Application and Performance Trends of Electric Motors for Aircraft Propulsion

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***Abstract*— The aircraft electrification is considered as a promising solution to reduce emissions from the aviation sector. This paper presents an overview of the enabling electric motor technologies for electrically propelled aircraft. The data are a collection of available information in the technical literature, including current applications, projects, and prototyped demonstrators. This critical analysis is conducted in the perspective of the most used technologies, cooling solutions and key performance indexes, such as specific power and rated speed. Finally, values for performance projections are discussed along with emerging technologies in electrical machines to enable a higher degree of electrifications for air transportation.**

Keywords*— *Electric aircraft, electric propulsion system, electric motors, transportation electrification, specific power, performance indexes.

I. INTRODUCTION

The transportation sector is a significant contributor to CO_2 emissions, accounting for up to 24% of emissions from fuel combustion, with air transport alone responsible for nearly 10% of the total amount [1]. To achieve the ambitious goal of net zero emissions by 2050, the aviation sector needs to undergo a significant transformation towards more or all electrified systems [2]-[4]. Aircraft can be classified according to their size, capacity, and final usage. General aviation is defined as civil aircraft operations except for commercial air transport. It's usually designed for a small number of passengers (up to 10 passengers) and shorter flight ranges (typically up to 1000 km). On the other hand, commercial aviation has most of the passenger and cargo traffic and thus, also the majority of greenhouse gasses emissions. For this category, narrow-body aircraft are usually single aisle airplanes with a capacity for up to 300 passengers and regional flight range. Wide-body aircraft typically have two aisles, a capacity of 200-850 passengers, and are well suited for long range intercontinental flights. Figure 1 illustrates this categorization together with the preferred electric power architectures and typical powertrain ratings for different aircraft sizes [5].

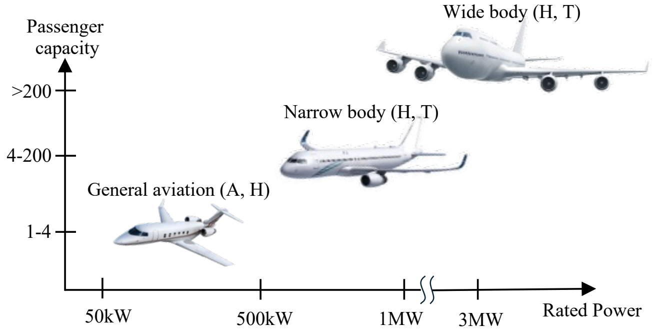

Fig. 1 Preferred electric power architectures for different aircraft sizes (A=all electric, H=hybrid electric, T=turbo-electric). Figure adapted from [5].

The electrification degree of an aircraft depends on the power rating of the components and the flight range. It can vary from turboelectric propulsion, through hybrid schemes, more electric aircraft (MEA) systems, up to all-electric aircraft (AEA) configurations [6].

However, the complete electrification of aircraft remains a challenging task, mainly because of the yet limited energy density of electrical storage systems [7], [8]. This particularly hinders the propulsion electrification of aircraft that requires extensive flight ranges. In these cases, hybrid solutions may represent a promising compromise to guarantee the required performance [9], [10]. Instead, general aviation aircraft could be effectively equipped with fully electrified propulsion systems. Indeed, the Technology Readiness Level (TRL) has advanced to the development of electric aircraft for commuter airplanes that has been prototyped, tested, and commercialized [11]-[14].

The aim of this paper is to provide an overview of the enabling electric motor technologies for electric aircraft propulsion systems. The paper briefly summarizes the main characteristics of electrical machines for aircraft applications as well as for the main components of an electric propulsion architecture. Then, literature solutions, medium-to-long-term research studies, and prototyped demonstrators of electrical machines for aircraft propulsion are reviewed to highlight the trends expected for their key performance indexes. The derived performance projections are critically discussed together with the research tendencies and emerging technologies for the development of high-performance electrical machines suitable to enable higher degrees of electrification for air transports.

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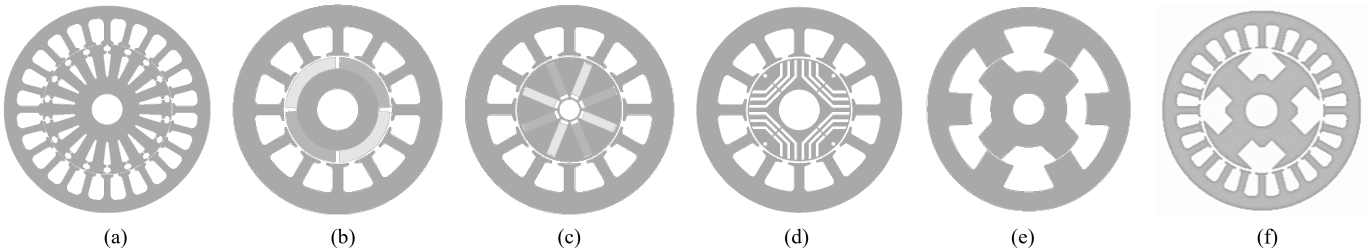
(a) (b) (c) (d) (e) (f)

Fig. 2 Electric machine topologies: (a) induction – IM, (b) surface mounted permanent magnets – SMPM, (c) internal permanent magnets – IPM, (d) synchronous reluctance – SynRM, (e) switched reluctance – SR, (f) wound field– WFSM

II. ELECTRIC MOTOR ALTERNATIVES FOR AICRAFT PROPULSION

In the definition of the propulsion architecture for an electrically propelled aircraft, the different types of electrical machines depicted in Fig. 2 can be considered. High power density and improved efficiency values represent the primary aspects in the definition of the most suitable electric motor type for a transportation application. In this perspective, a dedicated electromagnetic design and the use of high-performance electric and magnetic materials allow to enhance the electric motor torque production and the losses minimization in a wide range of operative speeds. In detail, for electromechanical devices for aeronautical applications, cobalt-iron soft magnetic materials are often preferred to the conventional silicon-iron counterpart because of their higher magnetic saturation levels (typically 2.2 – 2.4 T). Similarly, the use of rare-earth permanent magnets (PMs) allows maximizing the machine specific power and torque density indexes. Moreover, high rotational speeds can be considered as a design option to reduce the machine dimensions and weight, at the expense of increased system complexity to match the load toque-speed requirements, and higher machine losses. Anyway, high efficiencies can be preserved using thin lamination thickness for stator and rotor cores, Litz wires for the stator windings and segmented permanent magnets [15].

For safety-critical applications, such as aircraft propulsion systems, the fault tolerance capability of the electric machine is a crucial aspect. In this context, multiphase windings can be a solution to increase the system reliability due to their intrinsic redundant nature. Indeed, in multiphase windings, each stator phase or three-phase set of the machine can be supplied by an independent power electronics converter, thus extending the redundancy and fault tolerance capability to the whole electric drive system [16], [17]. Table I qualitatively compares the key features for the considered electrical machine types in the perspective of aircraft propulsion systems.

A. *Induction motors*

Induction motors (IMs) are a well-established and reliable technology that provides simplicity in construction combined with low costs. The IM solution can safely handle overload conditions for a limited time and can be completely de-energized in case of faults. The latter feature is particularly important for safety-critical applications since it avoids possible uncontrolled generation operations of the machine. However, the lower power factor and specific power values, compared to the alternatives, often limit their use for aircraft propulsion applications. Additionally, the presence of a current on the rotor side makes the machine cooling more challenging. However, the literature reports examples of induction motors used for aircraft starter/generator systems because of their high-speed and high-temperature operation capabilities compared to PM machines, and for fuel pumps due to their high reliability and low maintenance [18]-[20].

B. *Permanent magnet synchronous machines*

Permanent magnet synchronous machines offer high power density and specific power values due to the presence of PMs in the rotor. This translates into high efficiencies, and high power factor values which in turn reduces the power converter size. Permanent magnet synchronous machines are well suited for high pole pair count, reducing iron yoke dimension and thus the weight and volume of the machine.

This machine type can be realized with both surface mounted (SMPM) and internal (IPM) permanent magnet configurations. The main advantage offered by SMPM motor solutions is their high specific powers. They are usually characterized by lower inductance values than IPM machines, resulting in increased power factor at the cost of higher short circuit currents [21], [22]. However, retainer rings can be required to maintain the PMs in place for high-speed applications [23]. Furthermore, SMPM machines feature a limited flux weakening capability, and thus a reduced constant power speed range compared to the IPM alternatives.

Electrical machines equipped with PMs also present the risk of demagnetization, specifically at high temperatures or for high currents circulating in the stator windings, such as in case of short circuits. In addition, the presence of PMs does not allow to de-energize the machine in case of fault.

C. *Reluctance motors*

Synchronous reluctance (SynRM) and switched reluctance (SR) machines are characterized by a simpler rotor structure in comparison to the other topologies. In their basic configuration, these machines do not present windings or permanent magnets on the rotor side resulting in good overload and fault-tolerant capabilities.

According to the literature, SR motors represent an effective candidate for aircraft electrification applications due their inherent modularity and increased fault-tolerant capabilities because of their concentrated winding layout [24].

TABLE I. PERFORMANCE COMPARISON FOR THE CONSIDERED ELECTRIC MACHINE TYPES

	Induction	**Permanent Magnets**	**Reluctance**	**Wound Field**
Specific power	🟡	🟢	🔴	🟡
Fault tolerance	🟢	🟡	🟢	🟢
Efficiency	🔴	🟢	🟡	🟡
Thermal management	🔴	🟢	🟢	🔴
Cost	🟢	🔴	🟢	🟡
Axial Flux viability	🟡	🟢	🔴	🔴

Moreover, SR motors are suitable for high-speed operations due to their robust structure. Finally, the simplicity of these motors translates in lower costs and higher mass-production capabilities. However, SRs are often penalized by their relatively low specific power and power factor values. At the same time, due to the rotor topology, they are prone to unbalanced radial forces, increasing the wear on the bearings [25]. Finally, since the operation principle is based on reluctance variation in the magnetic circuit, this configuration suffers from high torque ripple values and acoustic noise during operation.

D. *Wound field synchronous machines*

Wound field synchronous machines (WFSMs) are commonly used in conventional aircraft mainly as onboard generators mechanically driven by the engine through a gearbox. In motoring operation, the possibility to independently vary the rotor current enables this machine type to achieve extended constant power speed ranges while maintaining high efficiencies and power factors. Moreover, the possibility to have complete control over the field excitation increases the fault-tolerant capability of the motor.

However, this machine type suffers from limited cooling capabilities because of the presence of the rotor current. Furthermore, the necessity to supply the current to the rotor implies the use of multi-stage machine configurations, slip rings or wireless power transfer systems [26]. These additional components and the dedicated power converters inevitably affect the specific power and final cost of the system.

E. *Axial flux topologies*

According to the magnetic flux line path across the air gap, the presented electric motors can be realized either in radial or axial flux configuration. In radial machines, the magnetic flux lines are perpendicular to the rotation axis, while in axial solutions they are parallel. As Table I indicates, permanent magnet machines are the most viable solutions for axial flux designs.

Axial flux machines are usually preferred to radial flux alternatives for applications that require high torque densities and a limited axial length with respect to the outer diameter [27]. In fact, axial flux machines typically feature '*disc*' or '*pancake*' shapes and can be designed in multistage configurations. At the same time, the pole and stator winding layout can be tailored to obtain yokeless designs, reducing the weight of the machine [28], [29].

III. AIRCRAFT PROPULSION SUBSYTEMS

An electrified driveline for aircraft propulsion includes several subsystems and enabling technologies besides the electric motor, such as electrical distribution systems, power electronics converters and energy storage devices. Each of them has unique specifications that must be tailored to the specific aircraft performance requirements, and they are all interconnected in their impact on each other. Therefore, it is important to provide a brief overview of the other systems and the impact of their characteristics on the propulsion motor.

A. *Electrical distribution systems*

The power distribution system on-board of conventional commercial aircraft traditionally consisted of a low power 28V DC bus for avionics and battery-driven services, and a high power 115Vrms – 400Hz supply for large loads. However, the ever-increasing electric power demand of modern MEA airplanes imposed to shift towards different on-board distribution systems, increasing the voltage levels and introducing the variable frequency [30]. As an example, the traditional 28V DC and 115V/400Hz are supplemented in the Airbus A380 with a 115Vrms distribution system at variable frequency in the range 360-800Hz, while the Boeing 787 introduced 230Vrms variable frequency and 540VDC (±270V) systems [5], [31].

The significant power demand of fully electrified propulsion systems will most likely push the electrical distribution of future AEA towards medium voltage DC systems with voltages expected to exceed the kV level [6], [32], [33]. The perspective shift towards DC transmission systems is mainly due to the elimination of skin and proximity effect losses, as well as to the lower corona effect compared to AC distributions [6]. On the other hand, the main advantage in increasing the voltage for high power ratings relies on the current reduction, thus lowering cables dimension and weight. However, the selection of optimal voltage level for wiring needs also to consider the increased insulation stress at high-altitude due to partial discharges, insulation ageing and arching issues [32], [34]. These challenges for the insulation system are further enhanced in electric motors for propulsion applications since most drives work under PWM modulation with very high pulse voltage change rate.

Obviously, the voltage level of the distribution system also impacts on the characteristics, dimensions, and weight of the energy storage system.

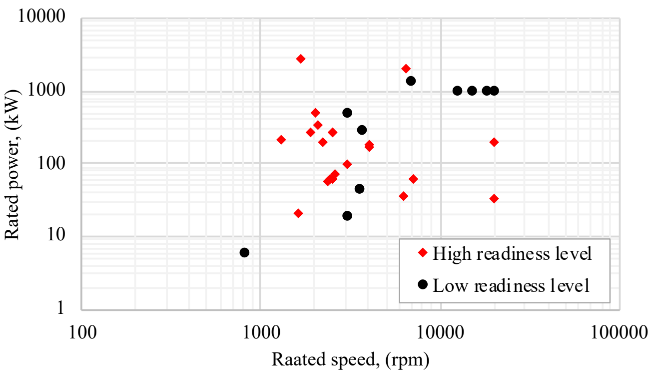

Fig. 3 Rated power vs. rated speed for the considered study cases.

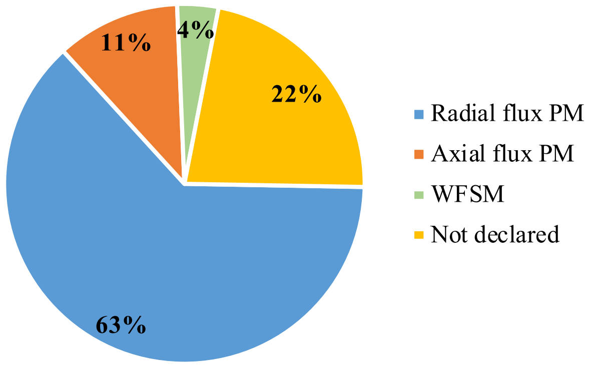

Fig. 4 Motor type distribution of the study cases.

B. *Power electronics converters*

The different aircraft architectures, as well as the presence of multiple electrical distribution systems implies the use of several power electronics converters. For instance, AC/DC power converters are used in hybrid and turboelectric architectures to interface the on-board electric generators with the DC bus, while AC/AC power converters allow interfacing systems and components at different voltage and frequency levels avoiding bulky intermediate DC-link capacitors or DC inductors. The DC/DC converters are present in most of the electrified architectures to feed DC loads and other power sources onboard, or step down the distribution level for low-voltage loads [6]. Instead, DC/AC power converters are in charge of powering AC electric actuators as well as to supply the propulsion motors in electrified aircraft.

Depending on the aircraft type, the power ratings and voltage levels of DC/AC power converters for propulsion applications can greatly vary. For general aviation, low-voltage (< 1000 V) and low-power (< 500 kW) propulsion systems are sufficient for thrust generation. However, for larger size and long-range aircraft, these values can scale up to 1-3 kV and over 2 MW of power respectively. Often, power converters for aircraft propulsion applications are also parallelized for system redundancy as well as to overcome the power rating limits of power electronics components [5]. Recently, wide band-gap devices, such as SiC and GaN semiconductors, emerged as a replacement for traditional silicon technology due to their higher switching frequency that enables a weight reduction of passive components [33].

A significant parameter that impacts the size of the DC/AC power converter for propulsion applications is the power factor of the electric machine. In fact, for the same load power that needs to be delivered, a low power factor implies a higher rate of reactive power, thus increasing the power converter size.

C. *Energy storage systems*

The energy and power density of a storage system are among the key parameters that define the range and performance of an electrically propelled aircraft. Today's most used technologies for energy storage in electric aircraft propulsion systems are electrochemical batteries and fuel cells (FCs).

Among the different battery alternatives, Lithium-ion (Li-ion) are the most practicable option available todays for aircraft electrification. They present energy density values around 250 Wh/kg at cells level, that reduces to 110-160 Wh/kg for the complete battery pack, a power density that can reach up to 1500-2000 W/kg and energetic efficiency values up to 80% [6], [31]. Despite technological advancements are expected to further increase these values in the near future, significant developments are still required to increase the energy density values to enable the pure use of batteries in aircraft with significant flying range [8], [35]. On the other hand, storage systems based on low temperature FCs, such as proton exchange membrane, present energy densities in the range 600-800 Wh/kg [6], [36]. However, the main drawbacks of a FC system compared to batteries is their lower power density and lower efficiency, typically ≤ 100 W/kg and ≤ 50-60%, respectively [33], [35].

Hybrids storage power systems are often considered to take advantage of the energy density of fuel cell systems and the power density of batteries. In this case, the constant power required by the flight mission is supplied by the FC, while peak loads such as during take-off are covered by the battery.

IV. REVIEW OF ELECTRIC MOTORS IN AIRCRAFT PROPULSIONS

Regarding electric motors, key performance indexes are hereafter reported considering data collected for electric motors specifically designed or used in aircraft propulsion systems. In detail, the analysis is based on the information available for electrically propelled aircraft demonstrators and on-going projects [37]-[48], datasheets provided by motor manufacturers [49]-[53], and technical literature [54]-[64]. The complete dataset is composed of more than 30 study cases, selected only if the available information included or allowed the calculation of rated power, specific power, and rotational speed. Nevertheless, the available information not always specifies if the values of specific power and motor weight are based on active materials or the complete motor, i.e. including housing, shaft, bearings, etc. For sake of clarity, the figures reported in this paper adopt filled and hollow markers to respectively distinguish the study cases that explicitly declare the specific power value from those where this information has been computed based on the indicated power and weight data.

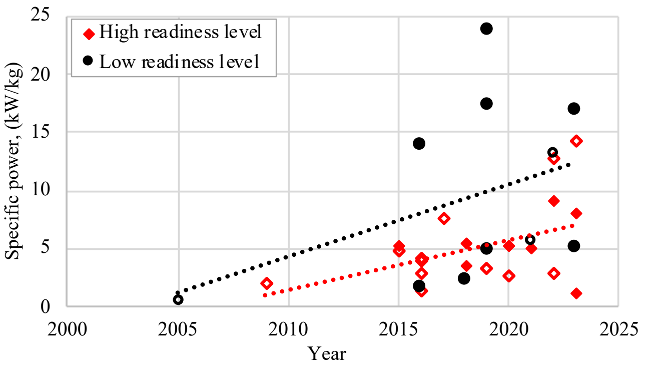

Fig. 5 Specific power yearly growth and associated trend lines.

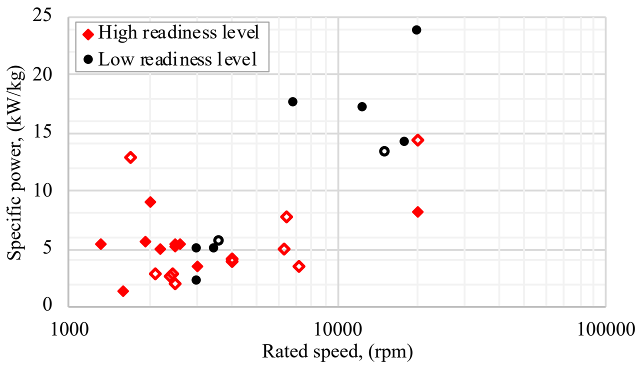

Fig. 6 Specific power vs. rated speed.

As Fig. 3 summarizes, the rated power for the considered study cases ranges from tens of kW up to few MW, with rated speeds approximately between 1-20 krpm. The figure also distinguishes the study cases between high and low technological readiness levels, where the former include those already mounted on an aircraft demonstrator or tested on a laboratory rig, while the latter consider machines that are still in the research and simulation stage.

The chart in Fig. 4 shows the distribution of the different motor types of the considered dataset. Note that for aircraft demonstrators, the provided information is often limited to the main motor rated values without details on the motor type. Considering the cases where this information was provided, most of the solutions are based on PM machines, mostly in their surface mounted configuration, consistently with the performance assessed in Table I. Indeed, they are well suited for propeller and fan loads as they do not require constant power speed range operations. Also, the chart shows that most of the analyzed study cases adopt radial flux topologies.

Figure 5 shows a plot with the specific power versus the development year. Although the available data are scattered, particularly for the case studies at low readiness level, the figure also includes linear trend lines. Even if the correlations between the data are quite low, the trends outline that is reasonable to consider that research case studies are at least 5-10 years ahead of the machines prototyped or ready to be tested on flying demonstrators.

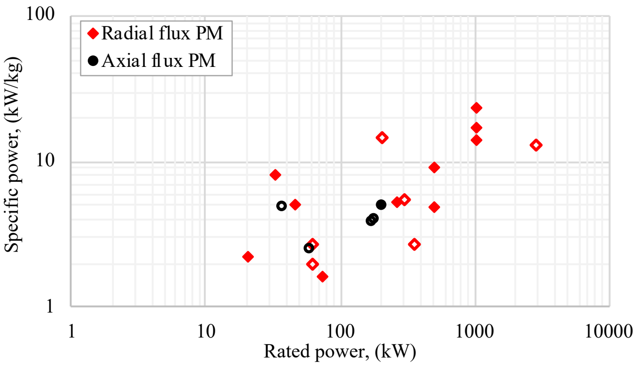

Fig. 7 Specific vs. rated power for radial and axial flux PM motors.

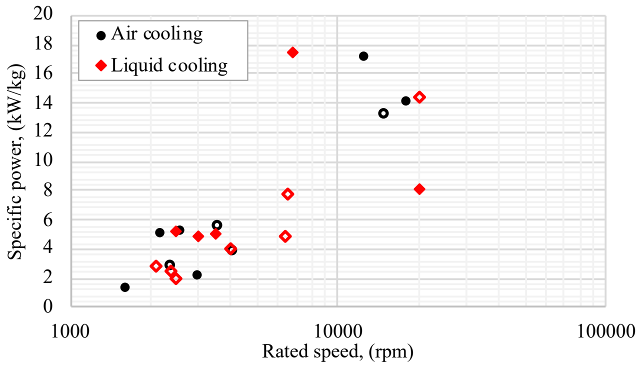

Fig. 8 Specific power vs. rated speed for different cooling systems.

The plot in Fig. 6 depicts the specific power versus the rated speed for the analyzed solutions. Again, the data are distinguished on the base of the readiness level. For the analyzed case studies, the trend shows that increasing the rated speed leads to higher specific power values. This translates in more compact machine designs at high rated speeds. In fact, the machine size depends on the rated torque that, for a defined rated power, diminishes increasing the rated speed. For rotational speeds above than those of the considered study cases, however, the power density increasing trend can be penalized by high frequency losses in the machine materials, as well as by the smaller surface available for the heat extraction because of the smaller machine dimensions.

However, most of the analyzed solutions are concentrated in the lower speed region. This is most likely due to the possibility to avoid a mechanical transmission to meet the load torque-speed requirements, thus increasing both the system safety and efficiency while reducing weight and maintenance requirements. Furthermore, higher speed often introduces challenges to maintain dynamic and structural stability of the rotor.

Figure 7 shows that case studies with lower power ratings present lower specific power values. This evidence becomes significant when considering distributed propulsion systems in the aircraft design stage, where the required propulsive power is provided by multiple smaller machines instead of a single motor.

Nevertheless, [65] surveys a wider range of electrical machines, not only limited to electric aircraft applications. In that case, even if a clear trend cannot be identified because of the scattered data, a reduction in the specific power can be observed with increasing power. Again, the reason can be related to the necessity of reducing the electromagnetic and electric loadings to maintain the same loss density and comply with the thermal constraints [66].

The data in Fig. 7 also highlight that axial flux machines present specific power values in line with the radial flux alternatives. However, radial flux machines seem to be preferred for high power solutions, at least for the considered study cases. Considering that the machine performance and dimensions strongly depend on the adopted cooling system, the graph in Fig. 8 shows the specific power versus the rated speed for air and liquid cooling of the study cases, when declared. The trend confirms that liquid cooling is the most adopted solution for higher speed and power density values. Note that the three air cooled cases at high speed and high specific power values refer to machine designs still at the research stage.

V. PERFORMANCE PROJECTION AND RESEARCH TRENDS FOR PROPULSION ELECTRIC MOTORS

For the considered study cases, the specific power values are mostly below 5 kW/kg for constructed machines or prototypes. Though, in the last few years some machines with higher specific values have been produced (see Fig. 5). Despite the considered data set includes study cases with very different power levels, performance, and design characteristics, the specific power projection suggests an increase of this value. This agrees with the estimation of ~9 kW/kg in 2035 projected by the Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions reported in [35] for the lowest end of regional and single-aisle aircraft.

The investigated research studies demonstrate that even higher specific power values can be achieved. However, their development is still at early stage. This is confirmed by Fig. 9 that reports the data collected in [11] for some electric machines applicable for aircraft propulsion systems along with their TRL. These data, clearly show that machines at higher development stage feature lower specific power values. This suggest that new research trends and advancements in the field of electrical machines are key enablers to achieve the specific power targets for increasing the electrification degree of the propulsion systems for aviation.

Among them, it is worth mentioning research activities on materials, that include carbon nanotubes as a promising replacement for copper because of their better electrical conductivity and lower density [67], or additive manufacturing for optimized design solutions and weight reduction.

Advanced cooling techniques, such as spray cooling on the machine end-windings, or direct conductor cooling are also key solutions to improve the machine specific performance. However, for aircraft electrification, the thermal management system selection is often a challenging task since the added weight of additional components required for liquid or oil cooling will impact on the aircraft performance.

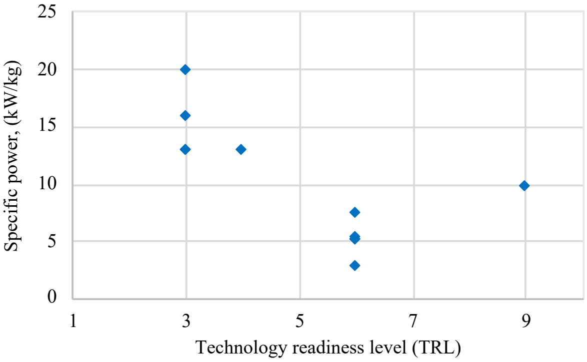

Fig. 9 Specific power vs. TRL (data from [11] using the minimum value reported for each TRL range).

The use of potting materials for thermal conductivity enhancement and composite materials are also thoroughly investigated as means of passive cooling techniques [68]. In the medium-to-long term, the replacement of traditional copper windings with superconducting materials is expected to enhance the specific power of electrical machines beyond 20-30 kW/kg [69]. Beside the still low development stage of superconducting machines, the main disadvantageous impacts of this technology are the complexity, weight and efficiency of the required cryogenic cooling system [70].

VI. CONCLUSION

The several examples of electric motors for electrified aircraft propulsion systems collected in this paper show that permanent magnet machines are often the preferred solution for this application. The main reason for this preference can be related to the higher specific power and improved efficiency compared to the alternatives, even if the impossibility of de-energize the machine can introduce some drawbacks from the fault tolerance standpoint. The analysis also compared radial and axial flux machine topologies, as well as air and liquid cooling solutions. For the considered study cases, axial flux machines present performance in line with radial flux counterparts, while liquid cooling allows higher motor performance. Obviously, a liquid cooling system implies an additional weight, if not already available on-board.

Despite the data set includes different machine types, a wide power range and different design solutions and technologies, the conducted analysis shows that for prototyped or produced machines the specific power is typically below 5 kW/kg, while the rotational speeds are generally in the range 3000 – 4000 rpm, thus suitable for direct-drive connections to the propeller or fan. However, some machines with higher values of specific power and higher rotational speeds are already available. Solutions still at research and design stages seem to promise further enhanced performance. The projection of the retrieved data in 10 – 15 years agrees with the estimations and target values reported by other institutions and agencies to enable the propulsion electrification, at least for general aviation or small regional aircraft. However, to achieve these targets, new design solutions, production technologies, advanced cooling systems as well as the application of innovative materials must be pursued in the research field of electrical machines.

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