

A Method for the Evaluation of the Effectiveness of Turboelectric Distributed Propulsion Power System Architectures

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ABSTRACT

Radical new electrically propelled aircraft are being considered to meet strict future performance goals. One concept design proposed is a Turboelectric Distributed Propulsion (TeDP) aircraft that utilises a number of electrically driven propulsors. Such concepts place a new and significant reliance on an aircraft's electrical system for safe and efficient flight. Accordingly, in addition to providing certainty that supply reliability targets are being met, a contingency analysis, evaluating the probability of component failure within the electrical network and the impact of that failure upon the available thrust must also be undertaken for architecture designs. Solutions that meet specified thrust requirements at a minimum associated weight are desired as these will likely achieve the greatest performance against the proposed emissions targets. This paper presents a Fault Tree Analysis (FTA) based design approach for the electrical system and thrust reliability analysis of TeDP aircraft architectures. This approach extends beyond the single failure rate provided by traditional FTA methods by profiling the reliability and thrust provision of each possible system configuration (i.e. following the failure of one or more components), which combined with a measure of total system weight and volume provides an effective design capability. The paper presents a case study for a TeDP design configuration showing how Thrust - Reliability (TR) dispatch targets may be achieved using a contingency analysis method utilising k-out-of-n probability and concludes by discussing plans to build upon the described work and utilise the method for more complex studies.

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INTRODUCTION

With the continuing increase in oil prices and stricter legislation governing fuel emissions into the environment [2], it has become necessary to design aircraft with a greater level of efficiency both in terms of shape, emissions and fuel burn. Aircraft efficiency improvements have been standardised in the form of short (N+1), medium (N+2) and longer term (N+3) goals as defined by NASA [3] [4]. Due to the timescale for the long term goals (new technologies are required to be at TRL 4-6 by 2030), the potential exists for a wide range of unconventional and novel aircraft concepts to be considered. In order to meet the N+3 goals as identified in [4], a Blended Wing Body (BWB) aircraft, powered by Turboelectric Distributed Propulsion (TeDP) is subject to intense study. TeDP is an encouraging design approach which offers a potentially highly reliable supply of propulsive power, even in the event of a single engine failure [5].

Power supplied to the high power propulsion motors utilised in TeDP systems must be of similar reliability to that provided for the traditional low power critical loads (such as avionics) in present day aircraft [6]. Necessary to achieving supply targets for current systems is the use of battery backup; however, the provision of reliability through additional supply for high power

loads, either through dedicated generators or bulk energy storage, is inefficient in terms of weight. A more effective solution appears to be to provide interconnectivity within the electrical system architecture and utilise available capacity in the generation mix, the drawbacks of this approach however include greater system complexity and dependency. Achieving the required reliability targets with minimal weight penalties and system complexity in TeDP systems therefore is a significant design challenge, placing new requirements on previously adequate design approaches. The associated optimisation problem should ideally provide a measure of the effectiveness of system redundancy in maximising available thrust whilst minimising system weight. More specifically, it is desirable to evaluate the available thrust provided by an architecture and its associated reliability for a broad range of system configurations, (i.e. following single and combination failures), which combined with a measure of total system mass and volume provides an effective design and rapid prototyping capability.

This paper considers these TeDP system evaluation requirements in more detail and proposes a method to provide the desired electrical functionality. Detailed descriptions of these concepts are supported through a demonstration case study to illustrate both functionality and the value added by the

approach on design and analysis capabilities. Finally this paper concludes by examining options to further enhance the methodology to complete network trade studies and determine the effects of component substitution.

THE TeDP CONCEPT

A Review of the TeDP Concept

The TeDP concept features a number of electrical propulsors, located along and spanning the aft of the airframe [7] as shown in Fig. 1. The propulsion motors can be electrically connected to a number of wingtip generators using a superconducting DC system which allows the generator and motor shaft speeds to be decoupled and minimises electrical losses [6]. Using electrical connections in this manner allows the electrical system to be used as a gearbox, with the addition of power electronics, providing a variable ratio [7]. DC transmission is further used to address synchronisation challenges when interconnecting multiple generators on a single bus [8]. The motors of the TeDP system are configured in such a fashion that if one motor or supply bus should fail, symmetrical thrust may still be maintained [7].

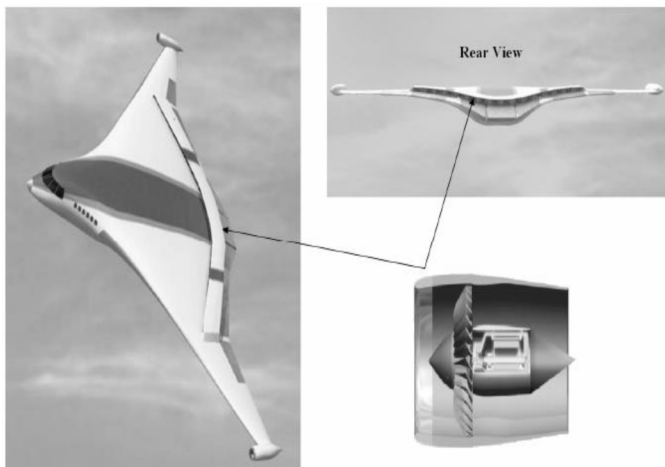


Fig. 1. TeDP Aircraft Concept [1]

In order for the TeDP concept to be competitive with more conventional propulsion system designs, the use of superconducting machines with power densities significantly in excess of the 3-4 kW/kg typically associated with current technologies will be required [8]. Cryogenic coolers are also needed to keep the temperature of the superconducting system within the required operating range [1], adding further weight to the system, detracting from available mass intended for other more commercial purposes.

Evolution of Aircraft Power Requirements

A key distinguishing factor between current more-electric aircraft (MEA) and TeDP network architecture designs is the power level at which critical loads must be supplied [7]. Specifically, the power supply to the high power propulsion motors in TeDP systems must be of similar reliability to the

traditional low power critical loads, such as the avionics in present day aircraft. In line with the increased power levels of the aircraft, the voltage levels are expected to rise accordingly. Specifically, the highest voltages utilised in the MEA generation of aircraft are ± 270 VDC and 230 VAC with current levels in line with these. Although there are no firm voltage levels for the TeDP concept aircraft yet, these will reflect the anticipated superconducting system current carrying capabilities [9].

TeDP Electrical Network Architecture

One proposed network architecture for the TeDP concept is shown in Fig. 2. This is the NASA N3-X baseline architecture [6, 10].

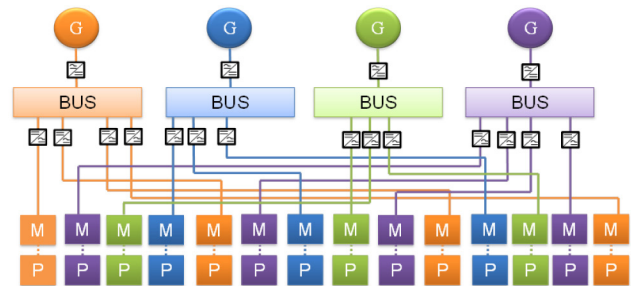


Fig. 2. N3 - X Baseline Architecture

As well as the airframe as illustrated in Fig. 1, the network architecture of the TeDP concept is radically different to conventional aircraft and MEA. For this particular architecture, the generators are interfaced to a DC distribution network via power converters. This power is then routed and conditioned via power busses and converters to individual motors and propulsors. Fig. 2 shows the physical configuration of the propulsors on the aircraft, illustrating how the provision of symmetrical thrust is maintained in the event of a single engine failure or loss of two generators. This network could be adapted through the inclusion of bus ties and additional redundant feeders, providing greater reliability of supply at the expense of adding additional network complexity.

TeDP DESIGN AND ANALYSIS REQUIREMENTS

SAE standard, SAE 4761, provides guidelines and methods for performing safety assessments for the certifications of civil aircraft [11]. One such tool as described by this standard is Fault Tree Analysis (FTA) which uses probability and logical operators to determine whether candidate network architectures meet specified parametric requirements [12].

One particular example of the use of FTA in the aerospace sector is determining the ability of a set network to meet the Civil Airworthiness Authority (CAA) requirement that catastrophic failures (e.g. leading to the complete loss of an aircraft) should occur less than once in 10^9 flight hours [13].

Hence the failure rate of components or combinations of components which would result in this occurrence must be less than 10^{-9} per flight hour.

For TeDP systems, the key reliability requirement is that any failure or series of failures which leaves the aircraft with less than 30,000 hp of rated thrust [6] (the minimum required for safe rolling take off for the aircraft size in consideration) should occur with a probability of less than 10^{-9} per flight hour [10]. Given that individual electrical components are unlikely to be this reliable, this target is expected to be achieved through the overrating of system generation components and provision of system redundancy. The process of assessing of the effectiveness of these measures to deliver the required thrust reliability is called contingency analysis. This is explored in further detail in the next section.

CONTINGENCY ANALYSIS

In a conventional utility grid setting, contingency analysis is used to determine the potential overloading in a network branch following the outage of a network line, usually focusing on the MW power flow before and after a contingency plan has been implemented [14]. Similarly when applied to TeDP, the flow of power before and after the contingency plan has been introduced is considered in addition to weight penalties. In an aircraft context, any network architecture should ideally exhibit the minimum possible take-off weight for the highest possible provision of power under any network outage scenario [8]. The effectiveness of contingency measures such as the oversizing of components or the addition of redundant feeders in enabling that particular design to meet the thrust probability specification are determined. The evaluation of the impact of such contingency measures on system mass and volume enables the most weight effective contingency measures or combination of measures to be determined, ultimately facilitating the optimisation of architecture designs. The following subsections illustrate an example TeDP contingency analysis.

Network Trade-Offs

One of the key design considerations for TeDP applications is determining the optimum number of generators and propulsors to produce the required propulsive power and deliver this as thrust. For example, it may be possible to employ two generators and just six motors in an architecture design (as illustrated in Fig. 3). However, unless the reliability of the network components is sufficiently high, it will be necessary to overrate generation and thrust providing components such that the required level of thrust is still delivered even following the failure of a number of key components.

Owing to the small number of generators and propulsors, considerable oversizing may be required to meet this requirement, resulting in significant weight penalties. Other architectural variations with a greater number of generators and propulsors may offer a lower weight solution.

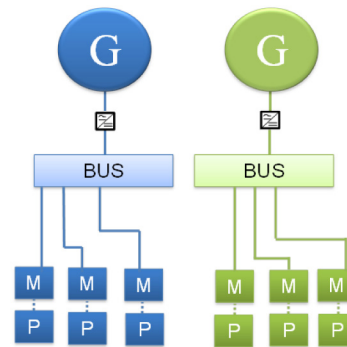


Fig. 3. An Example TeDP Network with Two Generators

Failure Scenarios

A key aspect of determining the required overrating of select network components is the evaluation of failure modes within the TeDP network and the probability of each failure event occurring. The architecture suggested in Fig. 2 for example, may have a number of failure modes including; failure of a motor, propulsor or motor feeder as illustrated in Fig. 4, failure of a generator or bus, Fig. 5, or failure of an engine, Fig. 6. The level of component overrating required in each of these cases would be dependent on the likelihood of these failure modes occurring more frequently than is specified in the minimum thrust requirements. For example, if it is likely that an engine will fail more than once in every 10^9 flight hours, then the architecture components for a two-engine TeDP aircraft will need to be rated to supply 30,000hp with only half the system available. In order to fully understand the required overrating of components and the impact of each failure mode, thrust-reliability trade-offs must be considered and an aircraft specific contingency analysis must be completed.

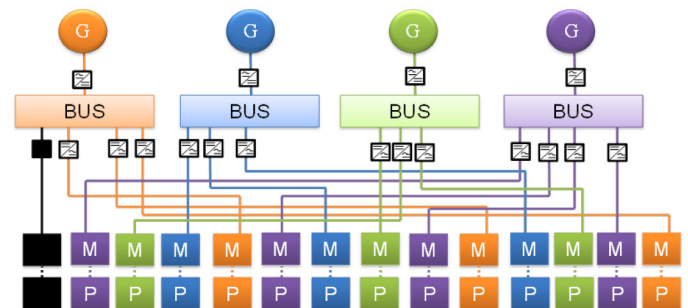


Fig. 4. TeDP Network Illustrating Loss of a Single Motor Feeder

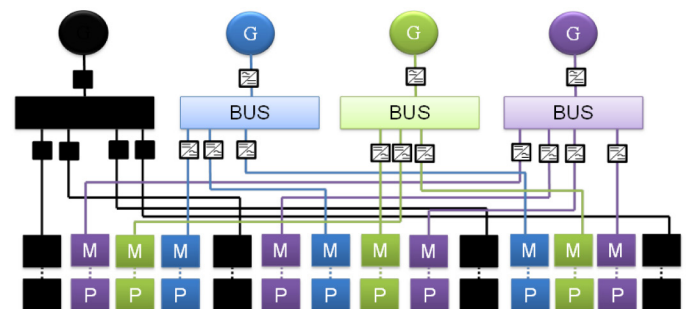


Fig. 5. TeDP Network Illustrating Loss of a Bus or Generator, Causing Loss of thrust