

An Optimisation Based Design Approach for Aircraft Electrical Power Systems

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ABSTRACT

The More Electric Aircraft (MEA) concept coupled with recent advances in power electronics has seen an increasing number of on-board tasks being facilitated by electrical power, as opposed to more conventional hydraulic, mechanical and pneumatic power systems. The migration to a predominantly electrical power system is expected to bring significant cost and performance benefits; however, the devices used to facilitate this change have led to an increasingly complicated electrical power system with heightened levels of system sophistication and interdependence. These developments have the potential to drastically alter the solution space of all feasible aircraft Electrical Power System (EPS) designs. The technological advancements facilitating the MEA progression have allowed for a broader range of design solutions to exist that increase the size of the solution space. Meanwhile increasing system sophistication has led to an increasingly non-linear and complex solution space. Optimal solutions in this setting are unlikely to be formed by simply modifying legacy designs. Therefore this paper proposes adopting an optimisation based design approach; one capable of effectively searching the optimisation landscape. This approach utilizes two distinct capabilities; firstly, an automated assessment framework capable of evaluating the performance of a design solution across a range of several design objectives and secondly a heuristic based optimisation procedure. A case study is then introduced in order to highlight the benefit of the proposed design approach.

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INTRODUCTION

Recent years have seen the MEA concept being explored further in the design of aircraft power systems [1]. Advances in the fields of power electronics, electric drives, control electronics and micro processing have enabled a gradual transition from the use of mechanical, pneumatic and hydraulic power towards the use of electric power to drive aircraft subsystems [2]. Subsystems which have already seen a migration towards electric power include flight controls and pumps [3]. In the near future subsystems will continue to adopt electrical power, such as: anti-ice systems; starters and generators; braking and air conditioning [3]. This transition towards a MEA has brought about significant performance benefits that primarily stem from a reduction in the overall complexity of the aircraft power system, enabling improvements in weight, reliability, efficiency, downtime and fuel-consumption. This development has magnified both the size and the criticality of the aircraft EPS and has prompted an increase in the level of complexity, system sophistication and interdependence.

Meanwhile, advances in the field of high power contactors, solid state switching devices and micro-electronics have enabled new concepts in electrical power distribution [4].

Recent research has identified the benefits and challenges of adopting these new concepts within aircraft Electrical Power Distribution System (EPDS) architectures, this has included the incorporation of:

- higher voltage level architectures [5];
- variable-frequency power supply architectures [6];
- advanced energy storage techniques [7]; and
- fuel cells [8].

Current design trends have seen the employment of these concepts with the A350 and B787 employing higher voltage architectures and the A380 adopting a variable frequency architecture. As a result of these developments the design of aircraft EPDSs and the subsequent integration with wider aircraft systems is an increasingly critical and complex combinatorial problem. Recent research has identified the need to quantify the potential benefits of new architectures; several attempts have been made at quantify the weight benefits of HVDC architectures [5][9]. The range of design objectives with which an aircraft should be assessed across has also been discussed [10].

This paper expands on this work by introducing a framework capable of assessing electrical power system distribution architectures across a range of design objectives. The framework introduced assesses solutions in an automated fashion, allowing fast and repeatable evaluation of design solutions.

The framework is combined with an optimisation procedure to enable exploration of the solution space of all candidate solutions. The optimisation procedure deployed is that of a Genetic Algorithm (GA); this has been selected due to the success of GAs in tackling similar design problems with solution spaces exhibiting comparable levels of complexity, non-linearity and non-convexity [11]. The concept of Pareto-optimality [12] is adopted as a means of comparing competing candidate solutions; this allows the inherent trade-offs between competing design objectives to be analyzed.

A case study is presented in order to highlight the benefit of the proposed design approach. The problem identified is that of designing a distribution system capable of providing power to a series of loads from two main engine generators. This problem is appraised with regards to two design objectives; that of weight reduction and reliability improvement. The range of Pareto-optimal trade-offs available in this design problem is outlined and several Pareto-optimal candidate solutions are fully detailed. The paper concludes by discussing the limitations of such an approach and offering a range of suggestions capable of addressing these shortcomings.

DESIGN OBJECTIVES

The objectives involved in an aircraft EPDS design problem vary subject to the technical-nature and purpose of the aircraft. From an engineering perspective the design objectives under consideration will include [10][13]:

- reduce cost;
- reduce size and weight;
- reduce design complexity;
- increase reliability;
- increase availability/reduce downtime;
- increase fuel efficiency;
- increase power density; and
- increase thermal robustness.

The performance of a design on this range of objectives determines its quality as a solution. To aid clarity, the assessment framework introduced here only considers several of the most vital design objectives. Specifically, the design objectives considered are reduction of converter weight, reduction of cabling weight and the improvement of systems level reliability.

A. Reduction of Weight

In 2007 fuel costs accounted for 26% of airline's operating costs [14]. Reductions in weight directly reduce the fuel required for an aircraft to perform its function; therefore the continued reduction of weight is a key design driver in modern aircrafts. For example, the reduction of 1kg in weight will save a small to mid-range aircraft approximately \$4500 over a lifespan of 20 years [9]. With this in mind the aviation industry has recently joined the European Union Emissions Trading System (EU ETS) [15], further incentivizing the reduction of weight and hence the reduction of associated emissions.

Quantifying System Weight

The total weight associated with an EPDS design can be described as the linear sum of the system's component weights. The EPDS is composed of the following components;

- Cabling
- Power converters
- Contactors
- Control systems
- Cooling systems

Power cabling and power conversion account for the majority of weight in EPDSs. Gohardani, Douleris and Singh [16] note that for a baseline 300-seater aircraft power cabling and power conversion account for 83% of the EPDS weight¹. This translates as an approximate ratio of combined weights of cabling and converters to contactors, cooling systems, protection systems and control systems of 4:1. Incorporating this approximation this framework proposes evaluating the simplified total systems weight, W as:

$$W_{system} = 1.2 \cdot (W_{cab} + W_{con}) \quad (1)$$

where W_{cab} describes the weight of the cabling and W_{con} describes the weight of the power converters.

Cabling

The weight of cabling is calculated in this automated framework on a branch by branch basis using:

$$W_{cab} = \sum_{b=1}^{n_branch} N_b l_b W_g \quad (2)$$

where n_branch describes the total number of branches; l_b refers to the relative distance between components connected by a branch (m), and W_g refers linear mass density of the required wire (kg/m); and N_b is the number of cables required in a given branch - a DC transmission branch requires two (with positive and negative polarity) and AC transmission

1. This framework is interested in the design of the distribution network and as such this figure excludes the weight implications of generators and motors.

requires three phases and therefore three cables². The linear mass density required for each branch is related to the required wire gauge; this is governed by three factors:

- the maximum continuous current the branch is exposed to under normal operating conditions;
- the allowable voltage drop over the length of the branch; and
- temperature considerations.

This automated framework evaluates the minimum gauge required to satisfy each of these three factors and the largest of these represents the minimum acceptable wire gauge.

The current carrying capacity of a wire must at least allow for the maximum continuous current the wire is exposed to. This framework performs detailed power flow studies to allow the maximum continuous current through each branch to be evaluated³. In practice, the protection device dedicated to upstream loads would also protect the wire. Therefore, the installed wires current carrying capacity must exceed the overcurrent protection setting:

$$I_{c_max} \leq I_p \leq I_w \quad (3)$$

where I_{c_max} is the maximum continuous load current, I_p is the over current protection setting and I_w is the current carrying capacity of the wire. Currently this framework incorporates this necessity by simply oversizing sizing cables at 110% of I_{c_max} .

On-board load consumers have an input voltage tolerance range, dropping below these tolerance levels can lead to load failure; therefore maximum voltage drops from source to load are specified within aircraft EPDS standards [18]. In order to ensure these standards are met this framework evaluates maximum voltage drops across all branches using:

$$V_{DC} = 2I_w R_w L_b \quad (4)$$

$$V_{3\phi AC} = \sqrt{3}I_w (R_w \cos \phi + X_w \sin \phi) L_b \quad (5)$$

which describe the voltage drop on a DC branch and AC branch respectively; where I_{c_max} is the maximum continuous load current (amps), I_b is the cable length (m), R_w is the DC resistance of the cable (Ω/m), X_w is the reactance of a cable (Ω/m) and $\cos \phi$ is the load power factor (pu). The maximum voltage drop of each branch is then analyzed in context of the paths these branches form between power sources and power loads to ensure voltage drop standards are satisfied.

Power Conversion

This framework calculates the total converter weight as the linear sum of the weight of all converters deployed throughout the EPDS. This is expressed mathematically as:

$$W_{con} = \sum_{i=1}^{n_{conv}} W_{i_conv} \cdot P_{i_max} \quad (6)$$

where: n_{conv} describes the number of converters, W_{i_conv} is the power to weight ratio of the i th converter and P_{i_max} is the maximum power converted by the i th converter. Extensive power flow studies allow P_{i_max} to be calculated for each branch³.

B. Improvement of System Reliability

The provision of electrical power is critical to the safe flight of modern aircrafts [20]. This criticality is heightened as the MEA concept increases the role and size of the electrical power system. Large civil aircraft must adhere by stringent certification standards which require the electrical power system to meet specific levels of reliability [21]; Table 1 outlines these requirements. For instance, the probability of the occurrence of a catastrophic failure must be less than (or shall not exceed) 1×10^{-9} Faults per Flight Hour (FFH). Improved reliability also increases aircraft availability and decreases downtime, improving profitability and reducing maintenance costs. Improving system reliability is therefore considered a vital design objective.

Table 1. Failure classification and safety objectives for large civil aircrafts [21]

Failure classification	Safety objectives	Probability of failure(FFH)
Catastrophic	Required	$< 1 \times 10^{-9}$
Hazardous	May be required	$< 1 \times 10^{-7}$
Major	May be required	$< 1 \times 10^{-5}$
Minor	Not required	None
No safety effect	Not required	None

Quantifying System Reliability

The measurands introduced in this framework to describe the reliability of an EPDS design solution relate to electrical power system certification standards [21]. These standards recognize that on-board loads have varying levels of importance; as such loads with different failure condition classifications must meet different standards (see Table 1). Therefore this framework proposes a measurand for each failure classification condition which must meet a specific standard. These three measurands are thus: catastrophic (R_{cat}), hazardous (R_{haz}), and major (R_{maj}). A further reliability measurand is introduced detailing the

2. It is assumed that the aluminum fuselage acts as a return conductor for both AC and DC transmission [17].

3. Automated power flow studies are empirically undertaken for each configuration of the system; accounting for varying power requirements and network redundancy configurations. (3)