A Modelling Framework for Efficient Design of Electrical Power Systems for Electrical Propulsion Aircraft

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Electrification of aircraft is a key enabler to reducing fuel burn, and hence emissions, from air travel. A combination of the low technical maturity of existing electrical power systems (EPS) and electrical technologies for electrical propulsion aircraft (EPA), and a lack of appropriate industry standards and significant interdependencies between electrical and non-electrical aircraft systems, results in significant challenges to the efficient design process of the EPS for EPA. A structured approach to the EPS design to enable an efficient design process from low to high technology and system readiness levels is required. Existing modelling standards for more-electric aircraft provide a pathway for EPS appraisal for established baseline architectures, but do not consider the process for disruptive technologies or interdependencies with non-electrical systems associated with EPA EPS design.

Hence this paper presents a novel EPS Modelling Framework which provides an efficient route to the design of de-risked, viable EPS's for concept EPA. The Modelling Framework enables design of concept EPS to meet predetermined performance criteria. Furthermore, it enables strategy mapping for both future systems and individual technology performance, with potential to interlink with design frameworks for non-electrical systems.

I. Introduction

Electrification of propulsive systems for aircraft has been proposed as a route to reducing greenhouse gas emissions and noise levels of future aircraft, and meeting targets such as those set by the European Commission's Flightpath 2050 [1]. The efficient development of viable designs for the electrical power systems for all sizes and variations of these aircraft is immensely challenging due to the low technology readiness level (TRL) of systems and technologies, lack of pre-existing, commercially operating systems and relevant industry standards, and the relatively short time frames for the development of these systems. For example, the ECO-150, which has a power system rated at 22 MW [2], is being considered for entry into service (EIS) by 2035 [3].

A further significant challenge is that an aircraft is comprised of many interdependent systems (e.g. thermal, electrical, propulsion, aerodynamic, structural), each of which influence the requirements of each other. The importance of these interdependencies with respect to the electrical power system (EPS) of an aircraft are significantly increased for aircraft utilizing electrical propulsion, compared to a more-electric aircraft (MEA). For aircraft with electrically driven propulsion systems, there is clearly a direct link between the electrical and propulsion systems. Electrification is also a key driver for the improved aerodynamic performance of the aircraft, thus providing a direct link between EPS design and aerodynamic and structural systems [4]. Further, the upwards step change in electrical power levels required for electrical propulsion compared to MEA, has a major impact on thermal management systems [5].

The low TRL and systems readiness level (SRL) of the EPS and associated technologies for electrical propulsion aircraft, the disruptive nature of the technology and the lack of established industry standards, combine to pose a significant challenge to the efficient design and down selection of viable EPS solutions for electric propulsion aircraft (EPA). The majority of existing approaches and methodologies for system design and performance optimization start

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with a pre-defined EPS (e.g. [6]). A challenge for future EPA aircraft is that there is no established baseline EPS. Automated approaches to EPS design to meet system performance standards are presented, but often focus on a single element of system performance (e.g. reliability in [7], [8]). Numerous approaches are presented in the literature for analysis of wider EPS performance criteria (weight, volume, reliability, cost and efficiency), e.g. [5][6][7][9]), and functionality (dynamic and transient response) of candidate EPS architectures, e.g. [10][11].

This paper presents an EPS Modelling Framework, which enables the efficient design and down selection of viable EPS architectures for disruptive technology applications. The framework provides a structure for modelling and simulation tools, road mapping for future technologies and provides an interface for integrated design with non-electrical systems. The remainder of this paper is structured as follows: Section II gives an overview of existing approaches to modelling and simulation for design and analysis of aircraft EPS; Section III describes the EPS Modelling Framework, Section IV demonstrates the operation of the framework with a conceptual hybrid-electric aircraft case study; Section V discusses the role of the framework for strategy mapping and wider integrated systems design, and Section VI provides conclusions and future work.

II. Existing Approaches to Aircraft EPS Design based on Modelling and Simulation

Methods for deriving candidate EPS architectures in the literature can be categorized into two broad types. The first approach is to cast system optimization as a mixed integer optimization problem which can be solved computationally, such as in [8],[12]. The challenges of this approach is that system requirements must be written as formal specifications, and subsequently the number of interdependencies between performance and functionality requirements lead to a very computationally expensive process. System optimization using pareto-front analysis can be difficult to apply for multiple different criteria. The second, alternative approach is to apply a heuristic approach where all options are captured and assessed in a transparent manner, for example in [13], where a heuristic approach is used to determine an EPS topology which a driven by fault management strategy. This approach enables the navigation of designing a system with functional interdependencies. Considering the importance of functional interdependencies to the design process for future EPA, and the desire to consider a range of performance requirements, a heuristic approach has been proposed as the starting point for the EPS Modelling Framework presented in this paper.

Fig. 1 shows the systems engineering "V" diagram, which is based on [14]. As a concept is stepped through this diagram, from left to right, it moves from simulation design to hardware prototypes, and ultimately production. By making appropriate design decisions during the preliminary design phase, the risk of redesign at later stages of the design process is significantly reduced [15]. In practice, for disruptive technologies, the process on the left hand side, from requirements to detailed design, requires system level verification of approaches at the subsystem and detailed design level, before hardware prototyping can commence. It is expected this will also involve some level of system iteration. This is indicated by the dashed arrows on Fig. 1.

By taking a systems level approach, rather than a technology driven approach, to EPS design for electrical propulsion aircraft, initial trades take place at a systems level. This approach provides requirements for subsystems and technologies. Subsequently the impact of the sub-systems and technology design on the overall aircraft performance is fed back up to the system level trades. This hierarchical, systems-based approach has been demonstrated for full aircraft systems development in [16],[17].

Modelling and simulation of electric propulsion aircraft EPS and technologies at steady state, e.g.[2][5][7][9]], and transient levels, e.g. [18][19][20][21] is very widely reported in the literature. However, an EPS Modelling Framework to co-ordinate these modelling approaches, optimize and de-risk the design process, and to translate between performance and functionality requirements is needed.

A standardized approach to modelling and simulation of electrical power systems for aircraft is set out in SAE AIR 6326 [11]. Within this standard, four levels of modelling fidelity have been identified: Architectural, Functional, Behavioral and Component Level (also known as "Device Physical"), as shown in Fig. 2. This standard minimizes computation time, whilst maintaining appropriate levels of fidelity at each of the levels described in the standard. At the Architectural Level, the full system is modelled in the steady state (step size >2.5 ms), with models performing system performance evaluation, including weight, reliability and efficiency. Models at the Functional (model step size ~0.5 ms), Behavioral (model step size ~1 µs) and Component Level (model step size <1 µs) are all time variant, but with increasing levels of fidelity. Functional models utilize state space average models of components with detailed control structure, enabling study of low frequency (up to 1/3 of fundamental frequency) dynamics and stability. Behavioral models include models of power electronic converters with ideal switches, enabling study of elements such as power quality, at frequencies in the range of 100's of kHz. Component Level models include component electromagnetic and thermal behavior, and physics-based models of switches and device-scale parasitics.

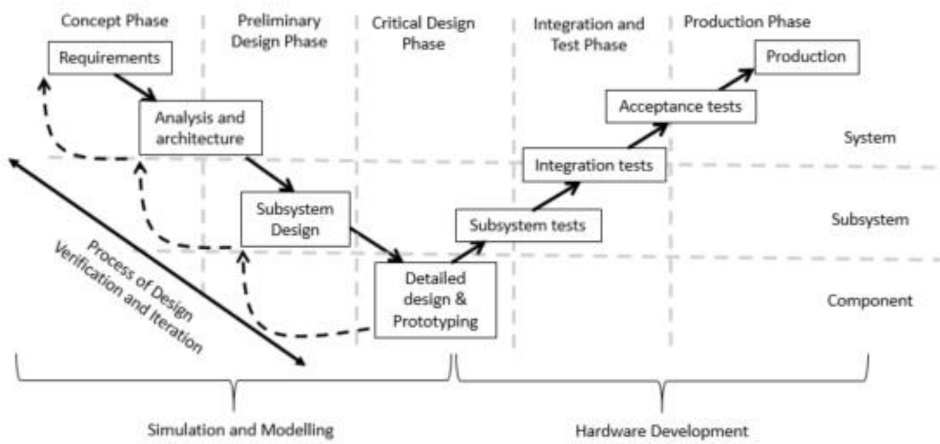

Fig. 1: Systems engineering process "V" diagram, with indication of the iterative system design process required prior to hardware prototyping.

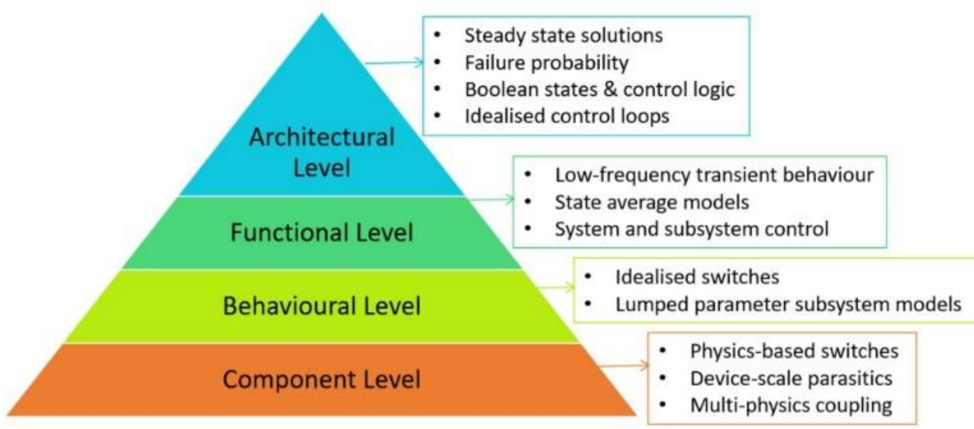

Fig. 2 SAE AIR 6326 modelling paradigm [11].

However, while SAE AIR 6326 provides a standardized approach to EPS modelling and simulation, for electrical propulsion applications, there are limitations. The aim of SAE AIR 6326 is to provide guidance for efficient modelling practices, rather than an efficient process for the full design of an aircraft EPS. The standard assumes a starting point is a pre-defined candidate architecture for an electrical power system. It does not provide a methodology for how an architecture for a concept EPS is designed, developed and refined, for example, the progression from a set of baseline system parameters to a viable EPS architecture. As a consequence of this, the process of interaction between the different levels of modelling fidelity is out with the scope of the standard. Thus, whilst it provides a good starting point for efficient modelling approaches, SAE AIR 6326 does not provide a comprehensive EPS Modeling Framework for electrical propulsion aircraft.

III. The EPS Modelling Framework

Aircraft EPS design is complex. It is interdependent not only with non-electrical systems on the aircraft, but within the EPS there are interdependencies between different subsystems and their desired functionality. For example, the approach taken to fault management is closely dependent on power distribution (AC or DC network), power electronic converter and grounding topologies. System stability, under both normal and faulted operation, is also closely linked to power electronic converter (PEC) and electrical machine topology and control. From the literature, a hierarchical approach to the design of such complex systems is presented as a route to the efficient design of these systems, where higher fidelity models of sub-systems and components enable informed decisions at a systems level, e.g. [16][22].

Hierarchical modelling approaches which specifically enable the optimized design of multiple different systems at an aircraft level are presented in the literature [16][17][21]. Electrical system specific approaches are detailed in the aforementioned SAE AIR 6326. Regardless of the system under consideration, in all of these hierarchical modelling approaches, as the level of modelling fidelity increases, the nature of the modelling parameters moves from generic to specific components, and from empirical or parametric models at low fidelity, to physics-based models at high fidelity. Further, as the level of modelling fidelity increases, computational requirements increase. Thus, there is a progression from systems level, to subsystem level and then to device level modelling and simulation.

The proposed EPS Modelling Framework builds on the concepts from SAE AIR 6326, optimizing and de-risking the design process for novel and disruptive architectures. This approach is described in Fig. 3, where the EPS Modelling Framework has been sub-divided into 8 levels, from Level 0 to Level 7. A description of level of modelling, and processes within each of these levels is given in Table 1. As a concept progresses through the EPS Modelling Framework, the technology description progresses from generic to specific. On a first pass, the selection of datasets from Level 4 to populate the system model at Level 1, may be very generic. However, at a later stage when specific equipment topologies have been determined due to studies at Levels 2, 3 or 7, the datasets used to populate the model at Level 1 will be updated accordingly.

System and sub-system models at levels 1 – 3 are supported by models of equipment at levels 4 – 6 respectively. The level of fidelity within these levels maps directly to the modelling levels described in SAE AIR 6326, as indicated in Fig. 3. Level 7 provides Device Physical modelling of equipment. Level 1 maps to the Concept Phase in the Systems Engineering process V diagram in Fig. 1, while Level 2 maps to the Preliminary Design Phase at Systems level, and Level 3 also maps to the Preliminary Design Phase but at subsystems level. Level 7 maps to the Critical Design Phase at Device Physical level.

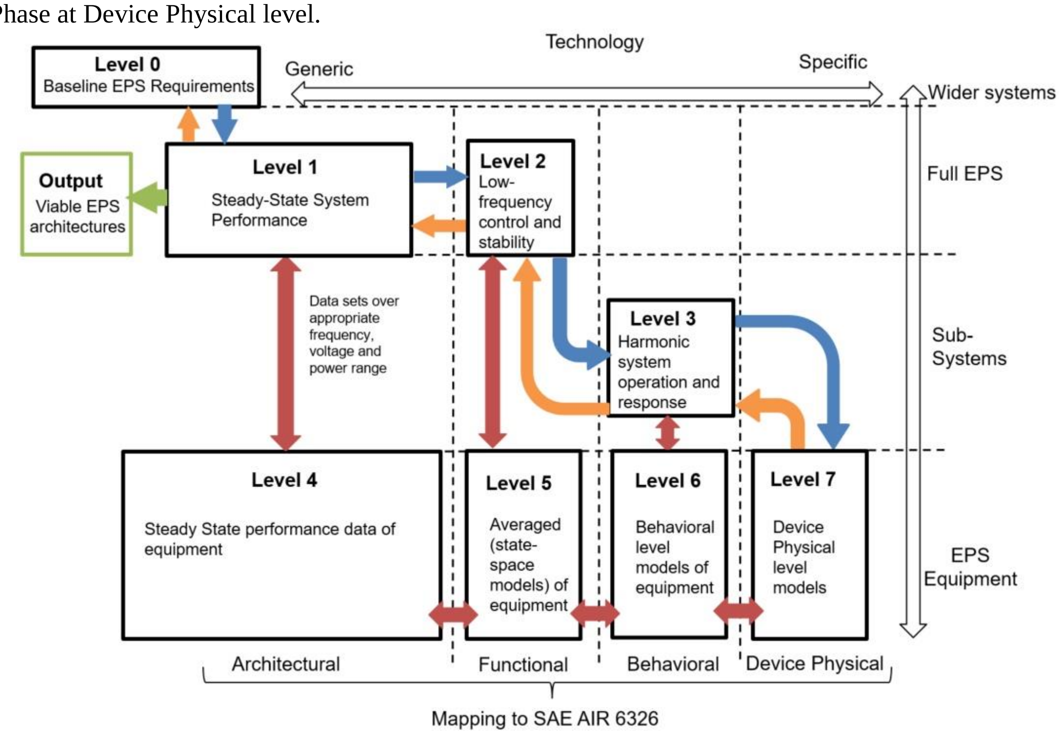

Fig. 3: Summary of proposed EPS Modelling Framework for future aircraft with electrical propulsion.

Table 1: Description of modelling levels within the proposed EPS modelling framework.

EPS Framework Level	Title	Input	Output	Internal Processes

0	• Baseline EPS requirements:
	  • Number of sources and loads.
	  • Baseline safety cases.
	  • Mission profile.
		• From wider aircraft systems, EPS requirements.	• Requirements from EPS for wider aircraft systems design.	• None. Interface between EPS Modelling Framework and other aircraft systems.

1	• Steady-state system performance:
	• Weight
	• Volume
	• Cost
	• Reliability
	• Losses
		• Baseline EPS performance requirements.	• EPS which meets performance requirements.
			• Range of system parameters for EPS subsystems and equipment, under normal mission operation and design corner cases:
			  • Frequency
			  • Voltage
			  • Power
				• Design and evaluation of candidate EPS architecture against performance criteria (e.g. weight, volume, reliability, efficiency, cost)

2	• Low frequency control and stability	• System, subsystem and equipment parameters as appropriate:
		  • Frequency
		  • Voltage
		  • Power
			• Requirements for system to meet stability and dynamic functionality requirements:
			• Recommended revisions to architecture design.
			• Refinement of range of system parameters.
				• Design of system control and evaluation of system performance under transient conditions, including abnormal and faulted conditions.

3	• Harmonic system operation and response.	• System parameters	• Identification of baseline component topologies. • Further refinement of system parameters. • Verification of transient response, e.g. fault response.	• Design of converter topologies and filters, testing and design of fault diagnostics and protection systems, ensure appropriate power quality.
4	• Steady state performance data for equipment.	• System parameters	• Performance data for equipment as a function of system parameters as appropriate.	• Selection of appropriate sets of data.
5	• Functional models of equipment.	• System parameters	• Functional models of equipment for system parameters	• Selection of appropriate equipment models.
6	• Behavioral models of equipment	• Sub-system parameters	• Behavioral models of equipment for sub- system parameters. (low frequency, <100 kHz range)	
7	• Device Physical Models	• Equipment parameters	• Device physical models for the parameters given (high frequency analysis >100 KHz).	

IV. Pathway through the EPS Modelling Framework

In order to demonstrate the EPS Modelling Framework, an example case study based on an ECO-150 type aircraft is presented. This indicates how the EPS Modelling Framework can take a concept, with a set of platform level requirements, and methodically apply the different Levels of the Modelling Framework to arrive at a set of candidate

EPS architectures for the aircraft which meet performance and functionality requirements in an efficient and traceable manner.

A. ECO-150 Aircraft Concept

The ECO-150 aircraft is a 154 passenger, subsonic turbo-electric propulsion aircraft, with a target entry into service of 2035 [3]. At a baseline level, electrical power is provided by 4 generators driven by 2 gas turbines (2 generators per engine). A hybrid generator – battery supply has been considered in the literature [23]. However, as a starting point for this case study, no energy storage is included. Electrical power is supplied to an array of 16 propulsor motors, which provide thrust for the aircraft. The engines, generators and propulsors are all located in the aircraft wings. The aircraft is designed for a 3,500 nautical mile still air range, with an economic mission range of 900 nautical miles. A maximum electrical power of 22 MW is required at the top-of-climb (TOC) phase of the mission. A breakdown of the mission profile is given in [3]. The aircraft must be able to operate with one engine inoperable, which will reduce the number of operational generators to 2. It is stated in [2] that no single point failure can result in more than a 25% reduction in thrust.

B. Level 1 of the EPS Modelling Framework

The output from Level 1 of the modelling framework is an EPS architecture which meets performance requirements, for example weight, efficiency, reliability, cost and volume. There are three main stages to Level 1: the Design Phase, Analysis Phase and Evaluation Phase. These are indicated in Fig. 4, where Level 1 is enclosed within the red dashed box. The Level 1 model is populated by datasets for performance of individual equipment from Level 4 (shown in Fig. 3). When a candidate architecture meets performance requirements at Level 1, progression is made to the transient modelling at Levels 2, 3 and 7.

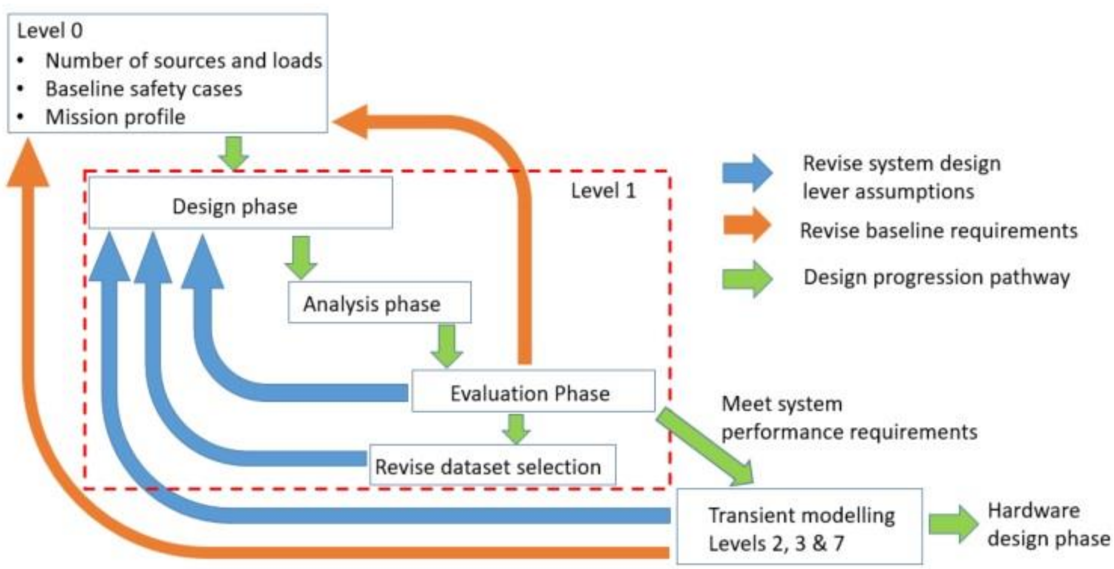

Fig. 4: Overview of the process at Level 1

1. Level 1 Design Phase

During the Design Phase a series of system design levers are worked through systematically to generate candidate architectures which comply with system level requirements and required functionality of the EPS. A fundamental aspect of the approach is that at each stage, more than one system design may be identified. It is critical that all of these options are captured. To provide an example, the design phase has been worked through for an aircraft based closely on the ECO-150. A summary of the stages and outputs from each stage are presented in Table 4 at the end of this section.

First Design Lever: Capture Baseline Power Requirements

The first design lever is to capture the baseline power requirements from Level 0, and create a very simplified, diagram of the EPS, which captures the number of sources and loads. The power ratings and duration for each mission stage of an example mission for the aircraft are also required. For the ECO-150 based case study, the architecture at this design lever is captured in Fig. 5. At this stage, number of channels, method of power distribution or type of electrical machine is left open.

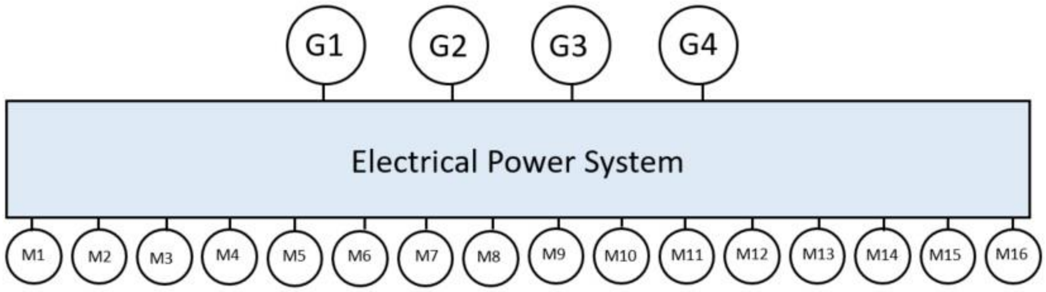

Fig. 5: EPS architecture for the ECO-150 after capturing baseline power requirements.

Second Design Lever: Fault Management Strategy

The second design lever is to determine the high level approach to fault management strategy. As stated above, the system level requirements are that a single failure must not lead to a reduction in thrust of more than 25% [2]. Hence if one generator fails, the system can still operate. Secondly, the minimum electrical power requirements for the propulsor fans to ensure sufficient thrust can be provided for the aircraft to ultimately land safely. This includes under the worst case off-nominal conditions, which are OEI on a missed approach, and loss of power to one or more propulsor fans. The maximum number of propulsor fans which can be lost is determined at this stage. Table 2 gives a comparison for the power rating of the motors with 16, 14 or 12 motors operational. The choice of minimum number of operational propulsor motors will be strongly influenced by non-electrical factors, such as yaw control [2], and electrical factors, such as the required rating of the motor and upstream electrical power system equipment. The latter element will be assessed within Level 1 of the Modelling Framework.

Table 2 shows the power required per propulsor motor to provide maximum power (22 MW) at TOC, operating on 2 out of 4 generators. The motors can either be rated for operation under faulted conditions, or the decision may be made to rate for normal operation if it is known that the motors can operate in an overloaded condition for the duration of the off-nominal condition. To provide 22 MW, the generators must be rated at 11 MW each.

Table 2: Example off-nominal operating conditions for the ECO-150.

Number of operational propulsor motors	Power rating per motor for maximum power (MW)
16 out of 16	~1.375
14 out of 16	~1.57
12 out of 16	~1.833

A significant consideration for this design lever is how the system will respond to an electrical fault, and what architecture requirements are needed to ensure that appropriate power is maintained to loads. A comprehensive description of the considerations and process around determining a viable fault management strategy is provided in [13]. At a high level, the decision is also made at this stage regarding grounding topology: whether to operate a solid grounded system (with fault detection based on a high fault current), or an isolated grounded system (which may enable some fault ride through capability). Further refinement of the grounding system will take place at a later stage.

Therefore at this stage both a solid grounded system, and a high resistance grounded system are considered for the ECO-150 case study. The high resistance grounded (HRG) system offers a further advantage as it has been proposed as an enabler for developing EPS which are closely integrated with composite structures [24]. It is known there is a very restricted physical space for the EPS in the wings of the ECO-150 [21], so reduced volume by integration with the composite structure would be advantageous. However a HRG system will require higher voltage ratings to operate under first rail to ground fault conditions, but will still require electrical protection devices in the event of a second rail to ground fault occurring, before a first rail to ground fault has been cleared.

For the solidly grounded system, and considering the response to a second rail to ground fault on the HRG system, the approach to fault management may be to divert or limit fault current, or to isolate the faulted section of network For a high power, compact microgrid on an aircraft such as the ECO-150, the approach taken must ensure that an electrical fault is isolated to prevent rapid propagation of a fault, and reconfigure the healthy network (if necessary) to meet the high level requirement that loss of >25% thrust cannot result from a single point of failure. The choice of protection devices is not chosen at this stage, as system parameters (frequency, voltage) and method of power distribution are yet to be determined.

Once Level 1 has been completed, dynamic and transient simulation at Levels 2 and 3 can be used at a later stage to capture transient protection requirements, such as required speed to detect and respond to a fault, or the impact of a fault management strategy on system stability.

Third Design Lever: Availability of Power

The third system design lever is to consider the availability of power. This design lever determines the number of channels and interconnections, and which loads can be supplied by which source. This includes decisions made regarding fault management strategy and the requirement for any load to be supplied by any source under the off-nominal OEI operating condition. Two baseline options are identified, either a two channel (one channel per engine) or 4 channel (one channel per generator) system, as indicated in Fig. 6 and Fig. 7. Both systems are based on a radial architecture, with the main channels connected into a ring to create redundancy. An alternative approach is a purely radial system, where it is assumed that appropriate redundancy between channels will be provided. Fig. 8 shows this approach for the 4 channel system.

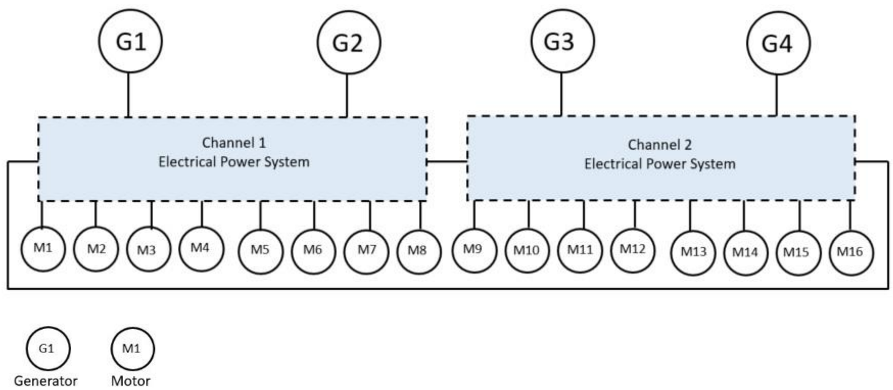

Fig. 6: 2 Channel architecture with ring connection for redundancy.

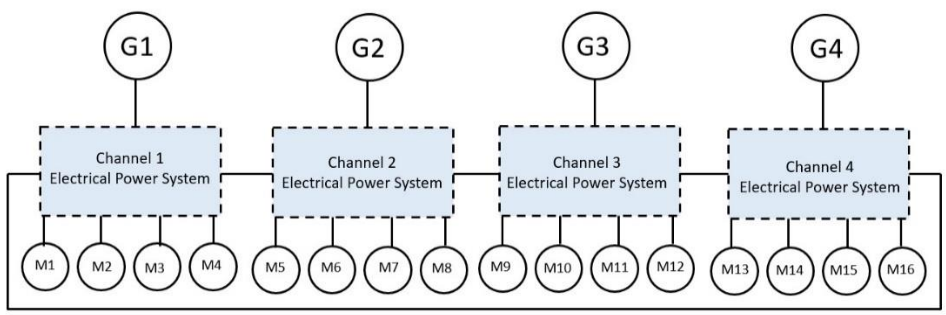

Fig. 7: 4 channel architecture with ring connection for redundancy.

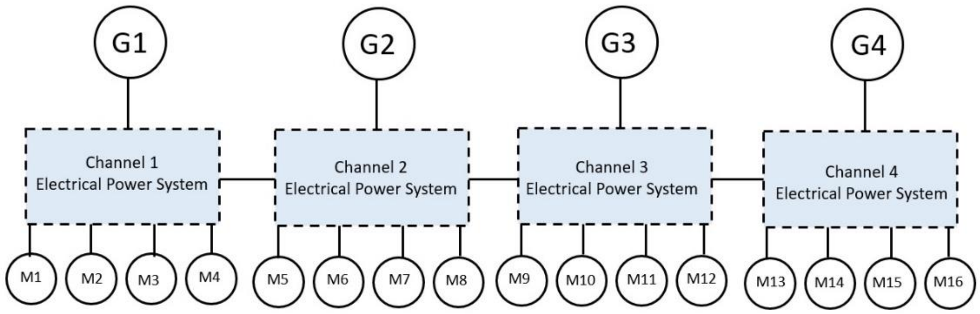

Fig. 8: Purely radial 4 channel architecture

Fourth Design Lever: Power Distribution

The fourth design lever is the selection of power distribution. At the first pass this is the choice of AC or DC power distribution. If it is assumed that propulsor speed is controlled by the power supply to the motors, then appropriate motor control is required. To electrically decouple the motors from the generators, the generated power AC power must be converted. To minimize the number of conversion stages, DC distribution is selected, with 4 rectifiers (one on each generator) and 16 inverters (one for each motor). At this stage specific electrical machines or power electronic converter (PEC) topologies are not considered. To meet the isolation requirements of the fault management strategy proposed, isolating protection devices are included, alongside bus ties. The bus ties between busses could either be nominally closed, as indicated in Fig. 9 for the 4 channel architecture, to maximize flexibility of load sharing between generators at all stages of a mission. Alternatively bus ties could be nominally open, to minimize any on-state losses, but this would require decisions to be made about when to close a bus tie to enable load sharing capability. For the case of the purely radial system, a redundant bus tie (nominally open) is connected, to allow for failure of a bus tie. This is approach is shown in Fig. 10. In all cases (2 and 4 channel) it is assumed that the busbars will not fail. The assumptions made regarding reliability at this stage will be checked during the analysis stage of Level 1.

For the 2 channel system, appropriate connections are included for redundancy (shown by blue and orange cables in Fig. 11). Whether this architecture offers any performance advantage over the 4 channel system in Fig. 9, would be investigated during the analysis stage at Level 1. All of the architecture options captured at this stage, are summarized in Table 3.

Finally, during this design lever, very broad values for system frequency and voltages are set. Voltage is expected to be in the kV range, up to 10 kV [2]. Overrating the voltage for the faulted operation of the HRG system must also be considered. System (voltage) frequency is set to be very broad, from dc (0 Hz), to 1 kHz. All sections of AC, to both generators and motors, is three phase.

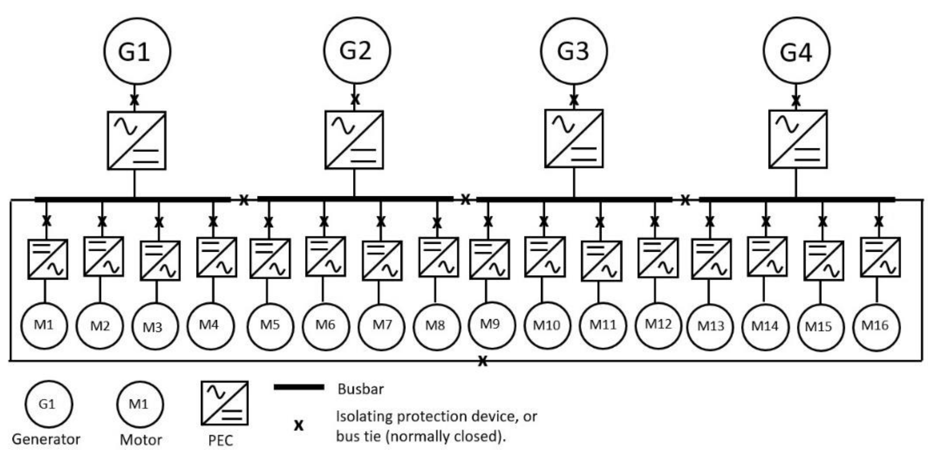

Fig. 9: 4 Channel architecture, hybrid ring – radial architecture.

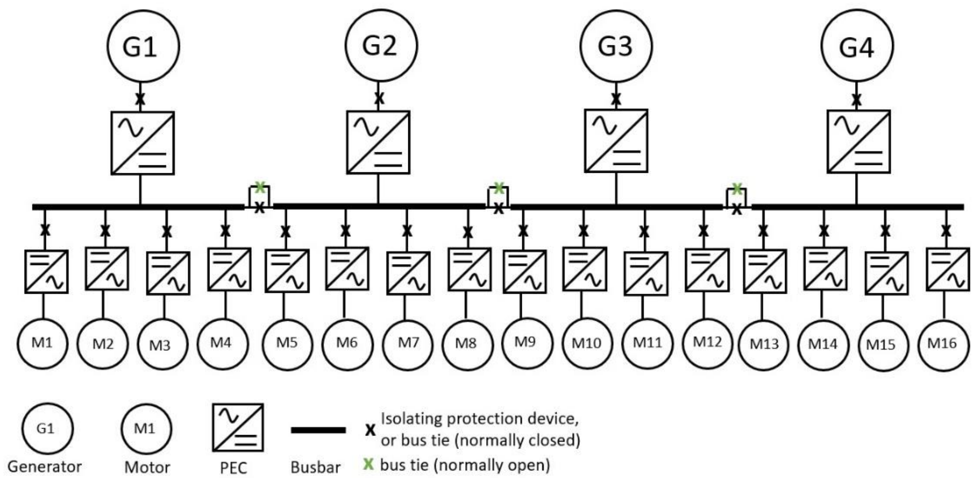

Fig. 10: 4 Channel, radial architecture with redundant bus ties.

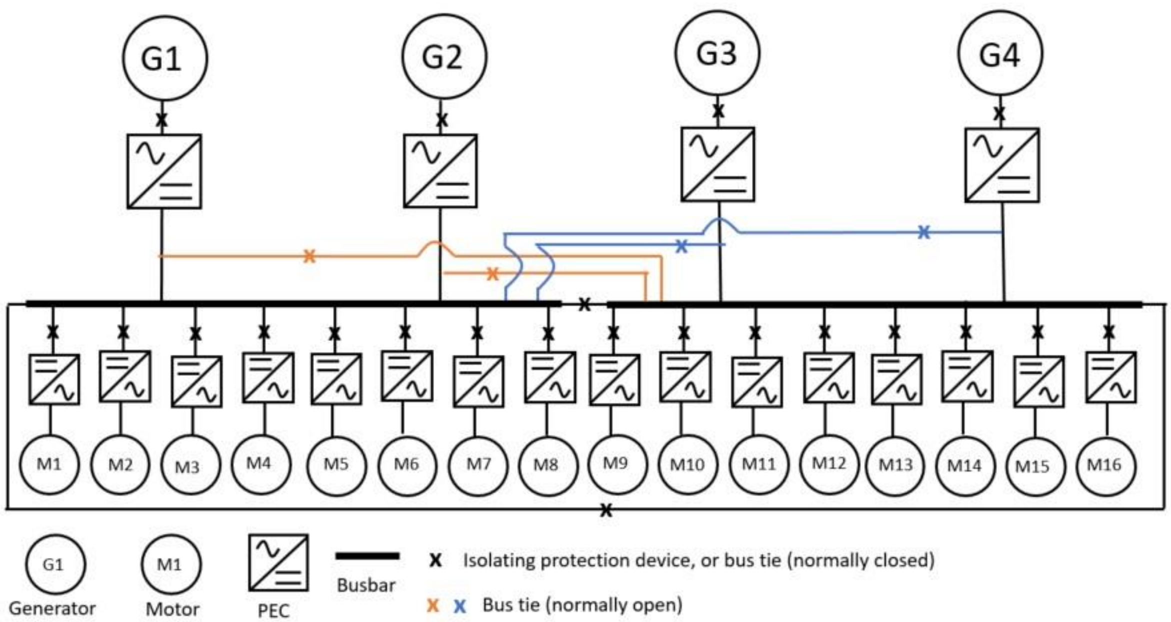

Fig. 11: 2 Channel, hybrid ring-radial architecture.

Table 3: Summary of architectures for initial analysis and subsequent down selection.

Architecture	Number of Channels	Ring architecture or purely radial	Status of interconnecting bus ties under normal operation
1	4	Ring	Closed
2		Ring	Open
3		Radial with bus tie redundancy	Closed
4		Radial with bus tie redundancy	Open
5	2	Ring	Closed
6		Ring	Open
7		Radial with bus tie redundancy	Closed
8		Radial with bus tie redundancy	Open

Fifth and Sixth Design Levers: Power Quality and Thermal Management

The fifth and sixth design levers of the design phase are the consideration of power quality and thermal management. On the first iteration, these are not considered in detail. Once transient studies at Levels 2 and 3 have taken place, more informed decisions regarding these design levers will be made. Performance analysis will indicate system losses, which will be an indicator for the thermal system requirements. For power quality, the use of PEC indicates that an allowance for appropriate filters must be made.

Seventh Design Lever: Determine Design Corner Cases.

The final design lever is to determine the design corner cases for the candidate architectures. This must include the power flows through the system under the normal mission profile, alongside the scenarios under off-nominal conditions where maximum power flows through sections of the network. Typically, the worst case scenario occurs under the maximum power requirement, with OEI and the loss of the maximum number of propulsor fans alongside failure of a bus tie (in the case of a ring architecture), such that maximum power must flow through one section of network. Table 4 summarizes the system design levers, the generalized outputs for each and for this case study.

2. Level 1: Analysis and Evaluation Phases

During the Analysis Phase, the overall performance of an EPS is investigated, alongside developing understanding of which system components are strongly influential on system performance. Once at least one baseline architecture has been determined, with reference to Fig. 3, Level 4 datasets for the electrical equipment that forms the EPS are used to estimate the system performance. Ideally, for the first pass, the datasets are as generic as possible. If this is not possible, the performance is analyzed using a range of different equipment topologies: for example, the system performance for a system with wound field synchronous and permanent magnet synchronous machines may be analyzed.

The Evaluation Phase considers the results from the Analysis Phase and considers whether an architecture meets performance requirements and now requires the application of transient modelling to investigate dynamic functionality at Levels 2, 3 and 7; or whether an architecture is close to, or above, performance limits and therefore further work is needed before moving to the transient modelling stages of the EPS Modelling Framework. This could be to identify which aspect of the power system design is causing performance limits to be reached, or overshot, and whether a different approach can be taken. For example, if the mass of the power electronic converters is too high, is it viable to improve power density, or should changes be made to power distribution? Alternatively, what is the operating condition when the system is at or above a performance limit, and can the system operate at that state for a short period of time (for example, if the losses during an off-nominal condition are too high)? What flexibility exists in the setting of the performance requirements, and can these be adapted in trades with critical EPS functionality? It will also be necessary to consider at this stage, which non-electrical systems are influencing EPS performance requirements. This is not an exhaustive list, but provides a flavor of the thought process at the Evaluation Phase.

At the end of the Evaluation Phase the different architecture options identified as viable options should be ranked to determine which should initially be considered during transient analysis (Levels 2, 3 and 7 in Fig. 3). The aim of the transient analysis is to examine whether an architecture which meets performance requirements has appropriate dynamic functionality under normal and faulted conditions.

C. Transient analysis at Levels 2, 3 and 7.

1. Functional System Operation at Level 2

Level 2 of the proposed modelling framework maps to functional modelling in SAE AIR 6326. During this stage the system stability is examined, in particular the dynamic performance, in response to acceptable system transients, such as load changes during different phases of flight and operation under off-nominal conditions. The system is modelled at ~ 1/3 basic EPS system frequency, with representation of 3 phase voltages using dq0 format, e.g. [10]. Ultimately simulation and modelling at this level indicates whether an architecture which meets basic system performance criteria, also meets stability and control requirements.

As an architecture progresses through the Modelling Framework, the choice of system equipment becomes less generic. For example, for the ECO-150 based case study, at this stage the modelling of the electrical machines requires the electrical machine topology to be chosen. The two options considered for the electrical machine are a permanent magnet synchronous machine, or a wound field synchronous machine. The advantage of the wound field machine is that in the event of an electrical fault, the excitation control to the machine can be turned off, and the power source isolated. A permanent magnet machine may have better power density, but it requires circuit breakers to isolate the machine in the event of a fault.

At level 2 the dynamic response with both a wound field and PM synchronous machine for the generator would be investigated, assuming appropriate models and data are available. For the electrical motors, PM synchronous machines would be used, due to their high power density. Studies at Level 2 may indicate a need for energy storage to provide stability support on the system under certain transients. This would require the baseline architecture for the EPS to be updated to include energy storage, alongside the 4 generators.

Once the functional operation of the architecture has been verified, the refined architecture which includes the choice of electrical machine topology, and refinements to voltage, frequency and power parameters, is re-evaluated at Level 1. Datasets used at Level 1 from Level 4 are also updated to reflect more specific choices of equipment topology. For example, for the ECO-150 case study, the choice of electrical machine would subsequently be fed back up to the system model at Level 1, and the dataset from Level 4 updated. The System Design Levers in the Design Phase at Level 1 would be revisited, and the approach to protection reconsidered in light of the choice of electrical machine topology.

Table 4: Summary of the Design Phase for Level 1 of the EPS Modelling Framework, including the ECO-150 based case study.

System Design Lever	Output	Case study example for the first iteration at Level 1.
1. Define baseline power requirements	• Identify for nominal and off-nominal conditions: • Numbers of loads and sources. • Load power requirements	• Confirm number of power sources and total number of propulsive loads: • 4 generators, no energy storage. • 16 propulsor motors • Determine load power ratings for: • Propulsive power requirements for each phase of normal flight.
2. Fault management strategy	• Determine desired response to an electrical fault, to determine if any overrating of components will be required.	• Determine off-nominal operating conditions: • 2 out of 4 generators operational (one engine inoperable) • Loss of 2 or 4 propulsor motors. • Two options: • Solidly grounded system, rapid detection of faults and isolation of faulted sections of network. • HRG topology, which enables fault ride through capability and detection of high resistance faults through CFRP. • In both cases, protection devices isolate a fault to prevent propagation.
3. Availability of power	• Determine the number of channels, connections between channels and which supplies can power which loads.	• Any load can be supplied by any power source. • 2 channel and 4 channel options were considered, with appropriate interconnections.
4. Power distribution	• Choice of AC, DC or a hybrid, for power distribution. • Determine the number of power conversion stages. • Select broad range for system frequency and voltages.	• DC distribution: • Enables individual control of electrical machines. • Minimises number of power conversion stages. • Select voltage range of 1 – 10 kV, 0 (dc) – 1 kHz, variable frequency for generators, fixed frequency for motors.
5. Power quality 6. Thermal management	• During the first iteration, the inclusion of generic filters and heat sinks is included by an addition of a predefined percentage to component models at level 4.	• Include a baseline for generic performance parameters of the thermal and power quality (filters) during the first iteration. • More detailed considerations at later iterations.
7. Determine design corner cases	• For derived candidate architectures: • Identify the cases where maximum power flow conditions occur. • Identify power flow levels in the system under normal operation.	• For off-nominal conditions, corner cases occur when: • OEI resulting in loss of two generators. • Loss of maximum number of motors. • Maximum load, TOC.

2. Behavioral System Operation at Level 3

Level 3 investigates the subsystem operation at a behavioral level of modelling, as defined in [11]. At this stage, baseline power, frequency and voltage from Level 2 are used with appropriate behavioral models of the subsystem to investigate switching transients and options for filters.

For the ECO-150 case study, it is during this level that the first selection of power electronic converter topologies will take place. For ECO-150, the choice of power electronic converter, solid state switching devices and protection topologies will be determined by the system voltage and frequency levels from the analysis at Levels 1 and 2, and by considering what technologies and topologies would realistically be at TRL 6 by 2025 [2]. It was indicated above that a high resistance grounding topology was chosen, to enable first fault ride through. However, a disadvantage of this approach is the higher rail to ground voltage that the system must be rated to, for operation under faulted conditions. Therefore at Level 3, it is critical that the fault response of this system is observed. On the one hand, this indicated whether the HRG system topology would be viable using components which are at an appropriate TRL within a pre-determined timeframe, driven by the timeline for the target EIS of the aircraft. However, this also demonstrates how the EPS Modelling Framework can be used to create technology roadmaps to enable future concept aircraft systems to be developed.

At the end of Level 3, the topology of the equipment has been determined at a behavioral level. The low frequency filters have been included (for example DC link capacitance). At this stage, equipment models at Levels 2 and 4 should be updated to reflect the more specific technology choices. The dynamic response at Level 2 is re-evaluated to ensure the system still meets dynamic stability requirements. The process at Level 1 should be re-run, to re-assess decisions made around System Design Levers and to check that the updated system still meets performance requirements.

3. Device Physical Operation at Level 7

Device level modelling concerns high frequency modelling of individual devices and components using physics-based modelling. For the conceptual ECO-150 example used for this paper, this would be to design and implement appropriate EMI filters, in particular for the power electronic converters. The requirements for high frequency power quality, which includes electromagnetic compatibility filters, are passed down from the power quality requirements captured at level 1. Once designed, the filters would be included in the component models at levels 4-6, to update transient models at Levels 2 and 3, and the steady state system model at Level 1. Functionality at Levels 2 and 3 should be re-evaluated to ensure requirements are still met, and the Level 1 process re-run to ensure performance requirements are still met.

V. Road Mapping and Wider Systems Design Implications

Therefore the final output from the EPS Modelling Framework is an EPS for a concept aircraft, which is demonstrated to meet performance requirements, and has appropriate transient functionality. For the case of the ECO-150 example the end point provides a set of target requirements for both system and technology development.

A. Road Mapping Support

For conceptual EPS designs for future concept aircraft, the EPS Modelling Framework provides significant support for identifying requirements at both a systems and a technology level for future concept aircraft EPS. Modelling the EPS in steady state, and then verifying the transient operation for different levels of fidelity, indicates the required response and functionality at equipment, sub-systems and full system level, and the full system performance. As such, the EPS Modelling Framework translates between performance and functionality requirements.

At the first pass Design, Analysis and Evaluation phase at Level 1, the generic choice of equipment topology enables the system performance to be analysed using equipment topology agnostic datasets for the performance analysis. On the one hand this facilitates the evaluation of system performance using datasets based on existing technology roadmaps for particular timeframes and TRL. However, it also provides an opportunity to investigate the required performance (for example power density or reliability) of a particular piece of equipment or sub-system, in order for a future EPS to be viable with a particular architecture. For example, for the ECO-150 case study, the performance analysis may be used to indicate the required reliability of sub-systems and equipment, such that the purely radial architecture (Fig. 8) can be chosen over the hybrid radial-ring architecture (Fig. 7). Analysis at Level 1 will indicate whether the additional bus ties included in the purely radial architecture for redundancy impact significantly on system performance, for example, volume, weight, and losses (including impact on thermal requirements). If they do then performance targets for the bus ties to reduce this impact can be set.

The EPS Modelling Framework also provides a pathway to road mapping for systems and technology functionality, and to link that directly to performance requirements. The EPS Modelling Framework provides a route to link functional and performance requirements together in a methodical way, for EPS design where there is no predefined standard baseline architecture. For the ECO-150 case study, an example is the approach to fault management. The high level approach of using HRG to allow first fault ride through can be investigated at a transient level for the capture of protection requirements and selection of appropriate protection solutions, and subsequently to enable the updating of system ratings and equipment models for Level 1 analysis. This then provides a set of equipment-focused functional and performance requirements, with a target timeframe to a particular TRL (e.g. TRL 6 by 2025).

B. Integration with Non-Electrical Systems Design

The Framework also provides a systems level road mapping. The hard limits for EPS performance criteria will be set by aircraft level specifications. As well as returning EPS architectures which are verified as meeting performance and functionality requirements, the EPS Modelling Framework can also be utilized to provide thresholds and requirements for non-electrical systems which have interdependencies with the EPS. For electrical propulsion aircraft, this includes gas turbines and propulsors, which combine with the EPS to form the propulsion system; the thermal system design which is very tightly coupled to the heat losses of the EPS; the aerodynamics and structure which impacts on the electrical power required from the EPS to provide sufficient thrust, and the volume available for the EPS. This leads to a number of inter-system design trades.

For example, for the ECO-150, a significant challenge outlined in the literature is the design of the wing [21] to include the electrical power system. In particular there is very little physical space available. The EPS Modelling Framework provides a route to sizing a number of different approaches to the EPS design and indicating what the minimum volume required for the electrical equipment is. If it is found that the ring-radial approach is necessary to meet reliability requirements, this may require revision of the structural wing design, to provide physical space for the cable that forms the ring element of the ring-radial architecture. An alternative approach may be to closely integrate the EPS with the structure of the wing to provide reduced volume and extra freedom for the EPS architecture design, allowing for the inclusion of the additional cable forming the ring element of the radial-ring architecture in Fig. 9.

Secondly, the HRG approach for the ECO-150 based system has been chosen to allow for a fault ride through capability. This approach requires overrating of equipment and additional insulation requirements for faulted operation. This will increase the volume of the EPS. Therefore, there is a further inter-system design trade to take place between the structural design and the EPS design.

VI. Conclusions and Future Work

The EPS Modelling Framework provides an efficient pathway for the design of the EPS for a range of different platforms and applications, which meets both performance and functionality requirements. When applied to future, concept electrical propulsion aircraft which have no established baseline EPS, the Modelling Framework provides a rapid performance assessment of outline architectures using generic technologies, and then provides a pathway to enable more specific equipment choices and transients' assessment. Ultimately this supports the creation of roadmaps, both at a technology and systems level, for the design of concept aircraft which meet performance requirements within a target timeline.

The EPS is one of a number of interdependent sub-systems which combine to form the full aircraft system. The Modelling Framework can take requirements set at this platform level, and translate them into EPS requirements at both performance and dynamic functionality levels. At the top level, performance level outputs provide requirements for non-electrical systems. Hence a future step for this work, is to integrate the closely interdependent non-electrical systems, such as thermal and structural, into a systems level framework, which enables inter-system trades of top-level performance requirements.

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