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Hybrid Electric Aircraft: State of the Art and Key Electrical System Challenges

1. Introduction

In both Europe and the USA, the aerospace sector is actively pursuing revolutionary design concepts to further improve the environmental impact of air travel. This is partly a result of increasing pressure on the industry from government and other organisations to reduce emissions, despite the continuing increase in air traffic [1]. The aggressive targets set by NASA and the EU [1, 2, 3] (e.g. the Advisory Council for Aviation Research and Innovation in Europe has a target of a 75% reduction in CO2 emissions and a 90% reduction of NOx emissions by 2050) cannot be achieved through marginal improvements in turbine technology or aircraft design. Rather, disruptive technologies and more innovative aircraft must be considered.

Hybrid electric aircraft are being seriously considered as one of these revolutionary design concepts. Such aircraft require a significant increase in on-board power generation capability, from 1.5 MW on a current state-of-the-art more-electric aircraft (i.e. the Boeing 787), to 25 MW upwards for a hybrid electric aircraft. This requires significant development both in the design of appropriate aero-electrical power systems and in the development of appropriate technologies to enable these aero-electrical power systems to be realised within the proposed 25 year time frame [2].

2. What is a hybrid electric aircraft?

Hybrid-electric aircraft have gas turbine engines which drive electrical generators to power electrically motor driven fans. Depending on the variant of hybrid-electric aircraft being considered, thrust may be provided via a combination of gas turbines and electrical propulsors, or only via the electrical propulsors [3]. This design philosophy is not new, and in fact is commonly found throughout industry in rail, marine and electric vehicles. Within these sectors electrical propulsion has been shown to have a number of benefits [4], including:

- Improved efficiency, particularly at part load
- Use of excess power generation for power supply to auxiliary loads such as pumps or pressurisation systems
- Greater flexibility in location of electrical loads
- Reduced volume of machinery
- Reduced vibration and noise

In principle the overall structure of a hybrid electric aircraft could be similar to conventional tube and wing designs (although more novel blended wing body aircraft or tilt rotor designs are being considered [3],[5]), with gas turbine engines used for electrical power generation for driving electrical propellers. An example of a hybrid-electric aircraft design concept for a nine passenger regional aircraft is shown in Figure 1. For this type of aircraft, it is claimed that electric propulsion and autonomy technologies can decrease total operating costs (by up to 30%), noise and emissions [6].

Figure 1: NASA SCEPTOR hybrid concept [6]

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One of the most significant benefits associated with hybrid electric aircraft is the flexibility in configuration and operation. For example, the electric propulsion can be used continuously throughout flight or for specific sections of the flight plan where the power demand is higher. Furthermore, there is the possibility to integrate appropriate energy storage systems alongside the gas turbine driven generators in order to fully optimise system performance. The inclusion of such systems also introduces a level of inherent redundancy.

Furthermore, hybrid aircraft represent an opportunity to increase aerodynamic efficiency. By means of propulsors integrated into the body of the aircraft, Boundary Layer Ingestion (BLI) can be effectively used to re-energise the wake behind the aircraft, reducing drag. This stipulates the placement of the propulsors typically towards the rear. Some designs seek to further exploit this effect by placing propulsors on top of the fuselage so that the aircraft itself forms a sound barrier [3]. Thus the use of hybrid electric propulsion offers gains in efficiency and noise reduction – both of which are key goals for next generation aircraft.

However, significant challenges do exist for the realisation of hybrid electric aircraft given the significant upscaling of electrical generation and distribution on-board.

The efficiency of aircraft is far more sensitive to weight than other applications where hybrid technologies have been employed. Traditionally electric components struggle to match the power density of their mechanical equivalents (particularly at higher power levels) and therefore any potential the weight penalty which comes with the addition of electrical components must be offset by the resulting gains in efficiency and reductions in noise in future hybrid electric designs.

Hybrid electrical propulsion also inherently adds losses to a system through the intermediate use of electrical power. The efficiency of the electrical-mechanical power conversion and the electrical distribution system, as well as the size of associated systems to deal with these losses (e.g. the thermal management system), will have a significant bearing on the viability of any hybrid electric aircraft design.

Beyond these two fundamental issues lie a range of electrical technology and integration issues. Some of the most significant of these are outlined in the following sections.

3. Key electrical architecture design questions

From the authors' perspective two key electrical architecture design questions exist, the answers to which will have a significant impact on the future direction for hybrid aircraft electric development. These are outlined below.

Should hybrid electric aircraft use superconducting or non-superconducting electrical power systems?

Superconducting electrical systems were initially proposed to enable efficiency and power density targets to be met. In particular, superconducting machines have the potential for significantly higher power densities than is possible with conventional designs [7]. Additionally the benefits of a cryogenic electrical system would be significant: the use of superconducting materials. For example the associated removal of Ohmic losses in superconducting cables enables power transmission at negligible losses.

A number of research programmes have looked at aircraft with superconducting electrical systems. One such NASA funded study [8], which the authors were involved in, investigated the electrical system architecture options for an aircraft with an electrical propulsive system with total on-board generating capability of 50MW. The study enabled the performance (in terms of weight and efficiency) of potential electrical power system architectures (with assumed improvements in electrical component performance) to be compared. The studies highlighted that the relatively poor power density of the associated cryogenic cooling system adds significant weight to the aircraft platform and amplifies the effects of electrical losses on the network. This was a particular issue in networks containing solid state switching components. Full results from this study are shown in [8].

With the target date to achieve aircraft which meet the improved environmental targets drawing closer, focus has moved towards non-superconducting systems, as companies involved look to achieve these types of systems in the nearer term and belief in their feasibility has grown [9] (albeit with the necessity for significant technology development). Current examples include the NASA SCEPTOR hybrid concept as shown in Figure 1 and the DARPA funded LightningStrike aircraft [5]. This is an experimental aircraft programme, involving Aurora Flight Sciences, Rolls-Royce and Honeywell, looking to demonstrate the use of distributed hybrid-electric propulsion for a Vertical Take-Off and Landing aircraft.

Should hybrid electric aircraft use AC distribution or DC distribution?

Initial power system architectures for turbo-electric distributed propulsion aircraft favoured DC for the electrical network [3, 8]. A significant benefit of DC distribution is that it allows electrical decoupling between electrical machines which enables the generators and propulsor motors to be run at their optimal speeds, without the need for a mechanical gear box.

However, significant challenges exist in terms of efficiency for DC networks given their dependence on solid switching components [8]. A DC system (assuming AC generators) would require at least two conversion stages with multiple converters for the array of electrical machines. Hence losses from the power electronic converters may be significant [10]. As discussed above, these losses impact on the thermal management system adding weight and reducing overall system efficiency.

AC synchronous systems have also been considered by projects such as the UK DEAP programme [7, 12]. The advantage of such a system is the removal of solid state switching losses, and the associated thermal management system requirements, which studies have indicated significantly improves the overall system performance [7, 10]. The main disadvantage of this system is the electrical coupling between electrical machines (generators and motors), reducing the level of controllability within the system. In particular, consideration would need to be given to maintaining stability should a motor fail and cause an imbalance of thrust.

Appropriate levels of controllability are likely to be achieved in an AC synchronous system via mechanical, rather than electrical, methods. Potential solutions to this include the use of variable pitch fan blades on the propellers (these would enable the motors to run at constant speed, with fan pitch dictating the amount of air upon which they act and hence the propeller output power) and mechanical gear boxes enabling generators to run at optimal speed.

4. Technology and systems integration enablers

There are a number of areas where significant electric technology development and systems integration understanding is required to enable hybrid electric aircraft to be realised. A few key areas, based on the authors' understanding and experience, are highlighted below.

Higher voltage power distribution

Within current state of the art more-electric-aircraft, the maximum voltage levels utilised are ±270VDC or 230VAC. Despite the growth of electrical generation voltages on aircraft, these voltage levels have remained relatively low (compared to ground based applications at least) because of concerns about breakdown voltages at higher altitudes.

However to enable lightweight design at the power levels required for hybrid electric aircraft, it is likely that these voltage levels will need to be increased substantially [13]. This will not only help to minimise the size and weight of conductors but also potentially increase the power density of machines and power electronics. For example, aligning voltage more closely with other related applications (e.g. other transportation applications) it may enable the aerospace sector to better capitalise on design improvements in other areas as well as minimise cost of components.

High power density electrical machines

By their very nature hybrid electric aircraft will contain multiple electrical machines, either for power generation or for driving propulsion fans. Power dense design and highly efficient operation of these machines is therefore fundamental to the feasibility of these aircraft types. Based on targets provided by Airbus for their hybrid electric concepts, the power density of electrical machines will need to improve by around four times that currently achievable for aircraft systems [9], with an overall target of between 10 to 15 kW/kg by 2030.

Siemens have already taken steps towards achieving this goal with their recent demonstration of a 260kW, 50kg electric motor [14]. The company view hybrid electric as a future area of business and aim to use this motor design as a basis for developing hybrid electric propulsion systems for regional aircraft.

Highly efficient and power density power electronics

As discussed above, debate continues around the role that power electronics will play in future hybrid electric aircraft. While they can offer controllability benefits this currently comes at a substantial cost in terms of system losses.

As shown in the NASA study [8], substantial improvements in component efficiency is required if large scale use of power electronics is going to be feasible. Within literature, efficiency targets are in the order of 99.8% [3, 10] for hybrid electric systems containing superconducting networks.

Energy dense energy storage

Energy storage could provide a range of functions for future aircraft platforms ranging from managing short term transients or electric taxiing to supporting some or all or the aircraft’s propulsion for parts of the flight cycle. Therefore the availability of energy storage with the appropriate energy density would open up a number of architectural design and energy management opportunities.

Again however significant challenges exist for these opportunities to be realised. Figures from Airbus highlight that energy density needs to improve by around six times from the current state of the art, with an overall energy density target of around 500 to 700 Wh/kg for their hybrid electric concepts.

Fault management strategies for high power aircraft systems

The scale of the electrical power increase for hybrid electric networks and the increased dependence on the electrical network for flight increases the criticality of effective fault management in the electrical system. When designing a fault management system, there are two main aspects to consider: the isolation of electrical faults (e.g. short circuits or arcing faults), to prevent damage to electrical components or there adjacent environment, and the management of failure conditions which can lead to a degradation in electrical performance, e.g. a loss of thrust.

Considering electrical faults, the power generation levels on hybrid aircraft coupled with the potential use of energy storage devices means that any electrical fault has as much greater available fault energy. It is therefore important that electrical faults are quickly contained. This has implications for both fault detection schemes and protection devices such as circuit breaker technologies and fault current limiters. The availability of these protection devices (at appropriate power density levels) may be a significant factor in overall system design. If circuit breakers with appropriate power density and voltage ratings cannot be developed in the required timeframe then the inclusion of fault current limiters or current limiting power converters may become more attractive. An example of how current limiting converters can be applied to help manage system protection within hybrid electric aircraft is provided by GE in reference [15].

The design of the electrical architecture and its associated redundancy will also have a significant impact on the availability of thrust following a failure of an electrical system component. Key to the safe operation of the aircraft is that the electrical power system must be robust and have fault ride-through capability. The way this is best and most efficiently achieved will strongly depend on where thrust is derived from on the aircraft (i.e. gas turbine and electrical propulsion or only electrical). For example, the electrical thruster fan on the NASA designed STARC-ABL concept accounts for only 20 % of the total thrust at the rolling take off (RTO) point and 44 percent of the thrust by the time the aircraft has reached top of climb (TOC) [16]. Other hybrid aircraft may require an altogether different distribution of thrust, depending on the aircraft configuration. In terms of the electrical system design, there must be a trade-off between the benefit of having a variety of power sources and power paths available (as well as redundancy at the propulsors themselves) against the weight penalty (and possible thermal load) associated with the additional components required to provide this functionality.

5. Next steps for hybrid electric aircraft

While a number of substantial challenges exist for the design of hybrid electric aircraft systems there is a growing belief within the industry that hybrid electric aircraft can deliver substantial benefits, particularly for smaller scale regional aircraft [6, 13].

Recent investments in demonstrator programmes (e.g. NASA SCEPTOR [6] and DARPA funded LightningStrike aircraft [5] discussed earlier) mean that we may begin to see these aircraft in flight within the next few years. Large scale ground based demonstrations are also planned through the EU funding initiative Clean Sky 2 [17]. These ongoing initiatives should reveal the long term feasibility of hybrid electric designs and whether these revolutionary design concepts will become reality.

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