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Barriers and Challenges Going From Conventional to Cryogenic Superconducting Propulsion for Hybrid and All-Electric Aircrafts

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Abstract: The development of electric aircrafts is becoming an important technology for achieving the goals set by the European Commission for the reduction of gases emissions by 2050 in the aeronautical transportation system. However, there is a gap between the values of specific power in commercial electric machines and the ones required for aeronautical applications. Therefore, the search for alternative materials and non-conventional designs is mandatory. One emergent solution is using superconducting machines and systems to overcome the current limits of conventional electrical machines. This work reviews the tendencies in the new hybrid and all-electric aircrafts, complementing it with recent research on the design and development of high specific power superconducting machines. This includes the main topologies for hybrid and all-electric aircrafts, with an overview of the ongoing worldwide projects of these types of aircrafts, systematizing the main characteristics of their propulsion systems. It also includes the research on superconducting machines for the purpose of high specific power, considering the impact on the redesign of aircraft systems in the electrical, cooling, and fuel source sense.

Keywords: Review; Electrical Machines; Superconducting Machines; Hybrid-Electric Aircraft; Propulsion Design; All-Electric Aircraft; Specific Power;

1. Introduction

In 2011, the EU published the Flightpath 2050: Europe's Vision for Aviation report, setting goals for commercial aircrafts for 2050 [1]. The goals are to reduce 75% in CO_2 emissions, 90% in NO_x and 65% in noise emission due to flying. In 2019, NASA also set similar goals, but for 2035 [2]. To meet these goals, the Advanced Research Projects Agency - Energy (ARPA-E) started in the same year a funded project for the development of an all-electric aircraft, with clear targets for efficiency, specific power, power, speed, and costs [3]. These two long-term projects incited worldwide research to develop Hybrid-Electric Aircraft (HEA) and All-Electric Aircraft (AEA) systems.

The research of aircraft electrification has been around since the 1980s. NASA issued a technical report in 1985 [4], detailing a study in which replacing several conventional systems with electrical ones reduces the aircraft's empty weight by 10%, consequently reducing required engine thrust and fuel consumption 13% and 9%, respectively. This electrification first started by electrically controlling the surface actuators, such as ailerons, elevators, rudders, and spoilers. These systems were previously manually controlled using mechanical and hydro-mechanical systems [5]. Another development towards electrification was the replacement of hydraulic systems by electrical equivalents. These increased the electric power requirements, increasing the need for more available power and thus the need to increase the number/volume of energy sources [6]. However, the advantages of using electrical systems are relevant. The reduction in weight and fuel consumption as stated above and reductions in engine noise and emissions are possible with electrical systems, increasing the overall efficiency in the aircraft's powertrain [4,5]. This initial research served as a stepping stone for more exhaustive research in power electronics, fault-tolerant power distribution systems and electrically driven actuators for the More Electric Aircraft (MEA) [5,7–11]. Successful implementations of the MEA are the Boeing 787 [12], and the Airbus A380 [6], with variable frequency starter-generators mechanically coupled to the aircraft jet engines. The starter-generators, coupled with a battery pack, provide all the electric power needed, successfully electrifying most aircraft systems.

With the successes of Boeing and Airbus, and combining with the policies for 2035 and 2050, the aeronautic industry is turning to hybrid and electric solutions for commercial aircrafts. Although there is extensive knowledge and research in these areas, few projects and companies invested in electric solutions. Also, there is still a proper gap between the values of specific power in commercial electric machines and the ones required for aeronautical applications. Therefore, the search for alternative materials and non-conventional designs is mandatory. One emergent solution is using superconducting machines (SMs) to overcome conventional electrical machines' current specific power limits. Although there is research on SMs for aircraft applications and a wide range of articles on the HEA and AEA subjects with the possibility of using SM technology, fewer analyze this through an integrative view involving the electrical machine, the cooling system, and new types of energy sources. Taking this view into account, the objective of this review article is to analyze research on superconducting electrical machines but now considering their impact on the redesign of aircraft systems: electrical, cooling and fuel source type.

This article is structured in the following way: first, it is made a review of HEAs and AEAs. The differences from conventional aircrafts are shown, and the most common proposed topologies are presented. Afterward, an overview of the ongoing worldwide projects of these aircrafts is shown, collecting the common characteristics of the propulsion systems. In the following section, using the information of the previous section, the propulsion system is discussed, focusing on the energy source and the propulsion system. In the next section, a review of SM for high specific power applications is done. In this section, the main focus will be on projects under development and prototypes, not excluding initial design and simulation. Next, the information on HEA and AEA will be complemented with the SM, and a detailed discussion on the implications of implementing SM in the aircraft's propulsion system is made. Finally, the conclusions are drawn, retaining the main topics of this review article.

2. Hybrid and All-Electric Aircrafts

Hybrid-Electric Aircrafts are categorized by having electrical and mechanical power sources or powertrains, depending on the configuration. The most common configurations for HEA are by having a power source of combustion type, and the propulsion being all-electric, or a combination of combustion and electrical (see Figure 1). To aid the energy source, batteries are present in most of the hybrid topologies. [13] refers to a degree of hybridization that starts from a turboelectric configuration and ends in the all-electric configuration (Figure 2).

In the turboelectric topology, the reconfiguration of the architecture of the powertrain system is similar to the MEA concept used in [6,12], as seen in Figure 1. In the MEA, the main power source is coming from the propulsion side, having an auxiliary power unit with a gas turbine in the aircraft's tail. Only the gas turbine and generator in the tail are used in a HEA with a turboelectric configuration. This removes the need for a starter-generator coupled with the propulsion engines since they can be started by smaller motors, or not having them all, since the propulsion can be completely electric.

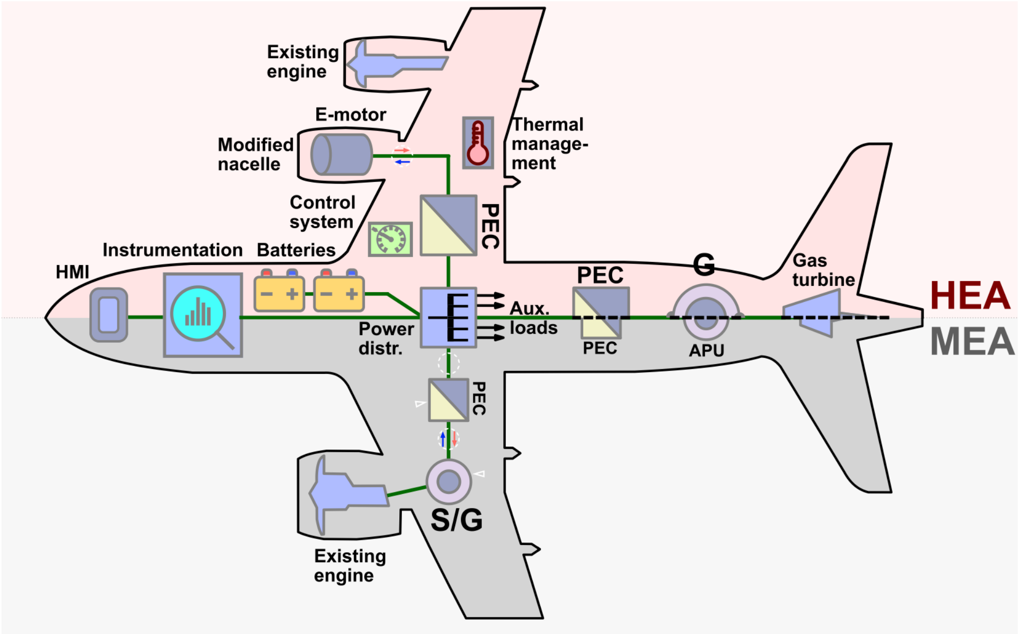


Figure 1. Side-by-side comparison of the MEA and HEA main topologies. (Adapted from [11]).

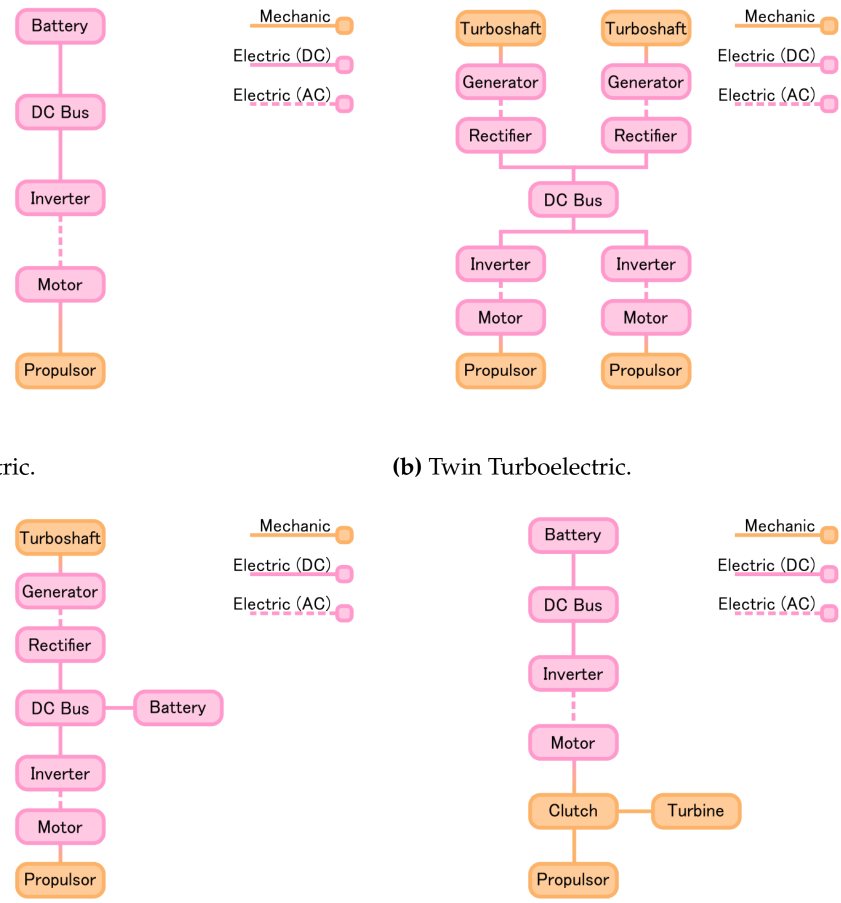
For the series and parallel hybrid (Figures 2c and 2d), batteries are used as an additional power source. Here, depending on the size of the aircraft, the batteries can be the main power source or a secondary auxiliary source. Having an additional energy source proves to be advantageous. Not only it increases redundancy in the powertrain system, with two power sources, but it is also possible to do a power balance management, optimizing the what level one system is the main source and the other is the auxiliary source [14].

Lastly, the AEA configuration, complete electrification of the aircraft is the end goal of [1,2]. Its propulsive power is provided by electrochemical energy, stored in batteries or fuel cells, having its propulsive power coming from electric motors. Main configurations were discussed in [15], and the most promising is a distributed propulsion kind, which uses several smaller electric motors (1 to 2 MW) instead of higher power motors. As stated in [15], the development and manufacturing of electric motors on the 1 to 2 MW power are currently achievable and economical compared to larger, higher power electric motors.

2.1. Worldwide Projects

2.1.1. NASA STARC-ABL

The STARC-ABL is a 150-passenger class commercial transport concept with a traditional "tube-and-wing" shape [16]. It is a turboelectric HEA concept developed by NASA. It combines several experiences from projects such as Subsonic Ultra Green Aircraft Research (SUGAR) and N3-X [17]. Like a traditional aircraft, the STARC-ABL has two jet engines mounted under each wing, and each engine is coupled to an electric generator. The generated electric power is transmitted to the aircraft's tail, where an all-electric propulsor is mounted. This propulsion configuration not only reduces the drag but also takes advantage of this extra flow to produce more trust, improving fuel efficiency [18]. The specifications of the STARC-ABL are to be able to achieve a cruising speed of 0.7 Mach (about 835 km/h), with a mission range of 6500 km. To achieve this, each engine generates electrical power of roughly 1.4 MW, and the all-electric propulsor provides a thrust power of 2.61 MW [19]. This project is currently active, and the necessary technology to develop a prototype is expected to be available from 2030 to 2035 [17].



(a) All Electric.

(b) Twin Turboelectric.

(c) Hybrid Series.

(d) Hybrid Parallel.

Figure 2. Main topologies for aircraft hybridization. (Adapted from [13]).

2.1.2. NASA N3-X

Another NASA project, the N3-X, is a fully turboelectric aircraft with distributed propulsion to reduce over 70% of fuel burn. The technology proposed for the propulsion is a superconducting one, spanning 16 SC motors through the aircraft's tail, all supplied by turboshaft engines, each in the tip of the wing. Coupled with the turboshafts are two electrical generators, also superconducting. The use of SC machines is due to their high efficiency and high specific power [20–23]. This aircraft makes the electric power transmission with SC power cables and cryogenic power inverters and rectifiers. For cooling, it is used liquid Hydrogen (LH_2) directly or by a reverse Brayton cycle refrigerator cryocooler. The LH_2 is also used to supply a portion of the fuel for the turboshafts. The aircraft is expected to have a cruising speed of 0.84 Mach (1029 km/h), a mission range of 13890 km, carrying 300 pax [17]. At cruise speed, the total thrust power provided by the SC motors is 25 MW (1.56 MW each motor) [24]. The design improvements permit to reduce aerodynamic drag, reduction of NO_x by 80% and a noise reduction to 64 Effective perceived noise in decibels (EPNdB) [25]. Considering the availability of new electric propulsion technology and new electric power transmission systems, a maiden flight can be achieved in 2040 [26].

2.1.3. Airbus E-Fan X

E-FAN X is a project led by Airbus, Rolls Royce, and Siemens, canceled in 2020. It was expected that the first test flights were in 2021. The project's aircraft, the BAe

Figure 3. STARC-ABL concept aircraft.

Figure 4. N3-X concept aircraft.

146, was powered by four engines. One propulsion unit was powered by a 2 MW electric motor connected to a 3 kV on-board power supply via an inverter. It was a serial hybrid system: a built-in gas turbine drives a 2.5 MW electric generator in the fuselage, with 2 MW of available power from batteries. The platform is designed to explore challenges such as thermal management, altitude, and dynamic effects in high-performance electrical propulsion systems while maintaining high reliability and safety [17]. The E-FAN X, being the first prototype and conception of a partial hybrid aircraft, had some major problems regarding its hybridization. In [27], an exhaustive analysis of this project's economic and technological viability is made. It is concluded there that due to the increased weight the installed batteries had (2000 kg), the project is not viable. This significant increase in weight is not supported by the added power, since batteries currently have low specific power (1 kW/kg), decreasing the aircraft's payload weight. This, in turn, increases the costs per passenger in every aspect for the E-FAN X. The author in [27] also states that, even without added batteries, the E-FAN X still needs to reduce payload weight, which makes this project not viable compared to conventional combustion engine aircrafts of the same type. However, it ends with a good remark on the project: due to reusing a BAe 146, there was no margin for design and aerodynamic optimization. One way to improve this project is to consider the design and parameter optimization of a new aircraft.

Figure 5. E-FAN X concept aircraft. The green engine was substituted by an electric motor.

3. Propulsion System Requirements

The propulsion systems for the HEA and AEA can be sectioned into three parts: the energy source, the power transmission, and the propulsion. Each of these are critical parts of the propulsion system, having the same relevance and importance. In this section, a detailed discussion of the energy sources and the propulsion is made, not focusing on power transmission. Power transmission is a complex system on its own, having added complexity in aircraft applications, which deserves a separate topic on its own. However, for some information about power transmission systems, see, for example, [9,10,15,17].

3.1. Energy Source

For the HEA and AEA configurations, the selection of energy sources varies. For HEA, fuel combustion is still used, so using conventional jet fuel (kerosene) is still applicable. However, if gas turbines are used for power generation, other fuel sources, such as hydrogen or methane, can be used. For the auxiliary energy source, batteries or fuel cells can be used. For AEA, only electrochemical options are available: batteries and fuel cells. To discuss and compare each energy source, consider a typical 200 passenger commercial aircraft, which uses kerosene as a fuel source. To compare different energy sources, the best is to compare their specific energy, be it volumetric (kW/m^3), or gravimetric (kW/kg). Figure 7 resumes the specific energy of different energy sources. It can be seen that kerosene has sixty times higher mass-specific energy than batteries and eighteen times higher in volume-specific energy. For a full comparison, the efficiency of both energy sources must be considered. Using the values in Figure 7 of [28], the overall efficiency of a system using kerosene is 39%, while typical Li-ion batteries propulsion systems have an overall efficiency of 73%. Considering these efficiency values, the specific energy gap between both sources is narrower but still significant. Batteries still are around 32 times heavier and 10 times larger. This is a clear disadvantage for aircrafts since their mass and volume are important characteristics, affecting their thrust-to-weight ratio, terminal velocity, and maximum take-off weight. Therefore, the current battery technology is not suited for large aircraft applications, and that for AEA, the option is to use fuel cells for its energy source.

Fuel cells, with their use of hydrogen, can be a good candidate for AEA applications. Using the data from Figure 7, liquid hydrogen has four times higher mass-specific energy while having 30% of the volume-specific energy of kerosene. Using the values of [28], both systems have similar overall efficiency, which indicates the less mass is required using hydrogen, while storage volume must increase. Both these systems are similar, which indicates viability to use fuel cells in AEA. These calculations were obtained using liquid hydrogen, which is stored at a temperature below 20 K, which is suitable for cooling the aircraft, and the superconducting electrical machines [29].

3.2. Electric Propulsion

There are two major aspects to consider in the electric propulsion of HEA and AEA: specific power and efficiency. The current commercially available electric motors can achieve specific powers of around 4 to 10 kW/kg, proving sufficient for smaller aircrafts, e.g., 2-seaters [30]. However, for passenger-class aircrafts, there is a need for specific powers higher than 10 kW/kg [21]. One example is the NASA project, the STARC-ABL, referred in Section 3, which is projected to have electric motors with a specific power of 13 kW/kg. This indicates that there is a need to develop a new kind of electric motors, which can achieve higher specific powers. One main research topic is the use of superconducting materials. [31] and [23] specify target estimations for SC machines of 20 kW/kg to 30 kW/kg, respectively. These values are surplus for what is currently needed, which increases viability for HEA and AEA. Another advantage is the estimated efficiency of SC motors when compared to conventional motors. Although already in the 98% range for typical large power electric motors [30], the SC motors prove to have even higher efficiency [**?**], and their high specific power, lighter, and possibly more compact. One could argue that if SC motors have a 1% increase in efficiency is not a great achievement when discussing already high efficiencies. However, 1% in the reduction of energy consumption in the scale of an aircraft (power of the order of MW and energy consumptions of the order of MWh) can lead to savings in fuel.

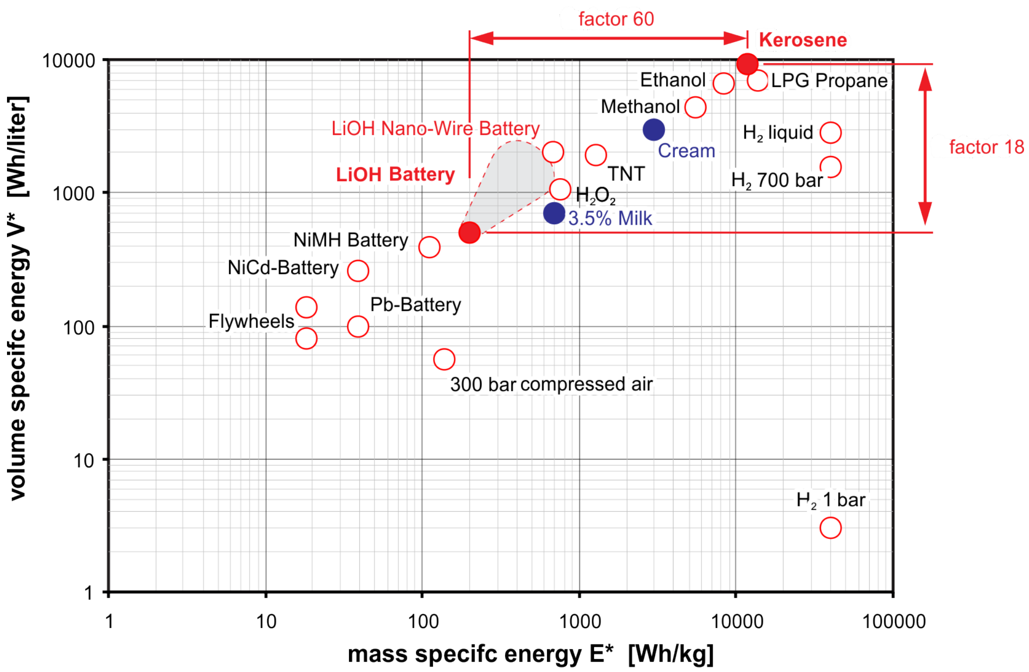


Figure 6. Volume and mass specific energy characteristics of different types of energy sources [28].

One advantage of using electrical propulsion with high specific power is allowing a distributed propulsion. With a distributed propulsion, new aircraft designs are possible that allow the aircraft to be more aerodynamic, reducing drag. This, in turn, can lead to higher efficiency and safety, cost reduction, and decreased noise [15]. Also, a distributed propulsion system can be considered safer due to its increased redundancy. This is what the N3-X design referred to in Section 2.1.2 proposed. The distributed propulsion is sectioned into 4 sectors, each with 4 electric motors. Each sector must be designed to provide 50% of the total required thrust power. This allows for extra redundancy in the propulsion, which ensures proper flight or a safe landing in case of an emergency if a single or multiple motor failures occur.

4. Superconducting Electrical Machines

4.1. Air-core radial flux

In [32], a design of a radial flux, air-core superconducting synchronous machine is proposed (Figure 8. Here, using similar technology to the magnetic resonance imaging machines, compensating SC coils are used to contain the machine's magnetic field instead of the conventional iron core. In this way, with the iron and its saturation limits gone, designs with increased air-gap flux densities can now be considered, due to the high magnetomotive force (MMF) capabilities the main SC coils have, comparing with copper, in the same lengths.

A basic sizing project was done, showing the design for a 10 MW, 3000 rpm machine. This is indicative of an increase of specific power relative to conventional electric machines, in which [20] points at 25 kW/kg. One drawback to consider is the length of SC wire needed to achieve the needed MMF and effective shielding. The results show a minimum of around 15 km length of SC wire for a magnetic flux density in the armature of 1.5 T. This greatly increases the costs of the motor, using the current price of SC, making it economically inviable. It is stated that by using LTS, the costs are reduced by ten-fold, compared with HTS. Although this is true, the use of LTS requires the system to be cooled in the region of 10 K or lower (4.2 K for the SC used in [32]). This requires a cooling system that uses liquid helium, and for commercial aircraft applications, it would increase overall production and maintenance costs, which is counterproductive.

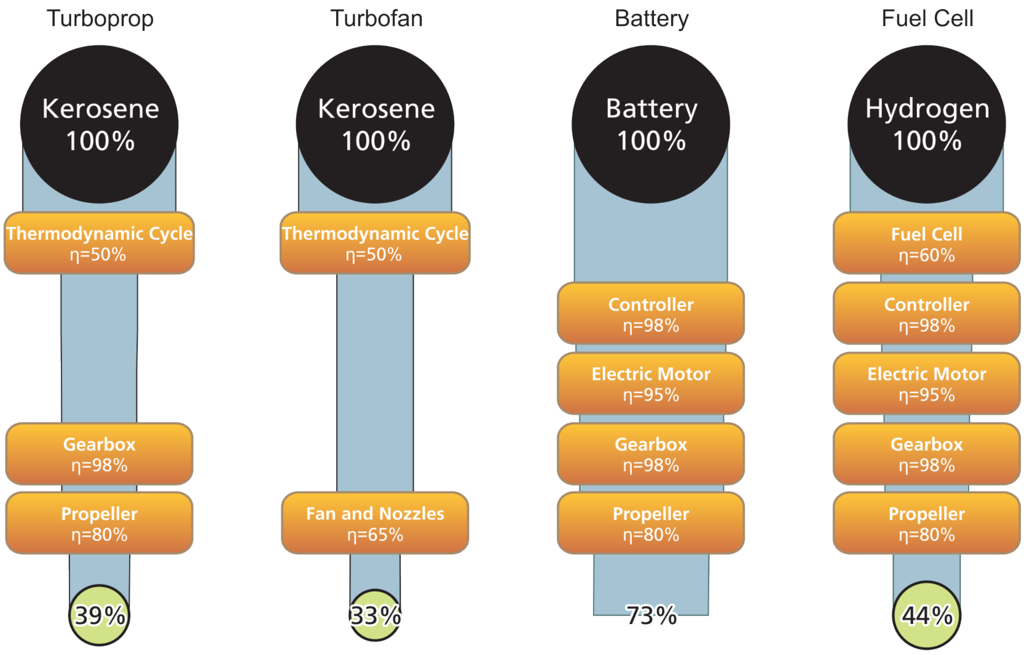


Figure 7. Typical on-board conversion chains with typical component efficiencies and total chain efficiency. [28].

One air-core design using HTS cooled with liquid hydrogen proves to be more useful due to the cooling and fuel source duality [29].

4.2. *Axial-flux partially superconducting machine*

Another design to impact the specific power of electrical machines is the one developed in [33–35]. Here, a partially superconducting electrical machine is designed and developed. It is a brushless axial flux machine (Figure 9) to avoid all the maintenance and safety issues of a brush system and the additional weight of a rotating diode system. This motor works on the principle of flux modulation. As shown in Figure 9, the HTS coil carries a DC current, which creates the main axial flux of the machine. Due to the diamagnetic nature of the HTS, the pellets create an effective magnetic shield, deviating the flux lines around the pellets, modulating them, which creates a space-periodic magnetic flux along the machine's azimuth. With this modulation, when the HTS shield rotates, it induces a back-electromotive force to the armature winding terminals, effectively creating a synchronous machine.

To have a high specific power, the machine's weight is important. In this sense, the materials used in its construction have a higher importance in the design than conventional machines. The prototype (Figure 10) consists of a rotor (Figure 10b) made with a fiberglass/epoxy composite and a titanium support. the HTS pellets are inserted in copper rings, soldered to the copper pipes that provide the cooling. The stator uses concentric double-layer windings with a lower length than distributed windings, successfully reducing weight. Also, to reduce weight and increase the specific power due to increased magnetic flux density, a thin hollow cylinder of laminated iron is used to support the armature windings. A closed-loop of helium under pressure is used for the cooling of the HTS coil and pellets. The cryostat is made of aluminum to make it more lightweight.

In [33], the 50 kW prototype was developed and no-load tests were made. The tests were performed using the prototype as a generator, with a speed of 250 rpm, and the HTS coil was supplied a current of 120 A. The armature voltage of one winding was measured. The no-load tests showed that the numerical analysis modeled well enough the behavior of the HTS pellets, successfully validating the flux modulation of the machine. Regarding developed voltage, the authors in [33] were expecting phase-to-phase voltage values

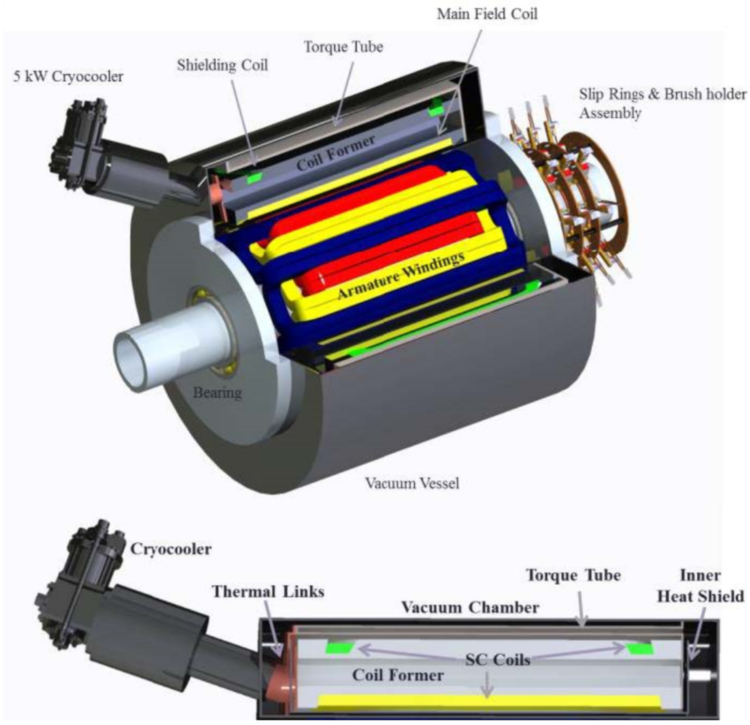


Figure 8. Conception of radial flux, air-core superconducting synchronous machine from [32].

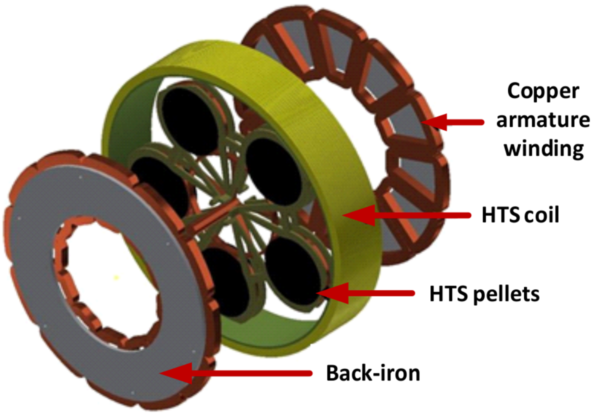
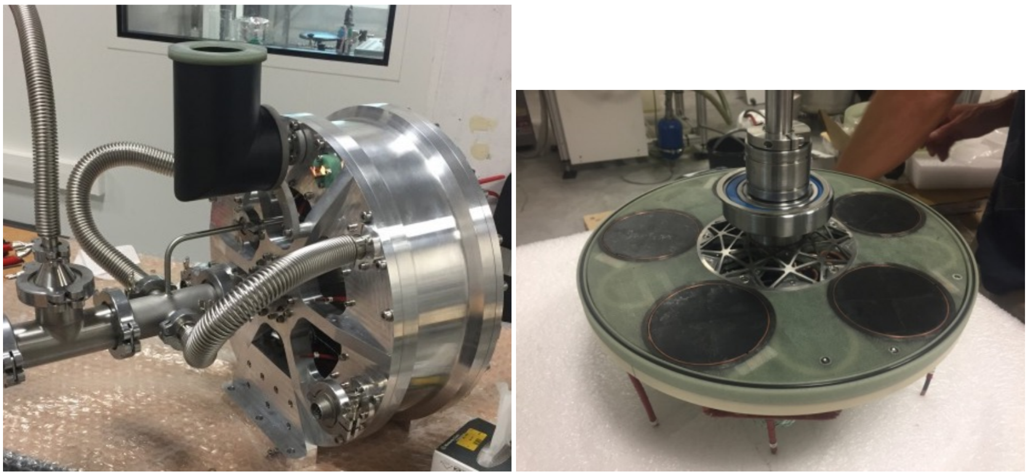


Figure 9. Concept of axial-flux partially HTS machine from [33].

of 535 V in the armature winding. Using the no-load experimental data, they made linear extrapolations to compute the total phase-to-phase armature voltage since the thin back-iron is rapidly saturated. The total expected armature voltage is between 296 V and 316 V, which do not correspond to the initial predicted value of 535 V. The authors point out two factors. First, the prototype's final air gap length and the number of turns in the armature windings were modified due to the initial design's construction feasibility. Second, due to the grain boundaries of the HTS pellets, which are zones where the flux penetration is higher, the modulation of the flux was not following the simulated models, reducing the flux through the armature windings. The final prototype was designed to achieve a power of 50 kW, with a total weight (machine and cryostat) of 52 kg. This project is still under development, and the research on superconducting bulk characteristics and machine's design is being conducted [34,35].

We see this design and its prototype as a major breakthrough in the development of new electrical machines for aircraft applications, where the key design aspects are *compactness* and *lightness* while maintaining the same overall power output conventional aircrafts need. However, its maturity is still not reached. First, the specific power is not



(a) Prototype withouth cryostat. **(b)** Rotor.
Figure 10. 50 kW superconducting machine prototype from [33].

high enough for aircrafts. The machine's specific power is under 1 kW/kg, far from the required $15 - 20$ kW/kg stated in Section 3.2. There are some possibilities for the increase of its specific power. One can consider, inspired by [32], the use of an HTS shielding instead of back iron to reduce the weight of the machine, since HTS bulks are less dense than iron (6.3 g/cm^3 instead of 7.1 g/cm^3), making the machine an air-core one. This can increase the magnetic flux density in the armature, also increasing the induced back-electromotive force.

The windings in the armature can also be made using HTS coils, making a fully superconducting electric machine. Due to their high current and low losses, fewer turns are needed, reducing the armature weight. Losses due to varying magnetic fields and AC currents in HTS coils can be disruptive in their operating conditions, leading to quenching and loss of superconductivity. However, if liquid Hydrogen is used for its cooling, the required magnetic fields and current densities are higher, without increasing their losses [36]. Additionally, there are more complex configurations of HTS tapes, such as stacks, Roebel [37], and CORC [38], which can prove useful in increasing the current transport and magnetic flux density creation [39,40].

Regarding the cooling aspects, the use of liquid helium can prove to be a disadvantage over liquid hydrogen or liquid methane since it cannot be used as a fuel source for HEA. Although not directly impacting the weight of the machine, having another reservoir for the cooling agent increases the aircraft's overall weight, which hinders its performance.

5. Conclusions

This review article sought to analyze the research on superconducting electrical machines considering their impact on redesigning the electrical, cooling, and fuel systems of aircrafts. It was presented propulsion topologies for aicrafts with their main characteristics. An overview of most worldwide projects was shown, stating their propulsion topology and main characteristics. The energy sources and electric propulsion were also discussed, referencing the use of liquid hydrogen as a cooling agent for the aircraft and the superconducting electrical propulsion systems. Finally, two main configurations for superconducting motors were analyzed and discussed.

The need for new designs of aircrafts, to take advantage of the electrical propulsion systems is of extreme importance to guarantee the projected plans of the EU and NASA. As seen in the NASA projects and the now canceled E-FAN X project, replacing the propulsion on the aircraft or complete redesign of a distributed propulsion system is key to progress towards lower fuel consumption and lower gas emissions, and an overall increase in efficiency.

Regarding energy sources, batteries have not currently high enough specific powers to be considered for aircrafts. Better alternatives lead towards the same end goals, such as using gas turbines, in the turboelectric case or fuel cells, in the all-electric case. Both these systems can use liquid hydrogen (in the fuel cell case, it is mandatory), meaning that the liquid hydrogen can be used as a fuel source or as a cooling agent. This proves advantageous in superconducting electric propulsion, which only requires one reservoir for the fuel and the cooling agent.

Using superconductors electric machines in aircrafts can prove quite advantageous regarding efficiency, specific power, and the possibility of a distributed propulsion system. However, special attention must be given to the use of superconductors. First and foremost, superconductors require to be cooled to cryogenic temperatures. This leads to cryogenic systems, which can increase the system's weight, proving counterproductive to superconducting machines. It is recommended to include the cryocooler system in the design of the machine to allow the possibility of its weight reduction. It includes the cryocooler in the computation of the specific power. Also, designs that use a low volume of iron or ferromagnetic materials prioritize ensuring that electric machines are lighter and more compact.

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