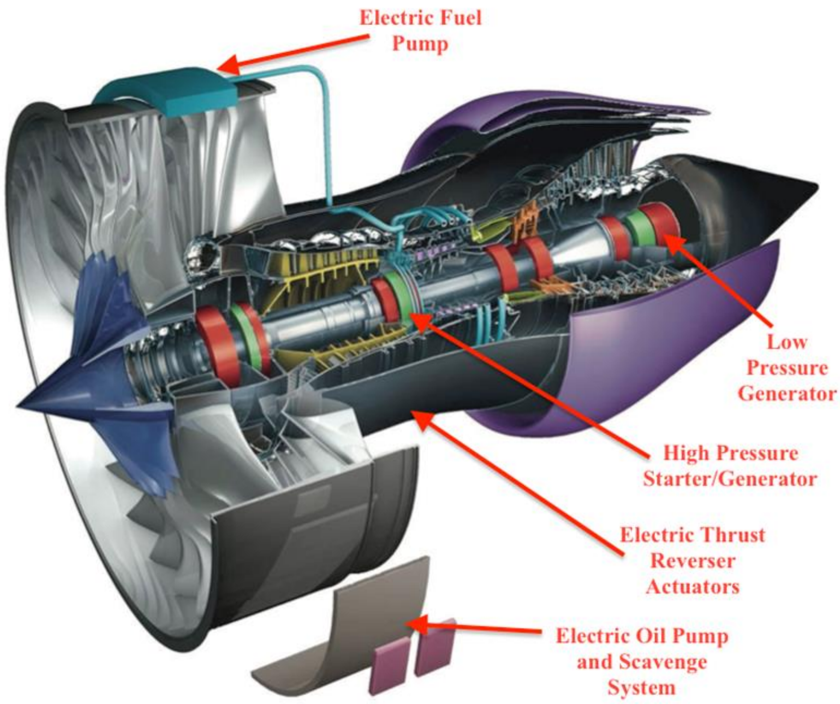


Figure 6. MEE concept that proposed by Rolls Royce [35]

deviation from conventional engine systems, whose auxiliary loads are supplied by local mechanical, pneumatic and hydraulic systems[35]. A number of feature specifications may require a clarification before starting the design process, more detail described in Chapter 3 and 4.

To date, large MEE applications are still in the conceptual stage of the design, shown in Figure 6 [35], and the most recognised feature of an MEE is the use of full electric architecture/ hybrid hydraulic architecture for engine actuations. Moreover, Figure 7 shows a hydraulic architecture of the recent wide-body commercial aircraft[36], which is a complex and heavy system. The next generation of MEA could be far improved in lighter weight and fuel burn efficiency if replacing the hydraulic source and hydraulic actuators by electric driven Actuators [37]. With the large electrical demand, a large electrically powered MEE is a promising and complementary solution for next generation of MEA.

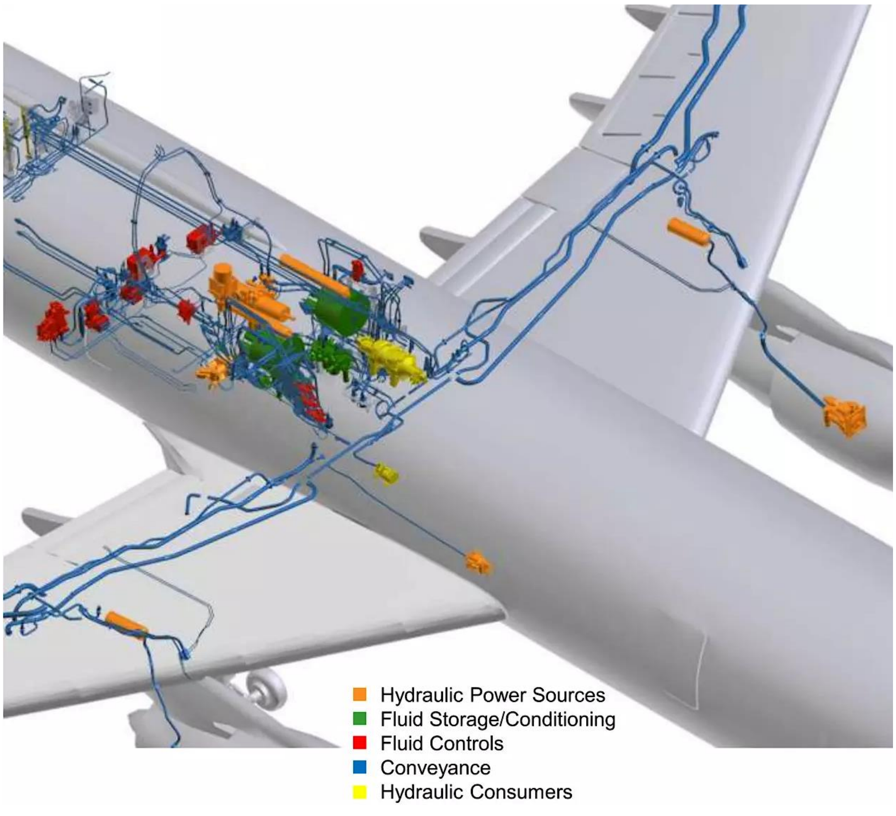


Figure 7. Hydraulic architecture of a commercial aircraft [36]

2.2. Electrical Power Architectures of Existing Engine and MEE Concept

The electrical power architecture is a vital subsystem for the engine system, and is typically composed of a dual-channel or multi-channel layout to ensure system reliability and redundancy [38][39]. When a fault is detected in a channel, the architecture can be reconfigured to deliver power through the other healthy channels [40].-The power architecture can have varied power channels to provide the power redundancy; also, the topology of architecture needs to be considered to enhance power supply reliability and resilience. To realise flexible reconfiguration to maintain power supply during fault conditions, the literature commonly recommends employing the radial-bus [28] and ring-bus [41] topologies.

An existing Dual-channel architecture with two HP shaft or two IP shaft driven Variable Frequency Starter/Generators (VFSG) [29], which have been implemented into GEnx or RR Trent 1000 engine for Boeing 787 and shown in Figure 8. This architecture achieves some power redundancy for current large commercial aircraft. However, whether it can play the role for the future MEE or future MEA is unknown.

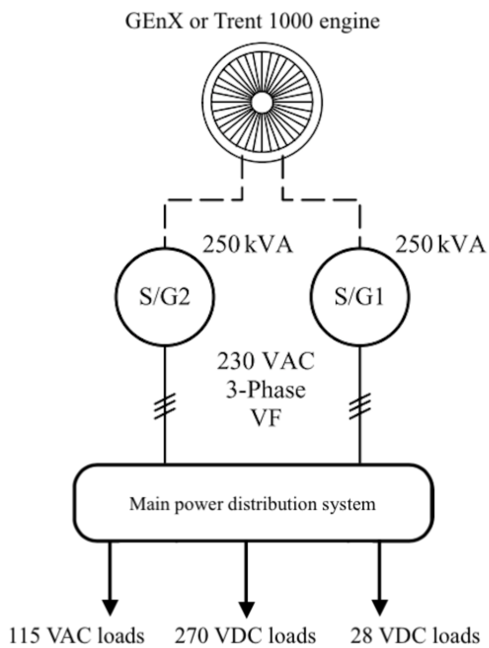


Figure 8. Boeing 787 engine power architecture [29]

Y. Zhang *et al.* [23] propose a Power and Load Management (PLM) system for MEE/MEA applications, which is demonstrated on a modelled MEE power system architecture [13][19][42], illustrated as Architecture A in Figure 9. This 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 single 540 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 *et al.* [43] 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. H. Edwards *et al.* [44] present an engine-based three-generator power system, which is illustrated as Architecture B in Figure 9 , 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 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.

S. Fletcher *et al.* [22] describe the impact of engine certification and design requirements on a two-channel MEE power architecture, which is shown as Architecture C in Figure 9. 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 *et al.* [31] present an MEE concept demonstrator, in which a single busbar distribution system is implemented. A simplified version of this architecture is shown as Architecture D in Figure 9.Architecture D features one high-pressure shaft driven generator and a fan shaft driven generator. Other dual-channel architectures with one HP and a Low-Pressure shaft (LP) generator can be found in [45][46].

N. Morioka *et al.* [47] describe the actuation control technologies for a simplified MEE power architecture, shown as Architecture E in Figure 9, 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 *et al.* [48] propose a three generator power architecture for a multi-spool engine, shown as Architecture F in Figure 9. In this, the low-pressure generator is connected to both HP generator AC channels by power electronic

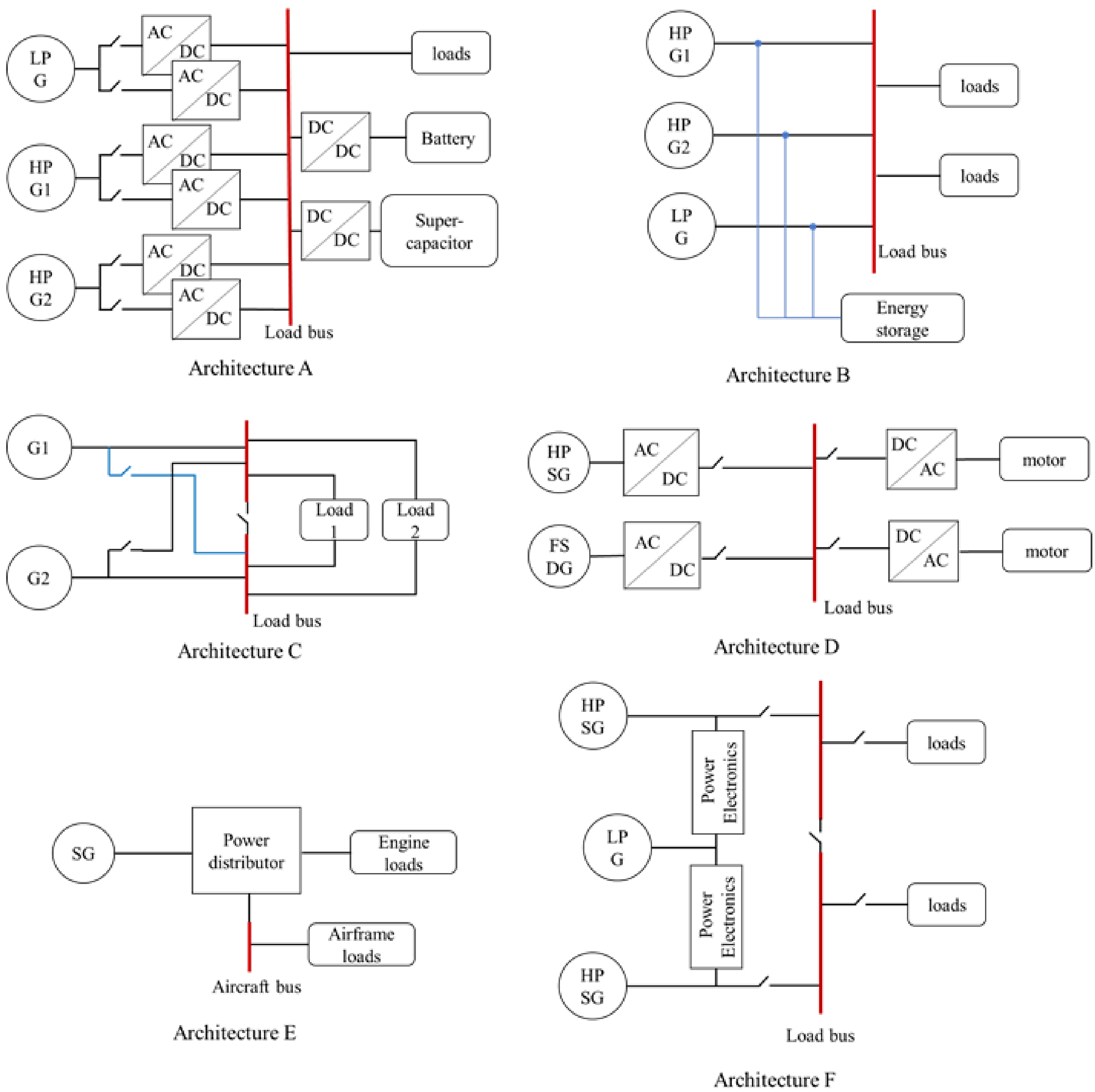


Figure 9. MEE architectures

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 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 a 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 [22] and requirements for the configuration and management of interconnected generation in MEE/MEA [49], 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 established, adherence to these requirements will then illustrate the necessary features and configuration of a MEE BPA concept. However, overdesign is still a possibility 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-TRL (range from TRL 7 to TRL 9) 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.

2.3. Existing Power and Load Management Strategies

The Power and Load Management (PLM) strategy is used to coordinate the power of each component in Electrical Power System(EPS) for ensuring stable and secure system operation. During normal conditions, PLM maintains a power balance by managing generators, Energy Storage System (ESS) and loads. However, in the case that the EPS is exposed to abnormal conditions, for example, cable fault or generator failure, the PLM should take measures to maintain the effective operation of the critical loads. An overview of general and MEA/MEE-specific management strategies/methods is given below:

1. ***Load shifting/removal under peak demand conditions*** [50] [51]:- Controls the connection of loads, removing non-essential loads during the periods of peak demand/a supply deficit, and/or shifting the connection of non-essential loads to occur during low demand periods.
2. ***Re-arrangement of power flow direction*** [52][53]:- Controls the power flow in a EPS by managing the statues of contactors, circuit breakers and channels.
3. ***Energy storage discharge*** [54]:- Manages the operation of back up sources/energy storage for autonomous system in an emergency.
4. ***Temporary shedding*** [55]***:-*** Some loads that are only essential during some particular flight phases. These loads can be temporaily shed in other flight phases.
5. ***Generator overloading***[56][57]***:-*** Different types of generators have overload rates and overload periods. For example, a HP Starter/ Generator has nominal rating of 120kVA (IDG of GE90), has the allowable overload capacities as 125% for 5mins per 1000hours. The overload time of the generator must be less than the recommended overload time to maintain the health of the generator. Although the generator has overload capacity in the short term, the PLM strategy can only use the generator overload capacity when necessary. Excessive use of generator overload will cause significant damage to large electronic equipment, such as generator converter and generator itself.

By reviewing the features of the proposed More Electric Engine power architectures, the novelty and also the inconsistency of physical layout is noticed, and more design options of power management can be potentially applicable into the MEE power system. However, as a novel power system, MEE is necessary to be optimised in term of mass, power generation capability, system reliability and power redundancy (operation resilience).

Weight and power generation capability of the MEE power architecture can be optimised by selecting suitable and high-power density components. However, the operational resilience of MEE power system could be related to both the architecture layout and the power management strategies. The MEE must be resilient to supply all critical loads for all the minimum required flight performance, which can be enhanced by the reconfiguration of the power flow. The reconfiguration of the EPS is both reliant on the power distribution control, and the availability of the power architecture and power electronics components.

Hence, the ‘hardware’ power architecture and the ‘software’ power management/control strategy are the vital elements for the EPS of MEE. However, there are too many degrees of freedom in design regards to these two aspects, and system interdependence between physical layout of the power architecture and order of using the PLM. Since there are much relevance between these two sub-systems in the design process, it will be a challenge to design such a multi-criteria power system in an orderly and logical manner. In regard to the orderly manner of design process, it shall enable to avoiding the dominant impacts from each of the individual subsystem design to others and maximise the design space at beginning of the design. And then follow by optimising the potential integrated solutions with an appropriate rapidly design space reduction. The distinction of different design processes will be mentioned in sections 2.5.

2.4. Current PLM Optimisation Methods to Improve the MEA/E System Performance

At present, in the face of various fault scenarios, most of the EPS designs of MEA/MEE are in the optimisation of power management. Y. Zhang *et al.*, presented an energy-efficient power management solution for an MEE, which employed the non-dominated genetic algorithm to solve the multiple objective optimisation problems [13],[23]. This requires the problem formulation of buses, load shedding priorities and additional sources. However, all of the activities of this optimisation are based on a given MEE power architecture. Similarly, M. Maasoumy *et al*. proposed an optimal load management for the aircraft power distribution, which provides a Mixed-Integer

Linear Program (MILP) to optimise the power management of load shedding, contactor switching and battery charge policies[58]. Again, all the optimisation assumption is based on an existing power system architecture. Furthermore, X. Giraud *et al.* offered a knowledge-based power system reconfiguration for aircraft power distribution system, which can provide the solutions based on the graph-theory algorithm [52].

From the existing literature, the optimisation of EPS operational performance seems never without the impacts of load shedding, this can mean that the load shedding is one of the vital elements on evaluating the EPS overall operational performance. In order to maintain the flight operations of MEA/MEE during any conditions, it is better to avoid load shedding [11][23]. Therefore, the time, amount and categories of load shedding would be dominating the operational performance of the MEE power network under fault conditions.

Although load shedding is an obvious judgment in aircraft power system design, the EPS operational performance does not have to rely solely on optimising the power management schemes and strategies. The implementation of power management highly depends on the availability and reliability of the power architecture. After all, in the face of designing the power system of novel aircraft and novel engine, the physical arrangement of the power architecture determines the inherent reconfiguration ability of the MEE. Therefore, improving the reconfiguration capability of power architecture can realistically address the shortfalls in the performance of MEE to operate in the event of failure. The approaches mentioned in the current literature mainly focus on how to optimise the power/load management, rather than studying the design of the relevant power architecture. Therefore, there is minimal literature investigating on the availability of the power architecture through the guidance lines of load shedding.

2.5. Review of Existing Engineering Design Methodologies for Aircraft and Engine Power System Development

The aircraft electrical power system design is generally based on a certain design process, combining engineering knowledge, practical experience, and design logic. Due to the increasing complexity of the MEE electrified demands and its multidisciplinary interaction with other aircraft systems, understanding the interdependence between MEE architecture and power management strategy is vital. Hence, the MEE architecture design process requires a specific flow route combined with the designer's expertise to make initial selections and define a design space for MEE power system.

Along with this awareness, most MEE related literature are focussed on the system and subsystem design based on a predefined architecture[23], and some combination of optimised design for MEA with the MILP[25][59], including some forms of design methods, performance evaluation, and optimisation selection. However, there has yet to be a design process for MEE power system, and there is little research on a comprehensive methodology for synthesis refinement a MEE power architecture design with its dedicated PLM.

In order to give the MEE a resilient EPS, not only the attributes of its components and the power control capability need to be determined, the compatibility of the performance of the integrated system is vitally important. Due to the complexity of the MEE power system, the coupling between product and design process must be given special attention. This important coupling can be realised by effective simulation of product parametric structure[60]. According to this, this section will review and determine the method that can exert the maximum effort of system functionalities in designing the MEE power system.

2.5.1. Existing Research for MEE Power System and the Gaps of MEE Design

Most of current studies have generally concentrated on the sub-system design of the MEE. Y. Zhang et.al[23][61] proposed a power management algorithm for the MEE. In the reliability analysis of MEE electrical system, S. Fletcher et.al [22] examined the availability of power redundancy in the MEE architectures. However, there is little published information on the MEE integration of power management and architecture. In order to design a resilient MEE electrical power system, not only the attributes of its components and the power control capability need to be determined, but the overall compatibility of EPS is also vitally important. This is because that the design iteration and the weight penalty of overdesign can be reduced while using an appropriate design process to achieve the compatibility of power architecture and power control capability. Due to the complexity of the MEE power system, the coupling between subsystems must be paid special attention. This important coupling can be realised by a suitable system design process and an effective simulation of product parametric structure[60].

There are three main types of design processes used in systems engineering [62][63][64] which are illustrated in Figure 10. The most common design process is sequentially designing different parts of the system and eventually integrated at end of the process [62], developing the system in a sequence [63], while iterative feedback can be added in the design process[63]. Due to the order of sequential design, the probability of design space/solution may be limited by the first part of design. Another inadequacy of sequential design is the absence of phasic evaluation, and solutions may eventually be found to fail to meet design expectations during the integration phase, requiring multiple iterations through the design cycle. Therefore, using sequential design to design an interdisciplinary system will be time-consuming and laborious, which is not suitable for the design of a MEE power system.

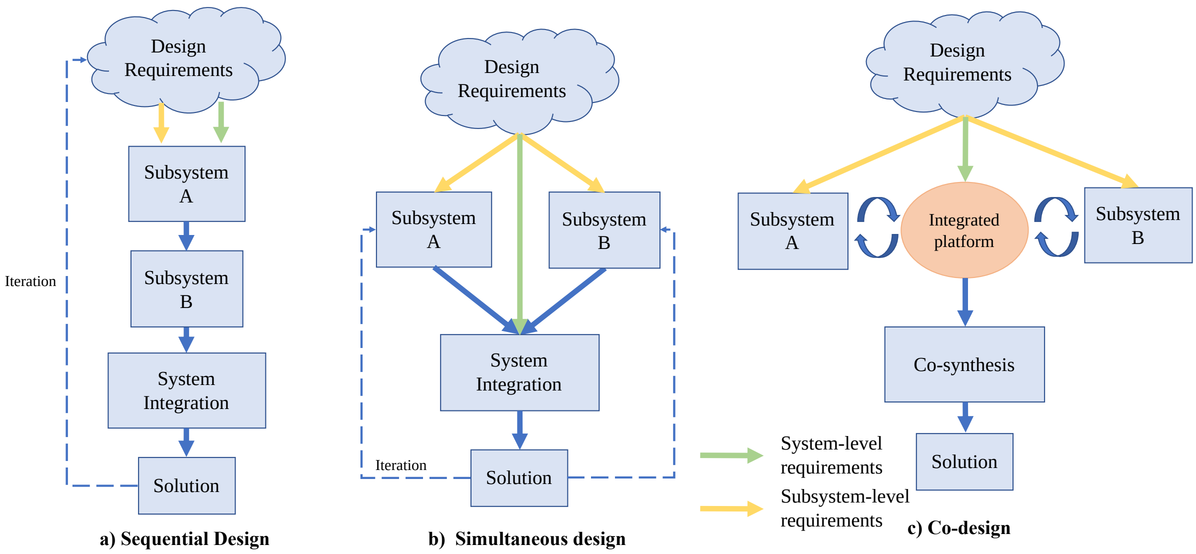


Figure 10. Engineering design processes

On the other hand, the simultaneous engineering design shown in Figure 10 b) which can be conducted with several separate subsystem design at the same time, and the parallel design can easily accept the interchanging of subsystem options without being dictated by the design order [62]. This helps to expand the solution range of MEE power system. Although there are more opportunities to find the optimal solutions in the simultaneous design, it is still not the ideal process for the design of MEE power system. This is because there is no analysis or interactive communication between subsystems design in the process[62], making the EPS integration more complicated and cumbersome in the final refine stage. With simultaneous design, at the integration stage, the subsystem compatibility to meet the systematic level requirements still needs to be assessed.

One aspect of the concurrent engineering is the co-design process, which is generalised and illustrated in Figure 10 c), commonly used in the field of Integrated Circuits (ICs) design [64]. It refers to hardware and software co-design process which is applied for electronic system design, such as Central Processing Units (CPU) and software language co-design [65]. The co-design process is characterised by two or more different subsystem design processes being simultaneously implemented into a preliminary integrated platform[66], which coordinates and supports information/data exchange between hardware and software design stages[67]. This integrated platform in the co-design allows integration of two sub-systems into a design synchronisation environment and applies the system-level requirements as additional constraints during this phase [68]. This can increase the predictability of system integration as early as possible, and determines the preliminary systems that satisfy the system design goals. With more design parameters/constraints at this stage, more non-feasible solutions can be filtered from the design space, minimising the down select effort and design iterations. P.Nuzzo *et al.* proposed a platform-based design methodology for aircraft electric power systems which has similar design logic of co-design process[25][69], but the thesis utilised power architecture concepts and conducted the design with a grey-box system modelling approach. This is provided a lack of information on preliminary concept selection and optimisation.

With the concept of a co-design process, it appears that a decisive prediction can be made for the integrated performance of the MEE power system (including architecture features and power management strategies). This allows identification of optimal system characteristics that meet design requirements in the early design stage. Accordingly, how to preliminarily analyse the design parameters from different subsystems on an integrated platform and manifest the features of the overall EPS becomes an inevitable challenge.

Regarding an MEE power system design with a large number of possibilities in solutions, optimising the EPS with the utilisation of parameter classification comparison in the integrated platform in the co-design process, can be both to preliminarily determine the required characteristics in potential EPS and without much in-depth design of the EPS at this stage. Specifically, the characteristics of the optimal EPS that fit the design requirements can be determined by coarsely filtering the EPS prototypes that combined electrical architecture and PLM, with the help of categorically distinguishing individual parameters of subsystems. Taking the EPS possessing the best characteristics as the core to conduct the fine design can guarantee the optimal performance and also the design fine-tuning can be done quickly. Thereby reducing the time spent in the stages of detail design and another potential benefit of using this approach is to determine the commonalities of the optimal systems in a large MEE design space.

Similar coarse selection concept is commonly used in imaging processes / machine learning algorithms [70][71], it can accelerate filtering a large set of 'low-resolution' version candidates, and then down-select to more 'finer' candidates, striving to achieve the size reduction in the design space. However, no relevant literature has been published on the use of parameter classification comparison to optimise the characteristics of MEE power systems. In order to define the EPS framework in the early stage of the co-design process, this paper proposes a selection method with comparison of parameter to optimise the characteristics of MEE power systems, but this may involve the implementation of interdisciplinary knowledge[72].

For an MEE power system with these two subsystems (power architecture and power management), it is a challenge to achieve all design requirements of both subsystems at the same time. After reviewing the literature of systems engineering and engineering design process, the search space of co-design design is greater than that of sequential design, and the subsystem will not dominate another subsystem in the co-design process. However, when utilising the logic of co-design to evaluate the subsystems at the same time, it may expand the already huge design space of MEE. The following challenge is that the compatibility and complementarity between the two subsystems still require to be maintained while rapidly reducing the design space to a manageable level.

2.5.1.1. The Integrate Platform of Co-design Process for Other Applications

It would then be a follow up challenge on how to actually couple both MEE architecture and PLM become to a combination. The integrated platform in the co-design allows the integration of two sub-systems into a design synchronisation environment and uses the system-level requirements (the constraints that related to both subsystems) to be additional constraints in the analysis of this platform[68]. The co-design process can minimise the search time in iterations and down-select the feasible solutions efficiently.

An integrated platform that has a coarse filtering process can effectively identify the appropriate and feasible systematic features and realise the overall design coordination for the complex system. Therefore, the co-design process seems to be the most appropriate design process for the MEE power system (including both design of architecture design and PLM strategy).

2.5.1.2. The Co-synthesis Process of Co-design for Other Applications

The co-synthesis process is a top-down system design approach and is a joint implementation for the designed subsystems[73] that is commonly used in ICs and embedded systems. A high level of co-synthesis procedure for an embedded system is illustrated in Figure 11, which presents a process of simultaneously designing the software architecture and hardware architecture[68][73][74]. In embedded system design, individual parts of the embedded system are specified and partitioned. Hardware synthesis is the process of transforming hardware design into a gate-level netlist (this is a description of the connectivity of an electronic circuit) for realising specific functionalities, and software compilation is the generation of the code that can be executed on the hardware. Co-synthesis attempts to integrate the hardware and software design paths by the refinement platform, increase the interaction between the hardware and software development, and unify the design space[66]. This avoids a sudden complete integration, which may not achieve optimal systematic functionality

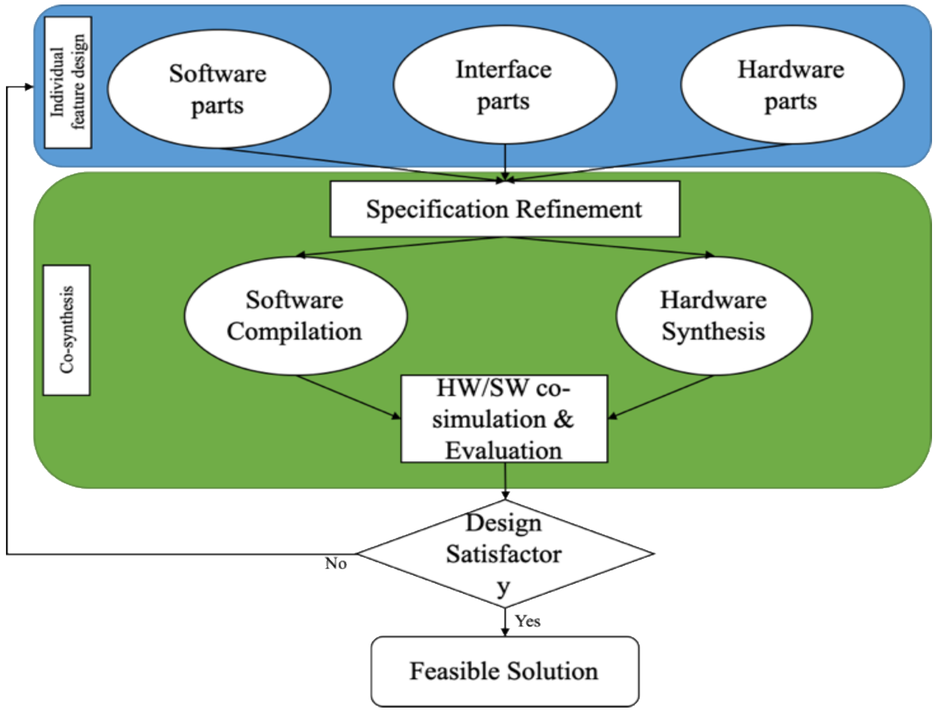


Figure 11. Co-synthesis procedure of embedded system [68] [73] [74]

at the last phase of the design process [66]. The co-synthesis process emphasises that hardware design and software design use an integrated platform, which demonstrates the overall system performance during the system evaluation. This synthesis stage can be a suitable slot for conducting the shedding factor analysis in MEE EPS design. Moreover, the principle of the co-synthesis process is to match the requirements of MEE design such as the incorporation of 'software' into 'hardware', which enhances intersystem dependence between the power architecture and PLM throughout the design.

Similarly, the optimisation of system performance by synthesising an EPS of MEA, then a specific evaluation method combined with a research technique has also been mentioned in recent literature. A. Recalde *et al.* has proposed a mathematical-based design framework with the potential to synthesise MEA EPS architectures to meet a set of safety specifications to supply critical loads in fault conditions. In additional, A. Recalde *et al.* use the mathematical model such as MILP combined with a reliability analysis to optimise system performance[59].

This thesis believes that when establishing an MEE power system, the design logic behind the co-design can be consulted. The value referred to is that the process of co-design could design subsystems both independently and when designed early to meet the requirements of the intersystem design, thereby enhancing the intersystem dependence between power architecture and power management throughout the design process. In practice, although the concept of co-design process can be consulted for the MEE power design, the newly proposed PM strategy/control approach and the newly proposed component/subsystem of the architecture must be designed such that later compliance with dedicated aviation standards is possible, e.g. DO178 (Software Considerations in Airborne Systems and Equipment Certification) and DO254 (Design Assurance Guidance for Airborne Electronic Hardware). The MEE requires the features of a co-design process to coordinate the design needs of the MEE power system. However directly copying from the IC circuit design process would not be feasible. Hence, Chapter 6 will present a proposed design process for MEE power system.

2.5.2. Justification on Mathematic-based vs Knowledge-based Design Approaches

Unlike the engineering design process, which is a design path for system design/development, case study design/mathematical programming methods is the patterns of design methods/tool. The types of design approach may also influence the system design evaluations and the designer's understanding of MEE power system.

There are many research methodologies can be employed to investigate the design of MEE/MEA power system and subsystems, one of the approaches is the implemented mathematical optimisation to solve the multi-objective problems [11][13][25][59]. Mathematic-based design requires problem formulation, design functions and program constraints. With extensive work in multi-objective optimisation problem (minimising mass and redundancy, maximising the reliability and power generation), this type of formulation can produce Pareto-front sets[75]; which still require further analysis to select the best trade-off. Indeed, feasible numerical solutions may be capable of defining the optimised architecture layout. However, mathematical optimisation has advantages on optimising individual and more specifically detailed architecture candidate, but it lacks flexibility in changing the mathematical constraints and functions that already have been initially set, which needs to restart the programme again. Moreover, the mathematical programme works in an abstract level of design, all the search paths are completed by mathematical tools and shows no visual development of the power architecture. Even though the designed power architecture is optimal solution, the user may not be able to understand the system performances and functionalities of the optimised architecture.

The alternative, knowledge-based approach is driven by design assumptions, engineering expertise and white box environmental analysis; this method can only be easily implemented if the engineer have relevant knowledge. Contrary to the black box method, white box testing shows the knowledge of the internal design of the application and analyse the power system during the design. Combined with visual diagrams, the causes of uncertainty in design can be understand by using the knowledge-based method. This will greatly contribute to the integrated phase of MEE power system design. The white box environment enables designers to understand how power system architecture are developed. According to that, this thesis believes that the knowledge-based design method is more suitable for the design of MEE power system.

2.6. Chapter Summary

From the literature review of the background and current situation of MEA and MEE, it is pointed out that MEE is at the conceptual development level and is a potential solution for the next generation of MEA.

However, the current literature does not specify standards or detailed metrics to guide designers to develop MEE power systems. Although some different power architectures are proposed for different sizes of MEE, there is no paper to describe the basic characteristics of MEE requirements. Although many subsystem designs have been developed around MEA/MEE, such as power management algorithms, efficient generators, and power electronic devices. However, there is no suitable design process to design the whole advanced MEE power network, and there is no test platform to evaluate the comprehensive performance of MEE power architecture. Therefore, this thesis will first provide a baseline model and a series of design rules for MEE power architecture for academic and industrial research.

Moreover, by reviewing different types of engineering design processes, collaborative design process flow logic may be a potential solution to realize complexity and interdependency between systems. Different from the sequential design process, collaborative design will be able to design subsystems in parallel. There is no design domination between subsystems, and the original design space will be expanded, giving more opportunities to maximize the boundaries of the design space. In addition, the collaborative design process has an interface / integration platform, which is used to evaluate the integration performance of subsystems in the preliminary design stage, early evaluate and screen feasible solutions, so as to further refine the detailed design. This can save a lot of time in the development of the entire MEE power network. At present, there is no literature research on this direction. This thesis will propose a design project that can provide an integrated platform for MEE power system in the early stage of design.

After the candidates of MEE power system are generated, the co-design process should also downward select and optimize all candidates. Therefore, in the joint design process stage, it is necessary to effectively filter some inflexible and over-designed MEE candidates. With this advantage, the co-design process concept can be implemented in the V diagram of ARP 4754 to support the design of the system requirement, design, and verification (not in the phase of item/component-level design and allocation). Therefore, this thesis will propose an evaluation method to optimise the availability of the system and the reconfiguration of power distribution.

Chapter 3.

Pre-design Reliability and Weight Analysis for MEE Multiple-Channel Power Architecture

3.1. Chapter Overview

To date, single or dual channel electrical power generation and distribution systems have been used in engines and aircraft. However, with the increasing electrification of flight-critical engine auxiliaries along with the requirement for greater load transfer flexibility, a three-channel or multiple-channel architecture should be considered.

This chapter firstly explores the probability in the different combinations of the MEE architecture. The potential electrical devices that may be suitable for a multi-channel architecture were then reviewed. The characteristics and features of those electrical components such as generators, busbar topologies, converters and loads are highlighted. With reasonable assumptions in technologies of MEE and MEA, this chapter then presents the pre-design analysis that includes reliability analysis and weight comparison for the literature-published MEE architectures, such as the variations of dual channel MEE power architecture and three channel power networks; and explains the differences between the dual and three channel MEE power architectures in multi-criteria design.

Those key outcomes that obtained from this chapter can be used to evaluate the insightful considerations of the baseline power architecture design of MEE (content of Chapter 4).

3.2. Investigation of Dual-channel and Three-channel Power Architecture for MEE

Currently, dual-channel electrical power generation system is employed on most aircraft engine electrical systems[28][76]. A single-channel MEE power system will have a higher risk of an in-flight shutdown, as the single channel electrical power system has no redundancies in case of component failure and may not be sufficiently reliable for such a flight critical system. Therefore, dual-channel and three-channel systems will be considered for MEE applications to attain the desired level of redundancy and load management.

3.2.1. Dual Channel Architecture

In a dual-channel electrical architecture, both channels would share the supply to essential loads, improving the reliability and flexibility of the system. For a dual-channel architecture, each one of the essential auxiliary systems of the engine would be conducting with two feeding lines. At the same time, each of the two channels will supply and distribute power to various non-essential loads. In the abnormal situation of a single fault or a minor power system failure, the dual-channel architecture should be able to isolate the faulted section of network and shed the non-essential loads to ensure continued unrestricted supply to critical loads, facilitating safe flight.

3.2.2. Three-Channel Architecture

The concept of the three-channel architecture has been proposed in accordance with the increasing electrification requirements of the MEA/MEE auxiliary systems[31],[76]. In a dual-channel architecture, two main engine-driven generators are typically employed. In the case of three-channel electrical architectures, the extra power source can be obtained from a different shaft which would operate in isolation from the two remaining power sources. The main advantage of the three-channel system is higher reliability of system operation, as well as higher level of flexibility for load management during normal operating conditions. With a minor or single fault scenario, a three-channel architecture should allow the isolation of a failed channel section while maintaining a non-interrupted supply to all essential loads.

3.2.3. Potential Features of Multi-Channel System

This section is used to describe the layout of the multi-channel electrical architecture and its potential features. The following section defines the layout of the architecture as:

1. Power generation: generators and storage used to supply electrical power.
2. Voltage levels of the entire potential electrical power system.
3. Feasible busbar topologies.
4. Critical electronic components: ATRU, rectifier and inverter.
5. Essential MEE loads, such as fuel pumps, oil pumps and thrust reverser actuation system.

3.2.4. Potential Generation/Sources in MEE

Some current MEA designs use two variable frequency AC synchronous generators per engine [8]. This type of generator is able to operate at a frequency range of 360Hz to 800Hz [77]. In order to distribute the power from the generator into an AC bus of 230V_{AC} at 400Hz, a power electronics component such as an active converter is needed at the busbar terminals. Additionally, a generator control unit (GCU) may be required to supervise the generator and converter and to support the terminal voltage regulation. Figure 12 illustrates the different types of generator system that may be utilised in MEE designs.

Wound field synchronous machines or permanent magnet (PM) machines are commonly proposed for the starter/generator in aircraft engines [78], although switched reluctance technologies have also been considered. These machines may either be gearbox driven from the main spool or directly embedded within the engine to facilitate the removal of the associated gear box components[31], [42],[79]. Given the wider speed range of the LP shaft in comparison to the HP shaft, the associated generator typically requires a power electronic conversion stage to achieve a network-compatible output voltage and frequency. Table I shows candidate generator designs for an MEE system. PM and SR technologies show good promise, although the entire mass of the system, including gearbox and electrical filtering components needs to be considered when making technology trades.

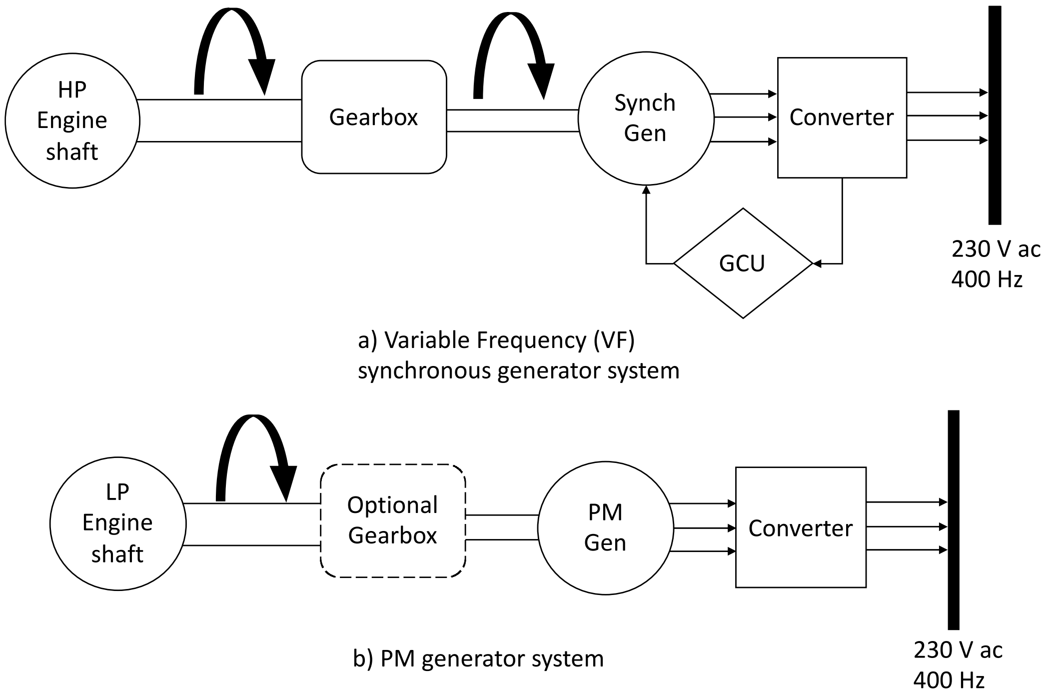


Figure 12.Different types of MEE generator system

Table I. Candidate generation source for EPS architecture design

Generator type	**Converter required**	**Power rating**	**Gearbox required**	**GCU required**
Wound field starter/generator	Yes; DC or AC-400Hz operation	250kVA	Yes, accessory gearbox	Yes
PM starter/generator	Yes	250kVA	Yes, coupling with an integral gearbox	No
Switched-Reluctance starter/generator	Yes	250kVA	Optional	No

3.2.5. Potential Energy Storage System for MEE

Energy storage systems (ESS) provide an emergency supply of electrical energy following an unexpected loss of power from the generators. High voltage battery systems are being proposed for MEE applications, with the authors in [15] proposing a battery bank interfaced directly to a $270V_{DC}$ HVDC bus through a bidirectional DC-DC converter. Lithium-based battery chemistries are commonly considered for MEA/MEE applications owing to their higher energy density, higher power efficiency and lighter mass than the nickel–cadmium and lead acid battery technologies [80].

3.2.6. Potential Voltage Characteristics and Levels on MEE

Multi-channel electrical architectures could potentially utilise different operational voltage levels and frequencies throughout the network. Often, power electronic converters are required to provide a system interface between these disparate points in the network, for example, between the output of the generators and the main distribution bus. All the electrical loads across the airframe, would typically be fed by an 115/230V ac distribution busbar (with further voltage/frequency conversion taking place on the airframe power architecture) [81]. In this section, it is assumed that an airframe requires each generator interfaced with an active converter to supply a dedicated generation bus, so that on-engine loads will have a minimum impact on the supply quality of airframe loads. As a consequence, the on-engine HVDC busbars - required to supply the essential auxiliary engine loads, are interfaced via passive converters, i.e. Auto Transformer Rectifier Units (ATRU). Due to safety and weight drivers [82], high voltage/low current ratings are utilised for auxiliary loads where possible. Additionally, the location of ETRA, which requires longer cable feeds, may encourage the use of HVDC distribution in order to reduce cable weight. Table II shows candidate voltage levels proposed for the electrical power structure for MEE.

The existing MEA (e.g., B787) engines are constructed as a dual-channel AC to HVDC architecture. To maintain consistency across weight comparisons and with limited public data, this subsection presents a multi-criteria design analysis (evaluation of weight and system supply reliability) for the dual and three channel AC to HVDC distribution architectures.

Table II. Voltage levels of candidate MEE EPS architecture

Voltage level	Sections	Power Outgoing to
VF/CF to 230V_{AC}	Power Generation	• Main distribution bus
230V_{AC} 400Hz	Main distribution bus	• Fuselage loads • HVDC distribution bus
± 270V_{DC}	HVDC distribution bus	• Engine auxiliaries level
115V_{AC}	Engine auxiliary systems level	• Oil pump Motors • Oil scavenge pump motors • Fuel pump motors • Actuators
28V_{DC}	LVDC level	• Energy storage • Fuel ignition

In other words, using the intuitiveness and measurability of the existing data of the AC to HVDC architecture to reflect and derive the feasibility of a multi-channel full DC architecture.

After all, AC to HVDC distributed architecture may require more power conversion equipment and may be heavier than a full HVDC distributed architecture, so a trade-off study of AC to HVDC distributed architecture actually maps the bottom line in terms of MEE power supply architecture design. If the three channel AC / HVDC power architecture all has certain advantages in the comparison, there will also be great confidence in the design feasibility of the full DC power architecture.

3.2.7. Feasible Busbar Arrangement in the MEE Architecture

The busbar configuration within an MEE system is essential to maximising load management flexibility and architecture redundancy whilst minimising weight. This section presents candidate MEE busbar arrangements, which are further analysed from a reliability perspective later in the later section.

Each of identified busbar arrangements below has a unique set of advantages for aircraft EPS architecture. Note that the single busbar arrangement is not considered in this section, as it lacks flexibility and reliability for the system redundant operation [83]. If any component in the single bus arrangement fails, the distribution system will be unable to remain operational. Hence, this section will focus on more advanced busbar arrangements suitable for the flight critical nature of the MEE power system.

3.2.7.1. Sectionalised Bus

The sectionalised bus is a common busbar arrangement that is used in aircraft electrical systems [84]. It divides the electrical system architecture into individual channels by using contactors to separate the busbar into individual sections. Figure 13. Three-channel architecture with sectionalised bus arrangement shows an example of the three-channel architecture for MEE with a sectionalised busbar.

The arrangement will significantly have a higher overall operational reliability than a single bus arrangement. Under normal operating conditions, the contactors on the sectionalised bus will be in an open state. This allows isolated operation of individual channels so that the occurrence of a single electrical fault will not disrupt the supply to all channels. Under abnormal operating conditions, for example, after a fault has occurred and the failed component of network section has been removed by protection device operation, [83], the system will be reconfigured in accordance with a dedicated power management strategy to restore power flow to as many loads as possible.

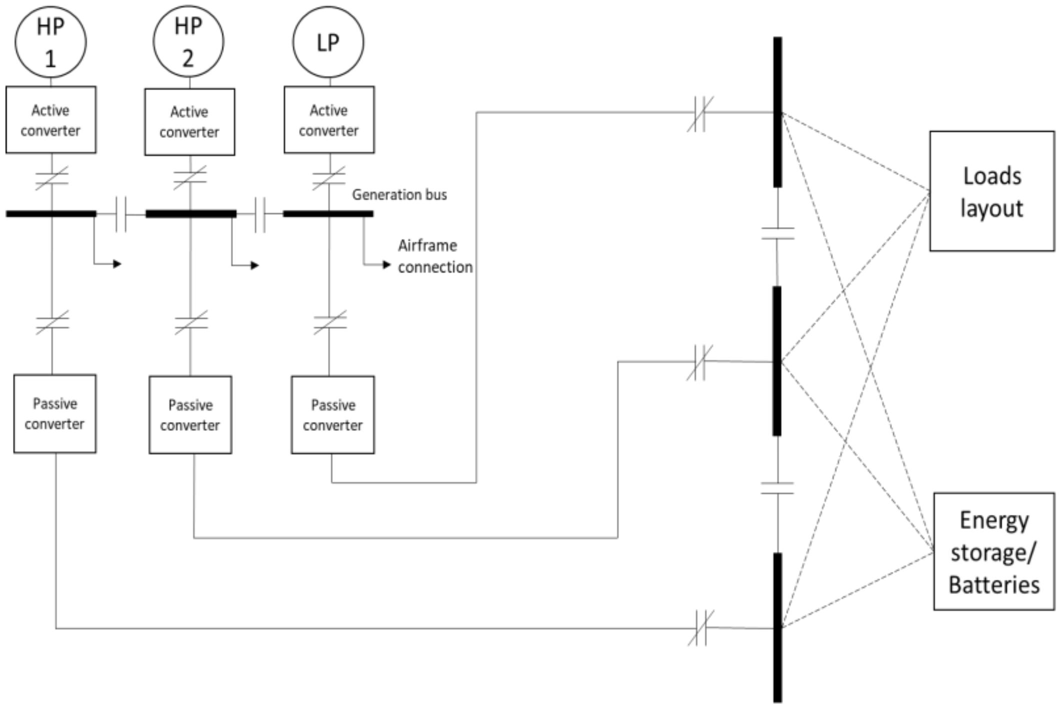


Figure 13. Three-channel architecture with sectionalised bus arrangement

However, if failures exist in multiple sections of the architecture, then maintaining the functionality of the electrical system may become unfeasible. Consequently, non-critical load shedding may be necessary to maintain the continuous supply to essential loads.

3.2.7.2. Ring Bus

A ring bus configuration is a commonly used topology in shipboard electrical distribution systems and it is commonly configured with sectionalising breakers [85].

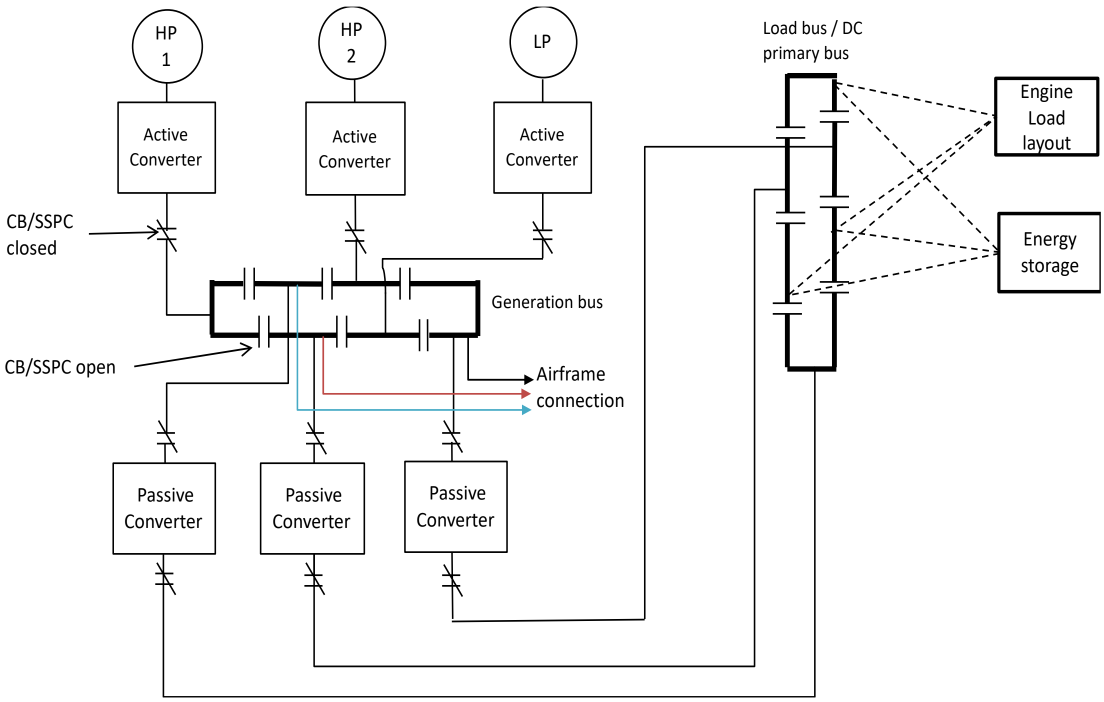


Figure 14. Three-channel architecture with ring bus configuration

Figure 14 illustrates an example concept of a three-channel MEE architecture adopting a ring bus topology. In an example of a ring bus arrangement, a power source supplies a feed bus. This feed bus is then connected to two receiving buses respectively, with contactors in place to provide the necessary isolation between buses. The electrical loads are supplied from the receiving buses. The physical location of the ring bus is flexible, for example it can be mounted around the shape of the engine. From the three receiving buses, power feeds into the critical engine loads such as the electric oil pumps for engine lubrication system, fuel system and ETRAs can be established. The ring bus configuration contains redundancy for each critical load supplied. As a result, a first-order failure such as an active fault or breakdown of insulation in a CB will not cause this configuration to fail [83], which should significantly increase the flexibility and reliability of the power flow to critical loads. The main disadvantage of the ring configuration is the limitation of circuit positions; six bus terminals would usually be the maximum for a ring bus topology [86], as a larger number of bus terminals could increase the difficulty of re-configuration.

3.2.7.3. Breaker-And-A-Half with Sectionalised Bus

The Breaker-And-A-Half (BAAH) busbar arrangement contains two parallel busbars that are connected by several conducting bays [85]. This concept has been developed for power substation and shipboard applications [83]. In each conducting bay, interconnections to either upstream sources or downstream loads can be utilised. An example three-channel BAAH network configuration is shown in Figure 15.

Three contactors are typically employed in each conducting bay. One of these is the main tie CB, which is located in the centre of the power line. The tie CB can contribute to either the connection or isolation of both lines in the conducting bay. The other two contactors facilitate the connection or disconnection of power from the corresponding upstream and downstream buses. In this manner, the BAAH busbar topology ensures that each of the distribution lines is protected by two contactors[81],[82],[83].

The BAAH configuration can provide a high level of EPS redundancy for MEE applications. By using sectionalised contactors on the two parallel busbars, channels can be completely isolated under the normal operation [83]. However, the increased number of electrical components may cause higher maintenance cost and system weight. Similar to a ring bus arrangement, this configuration is resilient to a single component failure.

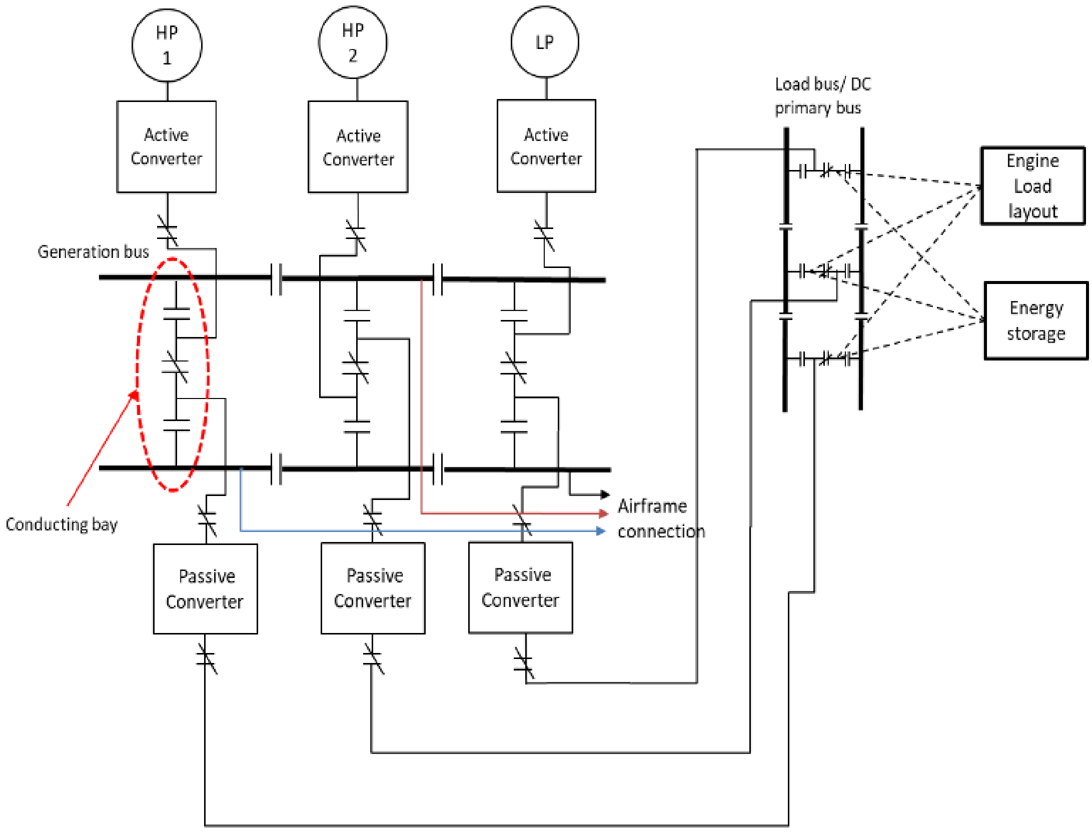


Figure 15.Three-channel architecture with breaker and a half bus configuration

Each of the example busbar arrangements presented in this section utilise only a single type of bus layout for the entire EPS architecture. However, a combination of various busbar topologies could also be considered for an MEE architecture. For example, a particular design could employ a high-reliability BAAH configuration for $230V_{AC}$ main distribution, while at the same time utilising a ring bus topology for HVDC distribution. In this combination, the number of contactors utilised is reduced.

3.2.8. Potential Power Electronic Converter Technologies in MEE

The choice of power electronic converter technologies for MEE architectures directly affects the design process. The following subsections present candidate power electronic converter technologies for MEE architectures.

- **Passive Converter**

  The Auto-Transformer Rectifier Unit (ATRU) provides unidirectional AC/DC power conversion between the main ac distribution and DC primary distribution.

The multi-pulse conversion consists of an auto-transformer and full wave rectifier diode bridges.

- **Active Converter**

  Due to the increased electrification of the systems on the MEE, active power converters may also be employed in the MEE/MEA electrical architecture. The AC/DC and DC/AC converters that are located at generators are used to stabilise the system frequency and output voltage. Separate DC-to-AC inverters can be used for essential passive and motor loads on the engine.

3.2.9. **Critical Loads in MEE**

In MEE architectures, a few potential critical electrical loads include:

- The engine fuel feed system. This would typically include at least one booster pump to draw fuel from the fuel tank, to increase the fuel flow pressure and inject fuel into combustion chamber[8].
- The engine lubrication system. This would typically feature at least one pressure pump to supply engine oil to lubricate mechanical components, several scavenge pumps to return the used oil to the oil filter system, and an oil breather pump to clean the used engine oil.
- An electric thrust reverser actuation System (ETRAS). This typically features two upper actuators, two center actuators and two lower actuators [87].

By way of example, the fuel and lubrication systems for a twin-engine commercial aircraft have been estimated to be rated at approximately 75kW and 20kW respectively [28]. In addition, the full operation ETRAS demand has been estimated at 35kW [28]. However, a detailed assessment of identifying the critical loads in MEE power system can be conducted through Functional Hazard Assessment (FHA) and Preliminary System Safety Assessment (PSSA).

3.3. The Methodology of EPS Reliability Analysis

System reliability analysis is a critical pre-process stage for the system design and development [88]. It can be perceived as a fundamental safety assessment process for the system design. The analysis performed in this section predicts numerical failure rates from the estimated system design. Basic component failure rates can be obtained from the public domain or determined from first principles using standard failure rate data handbooks [89].

One particular system reliability analysis method described in SAE ARP4761 [90] is Fault Tree Analysis (FTA). This is considered as a deductive, "top-down" approach [76][87]. FTA is a qualitative model that involves the backwards-stepping process to determine the relationships between the sub-systems (lower levels) and the top event [91]. In terms of FTA, the top event is a system failure event which is the beginning of the fault tree, and is the scenario to be analysed [92]. The main advantage of using the FTA technique is that it displays the system relationships in a structured manner, and is also suitable for the analysis of both large and small systems [93]. Reliability analyses carried out for aircraft systems are often done so with regards to aircraft system failure classifications [76], [89]. These are summarised below.

- Catastrophic failure conditions should be deemed to occur at a rate of less than 1×10^{-9} per flight hour. This failure condition is representative of a loss of an aircraft.

- The acceptable maximum rate for hazardous failure conditions is between 1×10^{-7} and 1×10^{-9} per flight hour. This failure condition represents a significant loss in functionality and safety of aircraft operation.

- The acceptable maximum rate for major failure conditions is between 1×10^{-5} and 1×10^{-7} per flight hour. The major failure condition results in a significant disruption to aircraft systems and represents a significant increase in operator workload.

- Minor failures are permissible to occur at a maximum rate of between 1×10^{-3} and 1×10^{-5} per flight hour. These failure types represent a small reduction in system functional capabilities.

In addition, according to the European Union Aviation Safety Agency (EASA) Certification Standard CS-25 [94], essential loads on aircraft should have at least one alternate source of power. This requirement encourages the use of either dual-channel or three-channel architectures for MEE applications.

3.4. MEE Architectures Trade Study

This section presents three trade studies of six MEE EPS architectures, comparing reliability and mass. The first trade study is only focused on busbar topologies (either for HVAC or HVDC) and defines the failure rate associated with the complete loss of power transfer through the busbar. This trade provides the necessary busbar failure rates for the second and third trade study presented as well as giving insight into the unique strengths and weaknesses of each busbar configuration.

The second study presented assesses the rate of complete loss of supply to the HVDC essential engine load bus. This study assumes that each of the concept architectures features generation supplying a $230V_{AC}$ bus configuration, which then supplies a downstream HVDC bus, to which the engine loads are connected (similar in concept to the architectures illustrated earlier). The detailed features are described in more detail later.

The third trade study culminates by considering the rate of loss of supply to each and any of the essential engine loads. As a result of the dataset assumptions and simplifications, the study results are representative at this stage, and indeed represent only a small subset of the potential architecture permutations. However, they are still useful in showing the impact of key architectural features on system mass and reliability. The failure rate of each component per flight hour is extracted from [90],[91] and is shown in Table III. The weight of each architecture is also estimated by summing the predicted component weights. Table IV provides a summary of their key characteristics[81], [95],[96]. The total generators mass was assumed as two geared PM generators and one ungeared PM generator for three-channel architecture design; three ATRUs were considered in each channel of the three-channel system. Likewise, two geared PM generators were implemented in a dual-channel architecture, and two ATRUs for dual-channel EPS.

Table III. The component failure rates on a general EPS architecture per flight hour

Electrical Component	Failure rate per flight hour
Generator (VF)	1.3×10^{-5}
GCU	2×10^{-5}
Cable	2×10^{-5}
ATRU/ TRU	7×10^{-5}
Battery discharged	2×10^{-4}
Busbar	1×10^{-7}
Circuit breaker, contactor, switch	3×10^{-5}
Rectifier/Inverter	2×10^{-5}
Position sensor	4×10^{-5}
Control signal	1.3×10^{-5}

Table IV. Mass data of electrical components for candidate MEE EPS

Component	Location of the architecture	Rating	Mass	
PM Generator	Generation	250kW	161.2kg (geared)	191.4kg (ungeared)
ATRU	Three-phase $230V_{AC}$ to $\pm 270V_{DC}$	250kW	100kg	
Rectifier/ Inverter	Generation output to $230V_{AC}$	250kW	28.7kg	
	Feed into load $\pm270V_{DC}$ to 115 V_{AC}	160kW	28.53kg	
Contactor	Generation bus	230Vac	5kg	
Contactor	Load bus	270Vdc	0.35kg	
CB	Generation bus	230Vac	0.78kg	
CB	Load bus	270Vdc	3.23kg	

3.4.1. Trade Study 1: Loss of Power Transfer through Busbar

Figure 16 shows the estimated weight and reliability of each of the six busbar arrangement concepts considered. Every busbar layout has a unique probability of failure, which relates to the associated components' failures as well as the limitations of the physical layout. The weight figure of each busbar topology concept is included both weight of HVDC busbar arrabngment and the weight of AC busbarrangment. A comparison of busbar arrangements is required to properly characterise this redundancy/failure rate trade. The six MEE EPS architectures considered were:

- Dual-channel, sectionalised bus configuration
- Dual-channel, ring bus configuration

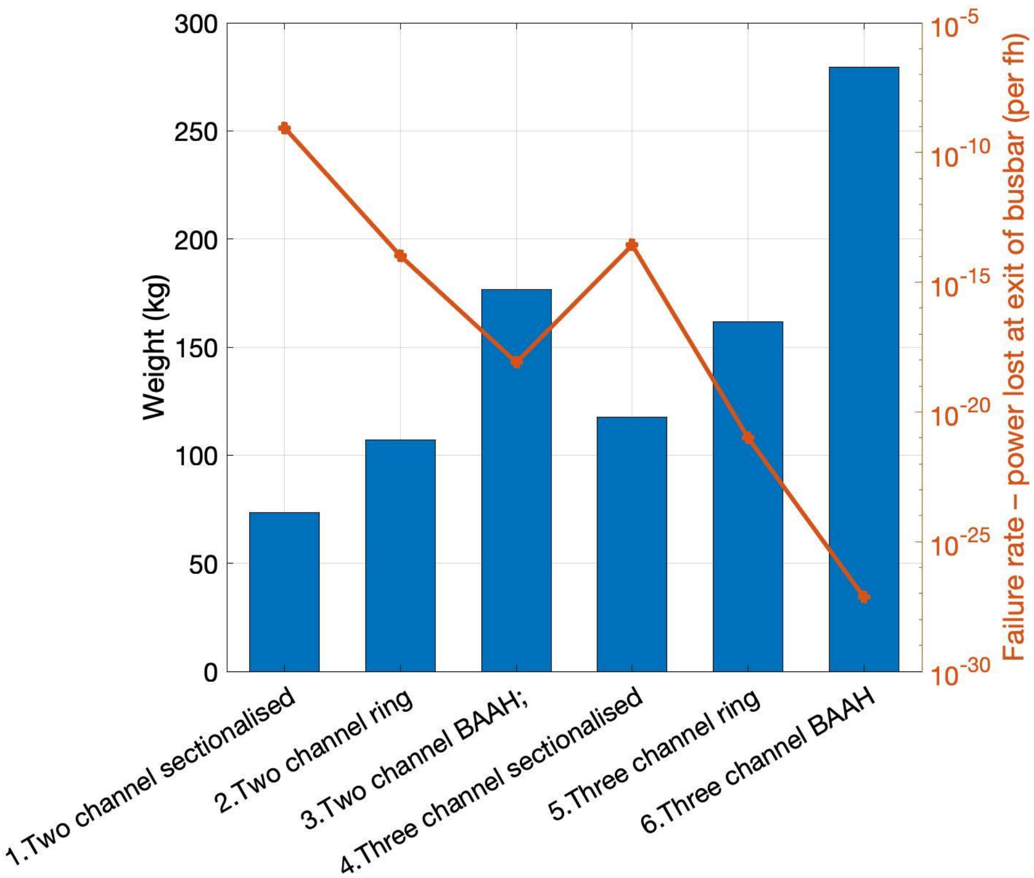


Figure 16. Busbar failure rates and weight

- Dual-channel, BAAH sectionalised bus configuration
- Three-channel, sectionalised bus configuration
- Three-channel, ring bus configuration
- Three-channel, BAAH sectionalised bus configuration

From Figure 16, it can be seen that rate of failure for the loss of supply from the HVAC busbar arrangement lies within the acceptable limits for catastrophic failure for all of the architectures considered. Furthermore, the three-channel BAAH architecture has the lowest rate of failure but is also the heaviest option considered. The increased number of components results in an increased expense while at the same time switch relaying in BAAH may become complicated. The three-channel ring bus architecture has the second lowest failure rate, but is approximately two-thirds the weight of the three-channel BAAH architecture considered. In terms of weight, two-channel

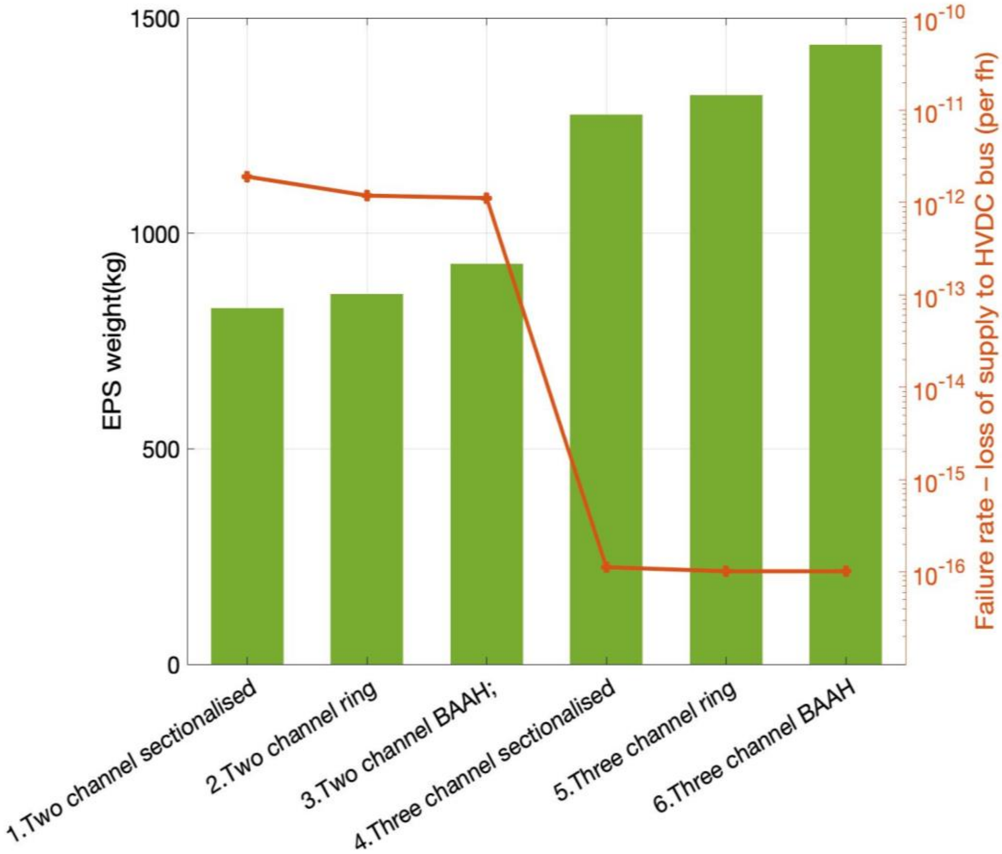


Figure 17. Reliability of power distribution architectures

architectures are understandably all lighter than the equivalent three-channel architectures.

3.4.2. Trade Study 2: Loss of Supply to HVDC Load Bus

For this case study, failure rates of generators, ATRUs, cables, contactors and an estimated busbar arrangement are accounted for. The top event of this FTA is focused on the catastrophic failure mode of a loss of supply to the HVDC critical load bus, Six architectures were again evaluated, with the results shown in Figure 17. Also, Figure 18 shows the example of a dual-channel distribution system FTA.

Because the failure rates of the generator and ATRU dominate the overall system failure rates, there is a less-significant difference between the architecture types, although the effect of the number of channels is notable. Additionally, it can be seen that both dual-channel and three-channel architectures are within the boundaries of the standard failure classification.

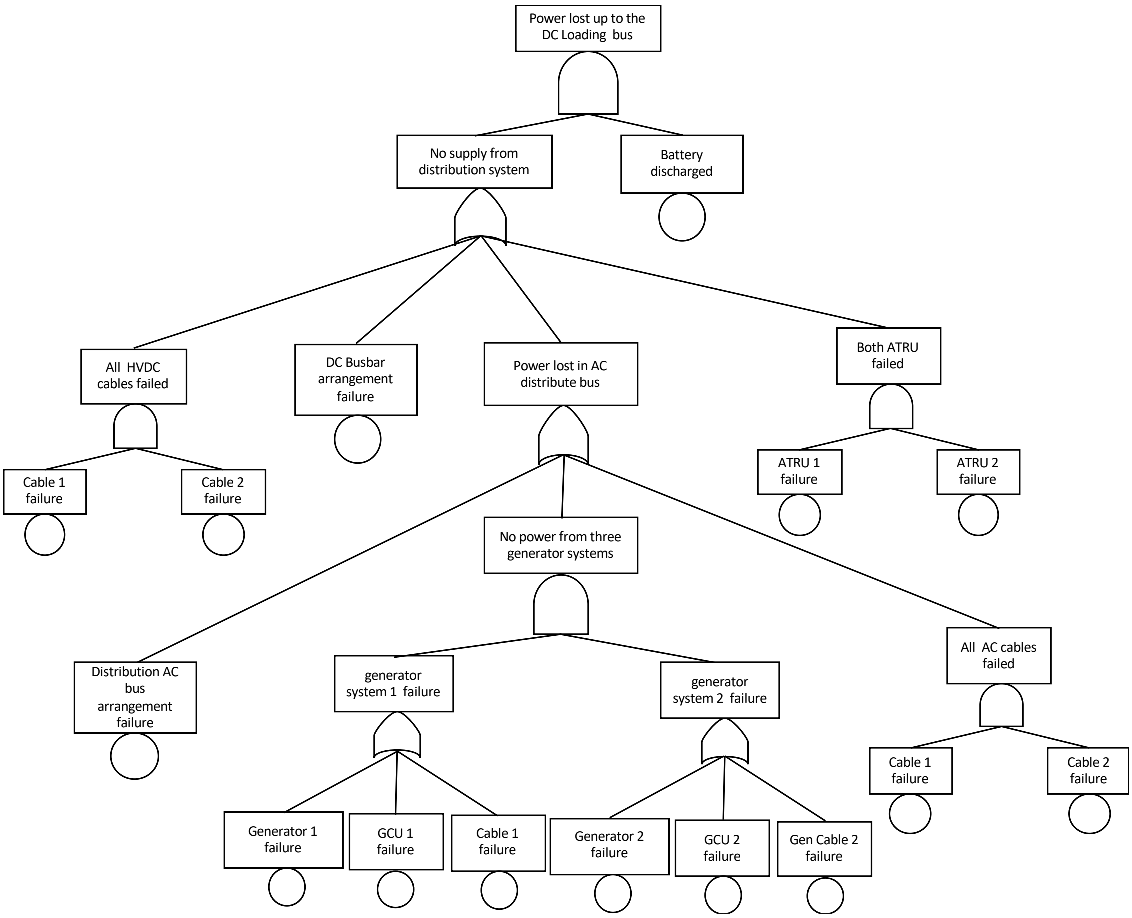


Figure 18. Fault tree analysis of the distribution system of MEE with a Dual-channel architecture, executed by Mobius software [58]

3.4.3. Trade Study 3: Loss of Supply to any Critical MEE Load

For this case study, the top event is the loss of supply to any single critical MEE load. The results of this study are presented in Table V and Figure 19 shows the Fault Tree of a dual-channel MEE EPS with the essential loads in MEE.

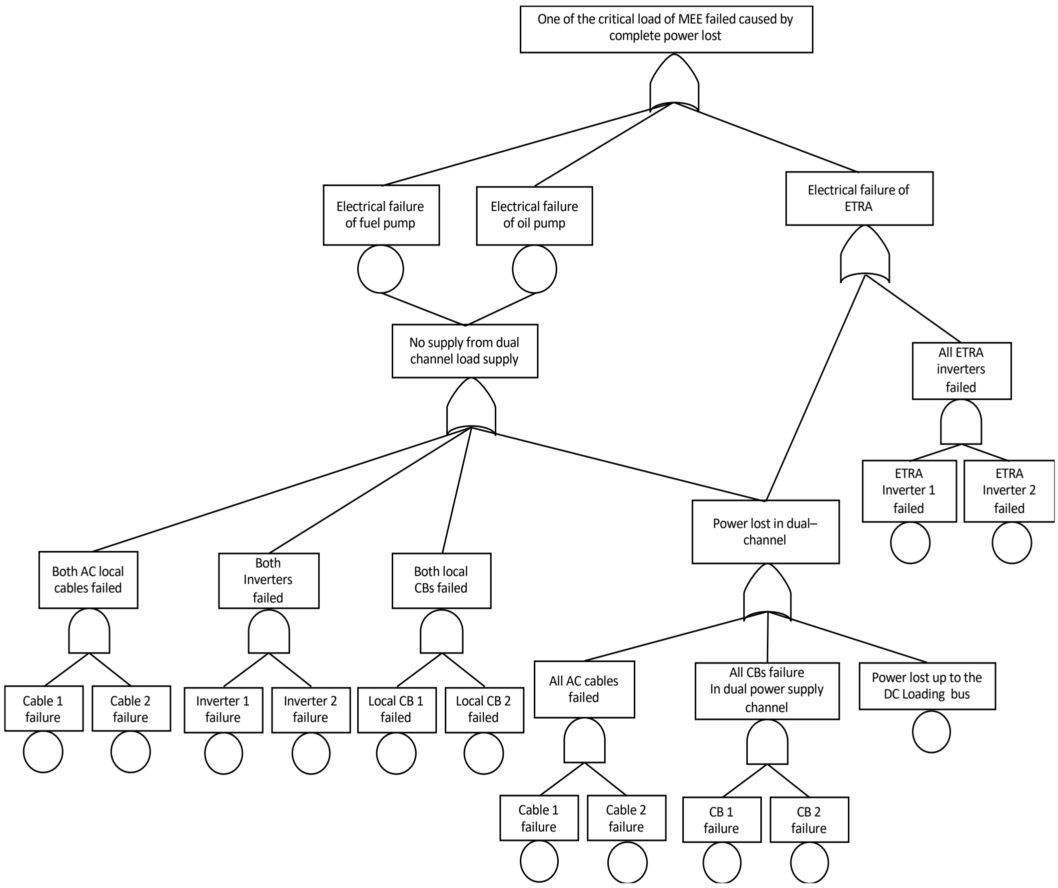


Figure 19. Fault tree analysis on power flow of the essential loads section of MEE with a Dual-channel architecture, executed by Mobius software [58]

The estimated dual-channel load system failure rates for this condition exceed the acceptable rates as defined in CS-25. As a result, the reliability of a dual channel-EPS may require some design improvements. On the other hand, when the load systems are configured within a three-channel EPS, the associated failure rate is more acceptable, although it should be noted that the failure of the loads themselves is still not accounted for.

The estimated dual-channel load system failure rates for this condition exceed the acceptable rates as defined in CS-25. As a result, the reliability of a dual channel-EPS may require some design improvements. On the other hand, when the load systems are configured within a three-channel EPS, the associated failure rate is more acceptable, although it should be noted that the failure of the loads themselves is still not accounted for.

Table V. Essential load failure probability comparison between Dual-channel and Three-Channel architecture

Architecture layout	**Top event per flight hour (one of the MEE functions IFSD caused by electrical power system)**	**Failure rate per flight hour**	
		ETRAs	**Oil electric Pump or Fuel electric Pump**
Dual-channel architecture	7.3042×10^{-9}	1.3014×10^{-9}	3.0014×10^{-9}
Three-channel architecture	1.9939×10^{-13}	4.311×10^{-14}	7.814×10^{-14}

3.4.4. Case Study Discussion

Section 3.2. has reviewed a range of multi-channel MEE architecture concepts, busbar configurations and associated underpinning technologies. It has provided a quantitative comparison of these architectures in terms of estimated supply failure rates and system mass. Of the architecture concepts considered, sectionalized bus and ring bus topologies showed a favourable compromise of reliability and mass, whilst three channel configurations appeared to be attractive for attaining high degrees of system reliability.

Although the characteristics of multi-channel architecture are explored and summarised, the root problem is how to determine if the given multi-channel architecture can meet the design requirements of MEE. Some design rules can be provided for MEE system, which can effectively determine the design intent of the power architecture, and will form the baseline model that meets the MEE design requirements. Based on this baseline model, candidate architecture solutions are adjusted to better accommodate specific device reliability through careful architecture design while further minimising overall system mass.

Furthermore, through the trade-off study on the weight and power supply reliability of AC / HVDC power architecture, it reflects a high degree of confidence in the feasibility of the design of three channel full DC distribution architecture of MEE power system. Hypothetically, the full HVDC system should be lighter than the AC/HVDC distributed architecture, and they both have the similar power supply reliability if same number of generator and channel is used.

In Section 3.3 and onwards, the analysis of certification requirements of the MEE baseline concept and assumptions around operational functionality, a range of design rules and guidance will give for the derivation of a BPA concept and key systems.

3.5. Chapter Summary

This chapter reviewed a range of multi-channel EPS architecture concepts, busbar configurations and associated underpinning technologies. It has provided a quantitative comparison of two-channel and three-channel architectures in terms of estimated supply failure rates and system mass. Although these two types of power architecture are often mentioned and recommended in the current literature, there is no comparative study on their weight, power flexibility and power supply reliability. Of the architecture concepts considered, ring bus topologies showed a favourable compromise of reliability and mass, whilst three channel configurations appeared to be attractive for attaining high degrees of system reliability. The overall result indicated that heavy power architectures may not all have a good standard of system reliability, but power architectures with high reliability are relatively heavyweight. However, the flexibility between power channels can provide better reconfiguration performance for MEE systems.

With more key characteristics and important operating performance of the MEE, it will develop toward a three-channel, high rated power architecture. This result defines a design direction for the baseline architecture of the MEE power system. To better accommodate particular equipment reliabilities through careful architecture design, whilst further minimising overall system mass, additional research is required to further explore the certification requirements and operational functionality for the MEE power architecture. Therefore, a range of design rules and guidance shall give for the derivation of a Baseline Power Architecture (BPA) concept and key systems.

Chapter 4.

Design Rules and the Baseline for MEE Multiple-Channel Power Architecture

4.1. Chapter Overview

The evaluated result of Chapter 3 shows that the published MEE power architectures have not been fully clarified in terms of design requirements matching. 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 chapter captures and defines key design rules that should be considered in the formation of a 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 chapter 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.

Whilst conventional aircraft and engine systems certification standards (such as CS-25/CS-E [3]) provide clear guidance on the design requirements for conventional engines and aircraft power systems, there are no established certification-driven requirements directly applicable to MEE designs yet. Some preliminary design requirements for MEE systems have recently been proposed in the literature [4], but these are limited to a subset of MEE design features. Although EASA recently issued the design specification for EVTOL[97], the concept of EVTOL has the fundamental differences to MEA/MEE; which cannot be directly referenced from it.

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 focusses 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 chapter proposes design rules to enable the establishment of the first generic MEE 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 chapter establishes a baseline architecture which eliminates a range of infeasible and overdesigned concepts at an early stage of the design process. The focus of chapter 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 here. In addition, full transparency of the preliminary design process is provided, facilitating subsequent revisions to the candidate MEE architecture in order to capture application-specific requirements.

It defines the design scope of different aspects of MEE electrical architecture, such as the number of generators, the number of electrical channels, the application of emergency power supply and the improvement of power independence. According to the proposed design scope and recommendations, a credible baseline power architecture has been established, highlighting the characteristics of MEE electrical system.

4.2. Generators and Reconfiguration Considerations for MEE

System safety is the most significant design feature for any type of aircraft [98]. A summary of engine system failure rate specifications can be found in European Aviation Safety Agency (EASA) standards document CS-E [99]. 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 for a twin-engine aircraft (the level for extremely remote of failure). For an MEE power system, all essential loads are powered via the electrical power system architecture. As such, this section 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. Subsection 4.2.1 to subsection 4.2.3 briefly recalls a series of analysis that already detailed in Chapter 3 in order to provides a comprehensively reminding of the characteristics and design criteria of MEE power system.

4.2.1. Number of Power Channels

A power channel is defined in this section 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 (FTA). Although a detailed analysis of power channel reliability was conducted in Chapter 3, the importance of choosing power channels for MEE power systems still requires to be high-level reviewed for the BPA design in this chapter.

For example, the simplified power channel (with loads omitted for clarity) shown in Figure 20, featuring a Variable Speed Constant Frequency (VSCF) generator system, has a rate of complete power loss to the load bus of 2.50×10^{-4} failures per flight hour (using subsystem failure rate data from [100]). 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 (GCU)) 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

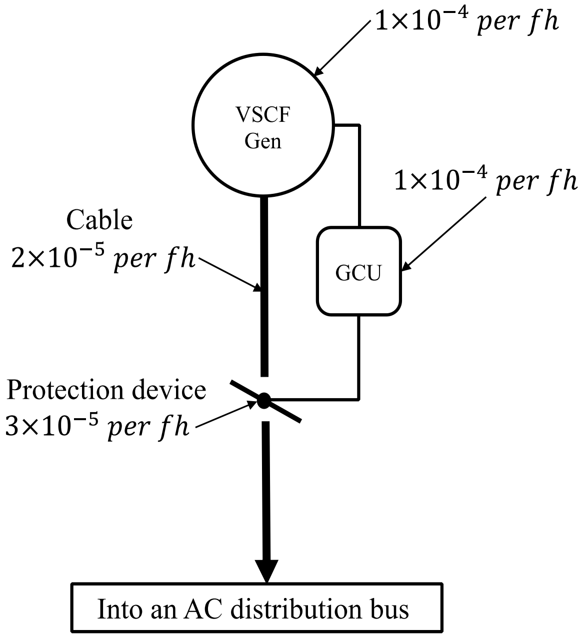


Figure 20. The VSCF generation system with component failure rates.

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. With Equation (1), these calculated failure rates are summarised in Table VI.

$$P_{fail} = 1 - e^{-\lambda t} \tag{1}$$

According to Table VI, 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

Table VI. Component Failure rate and Mission Reliability According to Number of Power Channels

Number of power channels	Failure rate of complete power supply loss (per flight hour)	Probability of complete loss of electrical power supply in a 5 hours flight	Probability of complete loss of electrical power supply in a 10 hours flight	Probability of complete loss of electrical power supply in a 15 hours flight
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}	1.88×10^{-14}	3.75×10^{-14}	5.63×10^{-14}

parameters may still yield acceptable failure rates. However, 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, it is recommend the implementation of a 3 power channel system for the MEE BPA concept.

4.2.2. The Busbar Topology for MEE BPA 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 21. Candidate busbar topologies for the MEE BPA 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 to be too complex for consideration at the baselining stage. This figure is reviewed and summarised from the detailed analysis that conducted in chapter 3 and helps to define the necessaries of busbar arrangement for MEE power system. Table VII provides a summary of the key characteristics of each of the illustrated busbar configurations. Note, that whilst this thesis acknowledges its previous recommendation for the use of a 3 channel architecture, the busbar topologies illustrated here are configured 2 channel systems for simplicity.

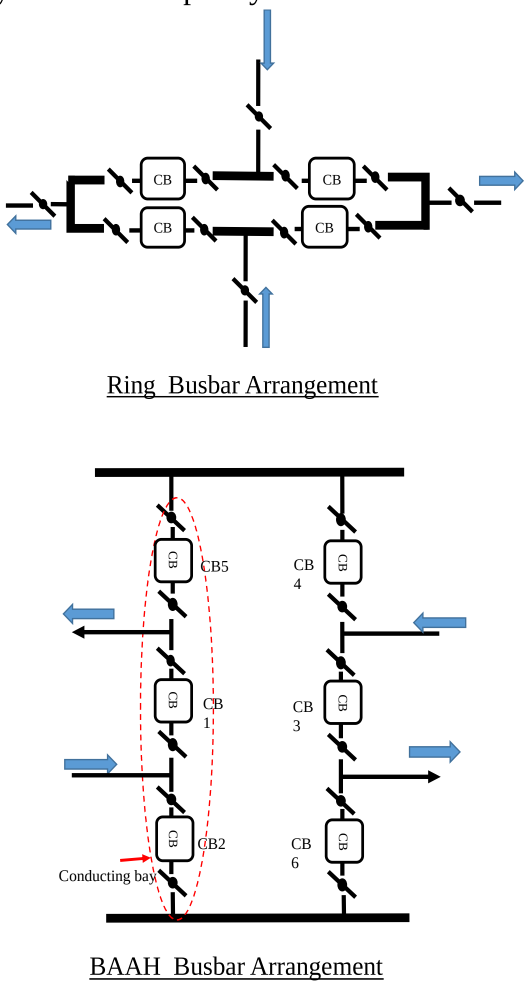


Figure 21. Candidate busbar topologies for the MEE BPA

Table VII. Potential Busbar Topologies for MEE

Type of busbar arrangement	Advantages and disadvantages
Single bus	• Simple operation. • Low initial cost. • Paralleling 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.

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 [101][102][103]. Alternatively, the ring bus has flexible power paths and is often used in other transportation facilities, such as shipboard power systems [104]. 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 [83].

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

Table VIII. 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

From Table VIII, 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. 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, this chapter recommends the use of either the sectionalised radial busbar or ring bus arrangements for the MEE BPA concept.

4.2.3. **Type of MEE Generators**

Although Chapter 3 has a briefly overview of the types of MEE generation system, a more comprehensive version of that should be undertaken in order to establish the MEE design rules and the BPA.

From Table IX, the Wound-Field (WF) generator with a Constant Frequency (CF) system is a mature technology which requires Constant Speed Drive(CSD) or DC link to stabilise AC frequency voltage input to EPS on aircraft [29][105]. However, it seems to have low power density due to the additional components in the generation system, which is not an effective choice to meet the expected feature of MEE.

Wound-field generation with Variable Speed Variable Frequency (VSVF) system requires less power electronics and controller, which widely used in MEA such as B787 and A380. The power density of WF-VSVF system is expected to be higher than the CF system due to less component required. Currently, most WF generator have a relative low power density but the new prototype of WFSM can achieve a power density of 7.9kW/kg [105].

Due to the structural characteristics of Switched Reluctance (SR) machines, it has rotor robustness and fault tolerance. Each power phase can be powered by an independent power electronic converter and the SR machine can operate safely when a converter fails. Although the SR machine has a high power density but the machine with dedicated power electronics makes the power density lower [106]. In addition, SR machines are able to accommodate a wider range of speeds from the engine shaft, but additional switches which can be heavier [107].

Table IX. Power Density of Engine Generators

Type of Generator	Shaft Implementation	Power Rating	System Power density kVA/kg	efficiency	References
Wound-field synchronous generator (in CSCF or VSCF) Boeing 777	HP shaft	90-120kVA	0.88 to1.5	78%-97%	[29],[105],[77]
Wound-field synchronous generator (in VSVF) B787 And A380	HP shaft	225,250 kVA	Assumed >0.88 to >1.5	78%-97%	[29],[105],[77]
SR generator F22, F35	LP shaft (Wider speed range)	80kVA, 120kW 150kW	1.65 to 5.30	90%-93%	[29],[105],[108],[109]
PM Synchronous generator (in VF) Light combat aircraft /Joint Strike Fighter	LP/HP shaft	30-60kW Or up to 140kW	3.3 to 8	>93%	[29],[77],[110],[111]
New PMSM (Uni of Nottingham) experimental	TBD	45 kVA	16	95%	[29],[105]

After all, the weight of the power generation system is a large part of the total weight of the BPA. Compared with wound-field and SR generation, Permanent Magnet (PM) generation has higher power density due to it has less dedicated components such as rotor winding, brush and slip ring. The control strategy of PM machine is also already established, but the demagnetisation of permanent magnet material may occur at high temperature, and the de-excitation problem will occur in some fault condition [112].

The power efficiency of all types of generators reaches around 95%, and the power rating depends on the electrical demand of the MEE that can be adopted. The generation failure rate is calculated with values in reference [100]. Under the condition of similar generation failure rate, the power density becoming the key influence on the MEE architecture. Considering the best combination of weight and safety of power generation system, it is necessary to balance the weight and fault tolerance of MEE generator. Taking this table as an example, PM power generation system [29]and SR system [113] are beneficial to the power architecture of MEE.

4.2.4. Generator Overload Rate with Overload Time

This section describes that overload capacity of generator could be a manageable power for emergency use. In architecture design, designer has to identify the overload ability in the power system which will tailored the design of PLM for the aircraft systems. The purpose of this topic is to understand the potential characteristics of generator performance. While forming MEE baseline, it also leaves a suitable hardware performance-based strategy for the design of power management scheme.

In MEE power architecture, whether PLM strategy uses generator overload may be the key to the power balance. Different types of generators have overload rate and overload period. For example, a HP Starter/ Generator has nominal rating of 120kVA（IDG of GE90), has the allowable overload capacities are as follows:

- 125% for 5mins per 1000hours[56].
- 167% for 5 seconds per 1000hours[56].

The generator overload capacity is a short-term additional power to ensure the operation of the essential loads only when necessary. However, the period of using generator overload must be less than the recommended overload time in order to maintain the health of the generator. Although the generator has overload capacity in the short term, but PLM strategy cannot use this function at will. As a lot of high-power electronic equipment are used in MEE, and excessive use of generator overload can cause significant damage to the large electronic equipment[114], such as generator converters and the generator itself [57].

4.3. DC Power Distribution for MEE

HVDC distribution is consistently proposed in the literature as the preferred power distribution method for MEE systems, 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 [28][115]. Indeed, the designer will consider a fast and robust protection scheme and the relevant technologies for the HVDC distribution protection. 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 [21]), the use of DC distribution provides a natural interface. As such, DC distribution is recommended for the MEE BPA concept.

4.4. Technical Functionalities of MEE 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.

4.4.1. Starter/Generator Functionalities for MEE

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 [18]. As such, it seems reasonable to recommend that the MEE BPA concept also features, as a minimum, 2 electrical starter/generators mounted on the HP/IP spool, per engine, although additional generators may also be required (as discussed in subsequent sections). From the research literature, permanent magnet synchronous machines and [29], [112] and switched reluctance technologies [113] appear to offer favourable characteristics for future aero-electrical applications.

4.4.2. HP/IP and LP Shaft Offtake

Whilst current state of the art more-electric aircraft feature HP- or IP-only driven generation (for example the B787 features 2 HP/IP driven starter/generators per engine [29]) 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 low pressure (LP) spool-driven generation [19] to supplement existing HP offtake power has been shown to potentially improve engine stability and fuel consumption [29][49]. 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 4.5.3). 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.

4.4.3. 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 type, functionality and directionality of the power converters can minimise uncertainty in subsequent design phases.

Table X shows the specified direction of converters [14][116][117] that can be options for MEE power architecture.

Table X. The Power Direction of Power Converters

Power distribution section	Direction of converters	Propose
ESS system, DC distribution	DC-DC bidirectional converter • Dual active bridge • Multiport active bridge	Discharge and charge the battery and step-down the DC voltage
AC distribution	AC-AC bidirectional converter • Matrix Converter • Indirect matrix converter	The converter needs to be bi-directional as APU may supply the engine starter.
AC generation to DC Distribution	AC-DC unidirectional converter • 12 and 18 pulse diode bridge rectifiers (ATRU) AC-DC bidirectional converter • 6 IGBT diode switches V2G	AC power source into HVDC/DC bus in order to have high stability and reduce the power electronic for VF generators
DC distribution/bus to AC loads/motors	DC to AC converter, bidirectional converter • six-switch voltage source inverter • three-level Neutral Point Clamped (NPC) power converter	Commonly used to control AC loads such as motors, from DC bus or power supplies

In order to identify all the system reconfiguration requirements when using converters during fault conditions, all the converters can first be considered with the bidirectional power conversion for the MEE baseline model. This is because the bidirectional converter has flexible current direction, which provides the basis for power reconfiguration. For example, the DC/DC bidirectional converters are easily parallelisable units; no synchronisation is needed, which is feasible for ESS system and emergency use. Overall, the bidirectional converter are smaller size high efficiency and higher power density[118]. The reason of not initially using unidirectional converter in BPA is that it will limiting the power reconfiguration options during the trade study on the flexibility of power flow.

Not only the direction of conversion impacts the BPA, the type of converter also needs to be considered. Active converters such as Space Vector Pulse-Width Modulation (SVPWM) switching converters can maintain power quality and reduce harmonics[119], which are more suitable for the variable frequency power generation systems of most current aircraft. As an active converter, the matrix converter has no DC link component and bidirectional switches are used to provide the blocking voltage and conduct current in both directions. However, it needs additional switches and related control systems. Therefore, it is essential to evaluate that the reduction in reliability due to additional switches and complex control can offset the increase in reliability resulting from no DC link components [120]. Compared with active converter, passive converter, such as 12 or 18 pulse autotransformers, has the advantages of simplicity and robustness, and is only heavier than active converter in sometime. However, they are easily affected by thermal loss, Electromagnetic interference (EMI) and the stress requirements to mounting on a mechanical design [120].

For the safety requirements such as preventing the direct current flow from input to output, the isolated converter is the better option for aerospace applications. It has the advantage of easy ground fault protection and high grid interference immunity. This may require independent ground systems on the aircraft body. However, to make the BPA in an architecture level of design, grounding in general is not consider in the baseline system. However, During the early design phase of MEE, non-isolated converters can be assumed in the BPA to facilitate the designers to estimate no switch losses for power flow during fault conditions. Also, the non-isolated converters tend to be smaller and higher efficiency than the isolated converters.

For the MEE BPA concept, this chapter recommends 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 chapter recommends 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 [121], [122], 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.

4.5. Nominal and Off-nominal Mode Considerations for MEE 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.

4.5.1. MEE Power Source Independence

The definition of an independent source can be found in amendment 5 of CS-23 [123]. In CS-23.2430 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 paralleled within the BPA. It is recognised that paralleled 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 paralleled sources following an electrical failure or fault. However, this chapter recommends the use of non-paralleled 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 paralleling of sources, and protection against fault and failure conditions are introduced.

4.5.2. ESS Use in Nominal and Off-Nominal Modes of BPA 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 2 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, this chapter recommends 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, this chapter recommends 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.

4.5.3. 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) [108]. Indeed, authors in [95] 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 [124]. As such, during the BPA concept definition, this chapter recommends 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.

4.5.4. Alternative Use of APU Generation

An Auxiliary Power Unit (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 [125]. 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 [126].

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, this chapter suggests that the use of APU as a supply for MEE loads purely the choice of designers.

4.6. Load Redundancy

Essential auxiliary MEE loads may include; fuel pump systems, oil lubrication systems and electric thrust reverser actuation system (ETRAS) [127]. For the MEE BPA concept definition, this chapter recommends that the preliminary design requirement for these essential load systems is the provision of single-fault tolerance [128]. 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 22 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 [129][130] or two single-stator motors powered by main and redundant local power electronic drives. As with the starter/generator machines, the

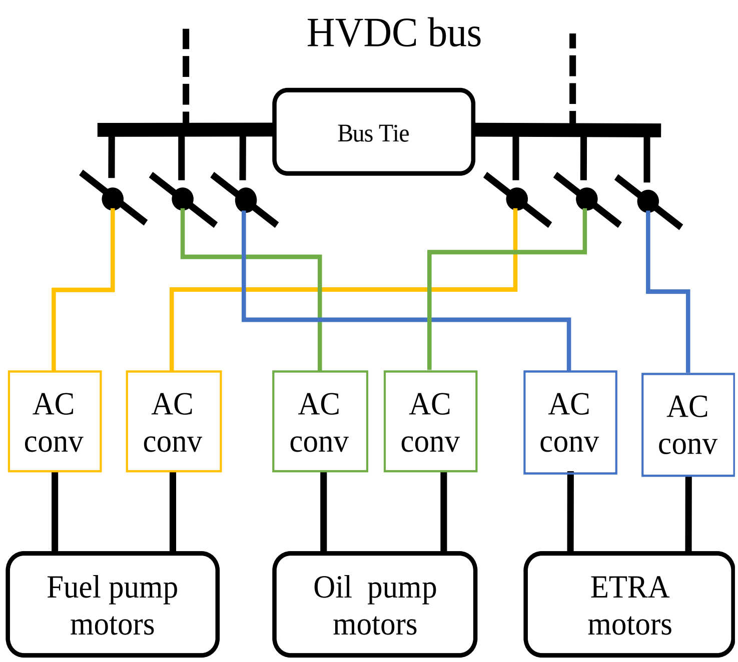


Figure 22. MEE essential loads redundancy

use of fault-tolerant multiphase machines and drives may potentially enable the deployment of just a single motor drive for each MEE load.

4.7. The MEE Design Recommendations and an MEE BPA

This section summaries the baseline architecture design recommendations given in detail between Section 4.1 to Section 4.6 and illustrates a potential MEE BPA concept configuration, which is established based on the prior recommendations given.

4.7.1. Summary of BPA 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, and PM or SR DC generators are 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.

4.7.2. Potential Multiple-Channel BPA for MEE

Figure 23 shows an illustration of the three-generator, three-channel MEE BPA concept, derived from the design recommendations provided earlier.

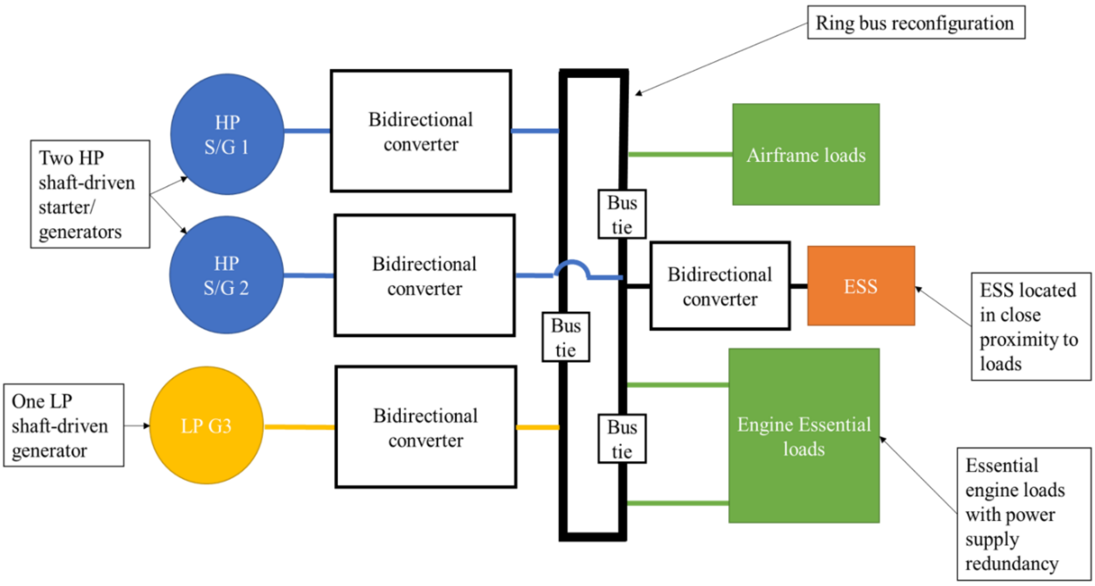


Figure 23.The example of baseline power architecture for MEE

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 with dedicated bidirectional power electronic converters (see Table X) to interface the generators to the DC network. This design allows the distribution network to supply power to the Starter/Generator for engine start. 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 paralleled 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).

4.8. Chapter Summary

Whilst significant research has been undertaken on MEE electrical systems and technologies to date, this chapter 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 chapter to facilitate this. These are derived using a combination of anticipated safety requirements, failure rates analysis, and logical functional system needs.

Whereas 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). Although this approach that using qualitative assessment and design suggestion is applicable to an interdisciplinary system design such MEE power architecture, the limitation was that it has not been fully describe in detail of use in technologies for system functions such as power management schemes, power converters or protection schedule. 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. However, it would be a great option for user who would using the BPA to design their own MEE architecture based on these open-end design rules.

For industry interests, the MEE electrical power architecture is theoretically easier to install and easier to maintain than hydraulic and mechanical architecture, improving the power efficiency of conversion. The dual-use advantages of an engine starter / generator offer significant physical space use and reduced components. The multi-channel power system of the MEE may generate a certain level of redundancy throughout the aircraft power system. These benefits undoubtedly play a decisive role for the production, operation, as well as maintenance of MEA.

Chapter 5.

Optimising the Intersystem Compatibility of MEE Electrical Power Network via Design Parameters Classification

5.1. Chapter Overview

In Chapter 3, a comprehensive pre-design analysis was provided for the MEE power network. Subsequently, the design rules and baseline power architecture were captured for designing MEE power architectures in Chapter 4. Although, the MEE architecture baseline has been identified, it is still necessary to consider the compatibility of the MEE power architecture with its dedicated PLM strategy. Therefore, this chapter will be focus on the approach of design and optimise the compatibility between the architecture prototypes that are considered in previous chapters and their dedicated power management.

When considering the increasing electrification of the engine auxiliary systems, the Electrical Power System (EPS) redundancy and reliability are of critical concern. Due to the critical supply requirements in MEE, the multi-channel power architecture would be a promising solution [31] through greater distribution flexibility between the channels. Regarding the increasing electrical demand and multiple power management parameters, the issue of optimising the operational compatibility between power management strategy and power architecture in a multi-channel EPS design most be solved. However, current literature shows limited investigation into systematic optimisation of the MEE power network. In order to ensure the designed power system is an optimal solution for the MEE, the challenge of systematically optimising a MEE power system will need to be addressed.

The co-design process (see literature review in Chapter 2) is an approach which has been widely used in interdisciplinary systems design [131][132], in other fields outside of aerospace electrical design. This design process can incorporate the concurrent design paths of two individual subsystems into an integrated 'platform' in an early stage of the design process, which can evaluate the preliminary integrated performance of the integrated system.

The background design manner of co-design process could potentially be a solution for MEE power system design, but it has not been developed in detail for such application.

In the generic co-design process, the first stage was that subsystems were designed in parallel and independently. In this way, the design space can be expanded, naturally offering wider a solution space. However, in order to manage such large scale of solutions and to find the optimal design, the proposed design parameter classification in this chapter is tailored for MEE design. This classification features qualitative scorings for the parameters of the MEE design requirements, and to compare the MEE power system prototypes based on those parameter scores. Such a method can allow the parameters of subsystems to be integrated, compared and optimised; and then to prioritise the perfect complemental designs of MEE power system.

Accordingly, this chapter presents a design parameter classification-based optimisation in a systematic integration platform at early stage of the co-design process. Through an MEE design case study, the demonstration of the effectiveness of the parameter classification-based optimisation is presented. The qualitative case study also demonstrates the efficient management of the large design space and systematic optimisation of MEE power system solutions, allowing the user to evaluate the integrated MEE power system in a reduced time and at a high-level with less specific deign [133]. This chapter is focussed on addressing the challenge of designing an integrated MEE system in terms of system engineering. Furthermore, the benefits of using parameter classification optimisation are not only the prioritisation of high-scoring MEE design concepts, but also the identification of low-ranked prototypes that similar to high-ranked designs. This helps to detect the potential alternative MEE candidates. With the proposed approach, the design scope of MEE power system can be captured, which addresses in the gap of current knowledge.

5.2. Parameter Classifications Optimisation for MEE Architecture and PLM Strategy

As shown within the literature in the previous section and chapter 2, there are a lack of clear methods to manage the integration of MEE power management and architecture solutions to realise an optimised design. The parameter-classification method was discussed as a possible solution to address these. Hence, this section presents a parameter-classification-based optimisation process applicable for MEE. The proposed process itself is part of a larger design methodology illustrated in Figure 24 which combines other researched components[24][59]. Block 4 within Figure 24 is

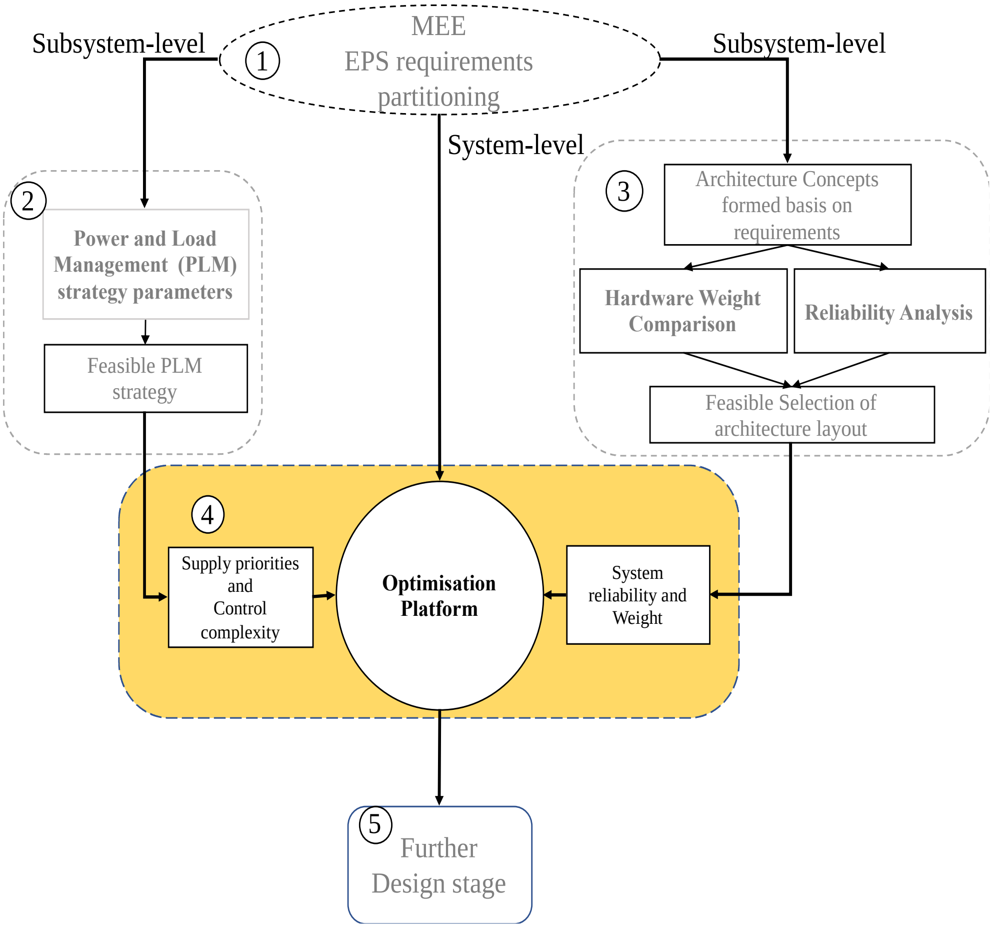


Figure 24. Co-design approach overview for optimisation of MEE integration

the proposed parameter-classification based optimisation process. This larger design methodology is a standard process of co-design that has been adapted for MEE, and a more comprehensive version is proposed in Chapter 7. In this chapter, Block 4 will be the focus. However, a briefly introduction about this large design process will be given to help understand the relationship between Block 4 and the remaining Blocks in the diagram.

Block 1 in Figure 24 is the requirement partitioning of the earlier design stage, which summarises all design requirements and then classifies them into the dedicated processes. In this stage, design requirements of MEE subsystems will be partitioning into their dedicated analysis and design processes, which are Block 2 and Block 3. MEE architecture design rules capture (detail shows in Chapter 4) would be an example of design requirement partitioning, followed by the independent analysis and design of power architecture in Block 3.

Similarly, Block 2 is the independent analysis for the Power and Load Management (PLM) strategy. Power balancing is critical for aircraft electrical system, and this relies on the power and load control and management in both generation-side and demand side. Various power management and load management approaches suitable for aircraft power system balancing can be considered in this stage, where the combined PLM options will be used as candidates for the parameter classification analysis. Although the design rule capture of PLM is also important, it is not within the scope of the thesis and may be a research gap for future.

Once the independent candidates of PLM strategy and MEE power architecture have been identified by first three Blocks of the co-design process, the Block 4 offers a integration platform for them with a qualitative evaluation. In result, integrated MEE power system candidates that are combined with the complementary PLM strategy and BPA will be realised.

In addition, block 5 is the further in detail design stages, which is to verify the behaviours of power balancing for the integrated MEE power system. (more information has been shown in Chapter 6).

5.2.1. The Procedure of Parameter Classication Optimsiaiton

In this section, the proposed parameter-classification based optimisation is presented in more detail. The main feature that distinguishes Co-design from common simultaneous/parallel design is the concurrent exchange of requirements and influence of subsystem design options as part the system design process. The proposed parameter-classification based optimisation is shown as Figure 25, which is an expanded version of Block 4 of Figure 24.

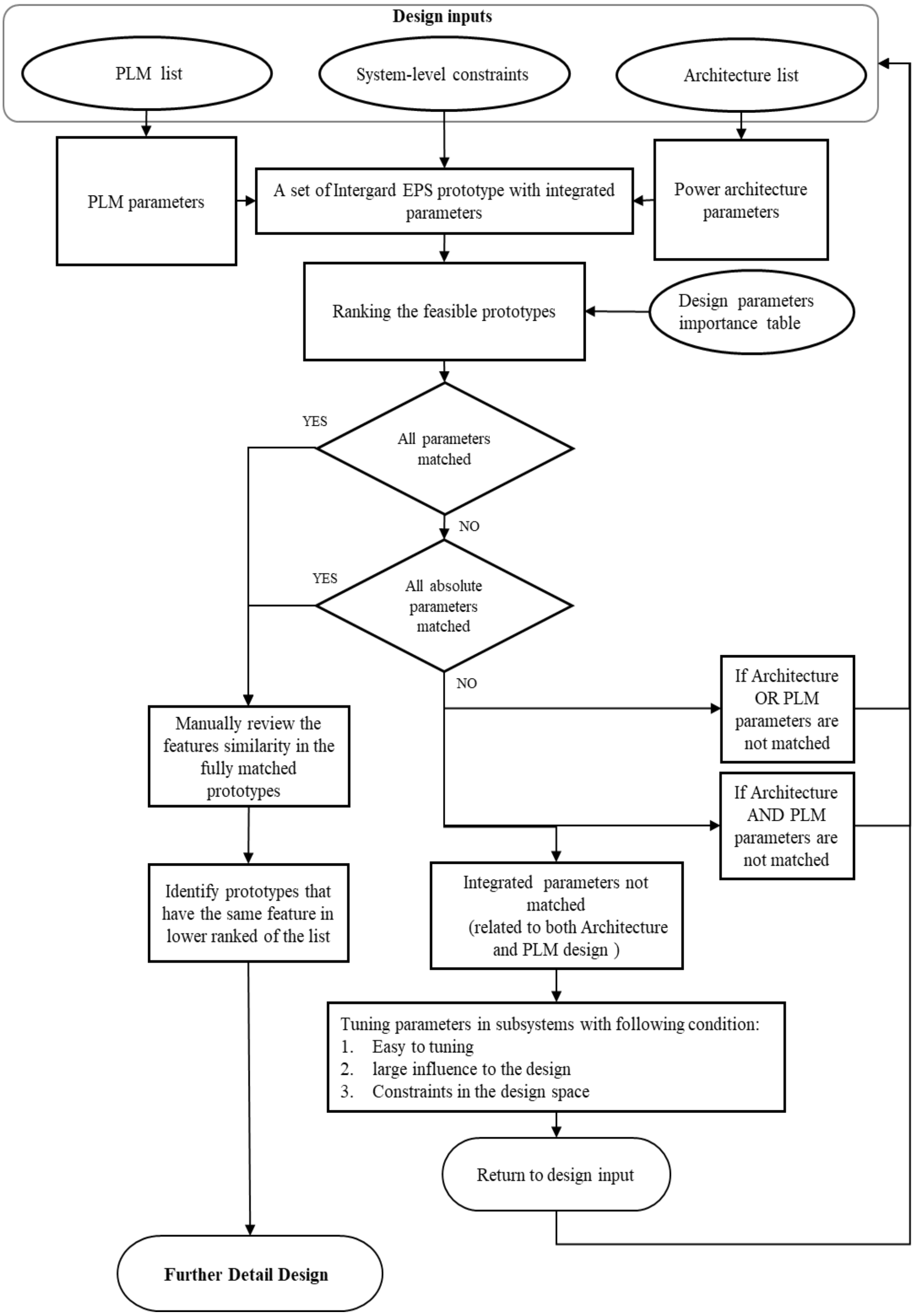


Figure 25. Detail flow chart of parameter classification for optimising the integrated MEE features

To begin the optimisation procedure, three inputs are required. They are the top lists of both subsystem options, and the system-level constraints as shown on the top of Figure 25. Top lists of both subsystems are generated by the ranking of subsystem options against the subsystem parameters individually as first shown in Table XI (more explanation later).

Table XI. Sample of Design Parameter Score in Acceptable Range

Design Aspects	**Type of indicators in MEE power system**	**Parameter Importance**	**The level of system constraint acceptable range**
Architecture design	System reliability	**Absolute**	High
	System weight	**Optional**	Medium/Low
PLM design	Control response time	**Absolute**	High
	Control approach	**Optional**	High/Medium
	Backup power supply priority	**All Levels Accept**	High/Medium/Low
	Power control simplicity	**Optional**	Medium/low
	Degree of freedom in control	**Optional**	High/Medium
System-level requirements	System load shedding as less as possible	**Optional**	High/Medium
Integrated parameters	Availability of power supply (types of power source)	**Optional**	High/Medium
	Single failure tolerance (isolation of subsystem)	**Absolute**	High
	Dispatch with one generator faulty	**Optional**	High/Medium
	Number of reconfiguration states	**Absolute**	High

Following from this stage, all combinations of the PLM scheme with architecture options are generated to form a list of integrated EPS prototypes. The prototype list is then ranked based on the system-level parameters (described in more detail in section

4.3). According to the ranked EPS prototypes, the designer can down-select the most compliant EPS prototypes. In this, the higher the match between EPS prototype parameters and design requirements, the higher the ranking in EPS prototypes. The high ranked EPS prototypes will have the higher probability to become a feasible solution for the MEE system.

In order to determine the importance of each parameter, Table XI specifies the design priority of each parameter, which categorises the design priorities in 'Absolute' (high-priority design and compulsory), 'Optional ranges' and 'All Levels Accept'. Absolute design parameters must adhere to a specified level. Optional parameters can accept a certain range of the levels, which has relatively loose restrictions on design requirements. All level acceptable parameters have the lowest design priority, which has the widest design region.

After the EPS prototypes are ranked, the top ranked prototype should match all requirements or at least match all absolute parameter requirements as part of the decision process. In the extremely rare cases, the top ranked EPS prototypes may not be valid due to low technology maturity, and maybe not be applicable for the intended design. This would then require the user/designer to identify the common design traits amongst the higher ranked prototypes. If a certain parameter is common amongst the higher-ranking EPS, it may be an indispensable part of the EPS design for MEE. The designers can then search for this in the lower ranked EPS. Any other EPS prototype with the common traits can also be a potential solution for the MEE. This proposed approach requires a manual review of the lower ranked prototypes with such common traits, which can reduce the chance of missing potential solutions. Figure 26 illustrates an example of searching the common traits on lower ranked prototypes. In this example, suppose that in an EPS ranking list, the best overall performance is a combination of the first architecture solution and the third PLM solution. In this case, the first and second power architectures are highlighted in the same colour, which means that they have some of the same features (e.g., the same number of power channels), which may be an indispensable design feature for MEE power systems. Accordingly, the designer can search for any low-ranked EPS prototypes with this feature. In addition, the same feature as the third PLM scheme can also be searched in the EPS rankings to ensure that all relevant EPS prototypes can be found. This subprocess is illustrated in Figure 26 as the feature similarity identification. In reality, due to the limitations of existing PLM and architecture, the scale of solutions is finite, so a manual review of the features of lower ranked EPS is feasible. After determining whether the selected prototype meets all the absolute design requirements, the EPS prototype can be considered as a feasible solution and will undergo further detailed design.

However, if only a few EPS prototypes are compared, then there may be a scenario where none of the derived EPS meets the absolute requirements. In this scenario, the designers should return to the PLM and/or architecture design and review/amend their parameters respectively. If all the EPS prototypes did not completely meet the requirements of system-level parameters and integrated parameters, the designer is required to review the parameters of both sub-systems, and determine the parameters that either can be; easy to tune, have a high influence on the design, or less constraints

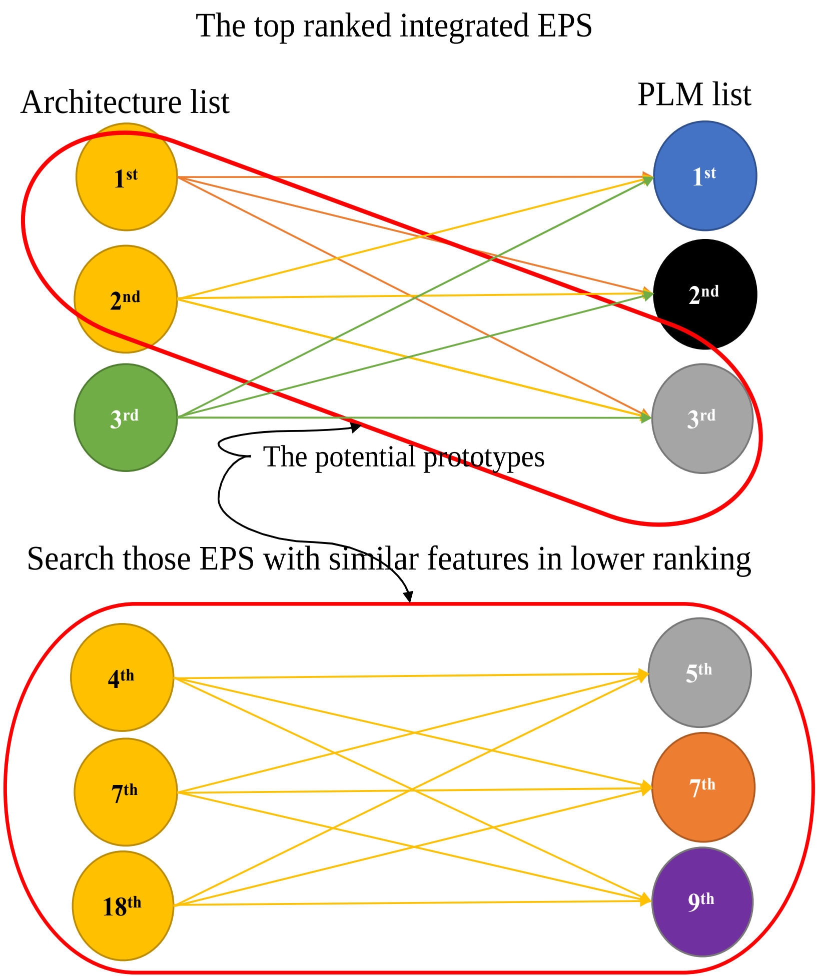


Figure 26. Feature similarity search in the parameter classification optimisation

on their design space. According to that, the independent design of PLM and architecture should be amended. In a further low probability, subsystem parameters and integrated parameters may both fail to meet design requirements and provide the parameter amendment in different directions. In this rare case, the designer should review the absolute design parameters in priority. If both subsystem and integrated parameters fail to meet the non-absolute requirements, the designer should follow the design amendment that provides the integrated parameter to achieve the intersystem compatibility.

In summary, this parameter classification optimisation is the key stage of the proposed co-design process for designing MEE power systems. This proposed process comprehensively describes and captures the subsystem-level and system-level requirements of EPS prototype as part of the initial design. Additionally, EPS features can be mapped and prioritised, which enable the timescales for the down-selection of the most suitable solutions to be reduced rapidly in the early stage of design.

5.3. Definition of MEE Network Subsytem Parameters

The previous section has described the procedure of parameter classification, which requires the parameters of each EPS candidate to meet the required acceptable range defined in the process (shown in the example as Table XI). In this section, details of this process of how to define and classify each parameter for MEE power system design are presented.

5.3.1. The Parameters of PLM Strategy Design

As described in previous sections, Block 2 in Figure 24is used to determine the feasible PLM strategy options for the MEE power system, including both power source management and demand-side management. This independent analysis is out of scope of this thesis, but further details can be found in [134]. In addition, M. Flynn *et al.* explains the design of fault and power management in similar applications[135]. However, the parameters of PLM strategy will mainly be described in this section, which is essential for the parameter classification optimisation.

Firstly, the order of using each of the combined strategies may affect the EPS performances. According to so many PLM strategies, multiple power/load control strategies can be adopted in a power management scheme for the MEE power system, such as the combination of emergency battery power supply and generator overloading supply. In a combined PLM scheme, the higher the number of combinations of management strategies, the greater the chance of reconfiguration of the EPS under abnormal conditions. Therefore, the designer should consider the usage of backup power supply priority.

Additionally, the system response time has a large impact on the success of the PLM strategy, and if the time delay is far too long, the power system may be permanently damaged by an electrical fault. A set of power management algorithms or schemes must respond as quick as possible in fault detection and system reconfiguration to avoid any damage in electronic components. In terms of different types of DC protection devices, the operational time can be 5ms-20ms. It is assumed that the BPA distribution is a full DC network. Therefore, the protection devices response time in power control need to be below 20ms [136]. The PLM is envisaged as the power control system of managing post fault response and rebalancing. Since the fault protection reaction is required to be fast, the post fault PLM action should response immediately after the protection action to ensure the power is rebalanced. However, it should not act ahead of protection. In regard to the response time post fault action, the simplicity of the PLM strategy when designing MEE systems shall therefore be considered.

Another indicator of PLM is the approach of the control system which can be categorised as preventive, detective and corrective control. Preventive control is designed to be applied before a failure event, and can reduce and/or completely avoid the potential impact of the failure event[137]. The detective control refers to the measurement after a failure event has occurred, ensuring that there is an effective PLM strategy to maintain the normal operation of EPS, and to avoid the recurrence of similar failures [137]. The corrective control aims to correct or mitigate the potential impact of each failure occurring in the EPS and to resume normal operation as much as possible[137], such as the on-time control with predictive power management with the deterministic rule-based controller or fuzzy logic controller[138]. As mentioned earlier in section 2.5.1, the newly proposed PM control approaches should be design in accordance to DO-178 for later certification.

Furthermore, the degree of control freedom in EPS secondary equipment also can reflect the performance of PLM scheme. In short, the greater degree of freedom of control in the PLM scheme, the more flexible the EPS reconfiguration can be during the fault conditions. For example, in the generation system section of the EPS, the generator voltage and frequency regulation can be manipulated by the Generator Control Unit (GCU)[139]. Also, the generator can be controlled by torque and rotational speed [113]. In the distribution section of the EPS, the power can be controlled by the converter with varied control techniques[113]. In the demand side of the EPS, the amount of power taken from the loads can be controlled/limited by the motor rotational speed, such as oil pumps. However, the higher degrees of control freedom in PLM may add complexity to the central control system, so designers should balance the advantages and disadvantages.

5.3.2. The Parameters of Power Architecture Design

The parameters in the MEE power architecture include reliability and some hardware capabilities[38], as shown in Block 3 of Figure 24. In terms of system reliability, different types of failure analysis can be used to evaluate the failure rate of available components and the overall EPS system failure rate [91][140]. Furthermore, parameters of hardware capability includes component mass or power density can be involved in the optimisation.

5.3.3. EPS Integrated Parameters

The parameters of EPS prototype can be summarised in the Venn diagram, as shown in Figure 27. This diagram indicates that PLM and MEE architecture design parameters are an integral part of design constraints. The design may also contain the constraints imposed by system-level requirements or from stakeholders.

The integration of the three design regions also enable the EPS prototypes to have some integrated indicator/parameters that can be used to design the overall system performance, and to further define the EPS. These integrated parameters can be listed as follows:

- Availability of power supply (Number and types of power source)
- Single fault tolerance

- Dispatch with one generator faulty
- Number of reconfiguration states (Ways to bring back to normal operation)

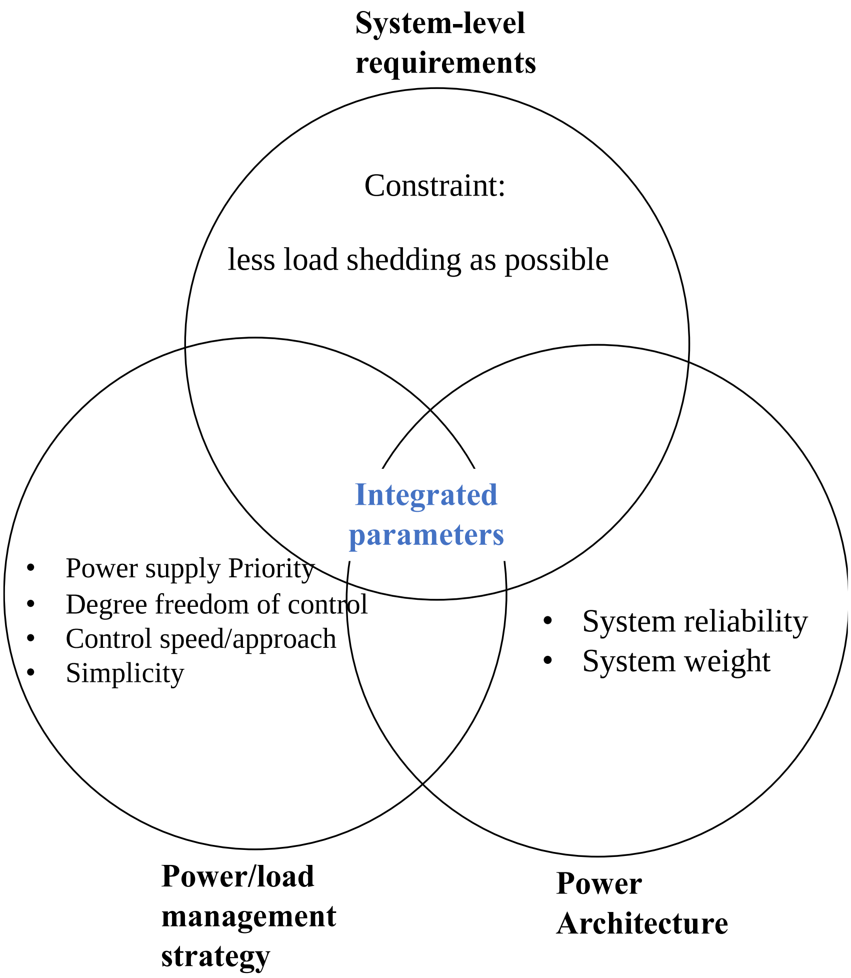


Figure 27. Venn diagram of MEE power design parameters

Because this chapter is mainly focused on the design of operational performance of MEE EPS and the compatibility that between PLM and architecture; the integrated parameter would be related to the power supply ability and operational reliability. However, the usage of this optimisation procedure is not limited by these four integrated parameters. In other words, different integration parameters formed by different design aspects such as cost, weight, noise, heat, and technologies can all be evaluated in this proposed optimisation procedure.

5.3.4. The Design Range Definition of EPS Parameters

According to the Venn diagram, a detail score level of each parameter is given in Table XII.

Table XII. An example of the prototype parameter classification

	Constraints of EPS prototype in coarse optimisation	EPS Prototype Score Level		
		High	Medium	Low
Architecture indicators/parameters	System reliability	$<10^{-9}$ per fh	10^{-9} to 10^{-7} per fh	$>10^{-7}$ per fh
	System Weight	More than three generator systems	More than two generator systems	Two or less generator systems
PLM indicators/parameters	Backup Power supply priority	Two or more backup supplies	one backup supply	No backup supply ca be acted
	Degree of freedom in secondary equipment control	• Generator control • Contactor control • Converter control • Load control	• Generator control • Contactor control • Load control	• Contactor control
	Control speed	<20 ms	20 ms to 250 ms	>250 ms
	Control approach	Preventative	Detective	Corrective
	Simplicity	One management strategy	Two PLM strategies in the management scheme	More than two PLM strategies in the management scheme
System-level requirement constraint	System-level constraint example: less load shedding as possible	Load shedding is used in lowest priority, which remains the high system performance.	Load shedding is used in less priority, which remain the essential system performance as long as possible.	Load shedding is used in first priority, which affects the MEE performance at the first place.
Integrated parameters	Availability of power supply (types of power source)	Three generators or more	Two generators	One generator
		Three generators with ESS	Two generators with ESS	One generator with ESS
	Single failure tolerance (isolation of subsystem)	Two or more than two redundant paths to supply the loads	One redundant path to supply the loads	No redundant path to supply the channel, only the dedicated source
	Dispatch with one generator faulty	Satisfied the demand of essential and non-essential loads	Satisfied the demand of essential loads	Satisfied partial demand of essential loads
	Number of reconfiguration states	Three or more redundancies	Two redundancies	One redundancy or not reconfigurable

* generator systems took a large percentage of the overall system weight

In Table XII, it illustrates the High, Medium and Low-level classification of each parameter, and emphasises the parameter constraints in the requirement capture. The main reason for classifying indicators is to filter out potentially non-feasible solutions from a large range of samples, rather than searching for some precise data in the samples. In addition, at the beginning of the design, the designer may not be sure of the accuracy of the data but only approximately range. In this way, each of the prototypes of EPS can be classified and sifted at the early stage of the design process.

5.4. Demonstration of The Parameter Classification Optimisation for MEE Power system

In order to evaluate the effectiveness of parameter classification on the EPS design optimisation, a demonstration based on the MEE power system was conducted. This case study is presented in this section, which involves the EPS design derived from eighteen architecture options and ten PLM schemes.

5.4.1. PLM and Architecture Scoring and Ranking

The scores of each case/scheme are established by judgements of the designer based on the variable range of Table XII. For example, if an architecture has four generators, it can be characterised as a 'High' level in the range of system weight. The scoring

	PLM feature charatertisics			Parameter	Required level	Score	ranking
PLM option 1	order of action	1st	shedding	power control simplicity	Medium/Low	High	5th
				level power supply priority	High/Medium/Low	Low	
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High/Medium	High	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High/Medium	High	
PLM option 2	order of action	1st	ESS supply	power control simplicity	Medium/Low	Medium	1st
		2nd	shedding non-essential load	level of power supply priority	High/Medium/Low	Medium	
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High/Medium	High	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High/Medium	High	
PLM option 3	order of action	1st	ESS supply	power control simplicity	Medium/Low	Low	2nd
		2nd	shedding non-essential load	level of power supply priority	High/Medium/Low	High	
		3rd	generator overloading				
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High/Medium	High	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High/Medium	High	
PLM option 4	order of action	1st	shedding	power control simplicity	Medium/Low	High	6th
				level power supply priority	High/Medium/Low	Low	
	ree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High/Medium	High	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		detective	power fLow monitoring apporach	High/Medium	Medium	

Figure 28. Sample of PLM options scores compared with required design scores via Excel tool

criterion for the cases was the designer's subjective judgment, which also depended on the whole range of comparisons based on Table XI and Table XII.

Case No.	Architecutre features	Parameter	Required design level	Score	Ranking
Case 1	2 generator 2channel	system reliability	High	Medium	3rd
	bi-directional converter	weight	Medium/Low	Low	
	ESS on load bus				
Case 2	3 generator 3 channel	system reliability	High	High	1st
	bi-directional converter	weight	Medium/Low	Medium	
	ESS on load bus				
Case 3	4 generator 4 channel	system reliability	High	High	2nd
	bi-directional converter	weight	Medium/Low	High	
	ESS on load bus				
Case 4	1 ESS, 1 generator, 2 channel	system reliability	High	Low	4th
	bi-directional converter	weight	Medium/Low	Low	
	ESS on load bus				

Figure 29. Sample of architecture case scores compared the required design scores via Excel tool

Accordingly, Figure 28 and Figure 29 have shown the examples of the scoring and ranking for PLM and architecture via excel tool. After the scoring procedure, the architecture cases and PLM schemes can then be ranked as subsystems based on this scoring. This case study involves 18 architecture cases and 10 PLM schemes as the investigated subjects, and the optimisation was conducted in an Excel-based framework. Each case and scheme conclude its own features and specified components, to avoid a long explanation of each architecture case and PLM scheme, the full version lists of architecture case and PLM scheme are shown in Appendix B. Table XIII illustrates a sample of the comparison of the case scores and subsequent ranking based on the scoring presented in Figure 28 and Figure 29. For example, if all scores of an architecture case matches the required acceptable range, this architecture case would be ranked on the top of the ranking list (such as Case 2). However, for example, Case 3 only matches the absolute design parameter of system reliability, but the optional parameter was out of range, then it is allocated as second class in the ranking list. Case 1 only matches the optional parameter requirement but not the absolute design requirement of system reliability and as such is it is allocated to the third class of the list. Finally, Case 4 has the most unmatched parameter score to the absolute design requirement, hence is allocated in fourth place. By using this similar approach, the PLM ranking can be also realised, which shown is also shown in Table XIII.

Table XIII. The individual ranking table of subsystem architecture and PLM

Architecture ranking		**PLM ranking**	
Case 2	1st	**PLM option 2**	1st
Case 8	1st	**PLM option 3**	2nd
Case 14	1st	**PLM option 8**	3rd
Case 3	2nd	**PLM option 5**	4th
Case 6	2nd	**PLM option 1**	5th
Case 9	2nd	**PLM option 4**	6th
Case 12	2nd	**PLM option 7**	7th
Case 15	2nd	**PLM option 6**	8th
Case 18	2nd	**PLM option 9**	9th
Case 1	3rd	**PLM option 10**	10th
Case 5	3rd		
Case 7	3rd		
Case 11	3rd		
Case 13	3rd		
Case 17	3rd		
Case 4	4th		
Case 10	4th		
Case 16	4th		

5.4.2. EPS Prototype Samples

When a ranked architecture case and a ranked PLM scheme is integrated to an EPS prototype, it has corresponding features related to both subsystems and can be represented as integrated parameters.

Subsystems	Design Parameters	Required score	Score
Case 2	System reliability	Absolute in 'High'	High
	System weight	Opitonal in 'Medium'/'Low'	Medium
PLM option 2	Power control simplicity	Opitonal in 'Medium'/'Low'	Medium
	Backup power supply priority	High'/'Medium'/'Low'	Medium
	Control freedom in secondary equipments	Opitonal in 'High'/'Medium'	High
	Fault protection response time	Absolute in 'High'	High
	Power flow monitoring apporach	Opitonal in 'High'/'Medium'	High

EPS pototype (Architerture Case2 combined with PLM Scheme 2)			
System	Design Parameters	Required score	Score
System-level requirement	System shedding as less as possible	Opitonal in 'High'/'Medium'	High
Integrated paramerters	Availability of power supply (types of power source)	Opitonal in 'High'/'Medium'	High
	Single failure tolerance （isolation of subsystem)	Absolute in 'High'	High
	Dispatch with one generator faulty	Opitonal in 'High'/'Medium'	High/Medium
	Number of reconfiguration states	Absolute in 'High'	High

Figure 30. a) Example of subsystems perfect matching, b) dedicate integrated parameters perfect matching

Figure 30 a) and b) show a good matching, high ranked EPS prototype. Where architecture case 2 and PLM option 2 show all subsystem parameter matching. Figure

Subsystems	Design Parameters	Required score	Score
Case 1	System reliability	Absolute in 'High'	Medium
	System weight	Opitonal in 'Medium'/'Low'	Low
PLM option 1	Power control simplicity	Opitonal in 'Medium'/'Low'	High
	Backup power supply priority	High'/'Medium'/'Low'	Low
	Control freedom in secondary equipments	Opitonal in 'High'/'Medium'	High
	Fault protection response time	Absolute in 'High'	High
	Power flow monitoring apporach	Opitonal in 'High'/'Medium'	High

EPS pototype (Architerture Case1 combined with PLM Scheme 1)			
System	Design Parameters	Required score	Score
System-level requirement	System shedding as less as possible	Opitonal in 'High'/'Medium'	Low
Integrated paramerters	Availability of power supply (types of power source)	Opitonal in 'High'/'Medium'	Medium
	Single failure tolerance （isolation of subsystem)	Absolute in 'High'	Medium
	Dispatch with one generator faulty	Opitonal in 'High'/'Medium'	Medium
	Number of reconfiguration states	Absolute in 'High'	Medium

Figure 31. a) Poorly matching in subsystems, b) Poorly matching with Dedicated integrated parameters

31a) and b) shows a poorly matching example in subsystem-level and integrated system level respectively.

5.5. EPS Prototypes Comparison

With the further system and integrated requirement scoring, Table XIV summarises the list of generated EPS prototypes ranked based on the matching of subsystem, system and integrated parameter.

Table XIV. Sample of feasible EPS prototypes

Intergard EPS prototype	Ranked design aspects	Integrated parameter match status
Case2 combined PLM 2	1st and 1st	Feasible
Case 14 combined PLM 3	1st and 3rd	Feasible
Case3 combined PLM8	2nd and 3rd	Feasible
Case 6 combined PLM 10	2nd and 10th	Infeasible
Case 1 combined PLM 1	3rd and 5th	Infeasible
Case 11 combined PLM 1	3rd and 5th	Infeasible
Case 4 combined PLM 6	4th and 8th	Infeasible
Case 13 combined PLM 2	3rd and 1st	Infeasible
Case 2 combined PLM 4	1st and 6th	Feasible
Case 16 combined PLM 2	4th and 1st	Infeasible

In a low probability scenario, where high ranking subsystems combined together do not provide a viable solution, an EPS generated from a top architecture case and a lower-ranking PLM scheme may still provide reasonable integrated system performance, as shown in Figure 32 a). In this example, although two parameters in the PLM option and the system-level requirement do not match the required design range, neither of them is an absolute requirement. All absolute requirements are matched in this EPS prototype example and the integrated parameters of this prototype satisfy the requirement score (shown in Figure 32 b)). As such this is still a feasible option for conducting the next step of detailed design.

Primarily, this optimisation approach can find a prototype EPS that generally meets all requirements. Additionally, this method can also be used to identify EPS with feasible integrated performance parameters even when the parameters of the subsystem do not match the requirements perfectly. In addition to finding the best solution in the first instance, the ranking and review approach can enhance understanding of the design rationale based on the commonalities of these candidates.

Subsystems	Design Parameters	Required score	Score
Case 2	System reliability	Absolute in 'High'	High
	System weight	Opitonal in 'Medium'/'Low'	Medium
PLM option 4	Power control simplicity	Opitonal in 'Medium'/'Low'	High
	Backup power supply priority	High'/'Medium'/'Low'	Low
	Control freedom in secondary equipments	Opitonal in 'High'/'Medium'	High
	Fault protection response time	Absolute in 'High'	High
	Power flow monitoring apporach	Opitonal in 'High'/'Medium'	Medium

EPS pototype (Architerture Case2 combined with PLM Scheme 4)			
System	Design Parameters	Required score	Score
System-level requirement	System shedding as less as possible	Opitonal in 'High'/'Medium'	Low
Integrated paramerters	Availability of power supply (types of power source)	Opitonal in 'High'/'Medium'	High
	Single failure tolerance （ isolation of subsystem)	Absolute in 'High'	High
	Dispatch with one generator faulty	Opitonal in 'High'/'Medium'	High/Medium
	Number of reconfiguration states	Absolute in 'High'	High

Figure 32. a) Subsystem parameter unmatched, b) Dedicated integrated parameters matched while subsystem parameters unmatched

5.6. Result Discussion

By demonstrating the classification, comparison and optimisation of EPS parameters in the preliminary design stage, the results show the approach can provide feasible co-dependent integrated solutions systematically.

With the large size of demonstration samples, it is shown that not all EPS prototypes can meet the absolute design requirements. However, if this optimisation process fails to select a viable EPS prototype, it may be that the size of samples is too small. The benefits of such optimisation are not significant for small design space.

From the results, top-ranking architecture cases can provide reasonable integration performance, and even be combined with lower-ranking PLM scenarios to provide a viable solution. It appears that the physical layout of power architecture dominates the design of MEE power system, and also dominates the feasibility of PLM strategy. Although, architecture is a critical dominant element during the design, the co-design process still can help to select the best dedicated PLM strategy for it in an early design stage. (This insightful find reflects that there is a fundamental difference between co-design logic and the sequential design process. If by using sequential design, PLM scheme might be firstly determined and dominates the design of power architecture. It is difficult to determine the optimal solution for the MEE power system in this way. Even if the power architecture is firstly designed in a sequential design process, the optimal solution still needs further validation before integrating with any PLM strategy.) Within the top-level architectures as part of the case study, similar design features such as multi-power sources and multi-channel have shown to be common amongst top subsystem ranking options. As such, this approach could potentially highlight to the user on such common design drivers in the MEE power system. Finally, the optimisation of parameter classification approach is only aimed at providing general characteristics review of EPS will systematically down selecting viable integrated solutions in a large design space. The viable EPS prototypes could then be taken to the next step of the design for further comprehensive trade-off study.

5.7. Chapter Summary

In conclusion, this chapter presents the optimisation process based on parameter classification for the design of MEE power system. In this process, two subsystems of the EPS are evaluated in parallel, to generate feasible EPS prototypes at the preliminary design selection stage. Since the main features of EPS are determined in the preliminary integration stage, the number of iterative comparisons will be reduced in the detail design stage. In addition, the concept of feature similarities between EPS prototypes has also been introduced. As such, if a feature appears frequently in feasible EPS prototypes, then this can be captured as a key design driver of the overall process. This allows searching for other viable solutions when the immediate top-ranking prototypes are not viable and greatly reduces the possibility of missing potential EPS prototypes.

The use of parameter classification to optimise EPS characterisation during the MEE synergistic design process is to accelerate the determination of feasible EPS prototypes and does not require a very detailed evaluation and analysis of each EPS prototype to determine its feasibility. The co-design process approach provides another advantage for the development of MEE power system, that is, two different aspects are designed separately and at the same time into a preliminary integrated platform, providing more comprehensive design space. With this proposed approach, the design amendment priority of subsystem and integrated parameters can be managed. However, this proposed approach has a potential weakness in the proposed methodology. Due to the small sample size can affect the effectiveness of this optimisation method, it can only be used in the system design with a wide design space. Further studies can make use of the selected EPS prototype after optimisation to conduct the detailed design of MEE power system, so as to comprehensively determine the optimal solution of MEE power system.

Chapter 6.

Co-synthesis Design Refinement for an MEE Power System via Load Shedding Factor

6.1. Chapter Overview

In previous chapter, a preliminary stage of MEE power system design process is established. Within this design stage, the integrated platform that can co-design and analyse the parameters of both power architecture and PLM is demonstrated. A MEE power system prototype should be defined by this design stage. However, a further available analysis of MEE power system should be conducted.

How to ensure that an EPS can cope with different fault scenarios has become an inevitable topic. When designing the availability of EPS, there is little mention in the existing literature of which methods designers should employ to find design vulnerabilities. Some literature was mentioned the optimisation of the PLM to achieve the power balance in the EPS [11][13], but the fundamental problem may be caused by the improper design of the power architecture. In this case, optimising the PLM strategy may cost too much design effort. Due to the time-consuming nature of developing PLM for the power architecture with unknown design vulnerability, an alternative design logic flow needs to be considered. It would be helpful if the power balance of the MEE EPS can be analysed with different scenarios. Thereby taking advantage of the analysed result to guide the direction of design improvement.

Because aerospace applications typically feature an autonomous power system, the power management of aircraft is relatively limited. Load shedding is one of the most common approaches [13][11], but shedding large electrical loads might cause in discomfort environment for the passengers. The amount of load shedding has to be controlled in each power channel, and to ensure the adequacy of aircraft power supply. Critical defects in power architecture can be identified by analysing the limitations of power distribution in various fault conditions. By enhancing the power architecture to cope with different fault scenarios, the system availability of MEE EPS can be maximised.

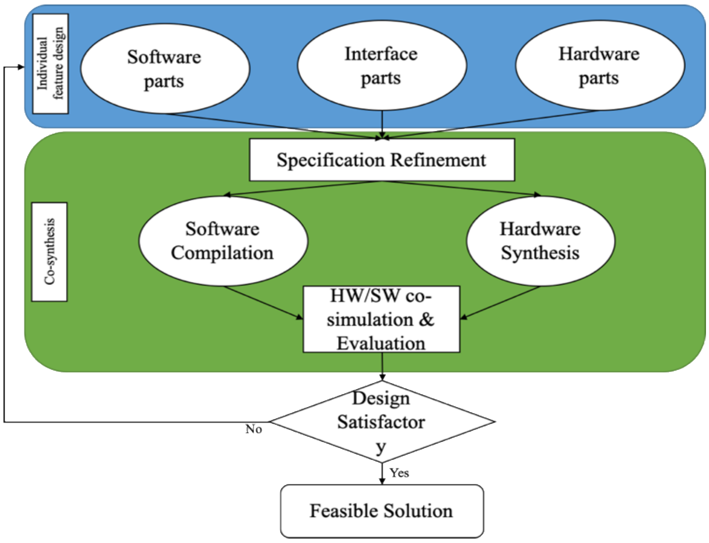
Therefore, this chapter presents a new approach to evaluate the operational performance of the MEE EPS; the Load Shedding Factor (LSF). This factor can be used to judge the power balance level of the EPS in response to different faults. When the power imbalance emerges from the EPS in a certain failure scenario, the designers identify the regions of design vulnerabilities through power/current trace. The main purpose of this evaluation method is not to directly enhance the performance of the EPS, but to identify the areas of the EPS that can be enhanced. The direction for design improvement can be determined through the designer’s knowledge.

For the power system design of MEE, the proposed LSF evaluation method combined within the synthesis stage of the parallel-based engineering design can be used to effectively discover the unbalanced state of the EPS. Based on precise and targeted improvements to the design issues, the preliminary optimised EPS will further expand its availability and utilisation.

In the case study demonstration of this chapter, several similar power architectures are investigated, they have the same number of power sources and similar reliabilities, but some components are located differently. However, by substituting an established PLM strategy combination into the all scenario cases of different power architectures, the shedding factor can also be used to prove that there is a great difference in the operation ability at similar power architectures. Through the analysis of the shedding factor, the designers are able to discover the operational scenarios that need to be improved in the MEE power architecture. As a result of the Case study, a feasible MEE EPS is determined, which provides a certain degree of freedom in power supply capability.

6.2. The Justification of Using Co-Design Process and Shedding Factor to Identify the Operational Deficiencies in EPS

As beforementioned, the load shedding behaviour would be a clear guideline to determine the design deficiencies of the MEE EPS. In order to using load shedding-related evaluation to study the MEE system availability, it needs to be implemented into the analysis of the integrated EPS. Therefore, the potential design stage to conduct this evaluation should be a synthesised platform, which can show the overall optional performance in case studies. There is such a design phase in concurrent/parallel-based engineering design, which is a synthesised platform for the overall system assembly (Figure 11 co-synthesis process shown in Section 2.5.1.2).



Recall Figure 11: co-synthesis process

The critical concerns of EPS design for MEE are the capability of single failure tolerance [98] and resilient power supply for the essential loads, which requires that the MEE power system should be highly interconnected and reconfigurable [106]. The existing design/optimisation is focused on PLM algorithms that are based on a specific EPS architecture, i.e., the EPS architecture is established before determining the best-fitting PLM strategies [13], [61].

If the power architecture design is not the most optimised design, the space of PLM optimisation will be limited. In the typical system design such as sequential design process, the entire design methodology was based on hardware preference. After a rough estimation on software requirements, the hardware will be firstly designed and optimised. Then the process will design and optimise the dedicated software or control approach based on the designed hardware. Due to the lack of clear understanding of the concept of software operations, hardware design may have certain blindness. In another words, if the architecture dominates the PLM, the design of PLM can only be a 'local' optimum. In fact, this dominant relationship can be broken by parallel design. Here the author does not deny the existence of mutual influences between the subsystems. Inevitably, the two subsystems affect each other more or less, but it is necessary to be careful to affect them in good ways, while trying to find methods to avoid them influencing each other in bad ways. For example, in Chapter 5, some high ranked architectures do counteract some of the shortcomings of low-ranked PLMs when they were combined as an EPS, and this was a good influence between each other. As designers, it is essential to be aware of the existence of this good mutual influence for better optimisation.

Therefore, there is a challenge on how to best observe the defects of power architecture design through the overall performance evaluation. After the discovery of the design defects, the challenge of how to select the improvement direction for the EPS system will follow.

6.3. EPS Availability and System Improvability Evaluation

According to the literature review, the challenge is now that the coping ability of the EPS needs to be observed, it is essential to see that the EPS is able to ride through most failure situations (some extreme situations are excluded such as all power sources are failed at the same time). In this chapter and later sections, the failure situation of the system will be visualised through a case study while the defects in the power architecture are demonstrated through an efficient analysis of the failure cases. Load shedding as the most relevant approach for system power balance, it will be employed to criticise and evaluate the design vulnerability on the EPS candidates. Hence, this section will propose an evaluation method based on the LSF for the system availability and improvability analysis and explain how the LSF can be conducted in the integrated power system design.

6.3.1. **EPS Integration For MEE**

Prior to employing the shedding factor to conduct the system availability analysis, the designers should aggregate the power architecture and PLM strategy. Figure 33 shows the flow chart of the aggregation of the MEE power system. The PLM scheme will be assigned to each architecture, making it an integrated EPS candidate. Each EPS candidate is represented by a single-line diagram, which is a simplified notation diagram for representing the power system.

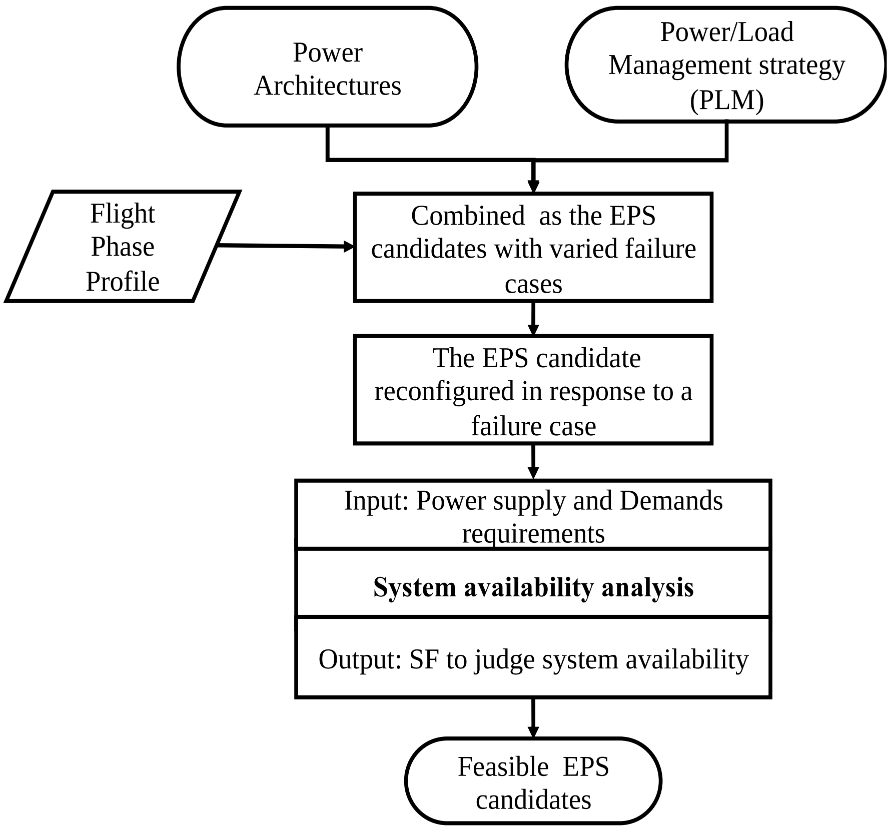


Figure 33. System availability analysis via a co-synthesis process

Classical system failure conditions, such as generator failure and channel failure, will be assigned to each EPS candidate, which will allow EPS single-line diagram to form different failure models. In each failure condition, different flight phases should be considered to realise a comprehensive case study. The flight phase profile will include the flight period and power requirements for each phase. The method of including flight phase profile in the case study also provides the conditions for evaluating the availability of the PLM strategy.

As shown in Figure 33, after all the failure modes and different flight phase are assigned to the EPS candidate, the EPS reconfiguration options can be determined for each EPS failure model according to different fault regions and flight conditions. In different failure scenarios, EPS reconfiguration may have multiple options. Some reconfiguration options may be significantly unsuitable for EPS candidates and can be ignored. Additionally, if an EPS candidate has an inevitable reconfiguration defect, it can be quickly identified as an infeasible solution, thus reducing the workload in the next steps. Once the potential options of power reconfiguration for the MEE EPS are determined, the system availability analysis can be conducted which is detailed in the following section.

6.3.2. EPS Availability Analysis and Improvement

This section provides the rationale of using LSF as an indicator for determining the availability of an EPS when designing its reconfiguration functions.

6.3.2.1. Load Shedding Factor Equation

After the case study of reconfiguration is completed, the available MEE EPS reconfiguration options are generated for different fault scenarios. In order to select the optimal EPS scheme during different faults in different flight phases, the load shedding-based evaluation will be used to quantify the system resilient capability according to the features of each option.

This section defines an LSF to represent the capability of the EPS to supply the critical

$$\boldsymbol{LSF = \frac{P_{load} - P_{supply}}{P_{load} - P_{ess}}} \quad (2)$$

loads under various fault conditions. LSF is a quantitative index to evaluate the power balance of EPS, derived by the Load Shedding Factor equation which shown as equation (2).

Where P_{load} is the total load power required during a certain flight phase; P_{supply} is the available power provided by the generators or/and energy storage, and P_{ess} is the power demand of the essential loads during the flight phase (including the airframe and engine loads). This equation assumes the power losses are negligible and an ideal power factor.

The LSF reflects the availability of load shedding:

- If LSF $\leq$ 0, it indicates that the EPS power supply is greater than or equal to the total required load power. In this case, the power generation is sufficient to maintain the normal operation of the EPS. In this situation, the generator/source may be controlled according to the extra amount of power supply.
- If 0 < LSF < 1, the power generation cannot supply all the required demands. EPS must shed the non-essential loads to recover the system.
- If LSF > 1, the power generation is not enough to supply the critical demands even if all the non-essential loads are shed. This should be avoided at all times; otherwise important functions of the aircraft/engine will fail and cause catastrophic consequences.
- If the essential demand equals the total demand in a particular phase, the denominator of the LSF becomes infinite, which means that the total demand should always be supplied. It will be judged from the numerator in LSF formula that if the numerator is negative, it means that the power supply is greater than the demand and can be expressed by a relatively negative real number such as -2, -10 or any larger integers. If the numerator is positive, the essential load cannot be supplied.

To select the suitable EPS candidates, LSF should be comprehensively considered under different failure mode to avoid LSF >1 to the greatest extent. Based on each selected EPS candidate, the designers will explore any opportunities to further improve the power system performance of MEE. This actually reflects the direction for the design improvement.

6.3.2.2. 'Hints' for the EPS Improvements

By reviewing the EPS candidates selected from LSF analysis, the designers may derive some hints for system improvements.

When the integrated system responds to different failure scenarios and needs to be reconfigured, the designers can observe whether the EPS reconfiguration option meets the minimum power balance standard for system operation, that is, 0<LSF<1. If the LSF is over 1 or positive infinity, it indicates that there may be a weakness in a certain area of the EPS. Tracing the power flow directions of the reconfigured system will reveal the problem, whether the system has insufficient power supply or there is sufficient power supply, but it cannot be allocated under some particular failures. Depending on the problem, designers can give different solutions according to software and hardware improvements, and then select the simpler solution that involves less changes in other parts of the system. For example, when the LSF of a single isolated power channel in the EPS system is greater than 1 and the critical loads on that channel need to be shed. The designer should modify the architecture/PLM to reduce the LSF value to improve power supply capability. If there is no simple modification to improve the EPS for this particular scenario, then the design values of the EPS need to be reviewed and reconsidered.

6.4. Demonstration of MEE Power Architecture Functional Refinements

This section will take an MEE system as an example to demonstrate the availability analysis of its power system via the LSF. Section 6.4.1 describes the assumptions for this demonstration, and Section 6.4.2 to Section 6.4.5 demonstrate the evaluation stages of the EPS availability and improvability.

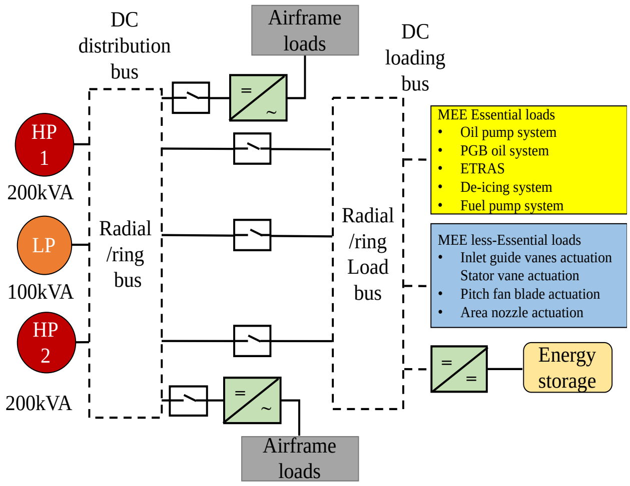
6.4.1. EPS Assumptions

6.4.1.1. Architecture Layout Assumptions

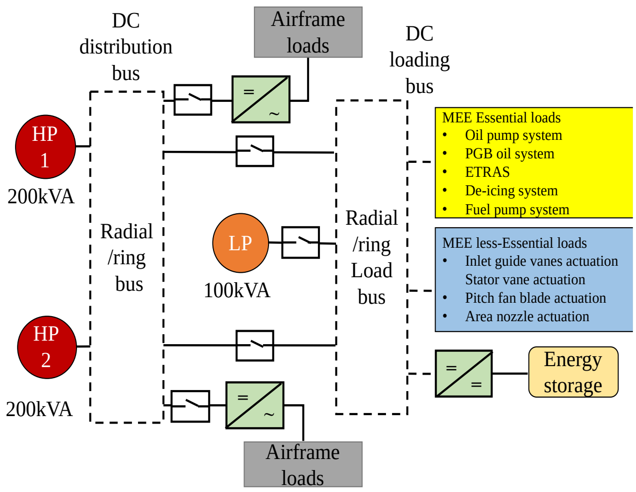
Under the premise of observing the overall performance of power architecture, this section will be based on the EPS of MEE shown in Figure 34 to demonstrate the use of load shedding factor evaluation.

This example is a three-generator system disclosed by aero-engine industry [13][31], which includes two High-Pressure (HP) shaft-driven PMSM generators and a Low-Pressure (LP) shaft-driven SR generator. The power rating of each of the HP generator is assumed as 200kVA and the LP generator is 100kVA. Besides, this demonstration assumes that the power system is in a steady state with nominal ratings of power supply.

Based on the three-generator power system, several multi-channel MEE architecture options can be considered to achieve the flexible power supply. Figure 34 presents two potential prototypes of MEE power system, where the generators are interfaced to a DC distribution bus for supplying the airframe loads. Using power channel and protection devices, the power is transmitted to the DC loading bus for supplying the engine loads, including oil pump, de-icing system, actuation device, etc. The bus topology of the architecture may employ two typical topologies widely used in large-scale transportation applications, sectionalised radial busbar and ring busbar. These



Architecture prototype 1



Architecture prototype 2

Figure 34. The MEE architecture prototypes

two MEE architecture prototypes have same units of power sources and power channel, but different bus topology and different locations for the LP generator. The following architecture layouts will be used in the demonstration:

1) The three generators are connected to the DC distribution ring/sectionalised radial busbar.
2) The two HP generators are connected to the DC distribution ring/ sectionalised radial busbar, and the LP generator is connected to engine loading DC bus.

For more specific detail of each the architecture layout candidates are listed as following:

- *Candidate 1 –LP-AIR/radial*:- this candidate is an extension of current MEA engine topology [28] in which an LP channel is added to the power architecture to provide additional power. The LP generator will be placed on the DC distribution bus to provide power for a channel. Since the sectionalised radial bus can be simply implemented for most of the electrical structures in aerospace, the radial bus structure is commonly adopted.

- *Candidate 2 - LP-MEE/radial*: - this candidate adopts the same busbar arrangement as LP-AIR/radial, but the LP generator is now connected to the DC loading bus through an associated drive.

- *Candidate 3 - LP-MEE/ring:*- this candidate replaces the radial buses in LP-MEE/radial with the ring busbar structure, which is typically used in the power architecture of large ships [41].

- *Candidate 4 - LP-AIR/ring:* - this candidate has a similar ring bus topology as LP-MEE/ring, but the LP generator is connected to the DC distribution bus.

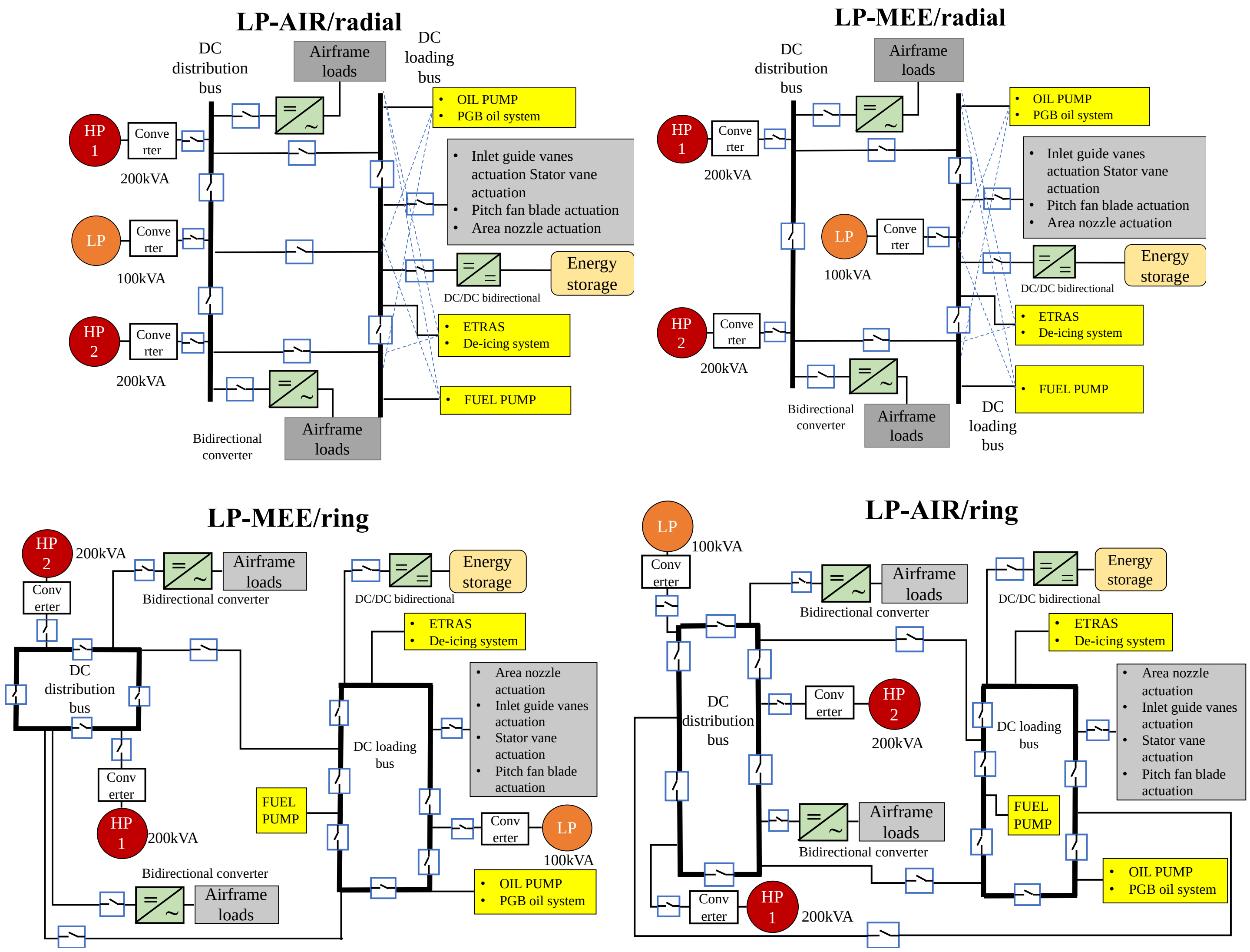


Figure 35. The MEE architecture candidates

The essential loads of each power architecture can be classified into the yellow blocks in Figure 35, which is convenient for load shedding analysis. This demonstration will investigate the features of these EPS, in order to verify the effectiveness of using the LSF to highlight the architecture improvability.

6.4.1.2. PLM Assumption

From the literature review of power management strategies, electrical power system can address most abnormal situations by simply increasing power ratings and power redundancy, but the overall weight of the system will rise significantly. The design objective of the MEE is to develop the availability of power system reconfiguration to meet power balance in most flight conditions without increasing generator ratings. Specifically, the power balance of the system depends on the availability of the power components and the operation of power management. In the MEE system, there are many PLM strategy combinations available, such as battery back-up with load shedding or battery back-up with generator overloading. In addition, the generator overload is assumed as a low priority strategy to be used, as overloading the generator is shorting its usage life. Table XV gives two examples that are available for the selected EPS baseline model and can be used to best demonstrate the effectiveness of the Load Shedding Factor evaluation.

Table XV. MEE PLM strategy options

PLM usage priority order	**PLM strategies illustrations**
1st ESS discharging 2nd shedding	PLM 1 -Figure 36
1st ESS discharging 2nd Shedding strategy 3rd Generators overload	PLM 2- Figure 37

Figure 36 shows the PLM that uses both ESS supply and load shedding strategy. Once the EPS is determined to be an imbalanced system, the PLM will again firstly check the availability of generators, if there are feasible generators and already in the max nominal rating, it will be using ESS to supply the shortage and then use shedding strategy to shed loads. If there are no generators available, the ESS will supply the power in first place and shed load until the system is balanced. In addition, if the power system is oversupplied, the ESS will charge the additional power supply based on the State of Charge conditions.

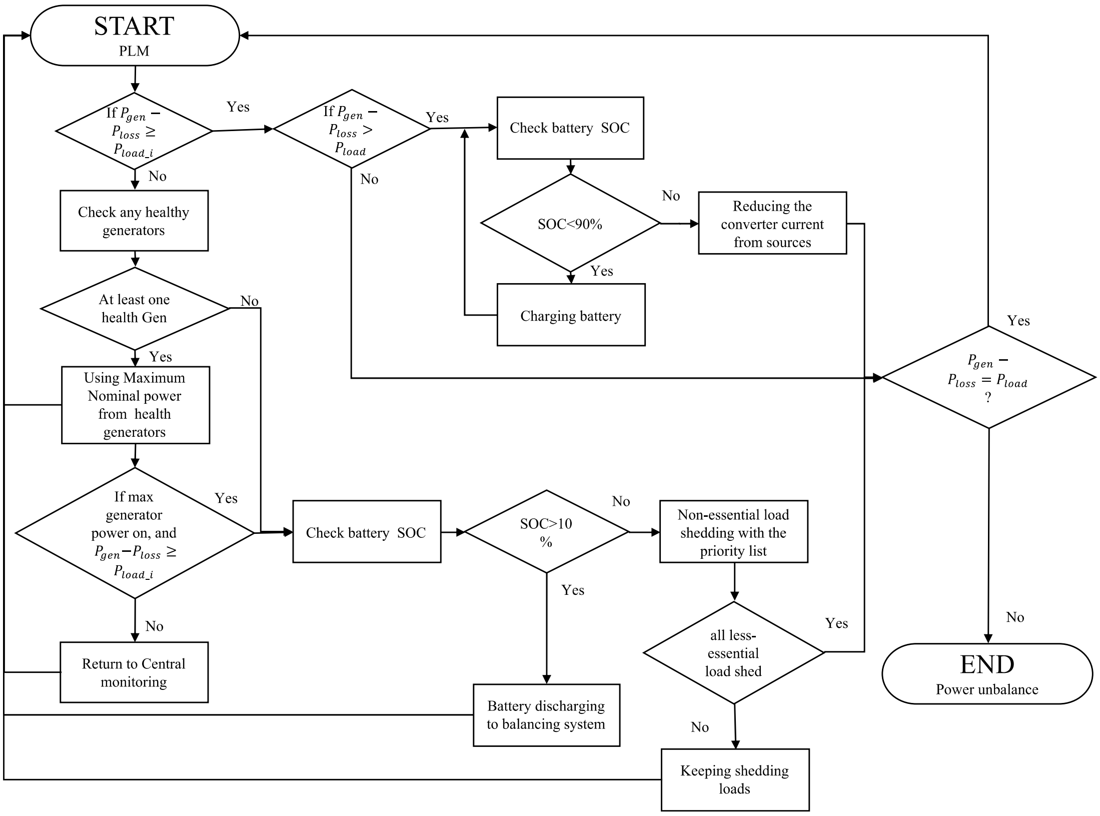


Figure 36. PLM strategy with ESS and Load shedding

Figure 37 shows the procedure of PLM that employs ESS, load shedding and generator overload strategies. This PLM strategy requires a battery bus, ESS and contactors on the connection of non-essential loads. It is similar to the previous PLM option, but it has an additional power supply function which is the generator overloading at the last priority order of the PLM. Although this last prioritised power supply function is time limited, it still offers more operational space on the EPS. If there are no generators available and the generator overload cannot be used, the ESS will supply the power in first place and shed load until the system is balanced. Similarly, if the generator power capacity exceeds the demand, the ESS will switch to the charging state (only if it is less than 90% of the storage capacity). Once the ESS is fully charged, the converter will limit the current passing through it.

These PLM options attempt to balance the benefits of using both ESS and load shedding, so the electrical loads will neither be completely disconnected, nor fully using ESS which will highly increase the weight of the architecture. In addition, it appears that when planning the PLM strategy, some design information can support the definition of ESS size and contactor position.

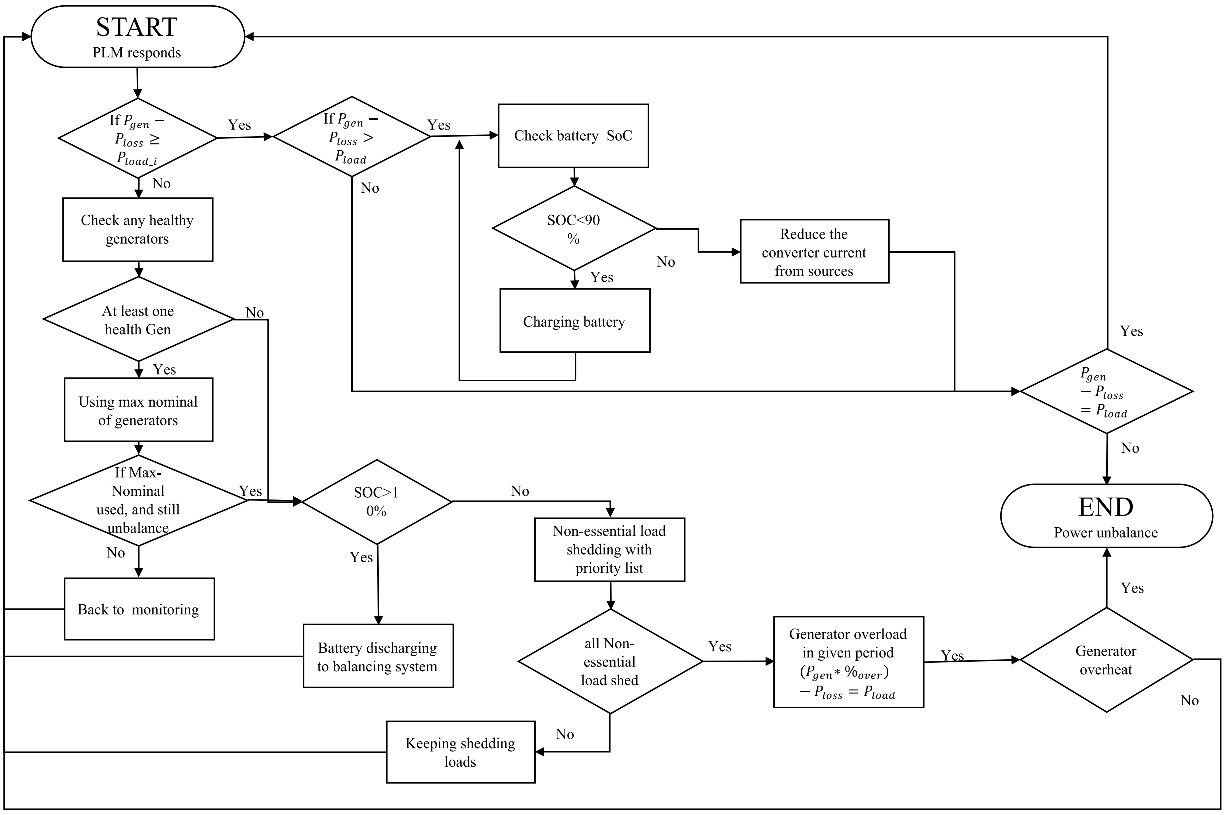


Figure 37. PLM strategy with ESS, Load shedding and Generator overloading

In summary of this section, 4 Architecture layouts and 2 PLMs are selected from section 6.4.1. Each of the MEE power architectures is combined with one of the selected PLM options respectively to form an EPS candidate. In total, 8 combinations of EPS are available for the MEE system availability study.

6.4.2. General Design Evaluation for MEE Power Architecture

In this section, the general design evaluation is conducted for the MEE EPS. First of all, the safety and weight evaluations have been conducted for these architecture candidates. This demonstration first uses Fault Tree Analysis (FTA) to evaluate the reliability of four EPS candidates, and then compares their overall weights.

The maximum failure rate allowance of the EPS distribution for MEE critical loads is set according to the extremely improbable condition, which equal to or less than 1×10^{-9} per flight hours. This is comes from the guides of CS-25 of European Aviation Safety Agency (EASA) [94]. Table XVI shows the critical demand failure rate of the MEE architecture candidates. These results are calculated by the FTA approach and with reasonable assumptions.

Table XVI. EPS reliability

Failure rate unit (1/fh)	LP-AIR/radial	LP-MEE/radial	LP-MEE/ring	LP-AIR/ring
Power lost Up to DC loading bus	1.0168×10^{-15}	1.4999×10^{-15}	8.1154×10^{-16}	7.2331×10^{-16}
Power supply lost at Fuel pump system	1.7290×10^{-12}	1.7295×10^{-12}	1.7288×10^{-12}	1.7287×10^{-12}
Power supply lost at Oil pump system	1.7290×10^{-12}	1.7295×10^{-12}	1.7288×10^{-12}	1.7287×10^{-12}
Power supply lost at ETRAs	1.7290×10^{-12}	1.7295×10^{-12}	1.7288×10^{-12}	1.7287×10^{-12}
Either one of the essential loads failed	$\mathbf{5.1871}\times10^{-12}$	$\mathbf{5.1885}\times10^{-12}$	$\mathbf{5.1864}\times10^{-12}$	$\mathbf{5.1862}\times10^{-12}$

It also assumed that this FTA did not focus on the reliability of the airframe loads/network, because the airframe loads should have other dedicated supply source, such as APU and RAT etc. Each of the MEE critical motor/ load is powered by three channels with dedicated inverter and protection devices. Due to the high reliability of the architecture distribution, there will be a very low failure rate of power supply lost at DC loading bus. Hence, the failure rate of each critical load is depending on the number of channel connection between the DC loading bus and the loads. Either one of the essential loads failed can causing catastrophic event for the aircraft, therefore it should below than the extremely improbable condition.

Although the data comes from the public domain database[140], it can be seen that the reliabilities of these architectures are all below than the maximum failure rate allowance, each of them can be a reliable power architecture. It is difficult to determine the optimal EPS by relying on this evaluation method alone, and it must be compared with the weight comparison. The weights of EPS candidates is listed in Table XVII and referred the data from [81], it is excluded the weight of MEE auxiliary systems e.g. pump motor and actuators and their redundant dedicated converters, as it will be a proportion of the total weight. From this table, there is no obvious difference between these four EPSs.

Table XVII. EPS weight comparison

		LP-AIR/radial	LP-MEE/radial	LP-MEE/ring	LP-AIR/ring
Generators Weight (assumed the driver weight included)		128.35kg	128.35kg	128.35kg	128.35kg
Protection devices	Contactor 270V_{DC}	10.78kg	9.24kg	14.63kg	16.94kg
	CB 270V_{DC}	45.22kg	38.76kg	61.37kg	71.06kg
Unit of battery and dedicated converter		46.31kg	46.31kg	46.31kg	46.31kg
2X DC to AC converter 270V to 115V		45.92kg	45.92kg	45.92kg	45.92kg
Total weight		**276.58kg**	**268.58kg**	**296.58kg**	**308.58kg**

According to the evaluated results in Figure 38, the *LP-MEE/radial* seems has the lightest weight and a reasonable power supply reliability. However, this figure barely indicates that the *LP-MEE/radial* has the best system reconfigure ability when fault occurs. When the designers face many similar potential solutions, an analysis related with the power balance is highly recommended to determine the EPS response capability in the face of different failures throughout the flight phase profile.

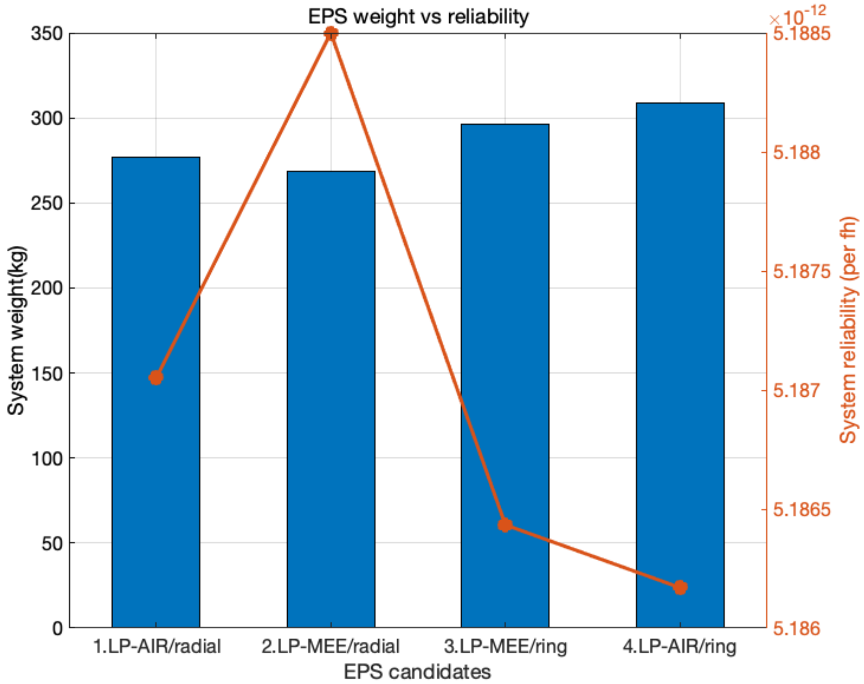


Figure 38. The MEE power architecture weight vs system reliability

6.4.3. Power System Reconfiguration Study for. MEE

In order to demonstrate the availability of the power system reconfiguration, EPS candidates can be detailed through the flight profile and different failure modes.Table XVIII presents a flight profile example that includes take-off, high-altitude, approach, and landing phases. As each flight phase has a different power requirement, the reconfiguration option could be unique during fault conditions. The failure modes include single-generator failure, two-generators failure, single-channel failure, two-channel failure, etc. After all the failure modes are applied to each EPS candidate, the designer can determine the reconfiguration option for the EPS according to the selected PLM scheme.

Table XVIII. A Flight Phase Profile Example for an MEE

Flight phases	**Take-off**	**High altitude**	**Approach**	**Landing**
Single More-Electric Engine total loads (kW)	142	82	152	187
MEE essential loads(kW)	72	82	82	117
Airframe loads supplied by single -MEE power system (kW). This will divide into to airframe loads of the architecture	350	400	245	275
Total power demand from an MEE (kW)	492	482	397	462

* Each load is assumed based on a percentage of MEA of approximately 1 MW of total power demand. The reference value of these numerical is open to discussion, but changes in reconfiguration can be shown more effectively using this quantitative method.

An example of the reconfiguration option is illustrated in Figure 39. This figure shows the *LP-MEE/ring* candidate with the failure scenario when both HP channels are failed, and the energy storage is not available during the landing phase. This failure limits both HP generators to supplying power into the engine load bus. According to the requirements of flight phase profile, a total of 187 kW is required for the loads in the MEE, of which 117kW is essential. In this unity power factor case, as the HP generators can only supply power to the airframe loads, only the LP generator is available to supply the engine loads.

Based on the given PLM scheme, the strategy of the battery power supply is no longer available, so only the sequence of load shedding will be considered. Firstly, the PLM attempts to discard the airframe loads of lower significance, but the power balance situation is not retrieved. This indicates the non-essential loads on the DC bus must also be discarded. Even so, the power of the LP generator is still not enough to supply

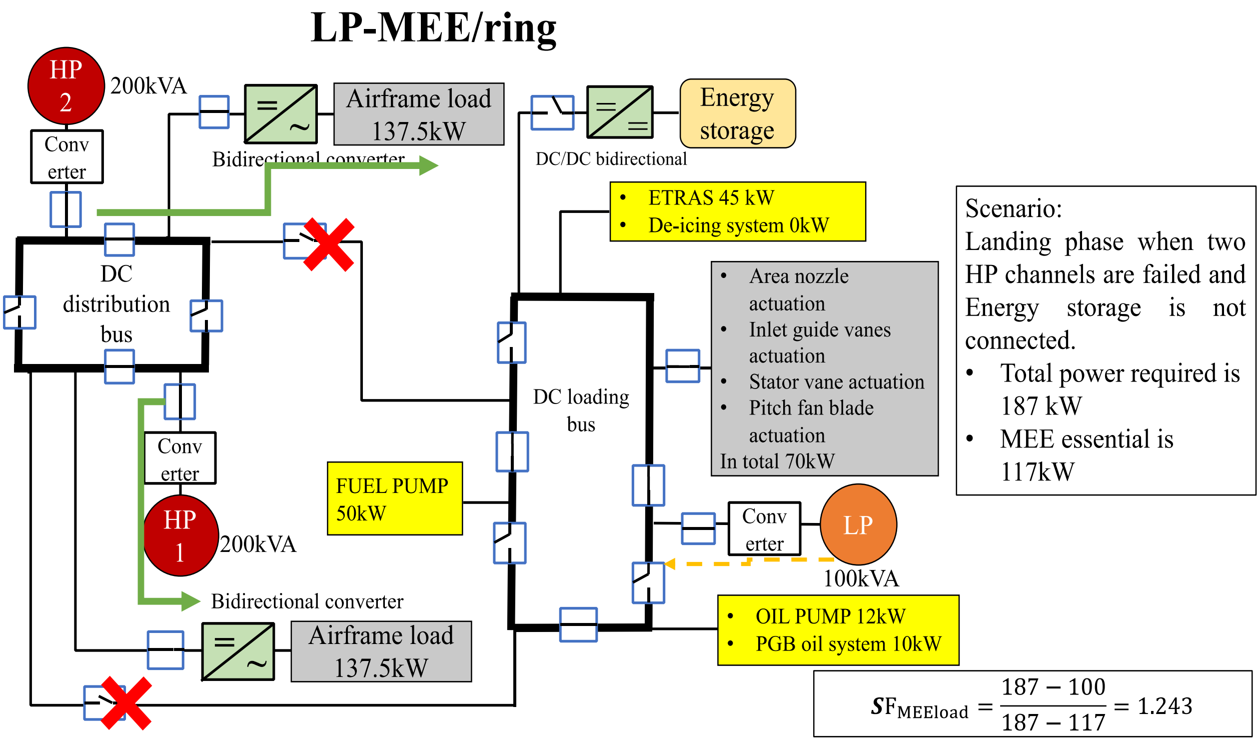


Figure 39. An example of the power reconfiguration case study

the essential demands and recover the power system. This reconfiguration option will cause this candidate to lose the advantage in the EPS candidate comparison (shown in section 6.4.4). Similarly, the reconfiguration options of the other EPS candidates can be evaluated in this way, and all architecture candidates will be further assessed in the EPS availability analysis.

6.4.4. EPS Availability Analysis

This section is used to demonstrate the usage of LSF on the determination of the EPS power system availability (the reconfiguration cases are shown in Appendix D).

6.4.4.1. The Scenario of Two HP Channels Failure in MEE

Figure 40 shows the LSF of the four candidate EPS with the PLM strategy 1 when two HP channels are failed and the ESS system is disconnected. The consequences of this failure case show that the *LP-MEE/radial* and *LP-MEE/ring* have shedding factors high than 1 in the landing phase, which indicates some of the essential loads must be shed and will causing serious failures in flight. In another hand, Figure 41 shows that when the four architecture candidates are independently coordinated with PLM strategy 2 (it has a 120% generator overloading function). The LSFs within the case of two HP channels failed are all below 1, which is acceptable for the power reconfiguration. The combination of architecture and PLM strategy 2 means the

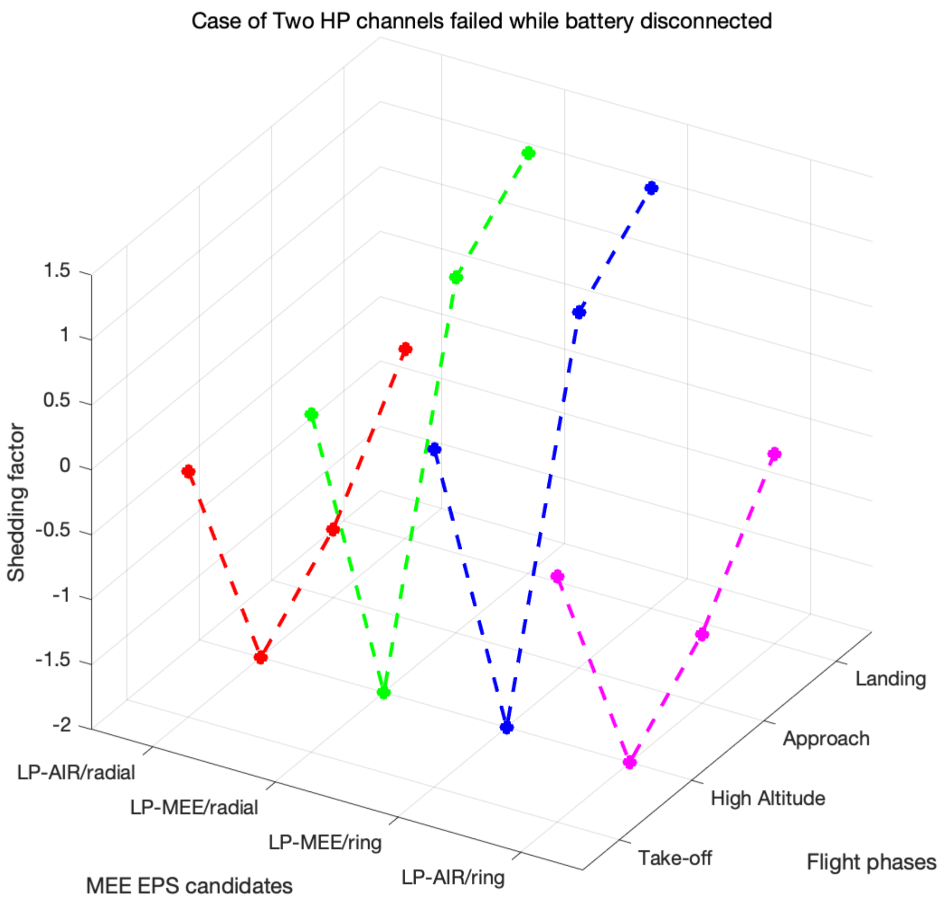


Figure 40. Initial candidate system availability in case of Two HP channels fail while battery disconnected.

critical functions of the MEE will bearing the scenario of two HP channel failure within the limited time of LP generator overloading.

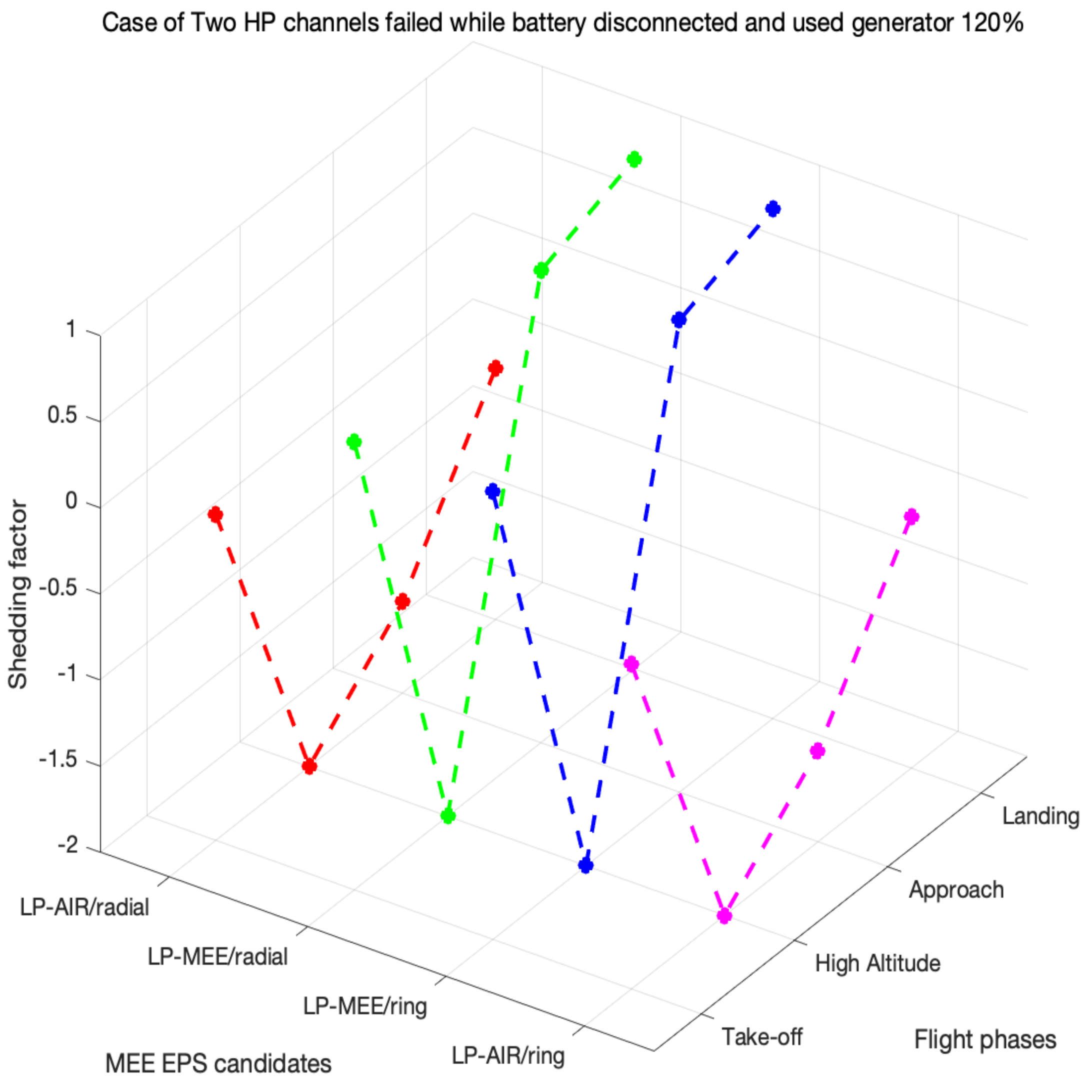


Figure 41. Using generator overloading in the power management strategy and SF below one

6.4.4.2. The Scenario of One HP Channel and One LP Channel Failure

Another case is under a condition of one HP channel and one LP channel failed while ESS is disconnected, the four candidates is again firstly coordinated with PLM strategy 1 that only involved ESS and shedding function. Figure 42 shows the LSF figures based on this condition, and LP-MEE/radial and LP-MEE/ring were not able to supply the power for critical loads in take-off and high-altitude phase (both over 1). Which is needed to be considered for further improvement.

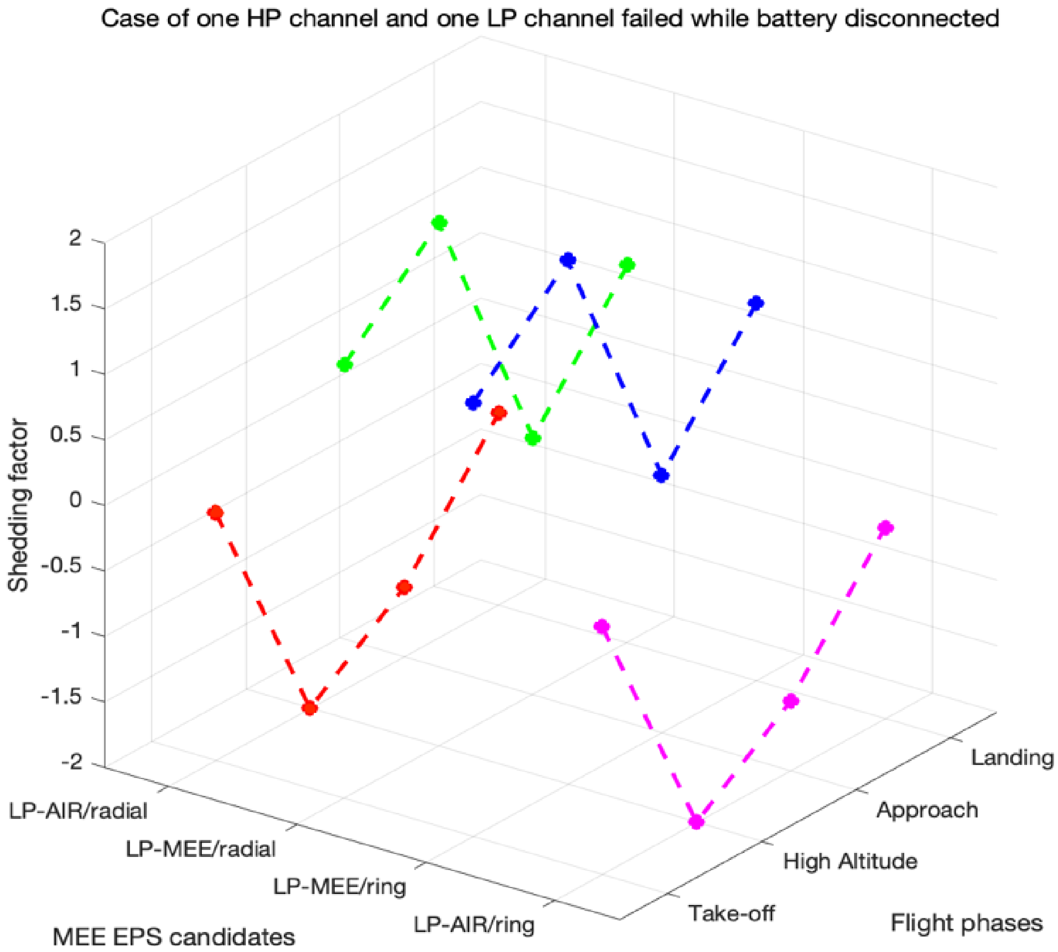


Figure 42. One HP and one LP channel failed with PLM that only considered ESS and shedding function

As the improvement, the case study has been replaced the coordinated PLM strategy. Figure 43 shows the LSF represented this case study when the candidates are coordinated with the PLM strategy 2 that includes ESS, shedding function and generator overloading function. The take-off phase of LP-MEE/radial and LP-MEE/ring can be improved and LSF is about below 1. However, the high-altitude phase of LP-MEE/radial and LP-MEE/ring still has not been satisfied, and the LSF is over 1.

Up to now, the results show that *LP-AIR/radial* and *LP-AIR /ring* have better system availability in power reconfiguration. Although the load shedding still happens in these two architectures, but the essential loads can be supplied under most failure scenarios.

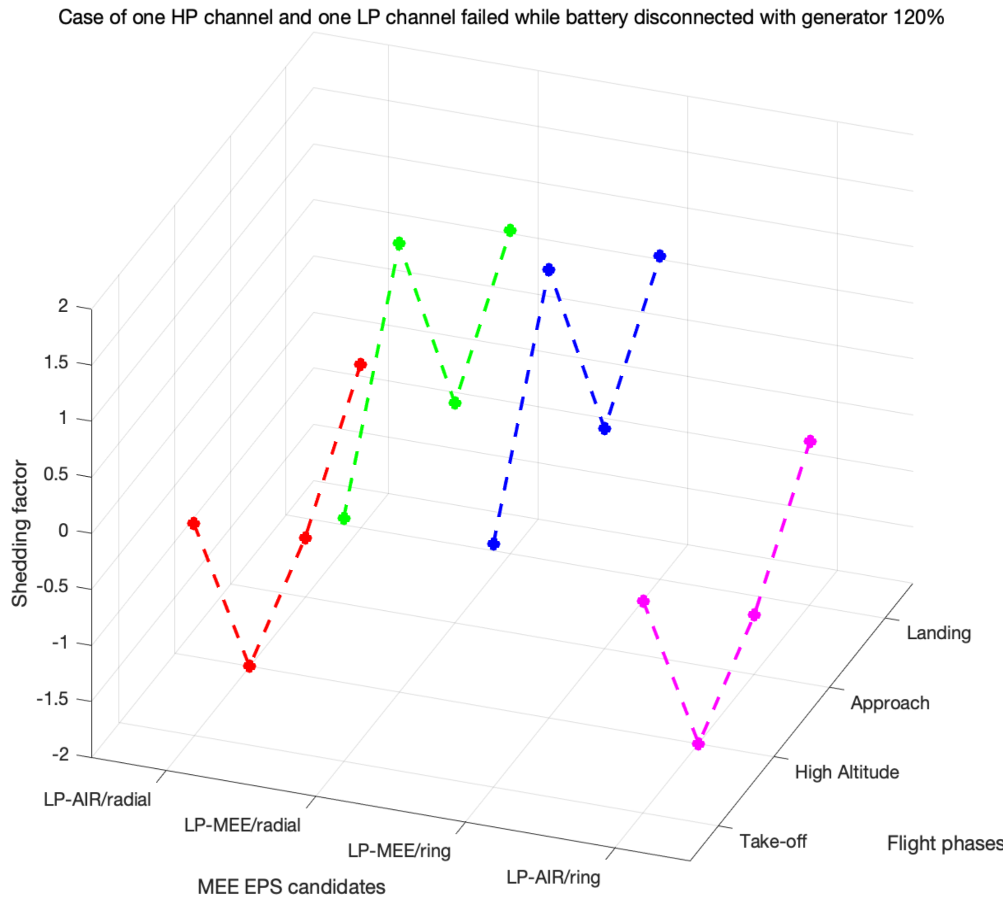


Figure 43. One HP and one LP channel failed with PLM that included generator overloading function

On the other hand, LP-*MEE/radial and LP-MEE/ring* appears to have power shortage for the essential loads and this can be an intolerant defect when specifying the design requirements for MEE power system. In reality, power reconfiguration is not always available. For example, if there is a catastrophic situation occurred in the engine and all power source channels on the power architecture are failed (the power system will be completely black out), and this is no possibility of reconfiguration at all. The target of this co-synthesis process was to refine/optimise the functional design for MEE power system concepts from a preliminary design, and the blackout situations were out of the research scope.

Furthermore, the EPS candidate of low system availability is not a dead end. Through system availability analysis and LSF values, the improvement areas of architecture design can be found. For example, *LP-MEE/Radial and LP-MEE/Ring* have lower power configuration capabilities regardless of coordination with any PLM options. Through LSF analysis, the design weakness of these two architectures lies in the channel connection, because the main power source depends on two single cables and cannot be coordinated with the LP generator connection. The flexibility of the power flow is not satisfactory under different fault conditions.

6.4.5. Power System Improvement via Shedding Factor

As design weaknesses were identified, this was readily able to improve the power reconfigured capability by adding reasonable components/devices to the existing architecture for increasing the ability of power system reconfiguration. Figure 44 shows two new concepts of the LP-MEE architecture, with added connections (circular

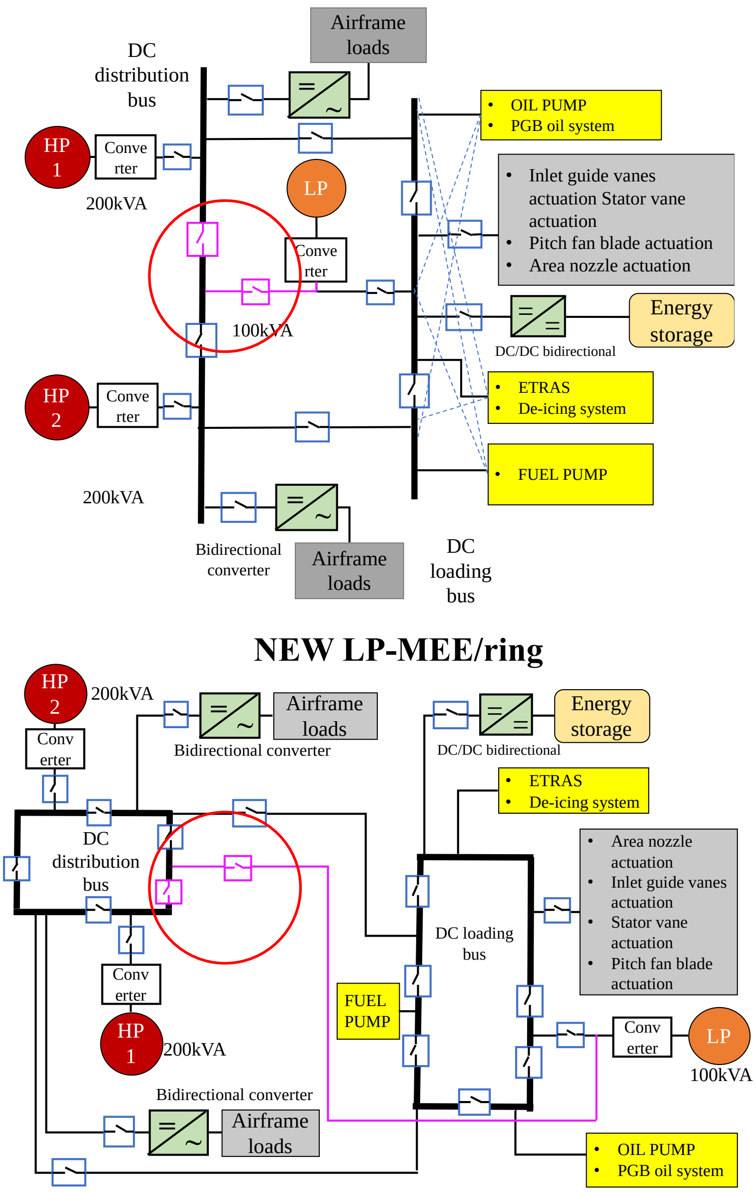


Figure 44. Two new EPS options based on LP-MEE/radial and LP-MEE/ring

highlighted) between the LP generator and the DC distribution bus. By means of creating more power paths in different scenarios, the new concepts of architecture are able to achieve the same LSF results as same as *LP-AIR/radial and LP_AIR/ring*, and the LSF is shown in Figure 45.

This case study is demonstrated the application of system availability evaluation and highlights the role of LSF on MEE power system design. This demonstration also provides various concepts and perspectives on PLM strategy and architectures of MEE power systems. Standard system design assessment such as power system reliability analysis and weight comparison may not fully realise the determination of power reconfiguration capability. LSF has been shown its benefit on judging the availability of MEE power system in different situations, but also combine cases to provide hints for the designers with corresponding architecture design improvements.

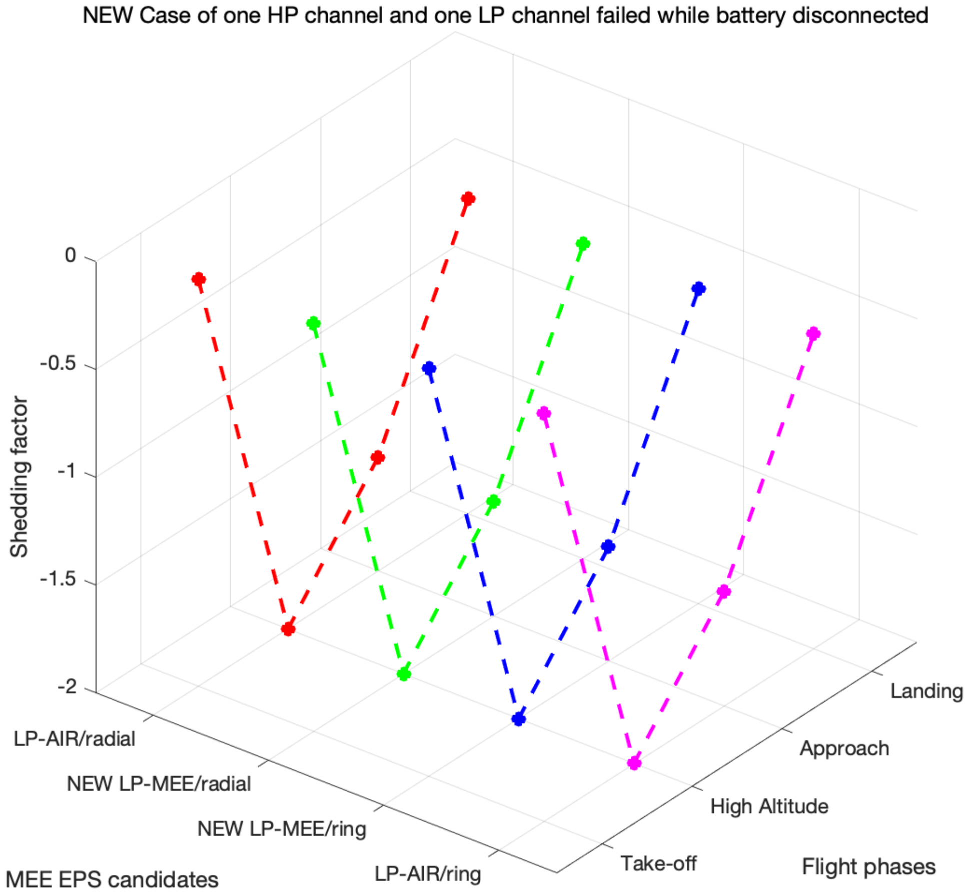


Figure 45. The new LP-MEE series concept has the same LSF as the LP-Air series concept

The availability of power system reconfiguration can only be analysed when the PLM and architecture are integrated. This is an impression that the synergistic cooperation of PLMs with architectures is an element to accomplish the operation of MEE power systems. Furthermore, if PLM has more different features to achieve power redundancy, it can balance the design weaknesses of the architecture. On the other hand, if the PLM options are less flexible and the power supply is time limited, this highlights a lower availability for power reconfiguration. Furthermore, vulnerable design in the architecture concept will cause direct impact on the operational flexibility and PLM strategy may not always able to cover the drawback of the inflexibility in the MEE power system.

6.5. Chapter Summary

This chapter has presented an effective evaluation of refining the EPS design for MEE system based on LSF, which determining the system availability and improvability.

This makes the research direction go beyond the general optimisation for MEA/MEE power management, but also improving the power distribution performance of the EPS, towards the enhancement/refinement of the entire electrical power architecture and an integrated operational performance in the power reconfiguration.

By using this method combined with a synthesis stage of parallel engineering design, the imbalanced states of EPS can be rapidly and easily determined. The design vulnerabilities based on the MEE power architecture can be perceived and subjected, which helps to targeted improvements such that a preliminary designed EPS will further expand its availability and utilisation.

This EPS system refinement includes an EPS integration and system availability evaluation (LSF analysis). The available architecture layouts would be allocated to the given PLM option, and integrated as EPS candidates. EPS candidates are combined with potential failure modes to identify the resilience system reconfigurations. Furthermore, EPS candidates can be evaluated by quantifying(by LSF) system availability can more standardise to ensure that the selected EPS has sufficient capacity to ride through as many failure modes as possible.

By this EPS design evaluation and system refinement, designers can comprehended the procedural knowledge about more-electric aerospace applications, and it can inspired designers to improve the EPS performance. In order to meet the high-performance requirements of MEE systems, this method could effectively highlight the deficiencies of electrical power architecture in the design. Thus, the targeted refinement/ enhancement could be carried out and found an EPS with high resilience and flexibility for the autonomous electrical system. This evaluation combined with the optimised methodology emphasised that it provides direction for the design of the next generation of aerospace electrical systems, promotes the realisation of more-electric applications and sustainable development of the aerospace industry in the future.

Last but not the least, as a justification point of selected the knowledge-based case studies was discussed in Chapter 1. The Chapter implemented the knowledge-based study for conducting the design refinement for MEE EPS. Unlike micro-grid, the detailed design of power architecture based on knowledge case studies is more necessary for an MEE that having a complicated system including both mechanical and electrical design requirements, which can have irreplaceable advantages for an unknown system design. Different to the mathematical optimisation, this study approach can observe all advantages and disadvantages of the design itself through practical cases. Via reviewing two subsystems and their design requirements, improving the original design can be easily achieved.

Chapter 7.

The Architecture and Power Management Co-Design for MEE Electrical Power System

7.1. Chapter Overview

This chapter presents the summarised design logic content of Chapters 3,4,5 and 6, integrated into a single comprehensive electrical system design process for MEE power network. This proposed Architecture and Power Management (APM) co-design comprises three core design steps and navigates the flow of MEE power system design. Firstly, design definition of the baseline model of the power architecture, and the parallel design of the PLM and the power architecture prototype. Subsequently, a power system initial feature capture framework is established to provide EPS feature optimisation through feature / parameter classification. The EPS refinement is then established for the power network to determine the system availability and operational flexibility in failure scenario studies. The feasible EPS candidates that determined by the APM co-design will achieve the critical requirements of MEE system such as high power resilient and redundancy.

The proposed APM co-design enables a highly flexible design process. The hardware architecture and power management strategy should first be designed independently and then should be introduced in the integration phase. In this design process, the entire EPS candidate scheme is not limited by some critical design stage. This design process can obtain more initial solutions from a larger design space that is using the same resources, thus providing more opportunities to find the optimal EPS design scheme for the power system of future electrified aircraft. The main attraction of this idea is not to simply expand the search scope of design space in vain, but to quickly down select an effective design solution after expanding the design space. In the process of co-design, an optimisation platform is employed to integrally analyse the design information and system characteristics of each subsystem, and the EPS prototype with strong feasibility can be extracted from a wide design space as early as possible. In this way, the detail design can be developed around the preliminary optimised EPS prototypes.

Since the optimised EPS prototypes become the main focus of the design, the number of feasible EPS at final design stage would be much less than the extensive design space that formed at the initial design stage. With using the APM co-design process, the comparison around the optimised EPS candidates will also be much less.

Figure 46 illustrates the MEE EPS design space changing in different design stages of APM co-design process. The thesis is mainly focussed on the architecture design path and the entire design process logic, design rule definition of PLM and PLM baseline scope is not in the scope of this research (highlighted as grey text).

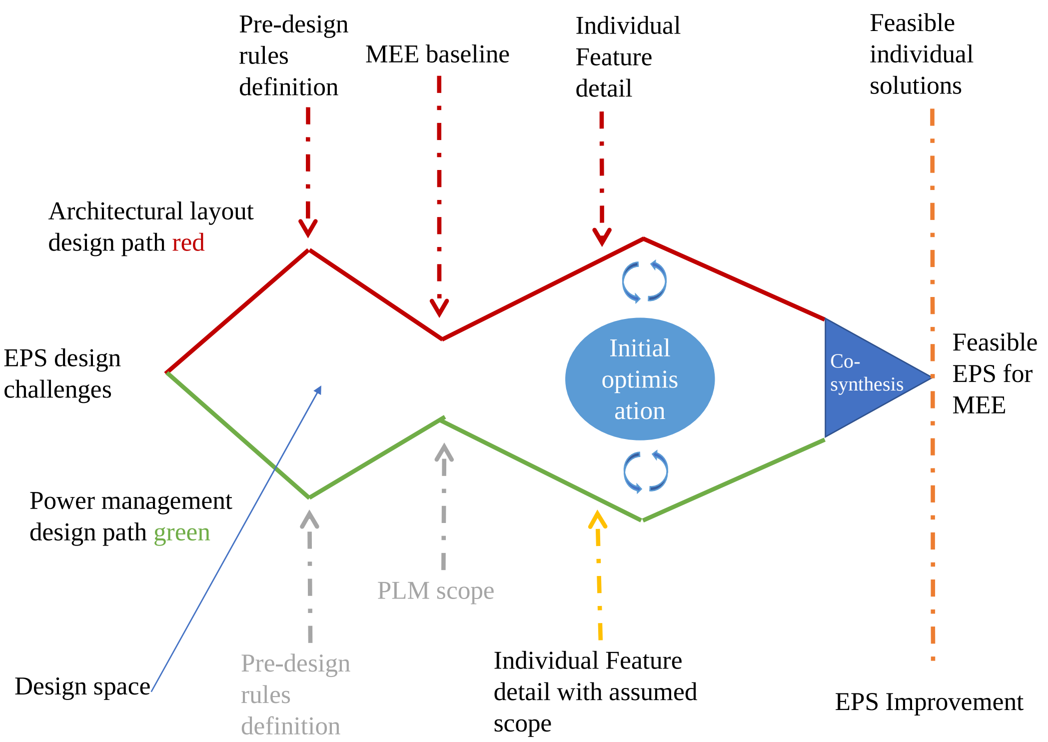


Figure 46. Design space illustration of APM co-design

To shape the integrity of the APM co-design, the individual feature design for the PLM strategy has been hypothesised and used to complete the flow of the entire design, detail assumptions were made in Chapter 5.

In addition, the power system design in literature often employs a mathematical-based optimisation method, which limits the designer's exploration of EPS operational performance. This is because using mathematical optimisation to design the EPS will hide the formation path of EPS. This does not help the designer to understand the "Know-How" progress during the design. Even if the optimal EPS is obtained by the mathematical optimisation, it will offer no explanations of why the optimal EPS is formed. In this way, designers may not able to better understand and fully utilise the advantages and performance of the optimal EPS. To achieve the visibility of the design process, a knowledge-based method will be a better choice to solve this specific problem.

Although the functions in the proposed APM co-design process have been proven to be applicable to MEE systems in the previous chapters, this chapter will present the APM co-design process as an overall flowchart, and the following subsections will describe each part of this co-design process in order.

7.2. An overview of the APM Co-design for MEE Electrical Power System

The high-level version of APM Co-Design process has been divided into different stages and shown in Figure 47. This design process can be divided into three layers. The first layer (block 1) is to collect and collate the design requirements for the MEE power system and describe the specification and definition of the MEE power system. Followed by partitioning the subsystem-level requirement into dedicated subsystem design, the system-level requirements will be taken as the constraints into the parameter-based optimisation.

The second layer (block 2,3 and 4) is to design all potential solutions of PLM and power architectures respectively. The features of the designed PLM and power architecture are collected into the parameter-based optimisation, this optimisation platform of the overall EPS system is performed to extract the PLM and power architecture that can be compatible and meet the design requirements.

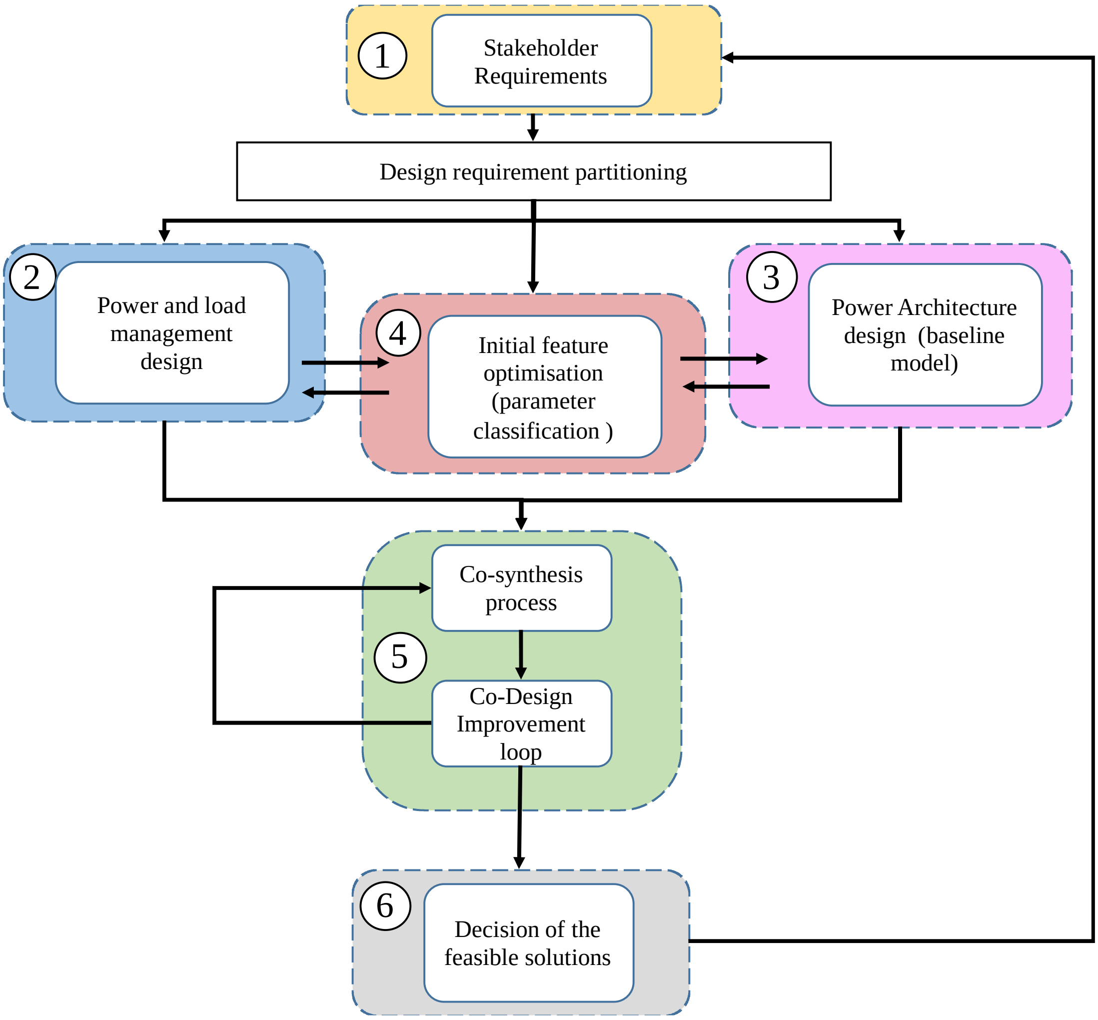


Figure 47. The flow chart of APM co-design

Once the feasible individual designs of PLM and architecture layout are ready for combination, the third layer is a co-synthesis procedure (block 5), it will be employed to conduct the system availability of the EPS through the flight profile case studies. Furthermore, an improvement loop would view the feasible combination of EPS which ensure there are any enhancement opportunities. Afterwards, the framework will recheck whether the defined concepts match with the MEE power system identification. This layer could be a validation of the case study, which is not included in the scope of this thesis.

7.3. Layer One: Design Requirements and Design Rule Definition

In the first layer of the APM process, the designer shall set up the feature specifications and requirements of the EPS of MEE. The design expectation of MEE power architecture are high-rated power sources with redundancy and multiple critical demands during different flight phases. The design considerations should include a multi-channel power system with flexibility in power reconfiguration, available power and load management methods shall be considered coordinating with the architecture to ride through complicated fault scenarios. The MEE power network can be developed into different ways for achieving and balancing the design criteria such as system safety, weight, operational flexibility, which is not easy to summarise the features of the power architecture and PLM strategy. Establishing a baseline framework of MEE power architecture and PLM would be useful to describe and define the scope of the EPS at the beginning stage of the design.

Since the existing aircraft design specifications and standards do not provide an appropriate and clear guidance for MEE design, the specific design rules of the MEE power network have been analysed and reviewed in Chapter 4. By demonstrating the requirements of these feature designs, a creditable baseline framework and related suggestions are established effectively. On the other hand, this design layer also establishes the definition of MEE power system requirements, which provides a good basis for classifying and portioning the design of subsystems of MEE power system. Regards to the PLM design definition, this is out of the scope of this thesis but similar method of establishing a PLM or Fault management framework can be found in [135][141].

7.3.1. Design Requirement Partitioning

When the definition and design requirements of MEE electrical system are determined, the characteristics of design requirements can be further divided. This stage of APM co-design is similar to the requirement identification section in the V diagram of ARP4754, but it provides better requirement listing and partitioning.

Subsystem design requirements for PLM strategy design or power architecture can be categorised separately, those requirements need to be identified and partitioned into specific blocks in the co-design. In this way, both the power architecture and PLM can be designed in parallel.

If the characteristics of some requirements are related to both subsystems, they can be considered as a system-level requirement and are directly referenced to the integral optimisation platform as parameter constraints.

7.4. Layer Two-Part 1: EPS Subsystem Designs

This section describes the individual design of both subsystems of EPS in the APM co-design.

7.4.1. **Power / Load** Management Strategy Design

This design block is used to design the sequence order of using the PLM strategy, and is represented by Block 2 in Figure 47. This PLM strategy supports power reconfiguration strategy and manages MEE loads under abnormal conditions. There are two examples of the MEE PLM strategy that were utilised in Chapter 6 , which are used to conduct the investigation of LSF analysis. More examples of PLM strategy can be found in Appendix C. This design block means to produce a series of PLM strategy options that met the design requirements. The features of these PLM strategy options can be used in the optimisation platform to analyse and optimise the functionality of the overall power system in combination with the power architecture design.

7.4.2. **Power Architecture Design**

This design block (Block 3 shown in Figure 47) is used to represent the MEE power architecture design. At the beginning of this design stage, the architecture baseline model will be formed according the design rule definition that from block 1. The varied architecture concepts can be generated via the baseline model, and then will be evaluated via dedicated reliability analysis and weight comparison (more information of each evaluation shows in following sections).

7.4.2.1. Reliability Analysis

Fault Tree Analysis (FTA) or a similar method such as Fault Mode & Effect Analysis could be employed to evaluate the system reliability of MEE power architecture. In this thesis, FTA has been utilised to assess the failure rate in flight hours of the MEE architecture concept. The FTA results are calculated by the failure rate of each power system component. Correspondingly, the FTA result becomes the expected failure rate of any MEE electrical load caused by electrical failures.

Having a reliability analysis is an indispensable part of the MEE power system design process, as it demonstrates the safety of a power system concept. The designed power system concept needs to be adhered to surrounding safety in the related design standard and commenting stringent safety check in place.

7.4.2.2. Hardware Capability Comparison

In addition to the reliability of the power architecture, another key point of the aerospace power system design that can improve the EPS performance is the mass and power density of the components.

7.5. Layer Two-Part 2: The Optimisation of Parameter Classification

Once the both subsystems of the MEE power system have been designed respectively, all the initial designed subsystem options will act as inputs into an integrated system-level optimisation (corresponding to Block 4 of Figure 47). This requires combining the power architecture and PLM scheme into an EPS prototype, and the parameters of the combined EPS need to match with the designed parameters. The parameter classification optimisation would rank all the EPS prototypes based on the design compliance. More specifically, the compatibility between subsystems and the overall operational performance of the EPS would be determined through using the parameter classification comparison in this optimisation process.

In the parameter classification, feasible EPS prototypes (containing a power architecture and a management scheme of PLM) can be preliminarily down-selected. Within this aspect, a full detail flow chart of the parameter classification optimisation is shown in Chapter 5. This optimisation would speed up the identification of feasible EPS prototypes, as it is not necessary to have a detailed assessment and analysis of each EPS to determine its feasibility at this stage. Furthermore, the concept of prototype feature similarity has been considered in this parameter classification optimisation. If a particular feature often appears in feasible EPS prototypes, it is considered for searching in low-ranked EPSs. This greatly reduces the possibility of losing potential EPS prototypes.

Once the overall features and functions of the EPS have been identified, more detailed design will be conducted around the core design of MEE power system, such as the location, quantity, and operational performance of the power components. This will be conducted in the next design layer which is the co-synthesis procedure.

7.6. Layer Three: The Co-synthesis Procedure for MEE Design

This section presents a co-synthesis procedure for the refinement of MEE EPS candidates. The procedure corresponds to Block 5 of Figure 47. This section details how a case study on the availability of the MEE EPS system can be carried out by this co-synthesis procedure.

Figure 48 illustrates an expanded flow-chart for explaining the MEE EPS co-synthesis procedures. In stage A, the power architecture and PLM options selected by the parameter classification optimisation (content of Chapter 5) were collected and combined as EPSs, which was defined as an EPS candidate.

Secondly, the power reconfiguration capability of each EPS candidate will be evaluated based on different failure conditions, and to determine that whether it can ride through the various electrical failures. Different failure conditions will be introduced into each EPS candidate, such as generator fault, converter fault, load fault, so that EPS can form a fault mode. At the same time, the power supply demand of each flight phase of aircraft should be introduced in stage B, which makes the case study more realistic.

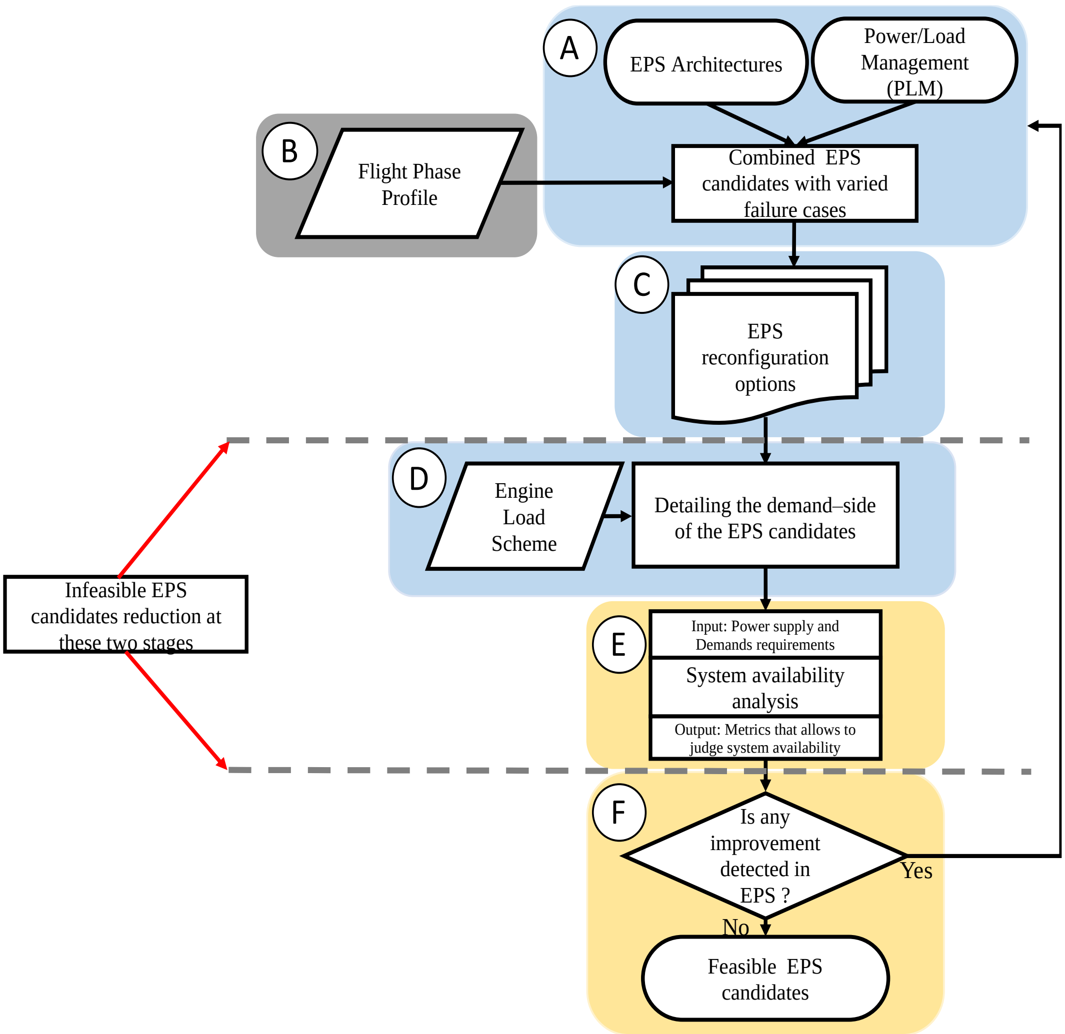


Figure 48. Co-synthesis flow chart

For each failure, the designer shall use the available power devices and the dedicated PLM strategy to minimise the impact of the failure on the EPS. In the case of a single component failure, the cooperation between the architecture layout and PLM strategy needs to enable the power system reconfiguration, and contain sufficient levels of redundancy such that nominal supply to the load is maintained.

When the remaining power supply is insufficient to meet all demand requirements, some non-critical loads may be abandoned to ensure system stability. The engine load scheme (shown in stage D) provides the priority supply list of the engine auxiliary systems, this list should be employed into in this procedure. With the engine load scheme, the reconfiguration option of EPS can specifically know the load shedding order. In stage D, the designer will determine whether the reconfiguration capability of EPS can be achieved when failure occurs.

In Stage E, the system availability analysis (via LSF) will be conducted to verify the effectiveness of the MEE EPS that having reconfiguration availability.

Finally, the EPS solution will be inspected in Stage F for identify if there are any enhancement can be made. If so, the designer should return to Stage A and repeat the procedure again. After the co-synthesis procedure, the selected MEE EPS candidate can be recognised as a feasible solution.

The overview of co-synthesis procedure is described above, the following subsections are used to explain the functionalities on each stage of this co-synthesis procedure.

7.6.1. Co-synthesising Power Architecture and PLM

In the first stage, designers should aggregate the prototypes of power architecture and PLM strategy from the parameter classfication optimisation. All PLM schemes will be assigned to each architecture, making it an integrated EPS candidate. Each EPS candidate is represented by a single-line diagram. Classical system failure conditions, such as generator failure and converter failure, will be assigned to each EPS candidate, which will allow EPS single-line diagram to form different failure models.

7.6.2. Flight Phases Profile

In each failure case, different flight phases should be considered to achieve a comprehensive case study. The flight phase overview will include the flight cycle and power requirements for each phase. The method of including flight phase profiles in the case study also provides conditions for evaluating the flexibility of PLM strategies. Due to different flight cycles and load requirements at different stages, the dedicated PLM scheme in EPS needs some flexibility to maintain a power balance under different failure modes.

For example, during takeoff, if there is an electrical failure in the architecture, batteries may be preferred to supplement the power shortage directly (critical loads are required remain to be on during takeoff, and non-critial load such as galley or cabin light being off). However, if the similar condition occurs during the cruise phase, discarding non-critial loads on the fuselage should be the primary consideration before using batteries to meet the critical loads.

7.6.3. EPS Reconfiguration Option Studies

After all the failure modes and different flight phases are assigned to the EPS candidate, reconfiguration options can be designed for each EPS failure model according to different fault regions and flight conditions. In different failure scenarios, EPS reconfiguration may have multiple options. Some reconfiguration options may be unsuitable for EPS candidates and can be ignored. Additionally, if an EPS candidate has an inevitable reconfiguration defect, it can be quickly identified as an infeasible solution, thus reducing the workload in future steps. However, the remaining suitable EPS reconfiguration options need to consider the supply priority of the engine loads.

7.6.4. Load Schedule

Load schedule is a dataset regarding supply priority for MEE loads. This dataset should also be considered in EPS reconfiguration to provide more design details, especially navigating the refinement of the management strategy related to load shedding. Under some EPS reconfiguration conditions, the power supply has enough capability, but the power flow path is blocked due to the isolation of the fault region. With this scenario, the design of the alternative path only needs to consider the power distribution and flow direction of EPS without discarding any loads (when both the cable and the filter are ideally capable of doing so).

However, in the case of power shortage and power path congestion, the EPS often needs to adopt appropriate load shedding strategies to ensure power balance. According to the importance of loads, the load schedule can be highlighted in EPS single line diagram. That is, the wiring location of each load needs to be listed on the EPS demand-side and indicates the priority for load shedding. When the EPS needs load shedding in the event of a failure, the designer can directly understand the impact of each load shedding on MEE.

The case study of EPS reconfiguration will be completed at this stage, but it is difficult to compare the ability of power reconfiguration of each diagram-based EPS. Therefore, some indicators such as LSF of the power system can be quantified to verify the availability of each EPS candidate.

7.6.5. System Availability Analysis and Improvement

Block E and F of Figure 48 is discussed and demonstrated in Chapter 6. The LSF analysis is utilised for the determination of power system availability and provided directions on the design improvement of power system concepts. The optimal solution of MEE power system will be finally determined through this entire co-synthesis procedure.

7.7. Chapter Summary

In summary, this chapter has proposed a framework of APM co-design for MEE electrical systems based on the content of Chapter 3,4,5 and 6. This methodology is also suitable for use in a wider range of aircraft electrical system design, and aiming to improve the power system design of the MEE or MEA power network.

This design framework includes the power architecture design, PLM strategy design, the platform for initially optimising the overall system characteristics and features of the EPS, and a co-synthesis procedure for the system enhancement coordinated with failure mode study.

The co-design process allows architecture and PLM strategies to be designed separately; making them more independent and no longer subject to each other's limitations. This expands the design space of the EPS. From the characteristics of these two designs, the complementary features can be identified, and an EPS prototype can be established. This allows the overall operational performance of EPS to be predicted the in advance and allows a rapid screening of the viable EPS candidates prior to any further detailed design. Finally, using the failure scenarios that may occur during flight to evaluate and improve the comprehensive EPS in detail via the co-synthesis procedure. Overall, a part of the general V diagram of ARP4754 can be modified to incorporate the proposed APM co-design approach adapted for MEE power system design.

Reviewing the entire MEE co-design process, the design subsystems have given each other design space. This is because that subsystems are designed separately to allow more exploring space. The preliminary feature optimisation (also called parameter classification optimisation) layer provides advantages for the development of MEE power system, but it does not need to study each prototype in depth. After the preliminary optimisation, each potential prototype will be refined in the co-synthesis procedure. This APM co-design fully conforms to the purpose of fast down-selection of effective EPS candidates in a more comprehensive design space.

In the face of the variability of the electrical system in the development of new generation aircraft and the challenges of using multiple power management strategies, the design process of EPS is a vital factor determining the success of the design. This design process framework established in this chapter will enable the power system of electrified aircraft forward to a new degree of development.

Chapter 8.
Thesis Conclusions and Future Work

The concept of More Electric Aircraft is well established within the aviation industry and has been developing in the past two decades to achieve better fuel combustion efficiency. The More Electric Engine, as a promotion solution of the most complementary system for MEA, its power architecture provides a vital opportunity for the operational performance of MEA to have a large power supply capability and the resilience of power distribution. Therefore, the MEE's power architecture needs multiple criteria design to meet the requirements of the electrified aircraft, to coordinate the weight, flexibility and reliability of the power system. The power system of MEE has the potential to promote the next generation of aircraft and will certainly become a hot research topic.

In reality, MEE system faces the challenges of limited design guidelines and unclear design process when designing the power architecture. Some conventional engine design guidelines cannot be directly used to design an MEE. Moreover, although EVTOL has some newly special condition standards, they cannot also be consulted due to the conceptual difference. In addition, for the advanced MEE power systems, the design process also needs to be adjusted. Therefore, the work done in this thesis demonstrated some credible MEE power architecture concepts and proposed an improved EPS design process for More Electric Engine. A summary of the thesis and a series of key conclusions are given below.

8.1. Thesis Summary

Firstly, the thesis presents the understandings of the design requirements of MEE. In Chapter 2, the concept of MEA and MEE are introduced. An in-depth literature review was conducted for the design of MEE power architecture. Although a variety of MEE power architectures are available from existing public literature, many of the power architectures of MEE are formed by following limited considerations or no rationale behind the design. Therefore, this thesis reviewed the existing MEE architectures, and determined the similarities and uncertainties of those architectures. Further literature review was focussed on identifying the suitable design logic of MEE power system. The justification of choosing Co-Design process concept for MEE power system design was given. More specifically, Chapter 2 also highlighted the needs of using the operational logic of Co-design process in MEE design, to provide better coordination between the design sequence and the MEE design requirements.

Secondly, based on the characteristics of MEE system, the thesis has used Chapter 3 to review and evaluate a range of multi-channel power architecture busbar configurations and associated underpinning technologies. Chapter 3 has provided a quantitative comparison of these architectures in terms of estimated supply failure rates and system mass. Whilst significant research has been undertaken on MEE electrical systems and technologies up to Chapter 3, Chapter 4 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 chapter to facilitate this. These are derived using a combination of anticipated safety requirements, failure rates analysis, and logical functional system needs.

Furthermore, this thesis has used Chapter 5 to present the investigation of optimising the initial integrated MEE EPS via a two-subsystem co-design process. The proposed coarsely optimisation process (called parameter classification optimisation) was used to highlight the essential features required for MEE power system design and the advantages and disadvantages of each subsystem options at very beginning stage of the design. It is also provided an integration platform for down-selecting EPS candidates, which can guide designers to explore the similarity between subsystems and rapidly shrink the enormous design space. This optimisation has provided a predication of the system functionalities of the EPS, which offers a clear and systematic picture for integrated system design. Although this research activity is an extension of the concept of co-design process, the stages of this optimisation are novel and specifically tailored for the 'More Electric' power system. Within use of the parameter classification optimisation, the repeated work of the subsequent detailed design and design iterations can be reduced.

The value of MEE subsystem synthesis research in Chapter 6 lies in the recognition of the interactive and implicative nature of subsystems of the MEE, echoing the research hypothesis of deficiencies in the conventional sequential design. Within the co-synthesis fine tuning procedure of MEE power network design, the proposed LSF analysis and reconfiguration case study are implemented to provide a visual hint on the key locations of the EPS concept, and the system availability and the power reconfiguration flexibility of power flow in the MEE network then can be improved.

In addition, this thesis has given much clarifications and assumptions on the strategy and design of PLMs, this is because of this thesis is mainly based on the perspective of MEE power architecture design. This does not represent that PLMs are not of equal importance. It is precisely because of its importance, this can be a topic for another PhD to investigate.

Finally, the aviation industry is planning to reduce emissions and greening the sky with real ambition. However, the biggest challenge faced by the aviation industry is that some real cutting-edge technology companies are unwilling to share their research results due to competition. Many academic researchers are repeating the design of MEE EPS or other similar applications. This thesis can provide an additional research resource for the aviation industry and the academic community to accelerate research in this field. The thesis also provides a theoretical design package for More Electric Engine design of a large future wide-body size aircraft (equivalent size as B787 and A350). More specifically, a co-design process was proposed for MEE in Chapter 7, it should bring greater motivation to the academic community and forward the electrical system design for various new aerospace applications.

8.2. Thesis Conclusions

The work contained in this thesis has demonstrated the design flow of MEE power architecture, a number of key conclusions are evident as following:

1. **A flexible bus topology is required for MEE power architecture.** Of the MEE power architecture concepts considered in Chapter 3, flexible bus topologies

showed a favourable compromise of reliability and mass, whilst three channel configurations appeared to be attractive for attaining high degrees of system reliability.

2. This thesis is believed that, in the conservative consideration of the application of off the shelf technologies, **the MEE power system should be expected as a multiple-power-source and multiple-channel electrical network**. The MEE power system is estimated to have three generators and three channels in the architecture to meet the failure rate requirements for certification. The MEE power system shall be a full DC distribution system, having at least two or more independent electrical power sources; and all the essential loads such as pumps and actuators require power supply redundancy and single fault tolerance. However, the future research can be carried out towards a reliable and stable dual channel power system to save a lot of operating costs and system weight. But the premise is that superior technologies are needed to improve the reliability of key components in the power system.
3. The author believes that since the DC power distribution systems require less power electronic devices than AC power generation, **DC architectures have better system reliability in three-channel power distribution. In addition to power redundancy and reliability, the weight reduction is still required between DC architectures and AC loads/ motors.** In the future as the technology matures, it may be necessary for an inverter to supply power to two different loads/motors at the same time to achieve the flexibility of the power architecture operation and maintain the normal operation of current and voltage.
4. **When the power architecture candidates that were developed based on the established BPA concept are down selected, it was noted that the variation of their features will not change significantly from one another.** Based on power supply capability and redundancy design considerations, if the generator and power channel quantity were identified, the variation of each concepts would be the decision on the usage of different technologies on the baseline power architecture.
5. **Capturing the rationale of these MEE power architecture design rules enables key decision points and even design recommendations themselves to be**

revisited as necessary in order to capture application-specific requirements. This enables 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).

6. **An optimisation is required at the preliminary integration phase of the MEE power system design to largely reduce the infeasible solutions as early as possible in the design cycle.** The thesis recommended that using the parameter classification optimisation to optimise the overall system performance of MEE power system prior to the subsystems are actually synthesised into an integrated system. This will eliminate infeasible solutions without large time consuming.
7. **In the preliminary integration design phase, the power architecture has been identified as the dominant element of MEE power system design.** As far as the overall performance research results are concerned, the defects of MEE architecture may not be remedied by a particular power management strategy, but if the power architecture is robust enough, the shortcomings of power management can be remedied. This reflects that MEE power architecture has the domination during the design. Optimising the power architecture in its individual design can significantly reduce the design iterations for the integrated MEE power system.
8. **In the fine-tuning stage of the MEE power system design, the availability and reconfiguration capability on the MEE power network are significantly depend on the location of equipment in the physical layout of the architecture itself and the decisions of using the power management strategy.** The location of some connection points and emergency power supply on the full DC distribution MEE architecture actually plays a key design direction for power redundancy and flexibility in power scheduling.

8.3. Review of Thesis Contributions

1. Chapter 3 presented a preliminary comparative study of the weight, power flexibility and power reliability analysis of dual-channel and three-channel MEE networks often mentioned in the current literature. The bus topology selection, power reliability and structure weights of two- and three-channel power networks were investigated in detail. The findings from this multi criteria

design analysis lead the research direction into the design requirement capture, underpin the creation of a baseline MEE architecture and its associated design rules.

2. Key functional requirements were captured for the future MEE architecture, and certification-compliant MEE baseline architecture were established in Chapter 4. A preliminary multi-criteria design statement is presented within this chapter for the corresponding the baseline power architecture for MEE system. This baseline architecture has been creditably reduced the uncertainties of the design of MEE power system into a manageable level. This contribution has provided a comprehensive reference to the power architecture design and utilisation of advanced technologies for more electric aircraft and engine.
3. Chapter 5 proposed a parameter classification optimisation for down-selecting the initial MEE power system concepts. The optimisation has provided a integrated platform for interacting the characteristics of power architecture and power/load management strategy. Those feasible EPS prototypes that met the overall design requirements are determined by the ranking comparison. This novel optimisation also offered the determination of the mutual compatibility between subsystems. Therefore, the design space of the initial MEE EPS can be significantly reduced and accelerates the selection of subsystem availability and complementarity for MEE EPS. This methodology has also solved the drawback of sequential design of subsystems, that is, there were no communication design between subsystems. In respect of next generation aircraft/engine, this methodology reflecting that the necessity of utilising an integrated platform to optimising the EPS concepts is essential in the design of More-electric applications in the near future.
4. Chapter 6 has proposed a case-study-based procedure for evaluating the synthesised MEE power system that combined the detailed power management strategy and power architecture. The detailed EPS was allocated with various failure modes to determine the feasible power reconfiguration options for the EPS. Furthermore, this novel co-synthesis procedure has provided a quantitative analysis (LSF) to determine the power balance state of the MEE EPS. This procedure provides a detailed refinement of the EPS and determines

that the component location in the power architecture has a vital impact to the capability of power reconfiguration of the EPS. Minor alternation of the EPS concept will made game-change result of power distribution capabilities. This ‘fine-toning’ procedure has indeed played a key role in the development of aerospace power systems.

5. In Chapter 7 a comprehensive co-design process oriented to MEE power system is established. Utilising of this design process enable to drive the design of electrical architectures and power management schemes in parallel. The design of the MEE power system is developed in term of the co-design flow manner, which ensures that the MEE power system possesses complementarity and collaboration in the concepts of power management strategy and power architecture. The utilisation of this co-design process has addressed uncertainties in MEE power system functionality after system integration and provided indispensable assumptions for simulation modelling the MEE power system.

8.4. Future Work

The author believes that the following points related to the design of MEE power system should be studied in depth in the future so as to gain a more comprehensive understanding of the rationale in the design of MEE power architecture and the EPS.

1. In the conclusion, it has mentioned that the necessary redundancy between DC distribution to local AC motors. (for the actuation of the engine variable bleed valve, engine fan blade etc,.) Hence, the feasibility of hardware that be selected should be necessarily studied and evaluated from flexible power dispatch. Developments could be made in the design of connections between multiple inverters and multiple loads, such as power transient simulation considering how to switch back and forth between two different AC loads in one inverter. The feasibility of the new technology needs to be analysed to ensure that the new power electronic device can ride through the instability in the transient mode. This work can prove that the innovation of MEE architecture designed

can withstand testing and give more confidence to the more electrified engine. However, how to integrate the feasibility analysis of new technologies into the co-design process is also a new challenge.

2. Due to the complexity of MEE architecture and more restricted requirements of failure rate, dual-channel MEE architecture with mature power system technologies currently may not able to achieve the goals. Although the dual-channel MEE power system may save the cost and weight of the whole system in design, the design of dual-channel architecture needs extremely superior technology to improve the failure rate. Therefore, if the MEE power system solutions want to be expanded and optimised, it is needing to provide more information about the reliability of advanced electronic power technology and its power supply availability in transient and steady-state simulation. Also, if the industry partners are willing to invest in research to improve the reliabilities of the power generator, power electronic devices and the topologies in the MEE power architecture, so as to reduce the failure rate, it has great prospects for the formation of a dual-channel MEE architecture. For further work on it, the overall performance of the dual-channel architecture could be predicted in the co-design process according to the superior technical parameter data. If the failure rate can be guaranteed to be sufficient, some continuous backup power supply/ power reconfiguring actions must occur before the MEE power system failed. This may use some superior electronic technologies to freely control the MEE performance, such as power converter connection redundancy, or some fault-tolerant generators. In this way, if these electronic technologies are not mature enough, the design conclusion may not see that there are two channels in the future. For safety respect, the MEE power system design should be started with three-channel concept, and needed significant improvements to striving a two channels solution.

3. The designer can also consider how the designed MEE power architecture can be compatible with existing MEA grid. Currently, the literature has a lack of information or investigation on this field. A perfect connection between the

MEE power architecture and MEA airframe architecture is required (such as power type level, connection protection between them) to make it an alternative to conventional engine. This aspect of the study may require more research on the existing MEA airframe power architecture and safety guidelines.

4. Establishing a design framework for the power management strategy of MEE. With the design framework of power management strategy, the design requirements could be intuitively studies and judged, and effective power management strategies can be easily selected for the MEE. (including its detection method, protection method, response time, etc. for example, the duration of using generator overload function, overload rate, when it can be used, and how to meet the power demand of MEE auxiliary equipment.) This will be another important branch of APM design process to further realise the synergy and complementarity required by power architecture and power management in integrated design.

References

[1] M. Darecki and C. Edelstenne, “Flightpath 2050 Europe’s vision for aviation: Report of the high level group on aviation research,” *Isbn 978-92-79-19724-6*, p. 28, 2011, doi: 10.2777/50266.

[2] A. Krein, “How can hydrogen technologies power the clean aircraft of the future?,” *Clean Aviation*, 2022. [Online]. Available: https://www.clean-aviation.eu/media/executive-directors-blog/how-can-hydrogen-technologies-power-the-clean-aircraft-of-the-future#:~:text=Hydrogen eliminates CO2 emissions,propulsion by up to 90%25 [Accessed: 27-Jan-2024].

[3] A. Schwab *et al.*, “Electrification of Aircraft : Challenges , Barriers , and Potential Impacts,” no. October, 2021.

[4] A. Rajagopalan, “Design of 4-seat, general aviation electric aircraft,” *San Jose State Univ.*, 2012.

[5] K. Reals, “How the future of electric aircraft lies beyond the engines,” *flight global*, 2019.

[6] McKinsey & Company, “Clean Sky 2 -Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050, ” *Clean Sky 2 JU*, no. May. 2020, ISBN 978-92-9246-342-7,doi:10.2843/471510

EG-04-20-214-EN-C

[7] E. Offsetting, “Climate Change and Aviation,” *Clim. Chang. Aviat.*, no. 615, pp. 1–6, 2012, doi: 10.4324/9781849770774.

[8] M. Sinnett, “Saving Fuel and Enhancing Operational Efficiencies,” *Aero Q.*, pp. 6–11, 2007.

[9] EASA, “Certification Specifications (CSs).” [Online]. Available:

https://www.easa.europa.eu/en/document-library/certification-specifications. [Accessed: 02-Oct-2022].

[10] FAA, “Regulations & Policies.” [Online]. Available: https://www.faa.gov/regulations_policies. [Accessed: 02-Oct-2022].

[11] A. Barzegar *et al.*, “Intelligent power allocation and load management of more electric aircraft,” *Proc. Int. Conf. Power Electron. Drive Syst.*, vol. 2015-Augus, no. June, 2015, doi: 10.1109/PEDS.2015.7203445.

[12] M. Kim, S. G. Lee, and S. Bae, “Decentralized power management for electrical power systems in more electric aircrafts,” *Electron.*, vol. 7, no. 9, pp. 1–19, 2018, doi: 10.3390/electronics7090187.

[13] R. Su, Y. Zhang, C. Wen, G. O. Heo Peng, M. Husband, and S. Dasgupta, “Design of the Power Management System for Electrical Power Systems in More Electric Engine / Aircraft,” *2018 IEEE Int. Conf. Electr. Syst. Aircraft, Railw. Sh. Propuls. Road Veh. Int. Transp. Electrif. Conf.*, no. 2, pp. 1–6, 2019, doi: 10.1109/esars-itec.2018.8607794.

[14] P. Akter, S. Mekhilef, N. M. L. Tan, and H. Akagi, “Model predictive control of bidirectional AC-DC converter for energy storage system,” *J. Electr. Eng. Technol.*, vol. 10, no. 1, pp. 165–175, 2015, doi: 10.5370/JEET.2015.10.1.165.

[15] N. M. L. Tan, T. Abe, and H. Akagi, “Design and performance of a bidirectional isolated DC-DC converter for a battery energy storage system,” *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1237–1248, 2012, doi: 10.1109/TPEL.2011.2108317.

[16] D. Ravi, B. M. Reddy, S. L. Shimi, and P. Samuel, “Bidirectional dc to dc converters: An overview of various topologies, switching schemes and control techniques,” *Int. J. Eng. Technol.*, vol. 7, no. 4, pp. 360–365, 2018, doi: 10.14419/ijet.v7i4.5.20107.

[17] R. Burgos, G. Chen, F. Wang, D. Boroyevich, W. G. Odendaal, and J. D. Van Wyk, “Reliability-oriented design of three-phase power converters for aircraft applications,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 48, no. 2, pp. 1249–1263, 2012, doi: 10.1109/TAES.2012.6178060.

[18] S. Bozhko *et al.*, “Development of Aircraft Electric Starter-Generator System Based on Active Rectification Technology,” *IEEE Trans. Transp. Electrif.*, vol. 4, no. 4, pp. 985–996, 2018, doi: 10.1109/TTE.2018.2863031.

[19] A. Cavagnino, Z. Li, A. Tenconi, and S. Vaschetto, “Integrated generator for more electric engine: Design and testing of a scaled-size prototype,” *IEEE Trans. Ind. Appl.*, vol. 49, no. 5, pp. 2034–2043, 2013, doi: 10.1109/TIA.2013.2259785.

[20] F. Gao, S. Yeoh, S. Bozhko, and G. Asher, “Coordinated Control of a DC Electrical Power System in the More Electric Aircraft Integrated with Energy Storage,” *2015 IEEE Energy Convers. Congr. Expo.*, pp. 5431–5438, 2015, doi: 10.1109/ECCE.2015.7310424.

[21] J. K. Noland, M. Leandro, J. A. Suul, and M. Molinas, “High-Power Machines and Starter-Generator Topologies for More Electric Aircraft: A Technology Outlook,” *IEEE Access*, vol. 8, pp. 130104–130123, 2020, doi: 10.1109/ACCESS.2020.3007791.

[22] S. D. A. Fletcher, P. Norman, S. Galloway, and G. Burt, “Impact of Engine Certification Standards on the Design Requirements of More-Electric Engine Electrical System Architectures,” *SAE Int. J. Aerosp.*, vol. 7, no. 1, pp. 2014-01–2119, 2014, doi: 10.4271/2014-01-2119.

[23] Y. Zhang *et al.*, “An energy efficient power management solution for a fault-tolerant more electric engine/aircraft,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 7, pp. 5663–5675, 2019, doi: 10.1109/TIE.2018.2877169.

[24] S. D. A. Fletcher, P. Norman, S. Galloway, and G. Burt, “Impact of Engine Certification Standards on the Design Requirements of More-Electric Engine Electrical System Architectures,” *SAE Int. J. Aerosp.*, vol. 7, no. 1, pp. 2014-01–2119, 2014, doi: 10.4271/2014-01-2119.

[25] P. Nuzzo *et al.*, “A contract-based methodology for aircraft electric power system design,” *IEEE Access*, vol. 2, pp. 1–25, 2014, doi: 10.1109/ACCESS.2013.2295764.

[26] EASA;Rolls-Royce Germany, “TYPE-CERTIFICATE DATA SHEET for

Trent 1000 Series Engines," 2020.

[27] B. Sarlioglu, S. Member, C. T. Morris, and A. E. P. System, "More Electric Aircraft : Review , Challenges , and Opportunities for Commercial Transport Aircraft," *IEEE Trans. Transp. Electrif.*, vol. 1, no. 1, pp. 54–64, 2015, doi: 10.1109/TTE.2015.2426499.

[28] I. Moir and A. Seabridge, *Aircraft systems: mechanical, electrical, and avionic subsystems integration*. 2008.

[29] V. Madonna, P. Giangrande, and M. Galea, "Electrical Power Generation in Aircraft: review, challenges and opportunities," *IEEE Trans. Transp. Electrif.*, no. 665468, pp. 1–1, 2018, doi: 10.1109/TTE.2018.2834142.

[30] K. Xu, N. Xie, C. Wang, and X. Shi, "Modeling and simulation of variable speed variable frequency electrical power system in more electric aircraft," *Open Electr. Electron. Eng. J.*, vol. 11, no. April 2017, pp. 87–98, 2017, doi: 10.2174/1874129001711010087.

[31] M. Hirst, A. McLoughlin, P. J. Norman, and S. J. Galloway, "Demonstrating the more electric engine: a step towards the power optimised aircraft," *IET Electr. Power Appl.*, vol. 5, no. 1, p. 3, 2011, doi: 10.1049/iet-epa.2009.0285.

[32] R. Thomson, N. Sachdeva, M. Nazukin, and N. Martinez, "Aircraft Electrical Propulsion – The Next Chapter of Aviation?," pp. 1–32, 2017.

[33] P. Wheeler and S. Bozhko, "The more electric aircraft: Technology and challenges," *IEEE Electrif. Mag.*, vol. 2, no. 4, pp. 6–12, 2014, doi: 10.1109/MELE.2014.2360720.

[34] Roll-Royce plc ,"Trent 1000 66 blades halving the noise footprint," 2017. [Available]https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/civil-aerospace-downloads/280717-Trent-1000-infographic.pdf.

[35] T. I. of E. and Technology, "Rolls-Royce PLC: More Electric Engines for More Electric Aircraft," *IET Essential Engineering Intelligence for Transport*, p. 2, 2013.

[36] B. Gudellis, “EATON Aerospace review 2013: Powering businesses worldwide for more than 100 years.” *EATON*, 2013.

[37] V. Mascre, “AIRCRAFT EQUIPMENT LANDING AND BRAKING,” *Safran*. Safran, pp. 1–21, 2016.

[38] Q. Zhang, M. Sztykiel, P. Norman, and G. Burt, “Towards Two and Three-Channel Electrical Architecture Design for More-Electric Engines,” in *SAE International*, 2018.

[39] U.S. Department of Transportation, “FAA Advisory Circular 25. 1309-1A System Design and Analysis,” *Area*, vol. 9, no. c, 1988, doi: AFS-800 AC 91-97.

[40] I. Moir and A. Seabridge, “Aircraft System Examples,” in *Design and Development of Aircraft Systems*, 2nd ed., John Wiley & Sons, 2012, 2012, p. 232.

[41] J. D. Schuddebeurs, C. D. Booth, G. M. Burt, and J. R. McDonald, “Impact of marine power system architectures on IFEP vessel availability and survivability,” *IEEE Electr. Sh. Technol. Symp. ESTS 2007*, pp. 14–21, 2007, doi: 10.1109/ESTS.2007.372058.

[42] A. J. Mitcham and N. Grum, “An Integrated LP Shaft Generator for the more Electric Aircraft,” *IEE Coloquium All Electr. Aircr.*, pp. 8/1--8/9, 1998, doi: 10.1049/ic:19980346.

[43] M. French, “Gas Turbine Engine Power System,” US 9601970 B2, 2015.

[44] H. L. Edwards and R. W. Slater, “Electrical Generation Arrangement for an Aircraft,” US 9938850 B2, 2018.

[45] M. S. P. Devisree and P. U. K. Reddy, “An Induction Generator-Based AC / DC Hybrid Electric Power Generation System for Electric Aircraft,” vol. IX, no. 2236, pp. 98–109, 2020.

[46] K. Muehlbauer and D. Gerling, “Two-Generator-Concepts for Electric Power Generation in More Electric Aircraft Engine,” *Int. Conf. Electr. Mach.*, pp. 1–5, 2010, doi: 10.1109/ICELMACH.2010.5607966.

[47] M. Noriko, K. Daiki, O. Kanji, S. Naoki, and O. Hitoshi, “Practical Development of Control Technology for the More Electric Engine,” *IHI Eng. Rev.*, vol. 45, no. 1, pp. 21–30, 2012.

[48] J. M. Kern and H. L. N. Wiegman, “INTEGRATED ELECTRICAL POWER EXTRACTION FOR AIRCRAFT ENGINES,” US 7468561 B2, 2008.

[49] T. Kostakis, P. J. Norman, and S. J. Galloway, “Assessing network architectures for the more electric engine and aircraft,” *Proc. Univ. Power Eng. Conf.*, 2014, doi: 10.1109/UPEC.2014.6934680.

[50] M. A. Kassem and A. A. Elahwil, “POWER LOAD MANAGEMENT Techniques and Methods in Electric Power System,” *Int. Res. J. Eng. Technol.*, pp. 2459–2466, 2015.

[51] A. Mahmood, N. Javaid, M. A. Khan, and S. Razzaq, “An overview of load management techniques in smart grid,” *Int. J. Energy Res.*, vol. 39, no. 11, pp. 1437–1450, 2015, doi: 10.1002/er.3350.

[52] X. Giraud, H. Piquet, M. Budinger, X. Roboam, M. Sartor, and S. Vial, “Knowledge-based system for aircraft electrical power system reconfiguration,” *Electr. Syst. Aircraft, Railw. Sh. Propulsion, ESARS*, vol. 2048, 2012, doi: 10.1109/ESARS.2012.6387377.

[53] K. R. Padamati, N. N. Schulz, and A. K. Srivastava, “Application of genetic algorithm for reconfiguration of shipboard power system,” *2007 39th North Am. Power Symp. NAPS*, vol. 92, no. 4, pp. 159–163, 2007, doi: 10.1109/NAPS.2007.4402304.

[54] D. Schlabe and J. Lienig, “Energy management of aircraft electrical systems - State of the art and further directions,” *Electr. Syst. Aircraft, Railw. Sh. Propulsion, ESARS*, no. August 2016, 2012, doi: 10.1109/ESARS.2012.6387387.

[55] O. Meier and D. Scholz, “A Handbook Method for the Estimation of Power Requirements for Electrical De-Icing Systems,” *Dlrk*, vol. 0, 2010.

[56] European Union Aviation Safety Agency, “TYPE-CERTIFICATE DATA SHEET of GE90 series Engines,” 2019.

[57] C. Spagnolo, S. Sumsurooah, C. I. Hill, and S. Bozhko, “Generator overload reduction using smart power management,” 2018, pp. 1–7, doi: 10.1109/ESARS-ITEC.2018.8607289.

[58] M. Maasoumy, P. Nuzzo, F. Iandola, M. Kamgarpour, A. Sangiovanni-Vincentelli, and C. J. Tomlin, “Optimal load management system for Aircraft Electric Power distribution,” *IEEE Conf. Decis. Control*, pp. 2939–2945, 2013, doi: 10.1109/CDC.2013.6760330.

[59] A. A. Recalde, J. A. Atkin, and S. V. Bozhko, “Optimal Design and Synthesis of MEA Power System Architectures Considering Reliability Specification,” *IEEE Trans. Transp. Electrif.*, vol. 6, no. 4, pp. 1801–1818, 2020, doi: 10.1109/TTE.2020.3002875.

[60] M. Efatmaneshnik and C. Reidsema, “A complex system engineering design model,” *Cybern. Syst.*, vol. 41, no. 8, pp. 554–576, 2010, doi: 10.1080/01969722.2010.520212.

[61] B. Tang, S. Yang, L. Wang, and H. Zhang, “Power priority algorithm in application to aircraft distribution network reconfiguration,” *2016 Int. Conf. Electr. Syst. Aircraft, Railw. Sh. Propuls. Road Veh. Int. Transp. Electrif. Conf. ESARS-ITEC 2016*, pp. 5–9, 2016, doi: 10.1109/ESARS-ITEC.2016.7841329.

[62] G. D. Putnik, Z. Putnik, and A. Etienne, “Defining Sequential Engineering (SeqE), Simultaneous Engineering (SE), Concurrent Engineering (CE) and Collaborative Engineering (ColE): On similarities and differences,” *29th CIRP Design 2019*, ScienceDirect, vol. 84, pp. 68–75, 2019.

[63] T. Bobbe, J. Krzywinski, and C. Woelfel, “A comparison of design process models from academic theory and professional practice,” *Proc. Int. Des. Conf. Des.*, vol. DS 84, pp. 1205–1214, 2016.

[64] R. Ganesh, “Design Issues in Hardware / Software Co-Design,” no. 1, pp. 1–5, 2014.

[65] J. Takalo, J. Kääriäinen, P. Parviainen, and T. Ihme, *Challenges of software-hardware co-design. prestudy in twins project*. 2008.

[66] S. Micaela and W. B.Gardner, “Hardware/Software Codesign - introducing an

interdisciplinary course," *WCCCE Conference - Vancouver*, 1998. [Online]. Available: https://www.cs.ubc.ca/wccce/program98/micaela/micaela.html.

[67] A. Jerraya and W. Wolf, "Hardware/software interface codesign for embedded systems," *Computer (Long. Beach. Calif).*, vol. 38, no. 2, pp. 63–69, 2005, doi: 10.1109/MC.2005.61.

[68] M. Platzner and L. Thiele, "Hardware / Software Codesign Vorwort," vol. 4, no. 1, 2007, doi: 10.21427/D7NB29.

[69] P. Nuzzo, J. Finn, M. Mozumdar, and A. Sangiovanni-Vincentelli, "Platform-Based Design Methodology and Modeling for Aircraft Electric Power Systems," pp. 1–7, 2013.

[70] H. Ryu, J.-C. Yoon, S. S. Chun, and S. Sull, "Coarse-to-Fine Classification for Image-Based Face Detection," in *Image and Video Retrieval*, 2006, pp. 291–299.

[71] A. Franco and L. Oliveira, "A coarse-to-fine deep learning for person re-identification," in *2016 IEEE Winter Conference on Applications of Computer Vision (WACV)*, 2016, pp. 1–7, doi: 10.1109/WACV.2016.7477677.

[72] S. Vajna, "Approaches of Knowledge-Based Design," pp. 375–382, 2008, doi: 10.1115/detc2003/dac-48741.

[73] R. K. Gupta, "Co-Synthesis of Hardware and Software for Digital Embedded Systems," *Co-Synthesis Hardw. Softw. Digit. Embed. Syst.*, 1995, doi: 10.1007/978-1-4615-2287-4.

[74] A. Shaout, A. H. El-mousa, and K. Mattar, "Specification and Modeling of HW/SW CO-Design for Heterogeneous Embedded Systems," *Lect. Notes Eng. Comput. Sci.*, vol. 2176, no. 1, pp. 273–278, 2009.

[75] A. Recalde, S. Bozhko, J. Atkin, and C. Hill, "A reliability approach for the MEA power system architecture design optimization problem," *2018 IEEE Int. Conf. Electr. Syst. Aircraft, Railw. Sh. Propuls. Road Veh. Int. Transp. Electrif. Conf. ESARS-ITEC 2018*, 2018, doi: 10.1109/ESARS-ITEC.2018.8607583.

[76] Federal Aviation Authority, "Aircraft Electrical System," *Aviat. Maint. Tech.*

Handb. - Airframe, pp. 1–106, 2014, doi: 10.4271/700303.

[77] Z. Zhang, J. Li, Y. Liu, Y. Xu, and Y. Yan, “Overview and development of variable frequency AC generators for more electric aircraft generation system,” *Chinese J. Electr. Eng.*, vol. 3, no. 2, pp. 32–40, 2017.

[78] P. Wheeler, “The more electric aircraft: Why aerospace needs power electronics?,” *Proc. 13th Conf. Power Electron. …*, vol. 44, no. 0, 2009.

[79] T. Sawata *et al.*, “Initial Test Results for the Fan Shaft Driven Generator,” *Power*, pp. 1–8.

[80] “Battery energy storage sytsem integration to the MEA 270V DC power distribution bus using peak current controlled dual active bridge converter,” pp. 2068–2073, 2017.

[81] R. Telford, C. Jones, P. Norman, and G. Burt, “Analysis Tool for Initial High Level Assessment of Candidate MEA Architectures,” pp. 1–10, 2016, doi: 10.4271/2016-01-2015.

[82] J. Brombach, T. Schröter, A. Lücken, and D. Schulz, “Optimized cabin power supply with a ± 270 Vdc grid on a modern aircraft,” *2011 7th Int. Conf. Compat. Power Electron. CPE 2011 - Conf. Proc.*, pp. 425–428, 2011, doi: 10.1109/CPE.2011.5942274.

[83] M. B. Stevens and S. Santoso, “Improving the reliability of breaker-and-a-half substations using sectionalized busbars,” *IEEE Power Energy Soc. Gen. Meet.*, 2013, doi: 10.1109/PESMG.2013.6672558.

[84] X. Roboam, B. Sareni, and A. De Andrade, “More Electricity in the Air,” *Ind. Electron. Mag. IEEE*, vol. 6, no. 4, pp. 6–17, 2012, doi: 10.1109/MIE.2012.2221355.

[85] ESRDC, *Improving the Reliability of Mvdc Ship Power Systems*, no. September. 2013.

[86] D. Nack, “Reliability of substation configurations,” *Iowa State Univ.*, pp. 1–19, 2005.

[87] R.Canope,“Education creation and support network- Assembly and

maintenance engineering of GP 7200 Engine of Airbus 380 (FR version),” *Brevet de technicien supérieur* ,2014.

[88] C. Johansson, *On system safety and reliability methods in early design phases*. 2013.

[89] Department of Defense of the USA, “Reliability Prediction of Electronic Equipment,” *Mil. Handb. MIL-HDBK-217F*, p. 205, 1991.

[90] M. For, C. The, S. Assessment, P. On, C. Airborne, and T. O. F. Contents, “Aerospace Recommended,” *Society*, pp. 1–331, 2012.

[91] Bryant *et al.*, “Fault Tree Handbook with Aerospace Applications,” *Uma ética para quantos?*, vol. XXXIII, no. 8, p. 218, 2002, doi: 10.1109/TC.1986.1676819.

[92] D. S. Part and I. D. Features, “Chapter 29 Fault / Success Tree Analysis Contents,” no. 1, pp. 1–18.

[93] B. Dhillon, “Fault Tree Analysis,” pp. 214–219, 1999, doi: 10.1201/9781420050141.ch7.

[94] EASA, “Certification Specifications for Large Aeroplanes,” *Cs-25*, no. September, p. 750, 2008, doi: 10.1002/9780470664797.

[95] A. Mitcham and J. Cullen, “Permanent magnet generator options for the More Electric Aircraft,” *Int. Conf. Power Electron. Mach. Drives*, no. 487, pp. 241–245, 2002.

[96] Crane Aerospace & Electronics, “Auto-Transformer Rectifier Units (ATRU),” *Crane Aerospace & Electronics*, p. 15, 2015.

[97] EASA, “Third Publication of Means of Compliance with the Special Condition VTOL,” pp. 1–12, 2023.

[98] (EASA) European Aviation Safety Agency, “Extended Range Operation with Two-Engine Aeroplanes ETOPS Certification and Operation Annex II - AMC 20-6 rev. 2,” 2010.

[99] EASA, “Certification Specifications for Large Aeroplanes,” *Cs-25*, no. September, p. 750, 2008.

[100] C. Schallert, "Integrated Safety and Reliability Analysis Methods for Aircraft System Development using Multi-Domain Object-Oriented Models," 2016.

[101] M. C. Flynn, C. E. Jones, P. J. Norman, and S. J. Galloway, "Fault management strategies and architecture design for turboelectric distributed propulsion," *2016 Int. Conf. Electr. Syst. Aircraft, Railw. Sh. Propuls. Road Veh. Int. Transp. Electrif. Conf. ESARS-ITEC 2016*, pp. 1–6, 2017, doi: 10.1109/ESARS-ITEC.2016.7841364.

[102] R. Abdel-Fadil, A. Eid, and M. Abdel-Salam, "Electrical Distribution Power Systems of Modern Civil Aircrafts," in *2nd International Conference on Energy Systems and Technologies*, 2013, no. February 2013, pp. 201–210.

[103] J. G. Webster, S. Bozhko, C. I. Hill, and T. Yang, "More-Electric Aircraft: Systems and Modeling," in *Wiley Encyclopedia of Electrical and Electronics Engineering*, no. July, 2018, pp. 1–31.

[104] R. Prenc, A. Cuculic, and I. Baumgartner, "Advantages of using a DC power system on board ship," *J. Marit. Transp. Sci.*, vol. 52, pp. 83–97, 2016.

[105] Y. Wang, S. Nuzzo, H. Zhang, W. Zhao, C. Gerada, and M. Galea, "Challenges and Opportunities for Wound Field Synchronous Generators in Future More Electric Aircraft," *IEEE Trans. Transp. Electrif.*, vol. 6, no. 4, pp. 1466–1477, 2020, doi: 10.1109/TTE.2020.2980189.

[106] W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett, and D. J. Atkinson, "Overview of electric motor technologies used for more electric aircraft (MEA)," *IEEE Trans. Ind. Electron.*, vol. 59, no. 9, pp. 3523–3531, 2012, doi: 10.1109/TIE.2011.2165453.

[107] N. Ali, Q. Gao, C. Xu, P. Makys, and M. Stulrajter, "Fault diagnosis and tolerant control for power converter in SRM drives," *J. Eng.*, vol. 2018, no. 13, pp. 546–551, 2018, doi: 10.1049/joe.2018.0012.

[108] J. R. Coles, M. Holme, and J. P. Doyle, "Electrical generator an aero-engine including such a generator, and an aircraft including such a generator," US 6467725 B1, 2002.

[109] M. Lafoz, P. Moreno-Torres, J. Torres, M. Blanco, and G. Navarro, "Design

methodology of a high speed switched reluctance generator drive for aircrafts," *2016 18th Eur. Conf. Power Electron. Appl. EPE 2016 ECCE Eur.*, pp. 1–9, 2016, doi: 10.1109/EPE.2016.7695549.

[110] Z. Zhang, J. Huang, Y. Jiang, W. Geng, and Y. Xu, "Overview and analysis of PM starter/generator for aircraft electrical power systems," *CES Trans. Electr. Mach. Syst.*, vol. 1, no. 2, pp. 117–131, 2020, doi: 10.23919/tems.2017.7961293.

[111] D. Arumugam, P. Logamani, S. Karuppiah, and B. Thangaraj, "Performance Evaluation of PMSG for Aircraft Applications," *Energy Procedia*, vol. 117, pp. 385–392, 2017, doi: 10.1016/j.egypro.2017.05.152.

[112] Z. Zhang, J. Huang, and Y. Jiang, "Overview and Analysis of PM Starter/Generator for Aircraft Electrical Power System.pdf," *CES Trans. Electr. Mach. Syst.*, vol. 1, p. 117, 2017.

[113] K. Ni *et al.*, "Electrical and Electronic Technologies in More-Electric Aircraft: A Review," *IEEE Access*, vol. 7, no. June, pp. 76145–76166, 2019, doi: 10.1109/ACCESS.2019.2921622.

[114] arnold charles Newton, arthur L. Rowe, and P. M. Hield, "Shaft Power transfer in gas turbine engines," EP0659234, 1997.

[115] Y. Xu, Z. Zhang, J. Li, and Y. Yan, "Architecture Analysis and Optimization of High Voltage DC Parallel Electric Power System for More Electric Aircraft *," *2016 IEEE Int. Conf. Aircr. Util. Syst.*, pp. 244–249, 2016, doi: 10.1109/AUS.2016.7748054.

[116] G. Buticchi, M. Liserre, and K. Al-Haddad, "On-Board Microgrids for the More Electric Aircraft," *IEEE Trans. Ind. Electron.*, vol. 66, no. 7, pp. 5585–5587, 2019, doi: 10.1109/TIE.2019.2897470.

[117] J. L. F. Vieira, J. A. Oliver, P. Alou, and J. A. Cobos, "Power converter topologies for a high performance transformer rectifier unit in aircraft applications," *2014 11th IEEE/IAS Int. Conf. Ind. Appl. IEEE INDUSCON 2014 - Electron. Proc.*, no. December, 2014, doi: 10.1109/INDUSCON.2014.7059403.

[118] S.-Y. Yu, X. Gong, G. Wang, and M. Bhardwaj, "Designing a High-Power

Bidirectional AC / DC Power Supply Using SiC FETs," *Power Supply Des. Semin.*, 2020.

[119] N. A. Losic, "Passive vs. active AC-DC power conversion in variable frequency aerospace applications," *5th IEEE Vehicle Power and Propulsion Conference, VPPC '09*. pp. 1139–1144, 2009, doi: 10.1109/VPPC.2009.5289723.

[120] B. Sarlioglu, "Comparison of power quality solutions using active and passive rectification for more electric aircraft," *ICAS-Secretariat - 25th Congr. Int. Counc. Aeronaut. Sci. 2006*, vol. 6, pp. 3679–3687, 2006.

[121] Y. Zhu, H. Wen, Q. Bu, G. Chu, and H. Shi, "Reliability Assessment for Dual-Active-Bridge Converter with Fault Tolerant Capability," *2022 IEEE IAS Glob. Conf. Emerg. Technol. GlobConET 2022*, pp. 381–386, 2022, doi: 10.1109/GlobConET53749.2022.9872346.

[122] G. Zu *et al.*, "Review of Pulse Test Setup for the Switching Characterization of GaN Power Devices," *IEEE Trans. Electron Devices*, vol. 69, no. 6, pp. 3003–3013, 2022, doi: 10.1109/TED.2022.3168238.

[123] European Aviation Safety Agency, "EASA CS-23: Certification Specifications for Normal-Category Aeroplanes, Amendment 5," no. March, p. 33, 2017.

[124] Y. Y. Zuo, "Gas turbine engines lubrication system design," *Adv. Mater. Res.*, vol. 900, pp. 773–776, 2014, doi: 10.4028/www.scientific.net/AMR.900.773.

[125] "Auxiliary Power Unit (APU)," *SKYbrary*. [Online]. Available: https://skybrary.aero/articles/auxiliary-power-unit-apu. [Accessed: 24-Feb-2022].

[126] "Power Sharing: Non-Propulsive Energy project investigates future aircraft architectures for electric flight," *Clean Sky's Non-Propulsive Energy*, 2021. [Online]. Available: https://www.clean-aviation.eu/media/results-stories/power-sharing-non-propulsive-energy-project-investigates-future-aircraft-architectures-for-electric. [Accessed: 23-Mar-2022].

[127] T. A. .Langston, A. T. Johnson, and T. J.Ahrendt, "Gearless Electric Thrust Reverser Actuators and Actuation System incorporating Same," US 6684623 B2, 2004.

[128] E. F. Hitt and D. Mulcare, “Fault-tolerant avionics,” in *Avionics: Development and Implementation*, 2006, pp. 8-1-8–24.

[129] A. R. Munoz, “Dual stator winding induction machine drive,” *IEEE Trans. Ind. Appl.*, vol. 36, no. 5, pp. 1369–1379, 2000, doi: 10.1109/28.871286.

[130] L. Thomas A and A. R. Munoz_garcia, “Dual Stator Winding Indurction Machine Drive,” US 6242884B1, 2001.

[131] N. Adamsson, “Interdisciplinary integration in complex product development : managerial implications of embedding software in manufactured ...,” 2007.

[132] S. M. Kwon, P. S. Wardrip, and L. M. Gomez, “Co-design of interdisciplinary projects as a mechanism for school capacity growth,” *Improv. Sch.*, vol. 17, no. 1, pp. 54–71, 2014, doi: 10.1177/1365480213519517.

[133] B. Ju, “Hardware / Software Codesign : The Past , the Present , and Predicting the Future,” *Proc. IEEE*, vol. 100, pp. 1411–1430, 2012, doi: 10.1109/JPROC.2011.2182009.

[134] K. Kostková, Ľ. Omelina, P. Kyčina, and P. Jamrich, “An introduction to load management,” *Electr. Power Syst. Res.*, vol. 95, pp. 184–191, 2013, doi: 10.1016/j.epsr.2012.09.006.

[135] M. Flynn, C. Jones, P. J. Norman, and G. M. Burt, “A Fault Management Oriented Early-Design Framework for Electrical Propulsion Aircraft,” *IEEE Trans. Transp. Electrif.*, vol. PP, no. c, p. 1, 2019, doi: 10.1109/TTE.2019.2913274.

[136] S. D. A. Fletcher, P. J. Norman, K. Fong, S. J. Galloway, and G. M. Burt, “High-speed differential protection for smart DC distribution systems,” *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2610–2617, 2014, doi: 10.1109/TSG.2014.2306064.

[137] T. Virtue and J. Rainey, “Chapter 6 - Information Risk Assessment,” in *HCISPP Study Guide*, T. Virtue and J. Rainey, Eds. Boston: Syngress, 2015, pp. 162–166.

[138] M. A. Karbaschian and D. Söffker, “Review and comparison of power

management approaches for hybrid vehicles with focus on hydraulic drives," *Energies*, vol. 7, no. 6, pp. 3512–3536, 2014, doi: 10.3390/en7063512.

[139] W. Li, Y. Yang, and X. Zhang, "Digital generator control unit design for a variable frequency synchronous generator in MEA," *Energies*, vol. 11, no. 1, 2018, doi: 10.3390/en11010096.

[140] I. Staack, *Aircraft Systems Conceptual Design - An object-oriented approach from element to aircraft*, no. 1805. 2016.

[141] M.-C. Flynn, "Electrical fault management orientated design of future electrical propulsion aircraft — University of Strathclyde," *PhD Thesis*, no. September, 2020.

Appendices

A. The Flight Profile of MEE/MEA Assumption

This flight demand profile table (Figure 49) shows the electrical consumption estimation of a twin-More Electric Engine MEA. The total power demand per engine auxiliaries is 197.5kW, and the maximum demand of 187 kW is required at the landing phase. The percentages of airframe loads are approximately assumed by a total electrical power of 1MW for a wide-body MEA. This table is used for the case studies of Chapter 6. The result of the case studies conducted with this data may be less accuracy as varied public resources are utilised. Nevertheless, this table still offering a comprehensive data of the varied system power requirements of a twin-MEE EMA, which provides a systematic overview and the conceptual knowledge for further MEA/ MEE investigation.

widebody Aircraft (787)		Flight phases									
Per engine (KW)	**Assumed power rating**	**Idle**	**Taxing**	**Take off**	**Climb**	**Cruise**	**Desent**	**Approach**	**Landing**	**Essential loa**	**Cotinuously need**
Electric Oil pumps	12	0	12	12	12	12	12	12	12	Y	Y
Electric Fuel pumps	50	0	50	50	50	50	50	50	50	Y	Y
ETRAs	45	0	0	0	0	0	0	0	45	Y	N
Electric PGB oil system	10	0	10	10	10	10	10	10	10	Y	Y
Area nozzle actuation	20	0	20	20	0	0	0	20	20	N	N
Inlet guide vanes actuation	10	0	10	10	0	0	0	10	10	N	N
Stator vane actuation	10	0	10	10	0	0	0	10	10	N	N
Pitch fan blade actuation	30	0	30	30	0	0	0	30	30	N	N
De-icing system	10	0	0	0	10	10	10	10	0	N	N
Total (kW)	197.5	0	142	142	82	82	82	152	187		
Two engine demand (kW)	395	0	285	285	165	165	165	305	375		
Airframe loads (KW)	**Assumed power rating**	**Idle**	**Taxing**	**Take off**	**Climb**	**Cruise**	**Desent**	**Approach**	**Landing**	**Essential loa**	**Cotinuously need**
Cabin Air Compressors conditioning	19% od 1MW	0	190	190	190	190	190	190	190	N	Y
Cabin systems, Environmental pressurisation control system	11% of 1MW	0	110	110	110	110	110	110	110	Y	Y
External lighting	5% of 1MW	0	50	50	50	50	50	50	50	Y	Y
Cabin lighting, Entertainment, toilet and Galley	33% of 1MW	0	200	200	330	330	330	0	0	N	Y
Water and waster	3%of 1MW	0	30	0	30	30	30	0	0	N	N
Avionic system (navigation, flight control, information system)	3%of 1MW	0	30	30	30	30	30	30	30	Y	Y
Instruments	0.5% of 1MW	5	5	5	5	5	5	5	5	Y	Y
Communication	0.5% of 1MW	5	5	5	5	5	5	5	5	Y	Y
Misc DC loads (small actuators)	5% of 1MW	0	0	50	0	0	0	50	50	Y	N
Ice protection/ de-icing	8% of 1MW	0	0	0	50	50	50	50	50	Y	N
Landing gear (EMA)	60kW	0	0	60	0	0	0	0	60	Y	N
Total airframe demand (kW)	890										
the loads supply by one MEE(total airframe demand) /2		10	620	700	800	800	800	490	550		
Total demad of A widebody MEA with twin MEE (kW)	1285										
A widebody MEA with twin MEE power rating assumption (kW)	total power supply need	10	905	985	965	965	965	795	925		
	total shedable power	0	443	413	453	453	453	233	258		
	total essential power	10	462	572	512	512	512	562	667		

Figure 49. The power consumption estimation profile of a twin-MEE MEA

B. Case Study of Parameter Classification Optimisation

When verifying the effectiveness of parameter classification optimisation; the author uses various power architectures and PLMs that with different characteristics for comparison and ranking. Figure 50 shows the complete rank of the power architecture used in Chapter 5. For this investigation, only two parameters are selected for the power architecture, namely system reliability and system weight. This does not mean that the MEE architecture has only two parameters/standards, and more parameters can be added to form a more refined level. However, the selected reliability and weight are the most important parameters of the aircraft power system, which represent the safety and efficiency of flight operations.

All the cases (concepts) of architecture that shown in Figure 50 were mainly divided into three aspects: 1) generator and power channel number, 2) type of converter and 3) whether ESS used in load bus as pack up source. Since the power availability can be impacted by the generator number, channel number or limited power source, this aspect can be large influencing the score of operational flexibility. Therefore, those concepts were chose based on the different number of source/channels that coordinated with bidirectional/uni-directional converter and/or ESS backup supply for loads. With the engineering judgements, different level of score were given for each of architecture.

The table shows that the system reliability is an absolute design requirement which need to be 'High', and highlighted as Red. The weight of system design requirement is less restricted, a medium weight or a low weight can be accepted. According to that, the scores of each architecture will compared with the requirement scores. Only when the architecture scores are fully matched with both absolute and less restricted requirement scores can be listed a 1st in the rank. Only when the absolute requirement score is matched with the concept score will be listed as 2nd rank. 3rd rank will be listed if the architectures score is less matched the absolute requirements but the fully matched with the less restricted requirements. and 4th rank of the table represented that the concept score is far not matched with the absolute requirement.

	Architecutre features	Parameter	Score	Required design level	Ranking
Case 1	2 generator 2channel	system reliability	Medium	High	3rd
	bi-directional converter	weight	Low	Medium/Low	
	ESS on load bus				
Case 2	3 generator 3 channel	system reliability	High	High	1st
	bi-directional converter	weight	Medium	Medium/Low	
	ESS on load bus				
Case 3	4 generator 4 channel	system reliability	High	High	2nd
	bi-directional converter	weight	High	Medium/Low	
	ESS on load bus				
Case 4	1 ESS, 1 generator, 2 channel	system reliability	Low	High	4th
	bi-directional converter	weight	Low	Medium/Low	
	ESS on load bus				
Case 5	1 ESS, 2 generators, 3 channel	system reliability	Medium	High	3rd
	bi-directional converter	weight	Medium	Medium/Low	
	ESS on load bus				
Case 6	1 ESS, 3 generators, 4channel	system reliability	High	High	2nd
	bi-directional converter	weight	High	Medium/Low	
	ESS on load bus				
Case 7	2 generator 2channel	system reliability	Medium	High	3rd
	bi-directional converter	weight	Low	Medium/Low	
	No ESS on load bus				
Case 8	3 generator 3 channel	system reliability	High	High	1st
	bi-directional converter	weight	Medium	Medium/Low	
	No ESS on load bus				
Case 9	4 generator 4 channel	system reliability	High	High	2nd
	bi-directional converter	weight	High	Medium/Low	
	No ESS on load bus				
Case10	1 ESS, 1 generator, 2 channel	system reliability	Low	High	4th
	bi-directional converter	weight	Low	Medium/Low	
	No ESS on load bus				
Case 11	1 ESS, 2 generators, 3 channel	system reliability	Medium	High	3rd
	bi-directional converter	weight	Medium	Medium/Low	
	No ESS on load bus				
Case 12	1 ESS, 3 generators, 4channel	system reliability	High	High	2nd
	bi-directional converter	weight	High	Medium/Low	
	No ESS on load bus				
Case 13	2 generator 2channel	system reliability	Medium	High	3rd
	uni-directional converter	weight	Low	Medium/Low	
	ESS on load bus				
Case 14	3 generator 3 channel	system reliability	High	High	1st
	uni-directional converter	weight	Medium	Medium/Low	
	ESS on load bus				
Case 15	4 generator 4 channel	system reliability	High	High	2nd
	uni-directional converter	weight	High	Medium/Low	
	ESS on load bus				
Case16	1 ESS, 1 generator, 2 channel	system reliability	Low	High	4th
	uni-directional converter	weight	Low	Medium/Low	
	ESS on load bus				
Case 17	1 ESS, 2 generators, 3 channel	system reliability	Medium	High	3rd
	uni-directional converter	weight	Medium	Medium/Low	
	ESS on load bus				
Case 18	1 ESS, 3 generators, 4channel	system reliability	High	High	2nd
	uni-directional converter	weight	High	Medium/Low	
	ESS on load bus				

Figure 50. Rank example of power architecture

	PLM Feature charatertisics			Parameters	Score	Required level	ranking
PLM option 1	order of action	1st	shedding	power control simplicity	High	Medium/Low	5th
				level power supply priority	Low	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 2	order of action	1st	ESS supply	power control simplicity	Medium	Medium/Low	1st
		2nd	shedding non-essential load	level of power supply priority	Medium	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 3	order of action	1st	ESS supply	power control simplicity	Low	Medium/Low	2nd
		2nd	shedding non-essential load	level of power supply priority	High	High/Medium/Low	
		3rd	generator overloading				
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 4	order of action	1st	shedding	power control simplicity	High	Medium/Low	6th
				level power supply priority	Low	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		detective	power fLow monitoring apporach	Medium	High/Medium	
PLM option 5	order of action	1st	ESS supply	power control simplicity	Medium	Medium/Low	4th
		2nd	shedding non-essential load	level of power supply priority	Medium	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+load control	secondary equipments	Medium	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 6	order of action	1st	ESS supply	power control simplicity	Low	Medium/Low	8th
		2nd	shedding non-essential load	level of power supply priority	High	High/Medium/Low	
		3rd	generator overloading				
	degree of freedom in control		generator control+contactor control+ARTU control+load control	secondary equipments	High	High/Medium	
	control speed		20-250ms	fault protection response time	Medium	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 7	order of action	1st	shedding	power control simplicity	High	Medium/Low	7th
				level power supply priority	Low	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+loads control	secondary equipments	Medium	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		corrective	power fLow monitoring apporach	Low	High/Medium	
PLM option 8	order of action	1st	ESS supply	power control simplicity	Medium	Medium/Low	3rd
		2nd	shedding non-essential load	level of power supply priority	Medium	High/Medium/Low	
	degree of freedom in control		generator control+contactor control+loads control	secondary equipments	Medium	High/Medium	
	control speed		5 ms- 20ms or beLow	fault protection response time	High	High	
	control Appoarch		detective	power fLow monitoring apporach	Medium	High/Medium	
PLM option 9	order of action	1st	ESS supply	power control simplicity	Low	Medium/Low	9th
		2nd	shedding non-essential load	level of power supply priority	High	High/Medium/Low	
		3rd	generator overloading				
	degree of freedom in control		generator control+contactor control+loads control	secondary equipments	Medium	High/Medium	
	control speed		20-250ms	fault protection response time	Medium	High	
	control Appoarch		preventive	power fLow monitoring apporach	High	High/Medium	
PLM option 10	order of action	1st	ESS supply	power control simplicity	High	Medium/Low	10th
				level of power supply priority	Low	High/Medium/Low	
	degree of freedom in control		contactor control	secondary equipments	Low	High/Medium	
	control speed		250ms	fault protection response time	Low	High	
	control Appoarch		corrective	power fLow monitoring apporach	Low	High/Medium	

Figure 51. Rank example of PLM strategy schemes

A similar process as the architecture ranking was conducted for the PLM schemes table to ranking the different PLM strategies that can used in MEE EPS, and shown in Figure 51. The PLM options that have been chose in this study is based on varied parameter measurements. In specifically, they are degree of control freedom, response time of PLM, control approach and the order of actions. The order of action is a priority list that contains the primary, secondary and tertiary actions for each PLM option to balance the power system. This can reflect the impacts on EPS when PLM scheme has using multiple layers of redundancy.

The integrated EPS was combined by an architecture case and a PLM scheme. There a few parameters were used for measuring the integrated performance, as shown as Figure 52. The EPS that combined by two 1st ranked subsystems shows its integrated parameters are perfectly matched with all requirements. The author also coordinated some top ranked architecture with medium ranked PLM scheme, and vice versa. The reason for chose these combinations was to understand whether a subsystem is enabling to cover the drawbacks of another subsystems. In addition, some low-ranking combinations were investigated to understand the infeasibility of matching the integrated design requirements.

EPS combination (dedicated ranking)	Parameters		SCORE	Stakeholder required score for Integrated performance	Design decision
Case2+PLM 2 (both 1st ranked)	System-level requirement constraint	system shedding as less as possible	High		**Feasible**
	Integrated performance	availability of power supply (types of power source)	High	High/Medium	
		single failure tolerance （ isolation of subsystem)	High	High	
		dispatch with one generator faulty	High/Medium	High/Medium	
		number of reconfiguration states	High	High	
Case 14+PLM 3 (1st and 3rd)	System-level requirement constraint	system shedding as less as possible	Medium		**Feasible**
	Integrated performance	availability of power supply (types of power source)	High	High/Medium	
		single failure tolerance （ isolation of subsystem)	High	High	
		dispatch with one generator faulty	High/Medium	High/Medium	
		number of reconfiguration states	High	High	
Case 1 +PLM 1 (3rd and 5th)	System-level requirement constraint	system shedding as less as possible	Low		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	Medium	High/Medium	
		single failure tolerance （ isolation of subsystem)	Medium	High	
		dispatch with one generator faulty	Medium	High/Medium	
		number of reconfiguration states	Medium	High	
Case3 +PLM8 (2nd and 3rd)	System-level requirement constraint	system shedding as less as possible	High		**Feasible**
	Integrated performance	availability of power supply (types of power source)	High	High/Medium	
		single failure tolerance （ isolation of subsystem)	High	High	
		dispatch with one generator faulty	High	High/Medium	
		number of reconfiguration states	High	High	
Case 4 +PLM 6 (4th and 8th)	System-level requirement constraint	system shedding as less as possible	Medium		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	Low	High/Medium	
		single failure tolerance （ isolation of subsystem)	Low	High	
		dispatch with one generator faulty	Low	High/Medium	
		number of reconfiguration states	Low	High	
Case11 +PLM1 (3rd and 5th)	System-level requirement constraint	system shedding as less as possible	Low		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	Medium	High/Medium	
		single failure tolerance （ isolation of subsystem)	High	High	
		dispatch with one generator faulty	High/Medium	High/Medium	
		number of reconfiguration states	Medium	High	
Case 6 + PLM 10 (2nd and 10th)	System-level requirement constraint	system shedding as less as possible	N/A No power shedding function		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	High	High/Medium	
		single failure tolerance （ isolation of subsystem)	Medium/Low	High	
		dispatch with one generator faulty	Medium	High/Medium	
		number of reconfiguration states	High	High	
Case 16 + PLM 2 (4th and 1st)	System-level requirement constraint	system shedding as less as possible	High		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	Low	High/Medium	
		single failure tolerance （ isolation of subsystem)	Medium	High	
		dispatch with one generator faulty	Low	High/Medium	
		number of reconfiguration states	Medium	High	
Case 2 + PLM 4 (1st and 6th)	System-level requirement constraint	system shedding as less as possible	Low		**Feasible**
	Integrated performance	availability of power supply (types of power source)	High	High/Medium	
		single failure tolerance （ isolation of subsystem)	High	High	
		dispatch with one generator faulty	High/Medium	High/Medium	
		number of reconfiguration states	High	High	
Case 13 + PLM 2 (3rd and 1st)	System-level requirement constraint	system shedding as less as possible	High		**Infeasible**
	Integrated performance	availability of power supply (types of power source)	Medium	High/Medium	
		single failure tolerance （ isolation of subsystem)	Medium	High	
		dispatch with one generator faulty	Medium/Low	High/Medium	
		number of reconfiguration states	Medium	High	

Figure 52. Feasibility of integrated EPS concepts

C. PLM Flow Diagram Examples

Power and load management refers to the response actions related to power sources and load demands when the power system needs to adjust available configurations to ensure power balance in the EPS. For example, when the fault zone is isolated, the main task of PLM is to maintain the health operation of rest the power architecture.

This section will focus on the operation schemes of PLM, because the availability of PLM is closely related to the formation of MEE EPS as same as the power architecture. Furthermore, some of the design requirements for the overall performance of EPS can be captured according to the characteristics of power supply capacity and load shedding approach in the PLM design scheme. The designer can select the most appropriate scheme according to the integrated performance requirements of MEE EPS.

Table XIX shows a few examples of PLM flow schemes for the MEE EPS. With the PLM usage priority order, the generator overload is assumed as the low priority strategy to be use. (not over 100% as much as possible).

Table XIX. Different schemes of PLM

PLM usage priority order	PLM scheme figures
1st Generators overload	Figure 53
1st ESS discharging 2nd Generators overload	Figure 54
1st Shedding strategy 2nd Generators overload	Figure 55
1st ESS discharging 2nd Shedding strategy	Figure 56
1st ESS discharging 2nd Shedding strategy 3rd Generators overload	Figure 57

Figure 53 is illustrated the scheme of a PLM strategy that only using generator overload function. If the power is exceeded than the demand, it may reduce the current by controlling the converter. Once the power architecture has a failure in one of the generators and cause power imbalance, there has no options of load shedding and power supply in this PLM scheme to balancing the power system. The only adjustable solution is the generator overload in this PLM scheme. However, it will depend on the quantity of healthy generators in the architecture. If the generator is overheated after allowed certain period, the generator may face a very serious damage. Accord to that, Figure 53. PLM with only Generator overload is a simpler power management strategy, but it is not an ideal solution for multiple-channel power system.

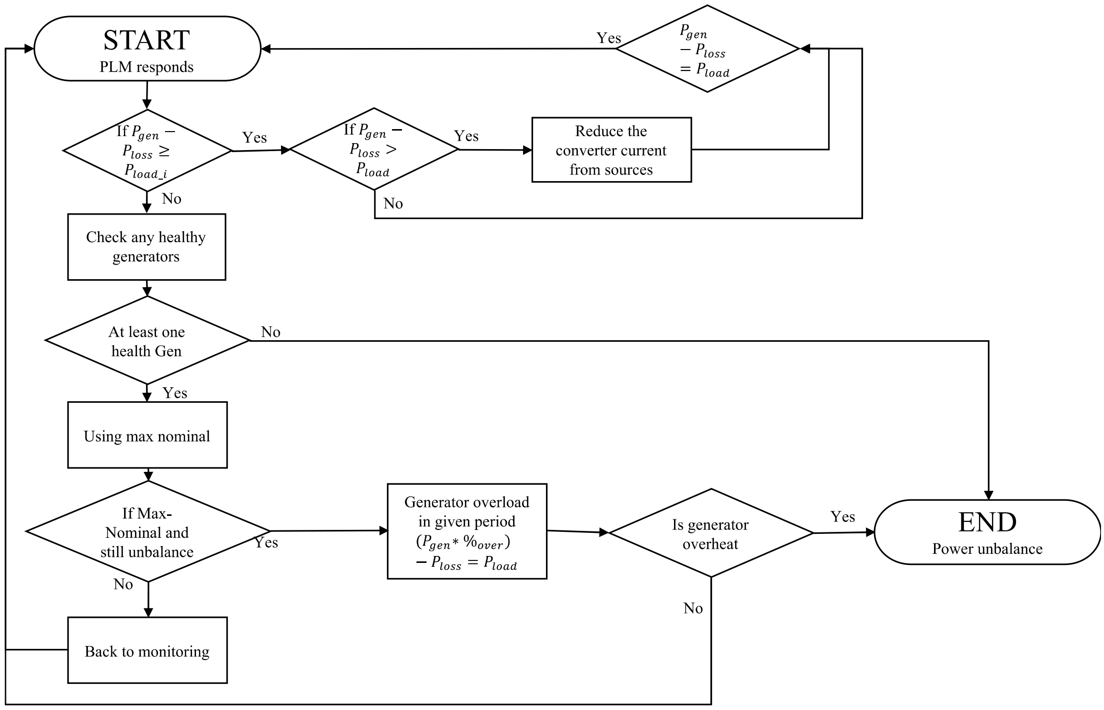


Figure 53. PLM with only Generator overload

Figure 54 shows the scheme of the PLM with load shedding and generator overload for MEE EPS. Once the architecture is power imbalance, this PLM scheme will firstly check the feasible generators and ensure they are all in maximum nominal ratings. If all generators are in maximum nominal rating and the power system still is unbalanced, it will temporarily shed non-essential loads and essential loads (depend on flight phases) in order to balance the system. If the power system still unbalanced, PLM will

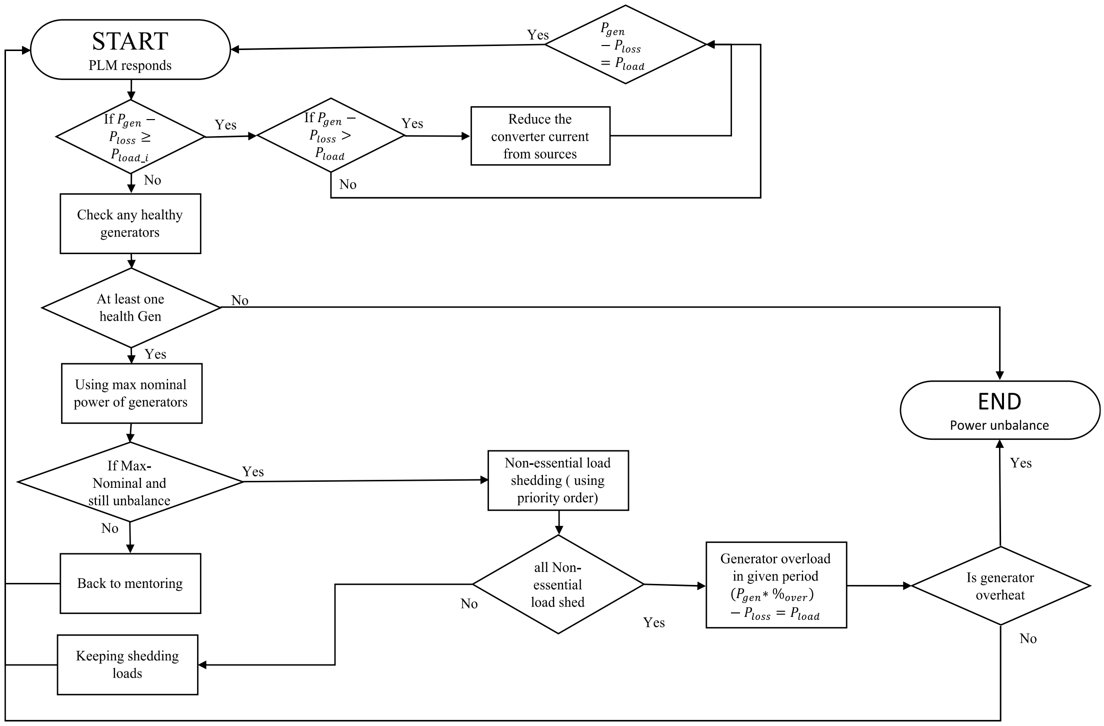


Figure 54. PLM scheme with shedding and generator overload

then use the generator overloading strategy. This PLM power balance produce is much better than the previous one.

Figure 55 shows the procedure of PLM that employed ESS and load shedding. Within this PLM strategy scheme, the EPS should have battery bus, ESS and contactors on the feeders of non-essential loads. Once the system detected as an imbalance system, the PLM will again firstly check the availability of generators, if all of generators are at maximum nominal rating, it will be using ESS to supply the shortage and then using shedding strategy to shed loads.

If there are no generator available, the ESS will supply the power in first place and then shedding load until the system is balanced. If aircraft is in cruise phase, load shedding will be in first place, then ESS supply. If the power is exceeded than demand, ESS can be charged while it is less than 90% (this is a general assumption of ESS top limit charge level and below that is enabling to charge whilst it is not in a full charged status) and once it is full, the generator driver/converter can be used limit the current pass through it.

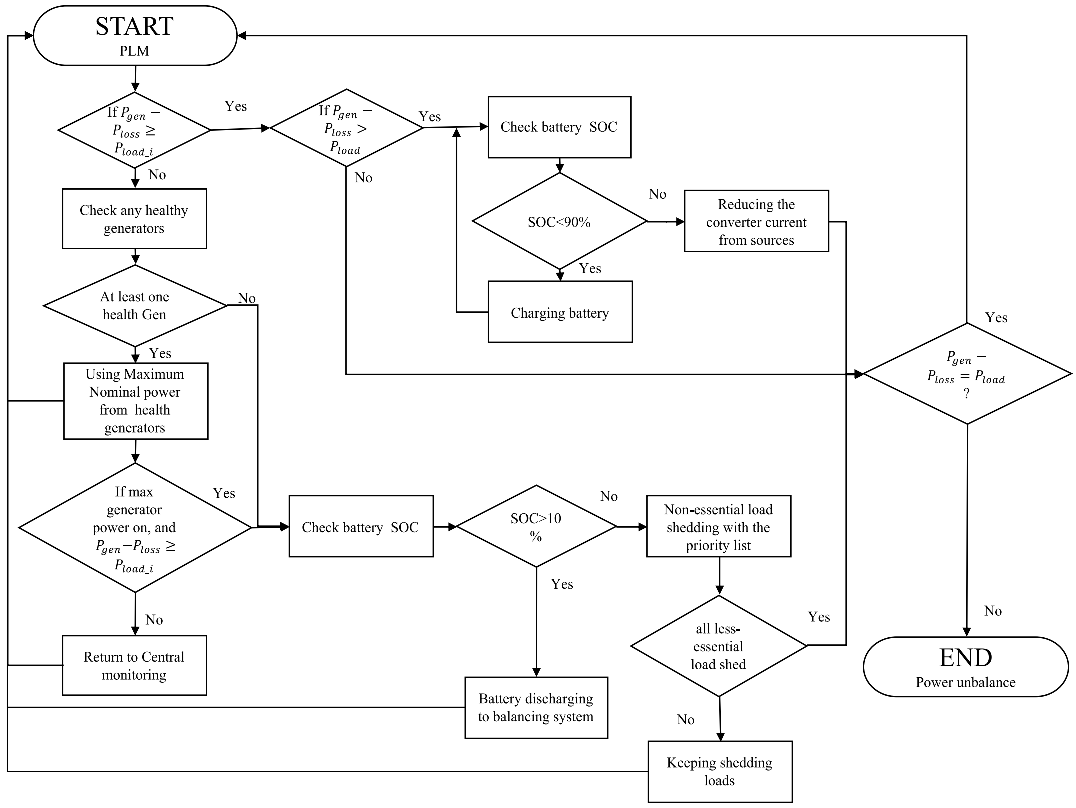


Figure 55. PLM scheme with ESS and load shedding

Figure 56 is illustrated a procedure of PLM scheme that using ESS as back up source and the generator overload. Once the architecture be detected as power imbalance, it will firstly check the feasible generators and ensure they are all in maximum nominal ratings. If so and the power system still is unbalance, it will safely connect the ESS to the load bus and supplying the power to cover the shortage, If the ESS power is fully discharged, the PLM will then be using the generator overloading strategy. The disadvantage is that large-scale ESS will increase the total mass of the EPS, so the sizing of ESS needs to be considered. As an advantage, the ESS allows to charge the power while the power generating is exceeded than the load demand.

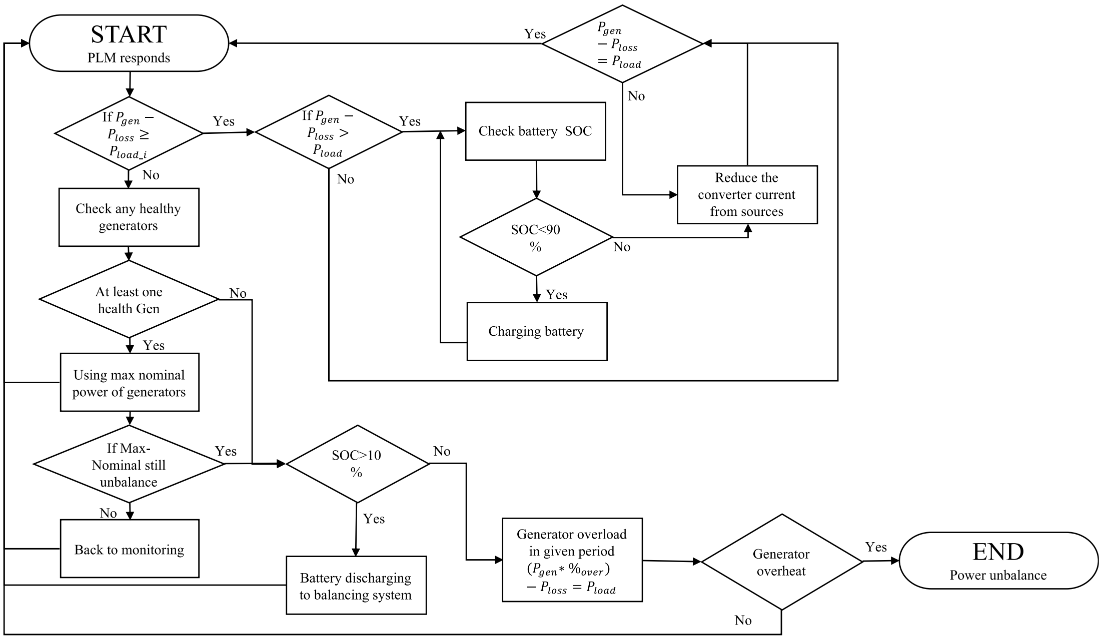


Figure 56. The PLM scheme with ESS and generator overload

Figure 57 shows the procedure of PLM that employed ESS, load shedding and generator overload. Once the system detected as an imbalance system, the PLM will again firstly check the availability of generators, if all available generators are in maximum nominal rating and system still is unbalance, it will be using ESS to supply

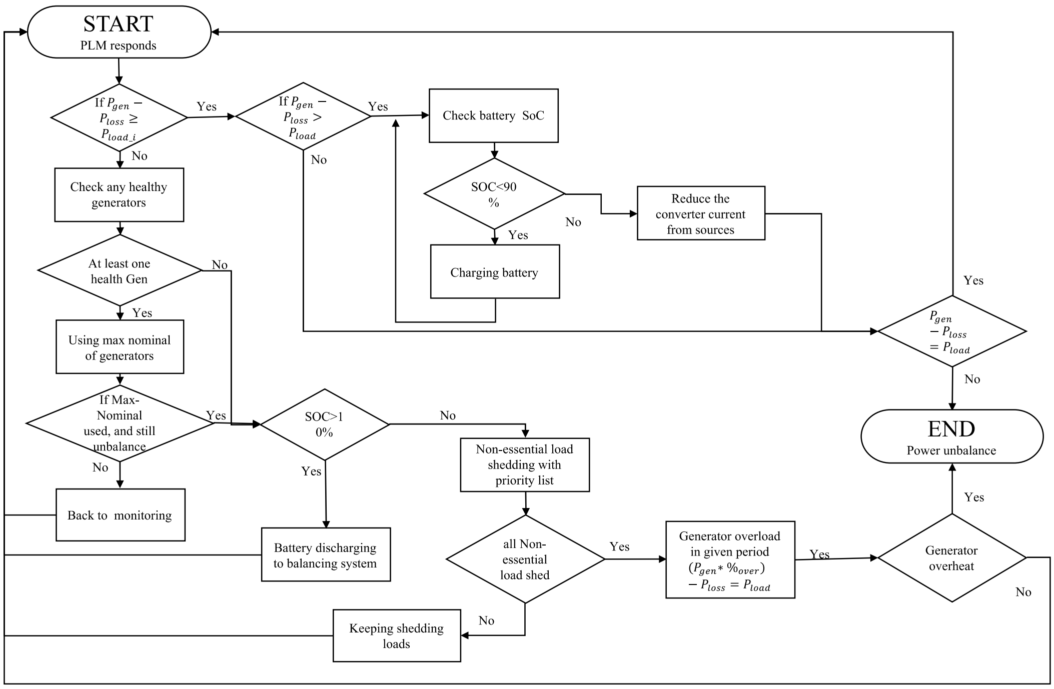


Figure 57.PLM scheme with ESS, shedding and generator overload

the shortage and then using shedding strategy to shed loads, then following by generator overload. If there are no generator available, the ESS will supply the power in first place and shedding load until the system is balanced, and the generator overload to be used if all actions have been tried. If the power generating is exceeded than demand, the ESS can charge the additional power until its capacity. This PLM scheme is tried to utilise the both benefits of using ESS and load shedding. Therefore, it will not be shedding all the non-essential loads in first place, neither fully using ESS to cover the power shortage.

These PLM scheme examples are inspired by the selected EPS characteristics, and they can be useful to support the detail design of EPS such as the size of ESS, location of contactors and contactor controlling.

D. Case Study of EPS Steady-State Power Reconfiguration Analysis

In order to conduct the power reconfiguration case study in Chapter 6, the research assumptions that need to be clarified are as follows:

1. Firstly, the airframe loads that showed in single line diagrams should always be supplied, even though the airframe loads can be shed first to alleviate the power supply stress of MEE load when the system is unbalanced. The reason for that is to test the MEE architecture and PLM capabilities with the most stringent restrictions (worst cases).
2. In addition, to making the comparison of different EPS concepts more consistently, the airframe loads have been assumed as always in full supplied.
3. ESS is a limited power source and for backup supply only, in most stringent test condition, it will be assumed as in disconnect status.
4. Thirdly, the LSF is representing shedding rate of the MEE loads in this research investigation, which not representing the entire aircraft level or airframe load. Therefore, the power supply availability P_{supply} in Equation (2) will depend on the available distribution paths for MEE loads, not the available power of generators. In specific, even though the generator has the capability enable to supplying enough amount to the grid, but if there are not feeders/path to distribute the power to MEE load bus, the power supply availability P_{supply} in Equation (2) shall make as 0.

After running the single converter or single channel failure modes on each of the EPS candidates, an example was shown in Figure 58. The result shows that all proposed architectures can maintain power in balance with/without shedding non-essential, but not require to shedding any essential MEE loads.

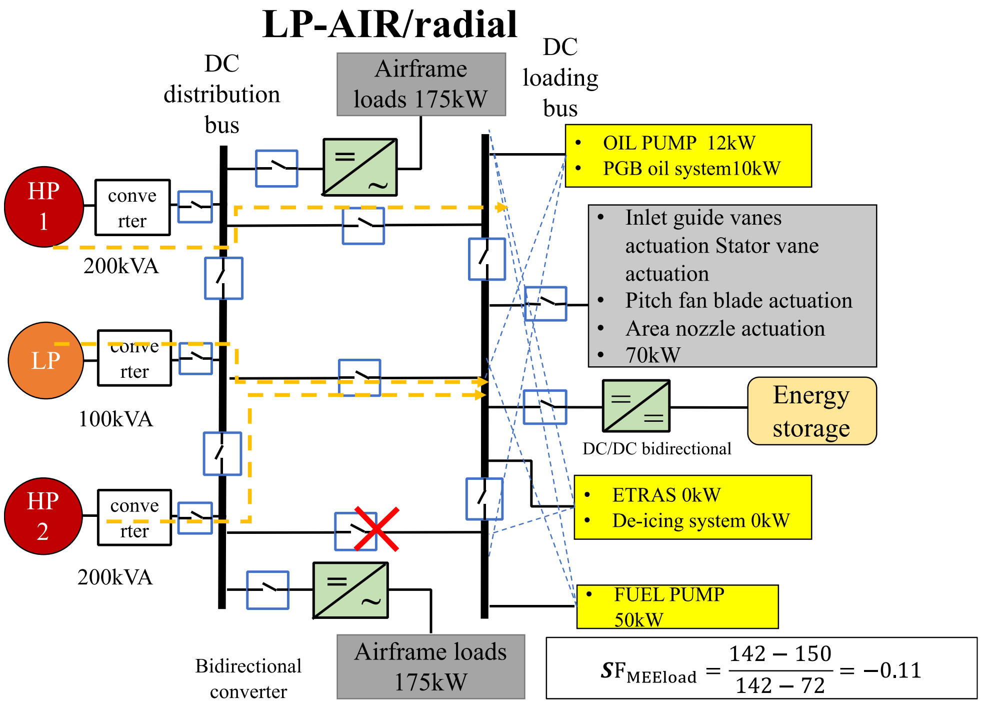


Figure 58. Single channel failure in take-off phase

Single generator failure mode that considered in cruise phase is showed in Figure 59 Losing a generator will not requires to shedding essential loads in MEE if the

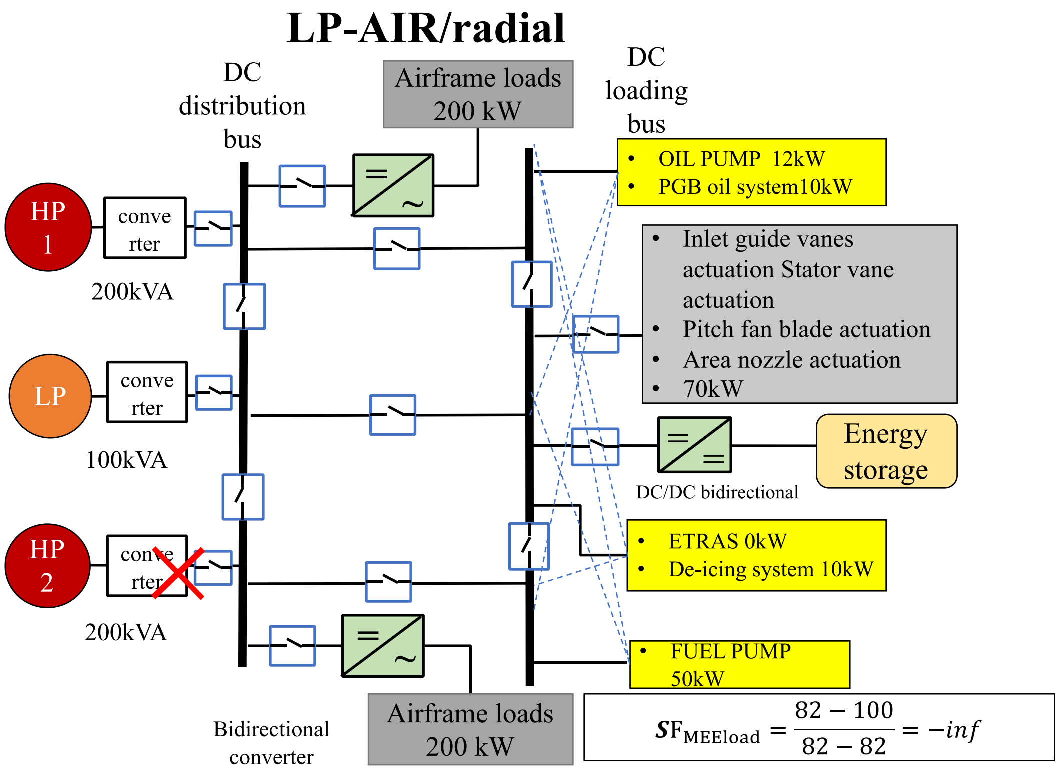
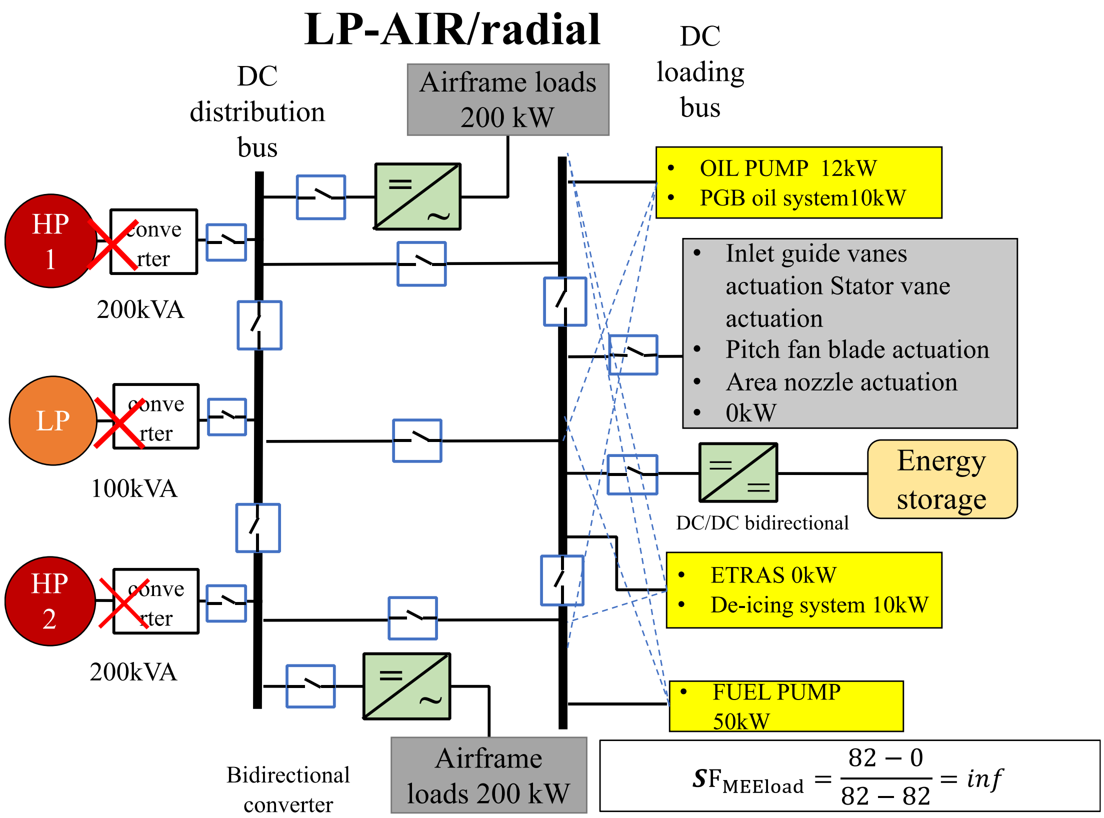


Figure 59. One HP generator failed in cruise phase

assumption of airframe load is always supplied. However, in the reality, the airframe loads can be easily disconnected and supplied by RAT or APU. Therefore, those available generators should be able to supply the MEE loads in this scenario. Figure 60 shows the case study that all generators failed. As a result, the MEE loads and airframe loads will not be supplied. Although the probability of this event is extremely low, but once it occurs, will leading the aircraft into a hazard or catastrophic situation. As long as safe condition permits, ESS can supply a time-limited power to remain the operation of essential systems for a while to allow the pilot shut down the faulty MEE smoothly.



$$SF_{\mathrm{MEEload}} = \frac{82 - 0}{82 - 82} = inf$$

Figure 60. All generator failed in cruise phase

The EPS concepts that selected by parameter classification optimisation can easily ride through the single failure modes via coordinate with proper power management. If extreme cases occurred such as all generator failed at the same time, there are no many supply flexibilities can be operated in the power architecture. However, the interesting design optimisation/enhancement lies in the failure mode of two channels. The design improvement for two-channel failure mode was discussed in Chapter 6, further supplementary information was listed as below:

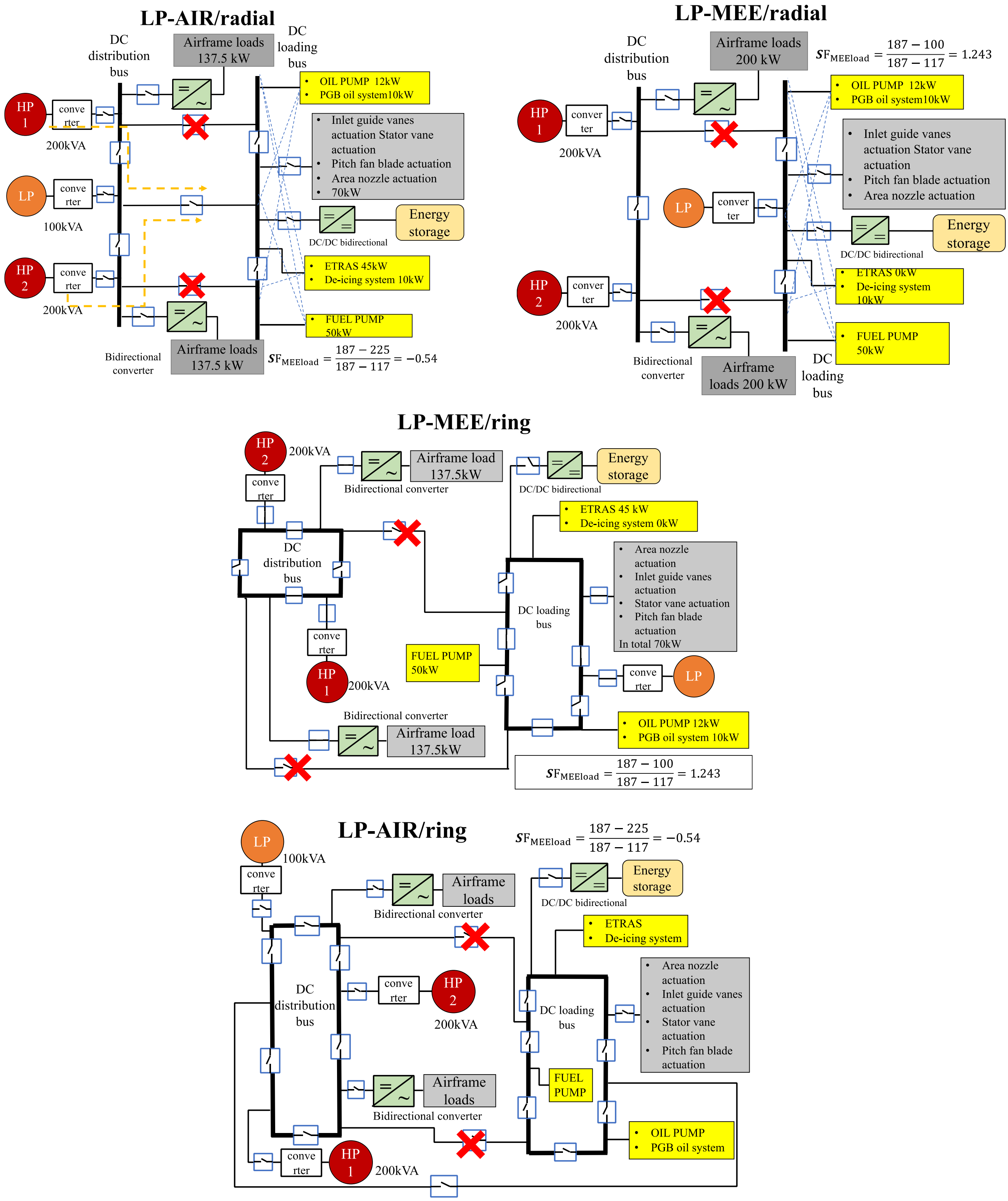


Figure 61. EPS concepts under two HP channel failure mode with PLM option: ESS and load shedding at Landing Phase

Figure 61 shows the four original MEE concepts under the two-HP-channels failure while using load shedding in the landing phase. Within this restricted condition, ESS is assumed as a disconnect status from the grid. Under this particular scenario, the shedding factor of LP-MEE/radial and LP-MEE/ring were over 1, which is not enough to supply the essential loads. LP-AIR/radial and LP-AIR/ring have the LSF in negative value, which means both concepts have sufficient power supply for MEE loads.

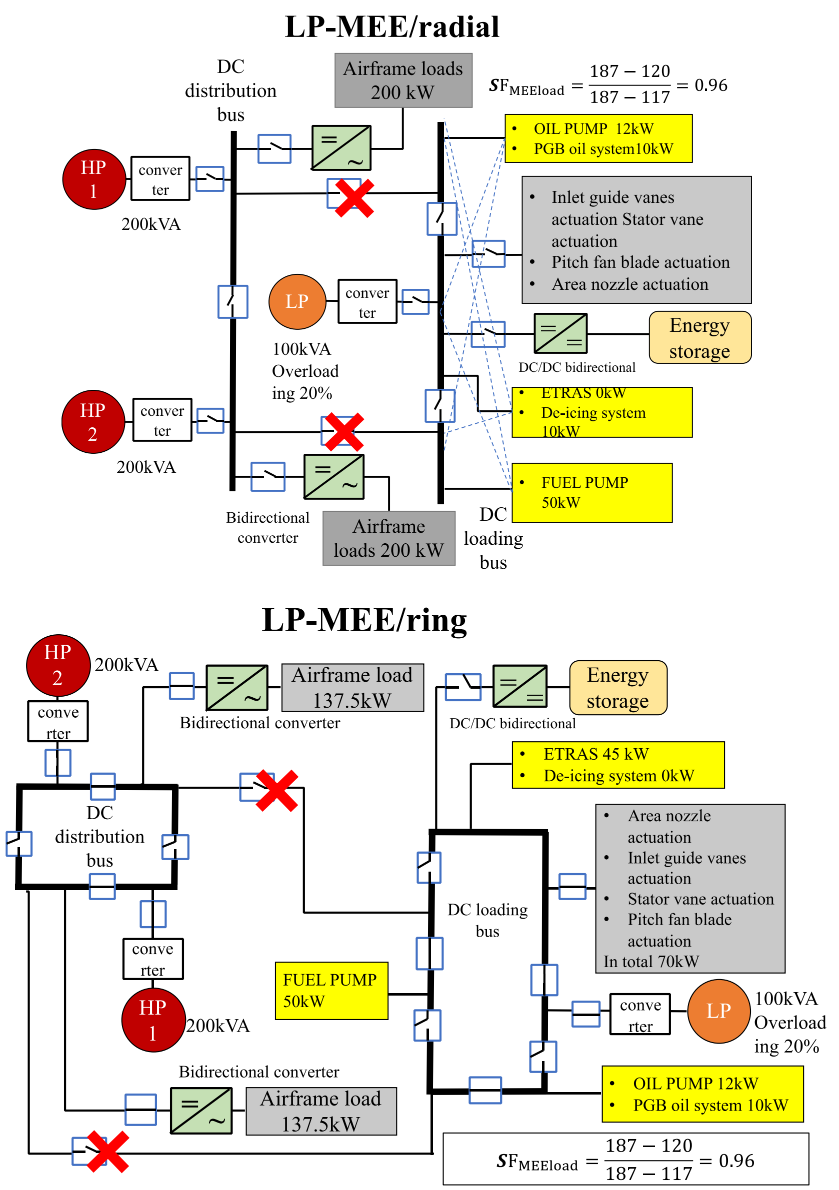


Figure 62. EPS concepts under two HP channel failure mode with PLM option: ESS and load shedding and 120% generator overload at Landing Phase.

Figure 62 is illustrated that LP-MEE/radial and LP-MEE/ring under the similar scenario but also used 120% generator overload allowance. This additional PLM function allows the EPS to supply all essential loads of MEE but still requires to shedding non-essential loads.

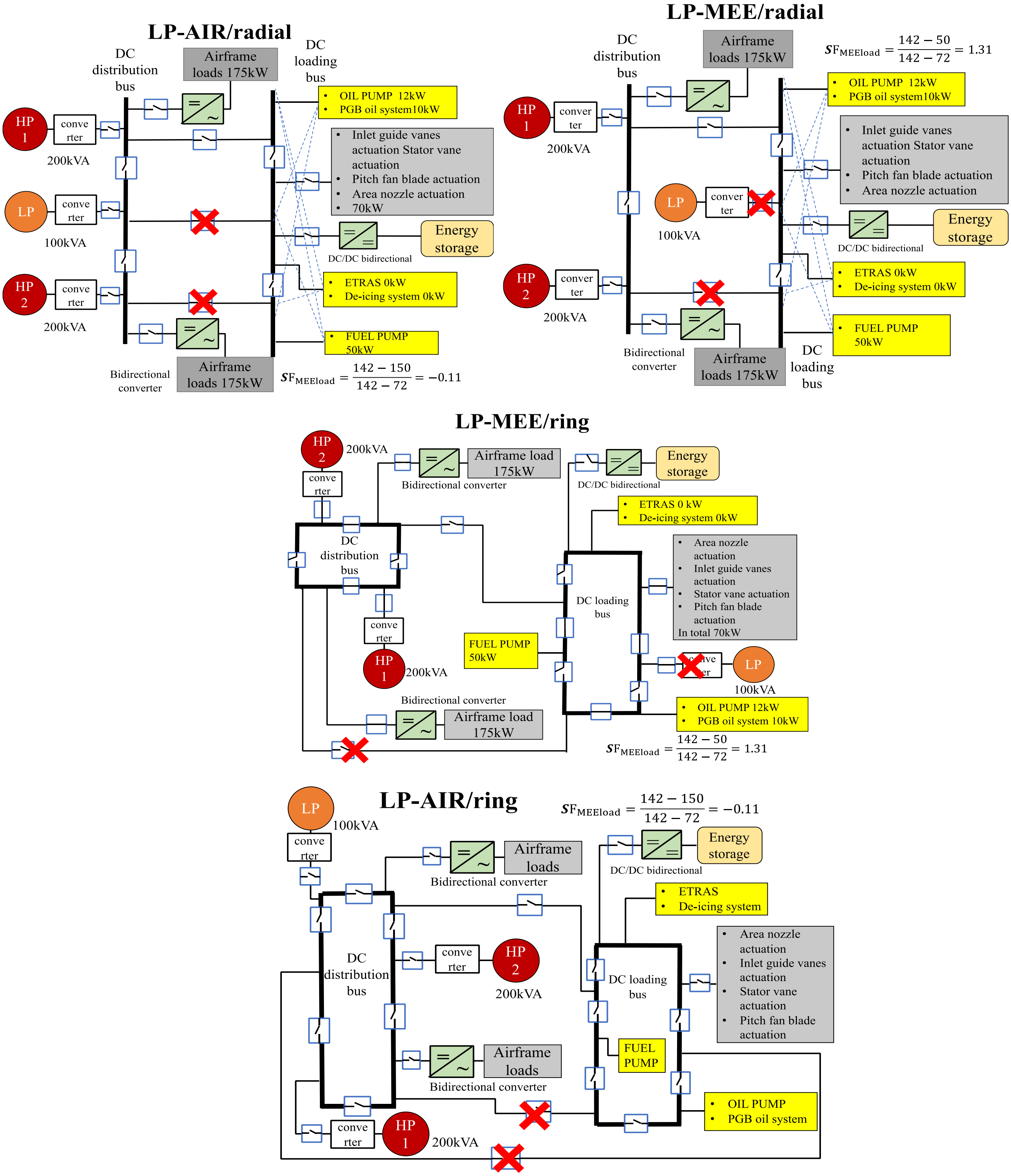


Figure 63. EPS concepts under One HP channel + One LP channel failure mode with PLM option: ESS and load shedding at Take-off Phase

Figure 63 shows the four original designed MEE concepts under the one HP channel+ one LP channel failure while using load shedding the Take-off phase. With the restricted condition, ESS is disconnected from the grid. Again, the MEE load shedding factor of LP-MEE/radial and LP-MEE/ring concepts were over 1. This situation can be alleviated while the 120% generator overload function was added into the PLM strategy, which shown in Figure 64.

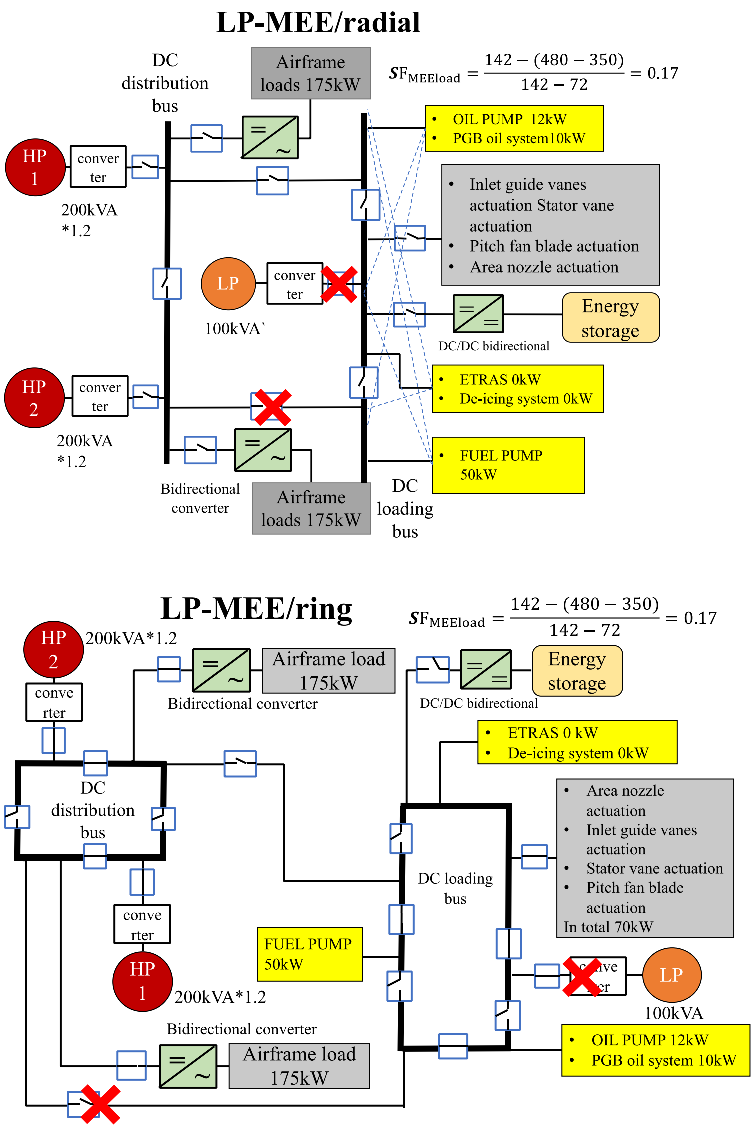


Figure 64. EPS concepts under One HP channel + One LP channel failure mode with PLM option: ESS and load shedding and 120% generator overload at Take-off Phase.

Figure 65 with the assumption of airframe loads is continuously supplied, MEE loads cannot been supplied while this situation was occurred during the High altitude (cruise) phase. The main reason for that is the available LP generator power source does not have any redundant feeder lines to distribute the power into the MEE load bus, which limited total available power supply. Even though the airframe loads have been shed, the cable current capacity of a single feeder line still cannot distribute all available power under this scenario.

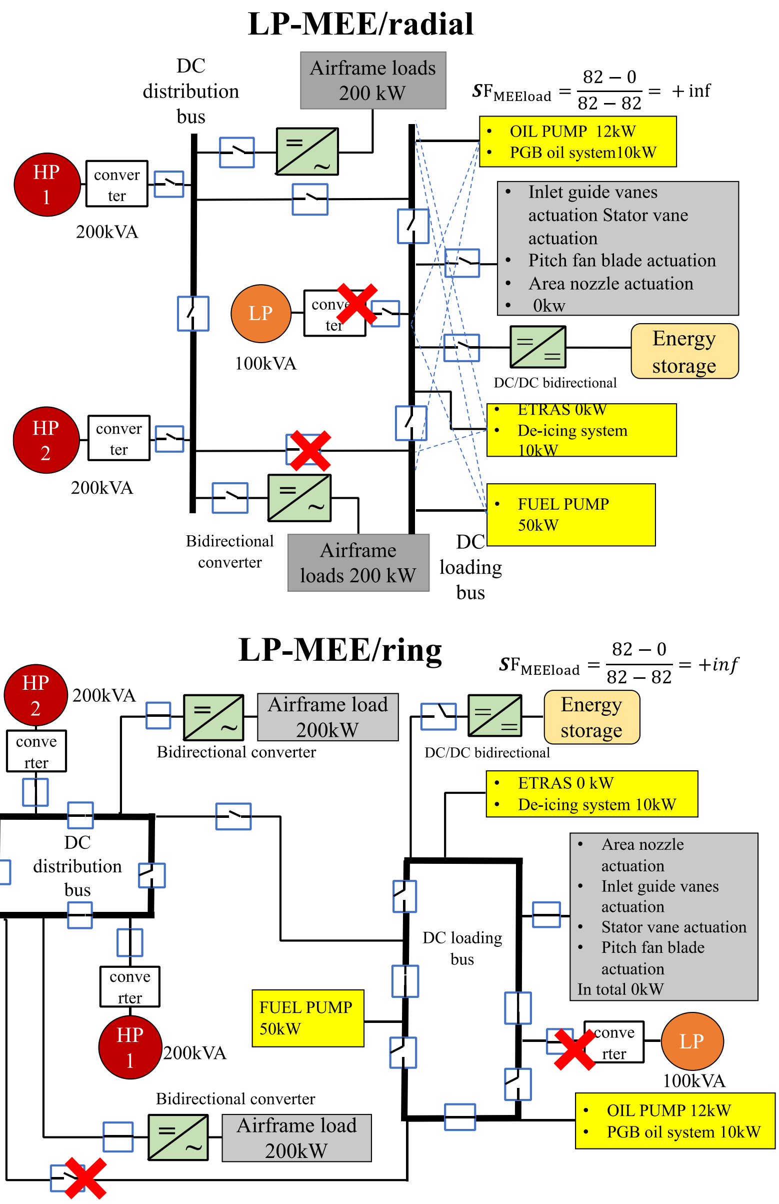


Figure 65. EPS concepts under One HP channel + One LP channel failure mode with PLM option: ESS and load shedding at High Altitude Phase

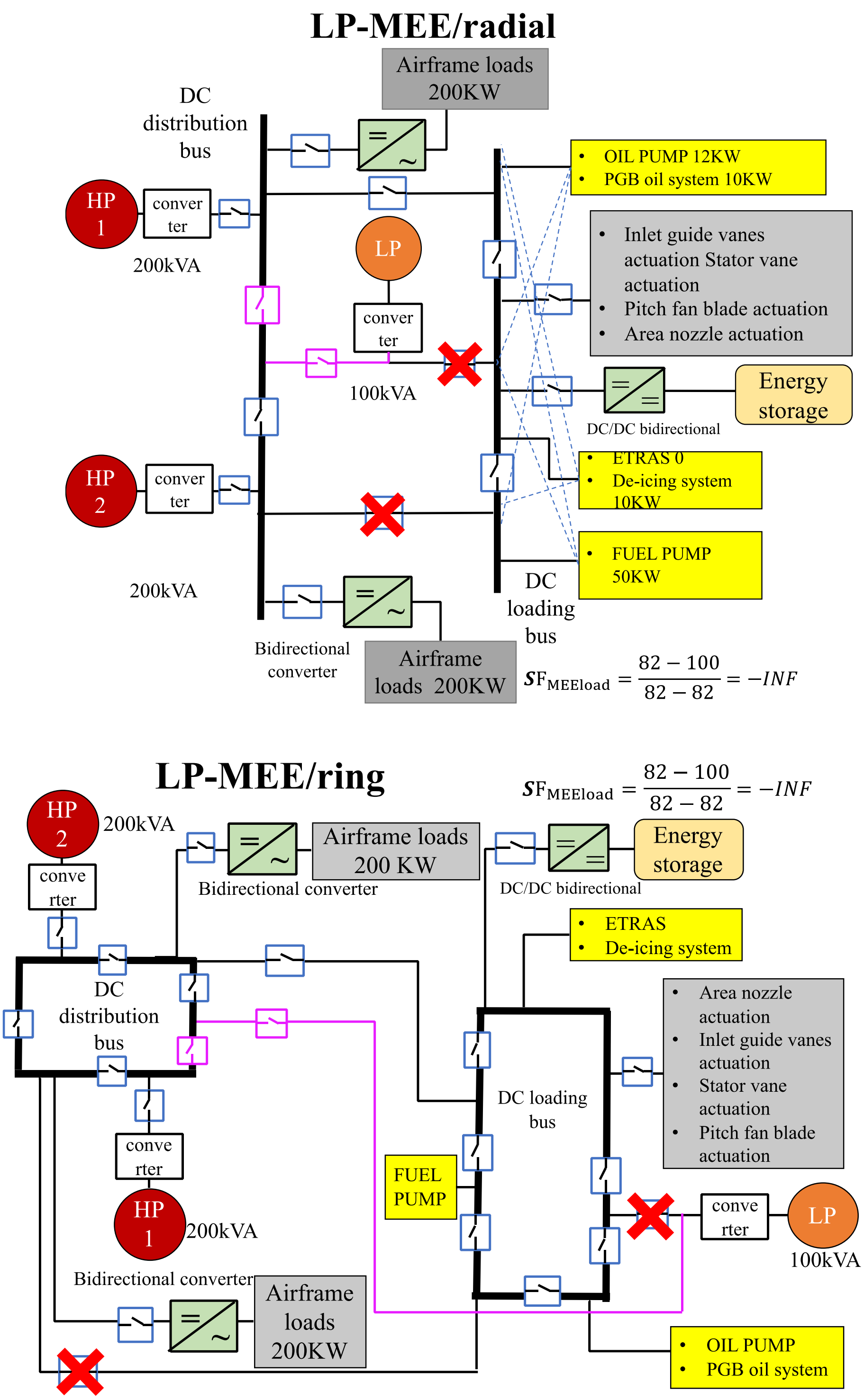


Figure 66. The improved EPS concepts under One HP channel + One LP channel failure mode with PLM option: ESS and load shedding at High Altitude Phase

To prevents this particular scenario, adding redundant feeder for the LP channel can increase the power supply availability. With the virtualised hints from the single-line diagrams, the additional components and feeder lines were highlighted in Figure 66.

The improved EPS concepts under One HP channel + One LP channel failure mode with PLM option: ESS and load shedding at High Altitude Phase. In addition, Table XX summarised the table of the shedding factors for all failure mode cases.

Table XX. The LSF of EPS concept under various failure modes

Two HP channel failure(when ESS is disconnected)				
PLM option: ESS and load shedding				
	takeoff	high	descent/approach	landing
LP-air/radial	-0.11	-2	-1.47	-0.54
LP_MEE/radial	0.6	-2	0.74	1.243
LP-MEE/ring	0.6	-2	0.74	1.243
LP-air/ring	-0.11	-2	-1.47	-0.54
PLM : ESS and shedding +overloading generator 20%				
	takeoff	high	descent/approach	landing
LP-air/radial	-0.11	-2	-1.47	-0.54
LP_MEE/radial	0.6	-2	0.74	0.96
LP-MEE/ring	0.6	-2	0.74	0.96
LP-air/ring	-0.11	-2	-1.47	-0.54
One HP channel and one HP channel failure (ESS disconnected)				
PLM option: ESS and load shedding				
	takeoff	high	descent/approach	landing
LP-air/radial	-0.11	-2	-1.47	-0.54
LP_MEE/radial	1.31	2	-0.04	0.88
LP-MEE/ring	1.31	2	-0.04	0.88
LP-air/ring	-0.11	-2	-1.47	-0.54
PLM : ess and sedding +generator overloading 20%				
	takeoff	high	descent/approach	landing
LP-air/radial	-0.11	-2	-1.47	-0.54
LP_MEE/radial	0.17	2	-0.04	0.88
LP-MEE/ring	0.17	2	-0.04	0.88
LP-air/ring	-0.11	-2	-1.47	-0.54
One HP channel and one HP channel failure (ESS disconnected)				
PLM option: ESS and load shedding				
	takeoff	high	approach	landing
LP-air/radial	-0.11	-2	-1.47	-0.54
NEW LP_MEE/radial	-0.11	-2	-1.47	-0.54
NEW LP-MEE/ring	-0.11	-2	-1.47	-0.54
LP-air/ring	-0.11	-2	-1.47	-0.54