IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 23 September 2022, accepted 16 October 2022, date of publication 19 October 2022, date of current version 2 November 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3215692

TOPICAL REVIEW

Review of High Power and High Voltage Electric Motors for Single-Aisle Regional Aircraft

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ABSTRACT This paper presents a review of the state of the art in electric propulsion for regional aircraft in the MW range. The implications surrounding the implementation of this technology, such as the need of high-power density or the use of high-voltage at high-altitude, are presented. Along with the challenges, the available technologies to face them are reviewed. Those are, as follows, the emerging new motor topologies for this purpose, the winding technologies, the materials employed for electric motors for aircraft propulsion and the ground-breaking use of high-temperature superconductors (HTS) as a high-power density enabler. Finally, a conclusion is presented gathering the main ideas of the paper.

INDEX TERMS Aircraft propulsion, electric motor, high-power, high-temperature superconductor, high-voltage.

I. INTRODUCTION

Aviation is one of the biggest pollutants today [1], [2], [3], which represents the 11.6% of the total transport emissions [4], being a serious threat due to the proximity of the vehicles to the ozone layer [5]. To tackle this problem, several studies are being carried out in various topics such new aircraft architectures, lighter materials, new clean fuels and electrification of major systems, including propulsion.

The adoption of electric propulsion in the regional aircraft would entail significant advantages in several areas. The most transcendent benefit is the reduction of nitrogen oxides (NO_x) and carbon (CO, CO_2) emissions due to the independency of fuels. Along with it, the noise produced by the airplane's turbofans will be significantly minimized. Moreover, new topologies are being studied to improve the aerodynamics of the aircraft. The introduction of the electric motor enables decoupling the motor and the generator or the energy source (the turbine and the compressor in a conventional turbofan engine), which allows to rearrange the configuration of the electrical system. Some of those ground-breaking configurations are the distributed propulsion [6], [7], [8] and the boundary layer ingestion (BLI) [9], [10] which are being deeply studied by several groups, e.g. for the NASA N3-X.

The main concern for aircraft propulsion electrification is weight. An aircraft has very specific load limitations depending on the power provided by the motors, requiring indeed high-power density electric motors. In the case of prototype or unmanned aircraft, these power density levels are more feasible since the mass of these models is much lower and the flight range is much shorter, whereas for larger passenger aircraft the power required ascends to MW-class range.

To date some remarkable work has been done regarding electric aircraft with developed and flyable models (FIGURE 1). The first model to make an official flight was the Lange Antares 20E in 2003 [11]. This first manned electric aircraft model is a 20-metre wingspan glider, equipped with a 42-kW electric motor. The first hybrid electric aircraft was the Diamond DA36 e-Star (in collaboration with Siemens) [12], in order to research the serial hybrid electric drive system on smaller aircraft or gliders to be scaled later on larger vehicles. Boeing presented the Boeing HK-36 fuel-cell demonstrator in 2008 [13]. Airbus, on the other hand, has continuously developed electric propelled gliders (e.g. the e-Genius [14]), small aircraft (e.g. the E-Fan 1.0 [15]) and even launched a hybrid-electric aircraft demonstrator for more than 70 passengers

The associate editor coordinating the review of this manuscript and approving it for publication was R. K. Saket.

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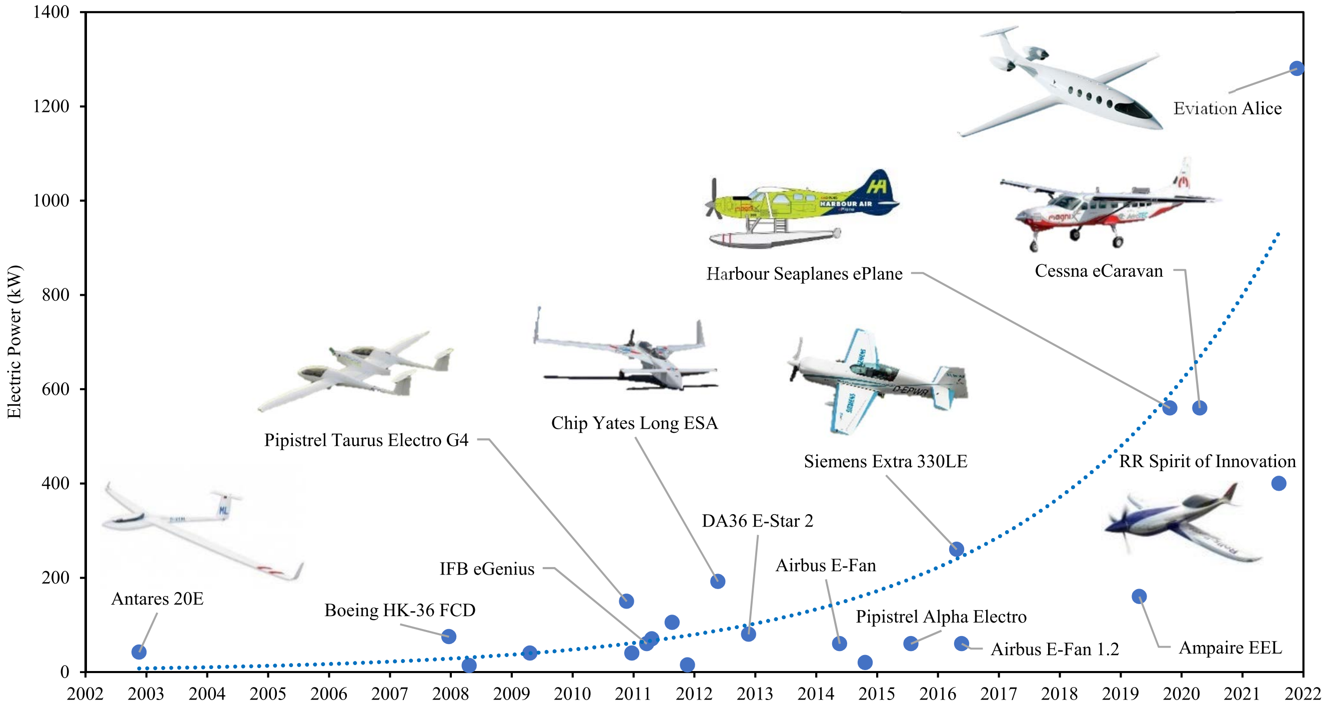


FIGURE 1. Evolution of electric propulsion power during the last 20 years [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26].

(the E-Fan X [16]), which was cancelled due to the drop of air travel caused by the COVID-19 pandemic [17]. Siemens has also produced its own aircraft (the Siemens Extra 330LE [18]) and there are several prototypes in which the motor used bears the manufacturer's signature such as the Diamond DA36 e-Star (70 kW) and e-Star 2 (80 kW) [19] or the Pipistrel WattsUP (85 kW) [20]. One of the most powerful electric aircraft designed to date is the Cessna eCaravan [21], which made its maiden flight in May 2020. This model is a Cessna Caravan 208 whose combustion engine has been replaced by a 560-kW electric motor from MagniX (the Magni500 [22]). This motor, which can provide a continuous torque of 2814 Nm, was also used on the Harbour ePlane, a Canadian seaplane that made its first flight six months earlier [23]. Rolls-Royce has also designed an electric propulsion aircraft, 'Spirit of Innovation' (September 2021) [24], [25], which can reach up to 480 km/h with a 400-kW motor designed by the automotive powertrain supplier YASA.

The most powerful electric aircraft designed to date and the one to have completed its first flight most recently (December 2021) is Eviation's Alice [26]. This aircraft is powered by two MagniX propulsion motors (the Magni650, each capable of delivering a peak power of 640 kW at the base speed of 1900 rpm). As is shown in FIGURE 1, there is an increasing trend in the power of developed aircraft in the last 20 years (from 40 kW to 1200 kW).

On the other hand, some projects with a medium or long-term regard are being studied (FIGURE 2). Aircraft that are expected to fly in 2024 are VoltAero's Cassio 330 [27], XTI Tri-Fan 600 [28] or Heart Aerospace's ES-19 [29], which have a propulsion power of 300 kW, 1 MW and 400 kW, respectively. Another aircraft that is meant to fly in the following years is NASA's X-57 'Maxwell' [30], part of NASA's Leading-Edge Asynchronous Propeller Technology (LEAPTech [31]) project which develops an experimental technology consisting on placing several small propellers along the edge of the wings (distributed propulsion aircraft). Over the last few years, different projects and studies have been developed with the aim of increasing the power density of aircraft electric motors to boost the planes' thrust power to the MW-class. Airbus' ZEROe Turbofan, Turboprop and Blended-Wing Body aircraft [32], Ampaire's Tailwind (1 MW [33]), the Zunum Aero (1 MW [34]), NASA's STARC-ABL (2.6 MW [35]) or Boeing's SUGAR Volt (1 MW [36]) are some of the currently being studied projects for the medium-term (2025-2035). Other prototypes with more peak power are being developed in a longer term (2035-2050) e.g. the Bauhaus Luftfahrt Ce-Liner (33.5 MW [37]) and NASA's N3-X (50 MW [6]). As can be seen in FIGURE 2, the trend in the upcoming years is not exceeding the 2 MW, however, the studies with further planning expect to reach the 10 MW-scale propulsion.

The main objective of this paper is to review the current challenges and technology regarding the electrically propelled single-aisle regional aircraft (50-100 passengers, 1000 km range) in order to contribute to the development of the more electric aircraft. In the literature several high-quality papers on the review of electric motors in aircraft propulsion

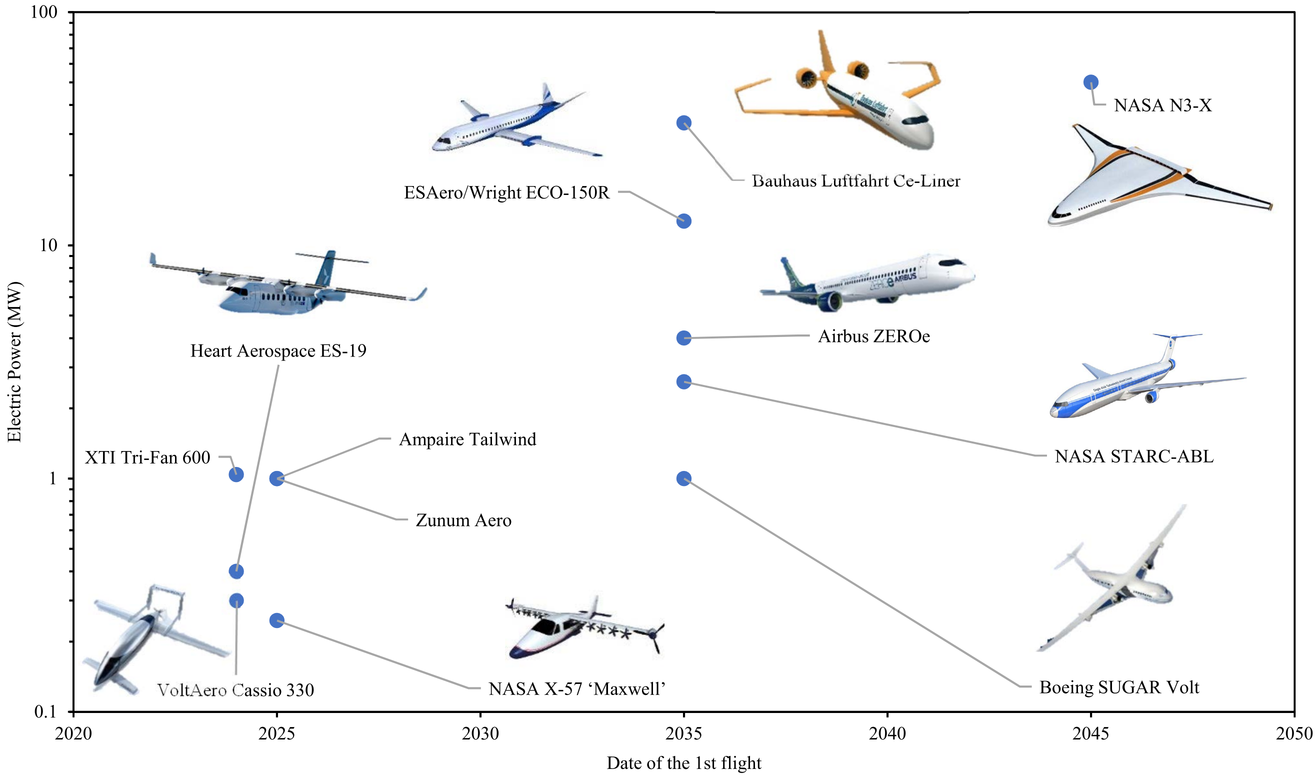


FIGURE 2. Ongoing studies and projects of electric propulsion [7], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37].

are available. On the literature work that analyses the state of the art of the different topologies of electric machines in a highly developed and sober way [38], papers that evaluate the thermal systems of this type of aircraft engines [39] and different documents that analyse the electric power systems in the more electric and all electric aircraft [40], [41], [42] are found. However, this paper synthesizes all the challenges that arise on the road to aircraft electrification and presents in a clear and detailed way the available technologies (electric machine topologies, innovative winding technologies, insulation systems and the different materials used in the design of electric motors) that serve as a tool to meet these challenges.

First, the emerging challenges concerning MW-class electric propulsion motors are discussed. Then, several identified technologies available to overcome those challenges are explained. Finally, some conclusions about the contribution of motor technology to the feasibility of short-term electrification of single aisle regional aircraft are pointed out.

II. EMERGING CHALLENGES

Even though electric propulsion in aviation has been studied for decades, there are still major obstacles to the application of this technology in large-scale aircraft, which require several megawatts of power for propulsion. First, the electric motors that substitute the conventional gas turbines should have similar or superior power-densities without their weight being a handicap. Thermal management is another key challenge for the successful realization of hybrid-electric powertrains. The heat produced in the active parts of the electric motor must be properly dissipated. Another challenge arising from the development of the electric aircraft is to ensure the safety of the electrical transmission and propulsion systems, along with that of the people on board.

A. POWER DENSITY

The following table (Table 1) shows different models of jet engines used in aircraft of different range and capacity to show the power densities that would be necessary to obtain with equivalent electric motors.

TABLE 1. Comparison between aircraft jet engines.

Airplane	ATR-72	Dash 8 Q400	Boeing 737-700	A350
Jet Engine	PW127D [43]	PW150A [44]	CFM56-7B20 [45]	Trent XWB-97 [46]
Type	Turboprop	Turboprop	Turbofan	Turbofan
Rotor Speed (rpm)	1200	1020	5000	2700
Torque (kNm)	33.4	71.2	75.6	662.8
Torque den. (Nm/kg)	33.9	49.0	15.9	43.9
Power (MW)	2 x 2.1	2 x 3.8	2 x 19.8	2 x 93.7
Power den. (kW/kg)	4.26	5.23	8.32	12.41
Airplane Capacity	80	90	126	350

As can be seen in the table above, the rotational speed of propulsion engines is between 1000 rpm and 5000 rpm. The trend in electric propulsion aircraft is the serial-hybrid configuration, in which the motor can be directly coupled to the propeller, thus avoiding the use of a gearbox. The disadvantage of this configuration is that the rotational speed of the propeller limits the rotational speed of the motor. This parameter is directly related to the power density of the motor (as shown in the following expressions), which is why the motors used in electric propulsion must achieve high power density values, with the handicap of the rotational speed of the shaft. The specific power density of an electrical machine [47] can be expressed as

$$P_{out}/M = \frac{1}{1+K_\phi}\frac{m}{m_1}\frac{\pi}{2}K_eK_iK_p\eta B_gA\frac{f}{p}\frac{D_g^2L_e}{M} \quad (1)$$

where K_ϕ is the ratio of electrical loading on rotor and stator, m is the number of phases, m_1 is the number of phases of each stator, K_e is the EMF factor, K_i is the current waveform factor, K_p is the electrical power waveform factor, η is the machine efficiency, B_g is the airgap flux density, A is the machine total electrical loading, f is the converter frequency, p is the machine pole pairs, D_g is the airgap diameter, L_e is the effective stack length and M is the mass of the machine.

In order to simplify the expression, the specific power density can be defined omitting the constant factors as a dependant of the following parameters:

$$P_{out}/M \propto B_gA\frac{f}{p}\frac{D_g^2L_e}{M}. \quad (2)$$

In (2), f/p and $D_g^2L_e$ are proportional to the rotational speed and the volume of the machine, respectively. Therefore, the specific power density of a rotational electric machine is proportional to the airgap flux density, the electrical loading and the rotational speed. The first two parameters should be deeply studied and assessed in order to achieve high power-density values. For a demanded power, maximizing those parameters the power density is increased.

The mean airgap flux density is a key parameter to increase the power of any electrical machine and for aircraft applications is usually between 0.4 and 1 T [48], [49], [50]. This parameter is limited by the saturation of the stator and rotor magnetic steel and by the magnet or field winding capability. Nevertheless, with the use of superconducting bulk magnets, the achieved value of trapped field is far stronger, beating a maximum of 17.6 T [51], [52], [53]. Even if the conditions for the study are inconceivable for a high-speed rotating electrical machine, it leads the way to the possibility of reaching higher mean airgap flux density values.

The electrical loading or linear current density of a machine is tightly related to the heat dissipation capacity and the current density of the slots. High electrical loading increases the airgap flux density but also heats the winding, requiring a bigger cooling system.

B. THERMAL MANAGEMENT

The power density of an electric motor depends on two thermal factors: the internal losses and cooling system of the electric motor itself. Conventional gas turbines have a natural cooling system such as the engine exhaust. With the introduction of electric motors, only a small part of the generated heat could be dissipated through the structure's conduction, what makes the cooling systems a critical aspect. Therefore, the thermal management system has to manage their entire heat load [54].

It has been investigated the potential of using existing aircraft surfaces as heat sinks, concluding that smaller aircraft can reject large parts of the heat load through those surfaces [55]. Moreover, recirculating fuel underneath the wing surfaces for cooling the propulsion system in larger aircraft was proposed [56]. Along with those studies, a ram air-based thermal management system was investigated by the same research group in [54]. That system could withstand hot-day take-off conditions with the help of a small puller fan installed behind the main heat exchanger. A predictive thermal control system is proposed to adjust the cooling system in order to manage the motor temperature and reduce the power loss in [57].

On the other hand, the cooling of the electric motor itself must also be considered. In the case of permanent magnet motors, since most of the losses occur in the stator winding, a common metric for measuring the capacity of different cooling systems is the allowable conductor current density. Table 2 shows some reference values for different forced cooling systems relevant for high specific power machines:

TABLE 2. Different electric motor cooling methods.

Cooling method	Max. current density [A/mm^2]	References
Natural convection	1.5-5	[58]–[60]
Forced air through rad./ax. channels	5-12	[58]–[62]
Housing water jacket	10-25	[59]–[61], [63]–[65]
Slot-through cooling	12-33	[66]–[69]
Spray, jet, dripping oil cooling	15-30	[60], [70]–[73]
Hollow conductors	15-50	[64], [74]–[78]
Oil flooded stator	15-90	[79]–[84]

The systems that allow a higher current density are the oil flooded stator, the direct cooling of conductors and the spray cooling system. Flooding the stator with oil, leaving gaps in the slot (either in the wedges or between coils) for oil circulation, has the advantage that both the conductors in the stack and the end-windings are simultaneously cooled. A huge advantage of these systems is that the oil acts as a secondary insulator, leading to the possibility of using thinner insulators when partial discharges are an issue, as in high voltage and altitude machines. Cooling a motor via oil spray (or a different dielectric fluid) is normally achieved by placing nozzles around the casing that project the oil at a high speed onto the end windings, making the fluid disperse into innumerable droplets that extract the heat through evaporation and are later condensed to be finally collected in the lower part of the motor. Spray cooling achieves huge heat transfer coefficients of the end-windings to the impinging fluid

FIGURE 3. Cross section of a coil with hollow conductors [77].

(above 900 W/(m·K)), allowing stator current densities well over 28 A/mm^2. The selection of the adequate fluid and nozzle geometry are important factors affecting the heat extraction capability of the system. Section III-B will further discuss the direct cooling method in more detail.

In addition to the optimisation of the cooling systems, another aspect to be considered with the aim of improving the thermal efficiency of electric motors is the winding technology employed, which will be discussed in more detail in Section III-B.

C. SAFETY AND HIGH VOLTAGE AT HIGH ALTITUDE

There are several risks associated with the implementation of an electric propulsion system at high altitude, as has been evaluated in several studies [85], [86], [87].

Safety issues are promoting the use of more reliable machine structures, such as multiphase or concentrated windings, as well as more reliable power electronics converter topologies; at the same time, diagnostic techniques are gaining importance along with control techniques for fault-tolerant management of drives. Some of the key hazards on which the studies focus are as follows: battery thermal runaway, battery energy uncertainty, common mode power failure at high altitude, a fly-by-wire system failure or a high level autonomy failure, all of them being of high risk for the aircraft's systems [85].

High-speed blades of the propellers are replaced by electric fans with much lower rotational speeds, thus reducing their hazard. Distributed propulsion, on the other hand, runs a higher risk of bird strike or engine loss as shown in [88]; however, the danger of a dual motor failure is not a concern as in conventional two-turbine [89]. A safety analysis was carried out in [88] on high-power electric propulsion systems.

Another major risk in the electrification of aircraft is the failure of conductor insulation. The main cause of accelerated degradation of insulation systems are partial discharges that occur in cavities in the motor winding. Therefore, the maximum size of these cavities must be controlled, so that the electric field in these air gaps is lower than the theoretical inception field [90].

The increase in the operating voltage of aircraft has been gradual, working both at the primary power system level as well as within aircraft subsystems (e.g., flight instruments, autopilot, electric flap gear motors, window heating, etc.). Electrical power systems for advanced aircraft employ voltages above the traditional levels of 12 to 42 VDC and 400 Hz [91]. Current airborne systems can contain 270 VDC, whereas bipolar systems with a 540 VDC differential are appearing in certain applications; moreover, some studies propose even a maximum operating voltage around 1500 V_{rms}.

The use of high-voltage systems could be beneficial for both energy transport system inside the aircraft and electric motor itself. The use of a high-voltage energy transportation system means that the required current value could be decreased and, therefore, the total mass of wiring would be considerably reduced, leading to a much lighter wire system [92].

Nevertheless, the use of high voltage involves much more challenges because of the atmospheric conditions that an aircraft endures than in ground level conditions. As the vast majority of applications of high voltage do not require specific pressure or temperature conditions, there are not many studies on the implementation of a high voltage system in aircraft. There has been some work developed around the Paschen Curve, which relates the air pressure at which a conductor is found and the partial discharge inception voltage (PDIV) (FIGURE 4) [93], [94]. According to this curve, when the atmospheric pressure is reduced, the limiting value at which partial discharges (PD) occur due to voltage breakdown also decreases to a minimum value. Therefore, such a system requires further study of the insulation of conductors and electrical machines working at cruising altitudes of the range of 10,000 to 15,000 m.

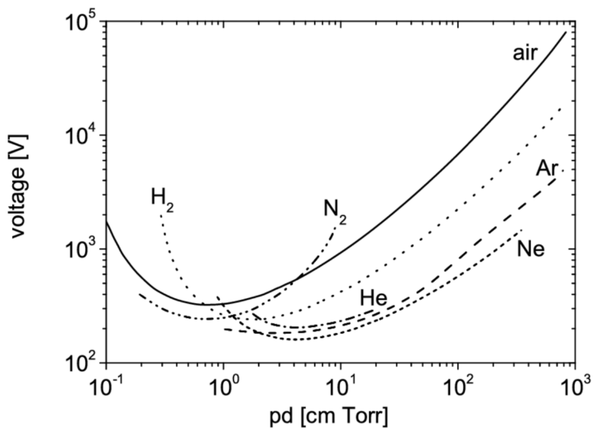


FIGURE 4. Paschen curves for different gases. The Paschen's Law defines the breakdown voltage as a function of the ambient pressure [94].

The PD is dependant of two main parameters: the electric field and the density of the surrounding air. The former is function of the thickness of the insulator while the latter is defined by the ambient temperature and pressure [95], [96], [97], thus, the atmospheric conditions should be deeply studied.

Even though the Paschen Curve can approximate the value of the PDIV for a given ambient pressure, the curve is only valid for a certain type of material, conductor geometry and conditions. The resulting curve depends on the condition of the model and it may vary drastically [98]. Regarding the specific case of electric airplanes, there are few works on the subject. In [99], the methods for assessing the risk of PD in the windings of electrical machines are studied. As an example, FIGURE 5 presents the voltage curves for different insulation thicknesses as a function of the distance between two conductors, along with Paschen's curve. It is shown in a very visual way if arcing would occur between two conductors depending on the boundary conditions.

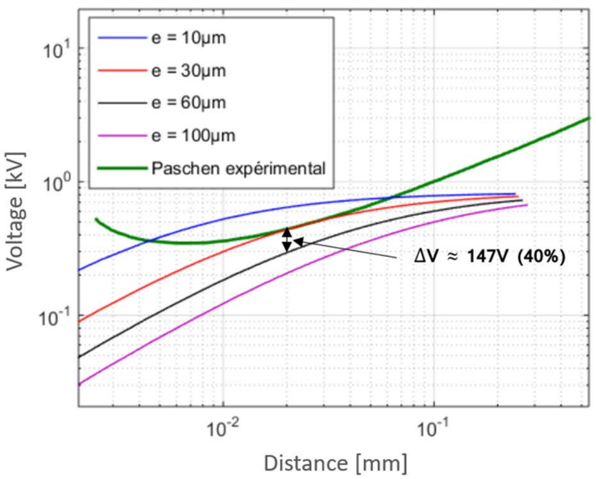


FIGURE 5. V(d) curves for different insulation thicknesses, $U = 830V$, $\varepsilon_r = 3.5$ [99].

Moreover, once electrical discharges and high voltage arcing events appear it is very difficult to mitigate them, leading to catastrophic results. For this reason, the modelling of the electrical insulation of the conductors within the motor is particularly important, e.g., in [100], some limitations of existing arcing protections for aircraft applications are described.

Regarding PD in inverted-fed electric motors at low pressures, some remarkable work has been done, with an approach partly directed at electric propulsion of aircraft [101], [102], [103], [104]. However, the modelling of this phenomenon is limited to a pair of twisted wires and very low voltage systems.

To tackle the aforementioned challenges regarding the implementation of electric propulsion in a regional transportation aircraft, conventional and ground-breaking technologies are being studied currently by several research groups.

III. AVAILABLE TECHNOLOGIES

This section will present and discuss some of the technologies that are currently being proposed and researched to address the more electric aircraft, as follows:

- Electric motor topologies for aviation propulsion
- Winding technologies and insulating systems
- Materials used in electric motors for aircraft propulsion
- High Temperature Superconductors

A. TOPOLOGIES OF AIRCRAFT ELECTRIC MOTORS

Among the different topologies that can be found in the design of high-power density machines (Permanent Magnet Synchronous Machine, Induction Machines, Switched Reluctance Machines, Wound Field Synchronous Machines and Reluctance Machines), those that provide the highest efficiency and power densities are the PMSM (both radial and axial flux). Within the PMSM motors, the radial machines seem to be more suitable for high-speed applications [105]. Several PMSM for the aircraft industry have been developed during the last years. Some of the most remarkable models and studies can be found in [18], [106], [107], [108], [109], and [110]. However, PMSM are affected by the uncontrolled voltage regeneration when the motor control unit does not perform properly flux weakening and the speed is high. The result is catastrophic high-voltage breakdown. Another disadvantage of this topology is the magnet demagnetization [111], [112], [113]. The Wound Field Synchronous Motor emerges as a suitable alternative to this adversity. In case of failure of the inverter, the rotor excitation is immediately turned off and there is no regeneration whatever is the rotor spinning speed.

The design trends regarding electric motors for propulsion have various common points. The outer diameter of the stator is not a constraint since the radial clearance is defined by the motor propellers (usually over 2 metres [114]). This is why in these cases the limiting parameter in the geometry is the axial length [115], leading to a large ratio of the outer diameter of the motor compared to the stack length (commonly known as pancake motors). FIGURE 6 depicts the geometries of the investigated nacelles. The blue box represents the volume that is required for the electric motor and the inverter based on the results from the electric drivetrain design. In order to keep bearing forces of the drive shaft low, the electric motor is located 0.25m behind the propeller plane for all cases. The position of the main wing leading edge is indicated by the red dashed line. The comparison of the geometries also illustrate the varying spinner diameter at the position of the propeller scaling with the nacelle diameter.

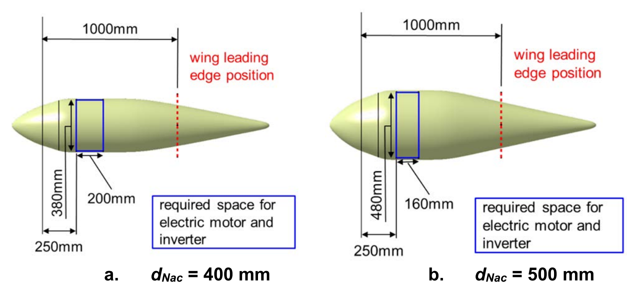


FIGURE 6. Visualized nacelle geometry for different diameters d_{Nac} [115].

Another common parameter is the substantial number of poles in the rotor to reduce the stator yoke. In FIGURE 7, the exploded view of a PMSM for aircraft propulsion can be seen, in which the length-to-diameter ratio and the large number of poles are visible.

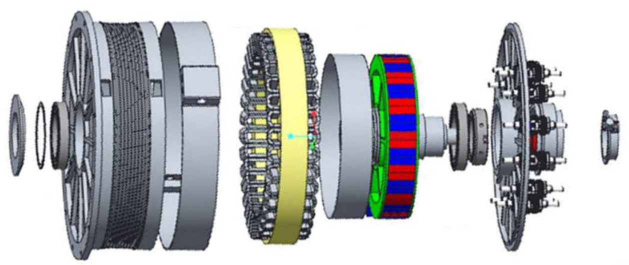


FIGURE 7. Illustration of an aircraft PMSM exploded view [109].

B. WINDING TECHNOLOGIES AND INSULATING SYSTEMS

To obtain a winding scheme with optimal characteristics, some electromagnetic and geometrical parameters should be achieved such as a sinusoidally distributed MMF waveform, the smallest possible end windings, a high slot fill factor, good heat transfer or a configuration with a reliable insulation system. In order to attain the aforementioned, diverse winding arrangements and technologies are being implemented in aircraft propulsion electric motors.

The stator winding arrangement can be concentrated or distributed. The concentrated winding leads to smaller copper losses and shorter end turn length, meaning less mass of copper and, thus, a reduction in the total weight of the motor. However, with the distributed winding higher average torque, lower torque ripple and higher efficiency are obtained [116], [117], and [118].

Another parameter to be discussed regarding the winding is the number of layers. In the case of concentrated windings, multilayer configurations improve the performance in terms of harmonics [119]. Nevertheless, normally, the advantages obtained do not compensate for the reduction in the slot fill factor due to the need to separate the coils of each layer to assure electrical insulation.

In the case of distributed windings, it is also possible to find windings with 3 or more layers. The electromagnetic performance in terms of torque ripple, harmonic generation and NVH are usually good enough to justify the use of 3 or more layers and the subsequent complexity in terms of loss of space, coil insertion, fixation and soldering [120].

Regarding the arrangement of the coils, form-wound winding is a well-proved and mature technology with low development costs, which offers the best performance in terms of insulation control and PD behaviour. In addition, some of the advantages are: high slot filling factors, flexible processing at different machine dimensions, number and dimensions of the conductor, all with a minimum investment in tools and production equipment [121]. In contrast, the end-windings of form-wound coils are extraordinarily large, and large space is required in the end-spaces for the connections between coils.

On the other hand, hairpin winding is a technology with growing acceptance in the automotive industry [122]. Compared to round wire distributed windings, hairpin technology has the advantages of higher fill factor, higher industrialization capacity, reduced end windings, better thermal dissipation and higher reliability and quality, with less variability between different units [123]. However, developing the hairpin industrialisation process is complex, the flexibility and scalability of the designs for other AC concepts is reduced, the end windings can be larger than with wire windings for low pole number machine designs (2-4) and, above all, the AC losses in the conductors at high frequencies can be very high unless solutions with a large number of pins are used and the transposition between pins is optimised [124], [125] (FIGURE 8).

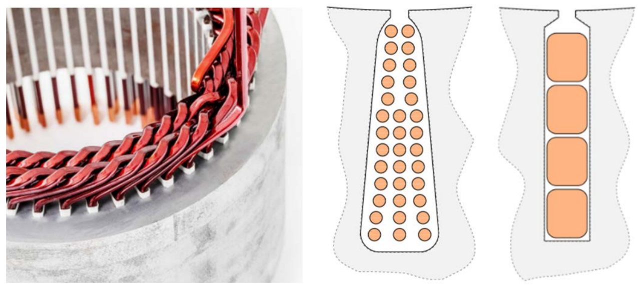


FIGURE 8. Illustration of a hairpin winding (left), a stator slot with round copper conductors in random winding (centre) and a stator slot with hairpin winding (right) [124].

It should be noted that the open slots required by continuous hairpins can be an interesting design feature for very high current density electrical machines in which the flux linkage due to the stator currents tends to close across the slots [126]. In these cases, it has been found that stator structures with semi-closed or trapezoidal slots can impair machine performance due to high levels of flux leakage, benefiting solutions with open slots [127] (FIGURE 9).

Litz wire is a great alternative to tackle the problem of high AC losses [128]. This type of conductor can be found in rectangular cross-section, which makes it very moldable. It is also possible to make hairpins with Litz [129]. The biggest problem is that it cannot be soldered; the connection must be made by hot crimping or thermomechanical compression, so it requires more space for the connections than the conventional hairpin. Moreover, Specialcorde [130] is working on a rectangular Litz wire with hollow center for air-cooled system.

Abovementioned technologies hardly achieve filling factors of 70-85%, even with rectangular or hexagonal conductors, especially in the case of distributed windings. In order to reach higher fill factors, profiled conductors (FIGURE 10 [131]) can be implemented, such as the form-wound and hairpin windings [132], [133], [134], [135].

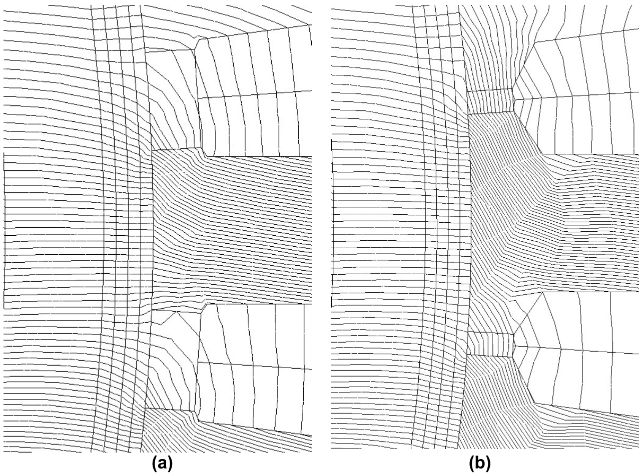


FIGURE 9. Flux leakage in the tooth tip of the slot with different slot openings. In (b), it can be seen that the flux leakage increases when the slot opening becomes smaller [127].

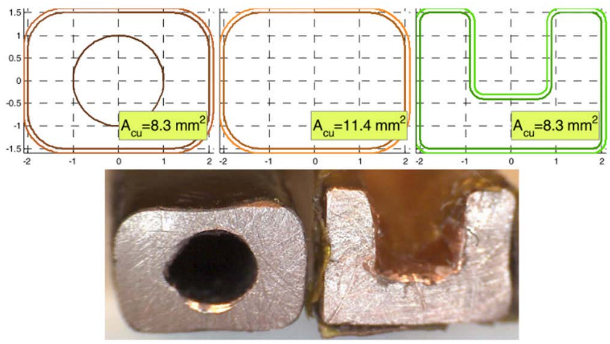


FIGURE 10. Cross-section area of predefined enamelled conductors used in the models (top) and the experimental work (bottom) [131].

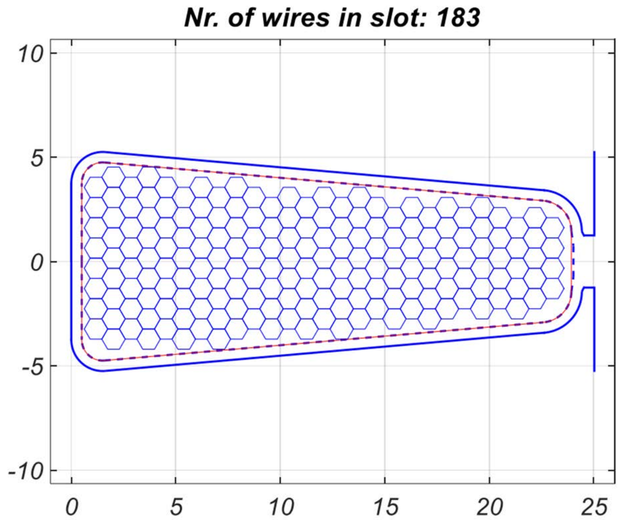


FIGURE 11. Orthocyclic distribution of the hexagonal profiled conductors in standard slot [136].

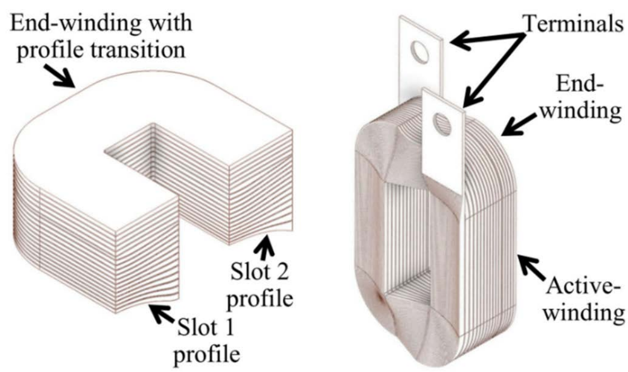


FIGURE 12. CAD illustrations of the shaped profile winding produced with additive manufacturing [137].

One of the technologies under development that increases the slot fill factor (theoretically as high as 90%) and reduces the end windings is the utilisation of linear, flyer or needle winding techniques as the one shown in FIGURE 11 [136]. Additional advantages over round conductors are better thermal conductivity and mechanical stability.

Moreover, the additive manufacturing process can also achieve high fill factors, while controlling absolutely the shape and position of the conductors in the slot and the end-spaces [137] (FIGURE 12). Hence, minimum end-windings can be achieved and the geometry of the conductor can be optimised to reduce AC losses [138] in high frequency applications (e.g. by reducing the height of the conductors in the slot closer to the stator bore, rounding the edges closer to the teeth, inserting voids in the conductors, leaving solid conductor sections in the end-windings where AC effects are weaker for improved overall resistance, etc.).

The flexibility of additive manufacturing makes it the ideal method to couple with the direct cooling of conductors in low pressure drop applications, as a large number of parallel channels can be built. Finally, the additive manufacturing of windings is becoming a common process to demonstrate proofs of concepts regarding machine topology or cooling designs prior to industrialisation.

Another technology that has been gaining popularity in recent years are hollow conductors (as shown in FIGURE 10) [75], [76]. These types of conductors generally have a rectangular cross-section with a circular or rectangular shaped hole inside, which allows direct cooling through the hole. The most serious drawback regarding the hollow conductors is that they require complex manufacturing processes to meet the requirements of flexibility, pressure drop limitation and reliability.

A not novel but unmatured technology regarding the stator winding is the skewed or helical configuration (FIGURE 13). Thanks to this winding proposed by several authors in the 1980's [139], [140], [141], the end windings are supressed with the corresponding weight and space optimisation, in a slotless configuration to properly fit the winding.

This configuration has been studied specially for superconducting machines, as the vast majority of them are slotless

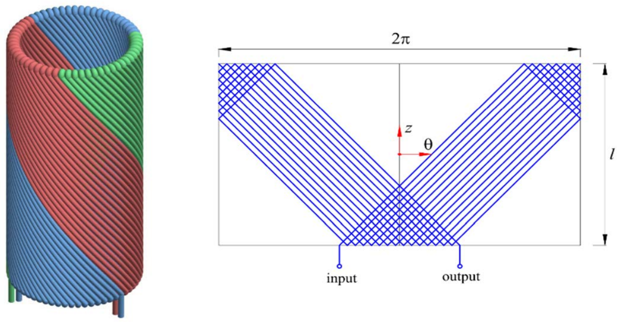


FIGURE 13. 3-D representation of a three-phase skewed winding (left) and diagram of one phase coil of skewed winding (right) [142].

due to the oversaturation of the teeth. The helical winding has been implemented more recently in a PMSM in [142] and for a superconducting generator for electric aircraft in [143].

In order to tackle the aforementioned challenge regarding the high voltage issue in high altitude, the insulation of the conductors needs to be carefully considered.

According to a study carried out by Jansen et al. [144], by elevating the line voltage of a 2.6-MW single-aisle electric aircraft from 540 V to 4.8 kV, 1.4 tons of cable conductor mass can be saved. Moreover, in the NASA N3-X design, a minimum of 6 kV was proposed for the voltage level [88].

There is not a clear procedure to determine the optimal voltage for the electrical system of an electrically propelled aircraft. The highest accepted power distribution voltage of existing electrical systems for aircraft is 270 VDC [145]. The main factor affecting PD is the environmental conditions of the surrounding gas, along with the magnitude and frequency of the line voltage, the configuration and geometry of the electrodes, and the type, properties and aging of the insulator [146]. The threat of PD in inverter-fed machines, especially at high-altitudes, imposes a serious reliability challenge that has urged researchers to work on new candidates, such as Litz wire [147], [148], [149], [150].

Secondly, high-frequency PWM pulses generated by power converters are another potential threat to insulation systems. Fast-rise voltage pulses can produce PDs and cause accelerate aging of the insulation. The Repetitive Partial Discharge Inception Voltage (RPDIV) has proved to be affected by the frequency. The higher the frequency, the lower the RPDIV [151]. Moreover, power dense machines are very demanded, so they must withstand high temperature gradients and mechanical stress; thus, the wire insulation should also have a high thermal conductivity.

C. MATERIALS FOR ELECTRIC MOTORS

The materials forming the active parts of an electric motor can be divided into:

- The lamination in the rotor and the stator (usually made of soft-magnetic material)
- The winding (copper or aluminum)
- The magnets (hard-magnetic material)

For high speed and power density motors, the selection of the soft magnetic material of the magnetic circuit is a key factor. It must be done attending to loss reduction, magnetic saturation and mechanical strength. Among the most common soft magnetic materials used in electrical devices, nickel-iron (Fe-Ni), silicon-iron (Fe-Si), cobalt-iron alloys (Fe-Co), amorphous and nanocrystalline alloys can be found. Fe-Ni presents a very high permeability, but its saturation flux density is far from being competitive for high power density machines (1.4 T). Amorphous and nanocrystalline materials are too thin to be laser-cut and too hard to be stamped. Thus, Fe-Si and Fe-Co alloys appear as the most used materials [152] (FIGURE 14).

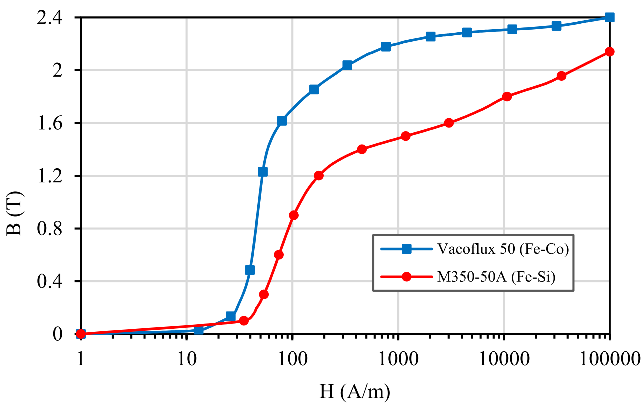


FIGURE 14. Magnetisation B-H curves for two different materials. Fe-Co alloy (Vacoflux 50, [159]) and Fe-Si alloy (M350-50A, [160]). This curve relates to the magnetisation properties of a material as a function of the magnetic field strength.

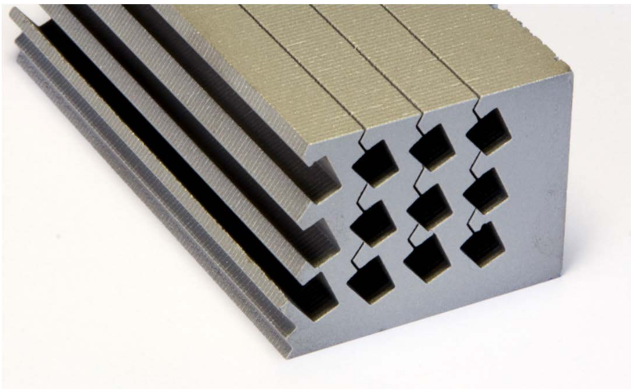
Fe-Si alloys present a good balance in terms of losses, saturation and improved mechanical properties [153], [154]. On the other hand, Fe-Co alloys present unbeatable magnetic properties (depending on the Co content, reaching values of 2.4 T) and less losses than the Fe-Si [155], with the disadvantages of poorer mechanical properties and more complex manufacturing techniques. It can be found in laminations as thin as 0.1 mm [156] by different manufacturers [157], [158].

Regarding hard-magnetic materials, the most used permanent magnets for high power density PMSM are NdFeB or SmCo. From the electrical point of view, both materials behave in a similar way, as is shown in Table 3; however, a machine with NdFeB magnet will be lighter than a machine with SmCo as it requires slightly less material for the same performance [161]. In order to differ between the materials, several PM grades from different manufacturers should be assessed [162]. Nevertheless, the aeronautical standard is to use SmCo because of its high operating temperature, high coercivity and low temperature coefficient [163].

In addition to the selection of the material, it is very important to carefully design the magnets in terms of geometry and segmentation to prevent eddy current losses (FIGURE 15). Some magnet suppliers offer magnets divided in segments as thin as 0.4 mm [167] or with different shapes, as the Snakeline

TABLE 3. Comparison between SmCo and NdFeB magnets.

Property	Sm_2Co_{17} [164]	N50H [165]	N38AH [166]
Remanent Field [T]	1.19	1.43	1.24
Coercivity [kA/m]	880	975	939
Intrinsic coercivity (kA/m)	1800	1274	2626
Remanence Temp. Coefficient [%/ºC]	-0.035	-0.12	-0.12
Coercivity Temp. Coefficient [%/ºC]	-0.25	-0.62	-0.38
Max. Energy Density [kJ/m^3]	265	390	299
Max. Operating Temperature [ºC]	300	150	220



(a)

(b)

FIGURE 15. In (a), L-type laminated magnets reduce eddy current loss in high-efficiency motors [169] are shown. In (b), an illustration of a Snakeline Magnet [168].

Magnets, which reduce the magnet losses keeping one single piece [168].

Lastly, another key parameter is the material of the winding. The vast majority of the produced and designed electric motors for aircraft applications have copper wires due to the wide spread of this material for conducting purposes. There are different varieties, e.g., ‘‘oxygen-free’’ copper, which offers higher conductivity, higher ductility and higher corrosion resistance, used for direct water cooling. In spite of this, recently some prototypes and studies have been carried out with High-Temperature Superconducting (HTS) windings [170], [171], [172], [173]. This unmatured technology leads to the groundbreaking attribute of having virtually zero electric resistance; however, it requests some specific geometrical and temperature conditions.

D. HIGH-TEMPERATURE SUPERCONDUCTORS (HTS)

The superconducting motor has grown its popularity in the mid/long-range aircraft sector due to its potential in terms of power-density. Although there are ongoing studies on superconductors, the technology is not very mature yet. However, it is a system that has many advantages and once developed, would help significantly towards all-electric aircraft. Even if the superconductivity could be the future of the electric aircraft propulsion (the current density provided by a superconducting motor can be 10 to 20 times higher than another one with conventional conductors [174]), it has a major disadvantage that hinders its employment: the cryogenic temperature at which it must be held during operation. The cryocooler that encloses the motor implies a large extra weight that reduces the efficiency of the whole system, and it should be deeply studied and assessed.

Until 1987 the most employed superconducting materials were the NbTi and the Nb_3Sn with a superconducting transition temperature of 10 and 18 K respectively (temperature above which a material becomes a superconductor). Nevertheless, from 1987 the superconducting critical temperature increased notoriously due to the discovery of layered cuprate superconductors (values up to 100 K) [175]. Despite their high cost, complicated implementation and other obstacles, various models and prototypes have been developed in the meantime that feature this technology. According to the BCS theory of superconductivity proposed in 1957 (named after Bardeen, Cooper and Schrieffer), there is no upper limit to the value of the critical superconducting temperature; all is needed is a favourable combination of high-frequency phonons, strong electron-phonon coupling and a high density of states [176].

There are hundreds of material alloys that are capable of being superconducting at conditions below the critical superconducting temperature. However, only a few are suitable for aeronautical applications due to the specific conditions to which they must be exposed. The most commonly used superconducting wire is the aforementioned NbTi, but as it is a low-temperature superconductor (LTS) it does not make sense to use it in electrical machines where a large cryocooler required to superconduct electricity would reduce the efficiency [175].

In the late 1980s, new superconducting materials called second generation (2G) HTS were developed. These materials are composed of cuprate and other metals such as bismuth (BSCCO) [175], yttrium (YBCO) [177] or lanthanum (LBCO) [178]. Some of these alloys are capable of reaching critical superconducting temperatures of up to 108 K, as in the case of Bi-2223 [179]. The complex manufacturing process of these materials makes them expensive, though the use of high operation temperatures may reduce the overall cost. Several electrical machines have already been developed using these 2G superconductors. Although the critical temperature is becoming progressively closer to the ambient temperature (FIGURE 16), auxiliary systems are required in order to obtain the specific environmental conditions for superconduction to occur.

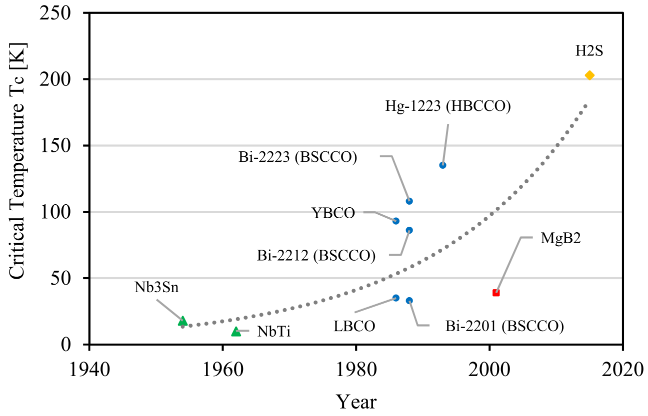


FIGURE 16. Temporary evolution of the critical temperature of different superconducting materials.

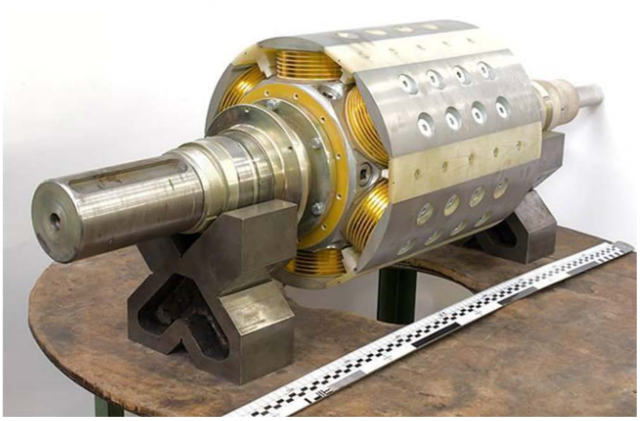


FIGURE 17. General view of a superconducting rotor with HTS coils, part of a 200 kW HTS motor [189].

Superconductors are feasible both in the electrical wiring of the aircraft and in its motors' windings. For the case of the electrical distribution, high currents can be achieved at lower voltages due to near zero resistance. The issue with superconductors is that they only operate at cryogenic temperatures, and therefore the increased weight and extra power consumption that such a cooling system would require must be considered.

On the other hand, superconductors can also be used in the motor windings. The optimal and most efficient configuration would be to use superconductors in the field and in the armature of the motor. However, with today's technology, most electrical machines that use superconductors do so only in the field winding as it is less technologically complex even though the potential is more limited than using HTS in the rotor and stator [7], [180], [181].

The mean airgap flux density is a key parameter to increase the power-density of any electrical machine and for aircraft applications is usually between 0.4 and 1 T [48], [49], [50]. This parameter is limited by the saturation of the metallic lamination and by the magnet or field winding capability. Nevertheless, with the use of superconducting bulk magnets, the achieved value of trapped field is far stronger, beating a maximum of 17.6 T [51], [52], [53]. Even if the conditions for the study are inconceivable for a high-speed rotating electrical machine, it leads the way to the possibility of reaching higher power-densities in electric motors.

One of the biggest challenges of superconducting windings are AC losses. Losses in superconductors occur whenever they are exposed to time-varying magnetic fields or transport currents [182]. Therefore, the quantitative evaluation of AC losses is transcendental for the design of SC windings and their applications to electrical power machines. Several studies have assessed this issue over the last half century by multiple authors in [183], [184], [185], [186], [187], and [188].

A number of motors and generators have been developed over the last few years by a number of authors such as Zhang et al. in [171] and [183], Dezhin et al. [189] (FIGURE 17), Luongo et al. [190], Nam et al. [191] or by Grilli et al. in the ASuMED project [192].

Moreover, in Table 4, a comparison of the power characteristics of the aforementioned electric drives is shown. Some of the parameters are not defined (ND) in the models.

TABLE 4. Comparison between developed aircraft electric motors.

Electric Motor	magni650 [22]	Zhang [171]	Dezhin [189]	Luongo [190]	Nam [191]	ASuMED [192]
Rotor Speed (rpm)	1900	1500	1500	2700	7200	6000
Torque (kNm)	2.8	6.4	1.3	0.6	3.3	1.6
Power (kW)	560	1000	200	160	2500	1000
Power dens. (kw/kg)	3.2	ND	ND	5.3	18.7	20
Phase voltage (V)	800	ND	450	ND	1800	ND

IV. CONCLUSION

In this paper, factors that hinder the development of the aircraft electrification have been reviewed. The difference of weight between conventional electric motors and the corresponding combustion engines which demands an increase in the power density, the necessity of innovative cooling systems and the risk and difficulties of the use of high voltage in the energy transportation system of an aircraft are reviewed.

To face up the aforementioned challenges, disruptive technologies are emerging such as new machine topologies and configurations, winding and insulation manufacturing techniques, new trends regarding materials for electric drives or the low- and high-temperature superconductors, of particular interest the latter, as its critical temperature is higher than the former. The presentation and synthesis of all these technologies in a single paper provides novelty in the field of electric propulsion in aviation pushing forward in the development of the all-electric aircraft.

As a result of the advances exposed in this paper, research will continue to explore methods to confront today's technological constraints and achieve higher power-densities than current machines, and, in turn, improve aircraft efficiency furthermore.

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