

OVERVIEW AND EVALUATION OF ELECTRIC MACHINES FOR ELECTRIC REGIONAL AIRCRAFT PROPULSION SYSTEMS

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Abstract

The article presents and evaluates the most common topologies of electric machines for use as propulsor drives in regional aircraft. The design, mode of operation, characteristic features and areas of application of the direct current machine, the permanently excited and externally excited synchronous machine, the reluctance machine and the induction machine as well as their topology variations are described. Evaluation criteria derived from aviation-specific requirements are weighted by means of a pairwise comparison. After a pre-selection by exclusion criteria, selected topologies are consequently evaluated. The results show the great potential of radial flux and axial flux permanently excited synchronous machines in terms of power density and efficiency as well as the advantages of the switched reluctance machine due to its simplicity and high level of safety. The challenges identified for future electric machines include high efficiency and power density with varying altitude and thus changing temperatures and ambient pressures, taking into account high system safety and durability. The need for research and further development is emphasized by the average values of the evaluation factors.

Keywords

Cylindrical Pole Synchronous Machine; Direct Current Machine; Electronically Commutated Machine; Induction Machine; Radial Flux/ Axial Flux/ Transverse Flux Permanent Magnet Synchronous Machine; Switched Reluctance Machine; Synchronous Reluctance Machine; Weighted Point Rating; Wound Field Synchronous Machine

1. INTRODUCTION

The aviation industry, which continues to grow, generates around 2 % of global greenhouse gas emissions, 90 % of which come from commercial aviation [1, 2]. Limiting the impact of global climate change can be achieved by reducing CO₂ emissions, as set out in the Paris Agreement and the European Commission's *Flightpath 2050* publication. Air transport plays an important role in this, regardless of the increase in traffic volume [3]. Hence, the architecture of the powertrain in current aviation must be rethought and further developed.

Several electrified powertrain topologies have already been identified for a wide range of requirements. Current entirely gasturbine-driven aero engines could be replaced by turbo-electric, hybrid-electric and all-electric powertrain topologies [4, 5]. In the turbo-electric approach, a gas turbine supplies an electric drive motor with electrical energy via a generator. Hybrid-electric concepts combine gas-turbine-driven and electrically driven propulsors, while the all-electric topology involves purely electric drives supplied by galvanic cells. The latter supply can be battery or fuel cell-based. Hybrid and all-electric topologies are limited in their implementation in large aircraft due to the high energy storage requirements in aviation and the low technology readiness level (TRL) [1]. Nevertheless, a technological shift towards electrified aviation offers numerous advantages, including the areas of noise

emissions, environmental friendliness and safety [6]. Sadraey [7] also points out the low-cost production and low-maintenance operation of an electric propulsion system compared to current gas turbine-powered propulsion systems. It is estimated that achieving an all-electric aircraft (AEA) can reduce aircraft weight by 10 % and fuel consumption by 9 % [8].

Electric motors have already been proven and tested in other sectors, such as the automotive, ship and railway industry, which means that existing knowledge can be transferred to the aviation sector. High performance classes, high power density, reliability and durability will be required here in the future, which is why research must be carried out in this area. In aviation in particular, there are extremely stringent requirements for electrical machines in terms of safety and reliability at varying altitude, temperature and air pressure during operation.

This article provides an overview of the most important topologies of electrical machines and deals specifically with their special features. In the two-stage evaluation method, the topologies are filtered out using exclusion criteria and after establishing weighted criteria from aviation-specific requirements, the remaining machine topologies are evaluated for their suitability for aircraft propulsion systems. Finally, the most promising options for use in commercial aircraft powertrains of a regional aircraft and their development challenges will be identified.

2. ELECTRIC MACHINES

Electrical machines (EM) are electromechanical energy converters that can be operated as motors or generators. A distinction is also made between stationary and rotating systems. In the following elaboration, only rotating EMs in motor operation in the form of electric drive motors are considered. The following designations of EMs are therefore representatives of this special form.

Many machine topologies have been established over the years. A possible categorisation of the most common EMs is shown in FIG 1. Depending on the application, certain topologies are more or less suitable. In the design of radial flux machines, which are the most commonly used, there is a choice between internal and external rotors in addition to the topology variation. In axial flux machines, on the other hand, the arrangement of the stator and rotor is varied along the axis of rotation. Furthermore, a gearbox is often used to operate the machine in the optimum working range. Direct drives, on the other hand, operate without this additional source of error. It is clear that a wide variety of topology options can be suitable for the same application.

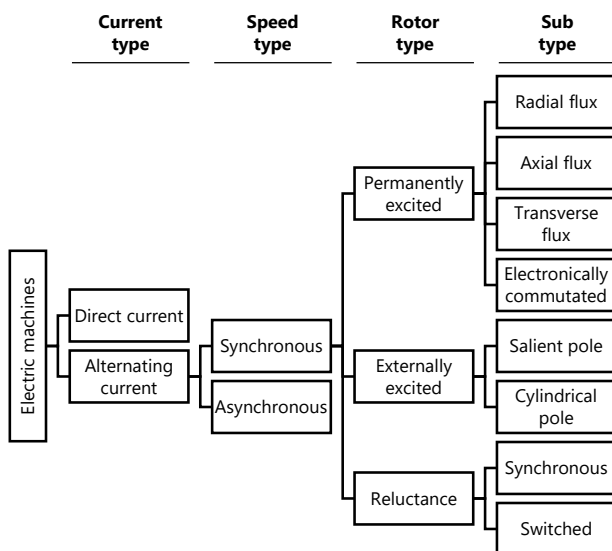


FIG 1: Overview of electric machine topologies

EMs are currently used in land vehicles in the range up to several hundred kilowatts with a maximum specific power of 1-3 kW/kg [1]. Forecasts show that power levels of up to several tens of megawatts will be required in aviation [9] and that specific power levels of over 10 kW/kg or, according to NASA, even over 13 kW/kg will be essential [1, 10, 11]. In order to achieve this, various approaches can be selected based on the characteristic features of the individual topologies. The power P of an EM results from the product of torque M and angular velocity ω . Equation 2.1 also shows the calculation of the power using the mean magnetic flux density in the air gap B , the current coating A , the power factor λ , the diameter d , the length l and the rotational speed n . The power per volume is therefore

directly proportional to the rotational speed, the average magnetic flux density and the current coating:

$$P = M \cdot \omega = \pi^2 \cdot \lambda \cdot A \cdot B \cdot d^2 \cdot l \cdot n \quad (2.1)$$

$$\frac{P}{V} \sim A \cdot B \cdot n \quad (2.2)$$

High-speed applications are therefore a promising choice for high volumetric power densities [12]. Higher power classes also lead to increasing machine volume, but relatively less surface area to dissipate the likewise increasing waste heat due to higher losses. The desired high power densities have the same effect. At the same time, new challenges arise for the power electronics (PE) due to the high voltage level and the increasing switching frequency. The thermal management of the EM and the PE are key components for future electrified aviation with regard to high specific power [10].

In the following explanations, the topologies of EMs and their characteristic features are analyzed in more detail and then evaluated with regard to their suitability for application in the powertrain of a regional aircraft.

2.1. Direct current machine

The direct current machine (DCM) was the first electromechanical energy converter. With the introduction of three-phase technology, it lost its dominant role in the field of electrical drives [13].

The brushed machines fed with direct current are divided into series-wound, shunt-wound, externally excited and permanently excited machines [13]. Their basic distinction lies in the energization of the exciter (stator coils)/ armature winding (rotor coils) and the way in which the stator field is generated. The mode of operation of all topologies is identical. FIG 2 shows the schematic structure of a DCM. The poles of the stator and rotor, each with a constant field amplitude, repel or attract each other. The commutation to maintain the torque and the constant rotation takes place via carbon brushes, which represent a sliding contact subject to wear [13]. The DCM is a constant field machine. The stator and rotor magnetic fields are perpendicular to each other with constant amplitude and thus 90°el (electrical degrees), as shown in FIG 3. Additionally, the fields do not rotate relatively to the stator [12].

In a series-wound machine, the rotor and stator are energized in series, which leads to a proportionality between excitation and load and makes the torque highly speed-dependent. The counter-induction voltage increases sharply at high speeds, resulting in a drop in torque. Due to their high starting torque, they are used in starters of large combustion engines [13]. The shunt-wound machine is energized in parallel, which decouples the excitation current from the load. Decoupling is particularly suitable for use with fluctuating load torque at almost constant speed. On

the other hand, start-up requires special precautions, as large armature currents can occur. Shunt-wound machines are used in conveyor systems due to their decoupled torque [13]. Externally excited DCMs have a separate armature and exciter circuit, which is essential for better speed control. The excitation field, which is constant over the speed, is weakened under high load, which is compensated for by a compound winding by increasing the flux depending on the load. This is shown as an additional winding on the stator pole in FIG 2. Externally excited DCMs are used in highly dynamic drive systems, such as machine tools in industry, due to their wide speed range [13]. In contrast to the other topologies, permanent magnets are used to excite the stator in permanent magnet DCMs. As with separately excited DCMs, the fields are formed separately, whereby the excitation field is generated without additional energy input, which leads to a higher level of efficiency. However, the speed control is limited by the constant excitation field in total. This topology is preferably used in small drives due to its high efficiency and high costs for increasing machine size [13].

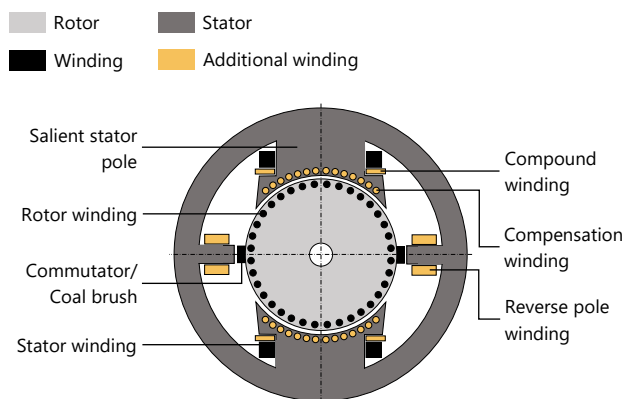


FIG 2: Direct current machine

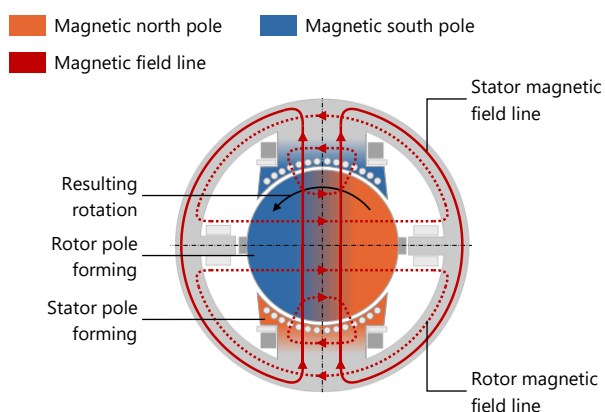


FIG 3: Magnetic field lines of stator and rotor excitation with resulting pole forming of direct current machine

The armature reaction characteristic of DCMs requires additional equipment, especially for machines of a higher power class. FIG 3 symbolises the magnetic stator and rotor

field lines at the stator pole. The stator field distortion resulting from the superposition and the resulting weakening of the excitation flux due to saturation effects in the stator pole material [13] can be clearly seen. Compensation windings counteract this armature transverse field by means of an opposing field. FIG 2 shows their positioning at the pole end in the direction of the air gap. Reverse pole windings, on the other hand, prevent delayed commutation and thus the potential of brush or even round fires from delayed discharge [13]. FIG 2 illustrates their installation in the vicinity of the commutation points.

To summarise, each DCM topology has its respective advantages and disadvantages. The rapid development of inverter technology is pushing DCMs into the background. Due to their simple design, control and the possibility of supply from a DC voltage source, they are still used in household and electrical tools. Occasionally, they are still used up to the megawatt range with low gravimetric and volumetric power density [13–15].

In contrast to DCMs, the AC machines listed below are rotating field machines. Here, the stator generates a magnetic field, which rotates and pulls the rotor along through interaction. The speed of the rotating field and the rotor is either synchronous or asynchronous [12].

To control these variable-speed drives, field-orientated control (FOC) prevails over the previously widespread voltage-to-frequency control due to its limited dynamic performance [16]. FOC is a vector control system in which the three-phase system is regarded as an orthogonal two-phase system and is therefore much easier to control [16]. The advanced technical development of microprocessors was essential for this. The mode of operation is described in Qi *et al.* [16]. Determining the position of the rotor is a necessity for the efficient control of an electric machine. While Hall-sensors can be used as commutation encoders in topologies with switched stator current, encoders and resolvers are used to determine the position in topologies with a three-phase current system [16]. These are designed in different operating principles, with the reluctance resolver being a good solution suitable for air and space applications [17].

2.2. Synchronous machine

Rotors of synchronous machines rotate at the same speed as their excitation field. The torque on the rotor is generated either by the interaction of two magnetic fields, whereby the magnetic field on the rotor is created by permanent magnets (PMs) or energized coils, and/or by the change in magnetic resistance, which is referred to as reluctance.

2.2.1. Radial flux permanently excited machine

In recent years, permanent magnet synchronous machines (PMSMs) have increasingly replaced DCMs and induction machines in traction applications such as automotive, marine and rail transport. In comparison, they offer higher efficiency and power density as well as less rotor waste heat and the non-necessity of energizing the rotor through self-excitation [1, 18]. FIG 4 shows the schematic design of two radial flux PM machines (RFPMSMs).

The PMs of an RFPMSM are either surface-mounted (SPMSM) or internally mounted (IPMSM) and are mostly made of neodymium-iron-boron due to the high energy density required [10]. Depending on the application, the magnets can be countersunk in a V-, I- or multi-layer U-shape [12, 18]. In the SPMSM configuration, a high-strength, antimagnetic metal sleeve or a bandage made of glass or carbon fibres, as shown in FIG 4, is essential to radially stabilise the magnets on the rotor, especially at high speeds. The magnets in the IPMSM are in turn bonded or moulded with resin [19].

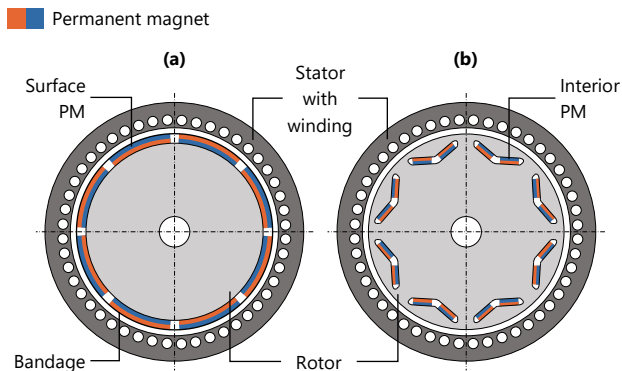


FIG 4: Radial flux (a) surface and (b) interior permanently excited synchronous machine

FIG 5 shows the characteristic current curve of a three-phase stator winding system for setting up a rotating magnetic field. The individual phases are energized sinusoidally and are shifted by 120° relative to each other. In the state "OP", a specific stator field results, which is shown symbolically for the two variants in FIG 6. An exemplary winding diagram is used for this purpose. During operation, the stator field rotates evenly with constant amplitude. The rotor follows this rotating field. Under load, an offset angle occurs, which leads to field distortion and creates a torque on the rotor.

In contrast to the SPMSM, the IPMSM also has a torque-forming reluctance component due to the internal flux barriers, which leads to better behaviour in the field weakening range [12]. In the event of a power failure, the PMs induce a retroactive voltage in the stator at high speed and thus also in the PEs. This voltage is many times higher in SPMSMs, which can lead to partial destruction of the PE if no protective circuit is integrated [12]. Another advantage

of IPMSMs is that in the event of a short circuit, the countersunk magnets are relatively less demagnetized by the overload than the surface magnets. High-frequency magnetic upper fields in the air gap also have less influence on the countersunk PMs [19]. A further measure against the heating of PMs is their subdivision to minimize eddy currents, which are proportional to the square of the frequency [12]. Heated magnets reduce their power, which is irreversible at high temperatures and/or excessive loads and thus partially demagnetise the PMs. The permissible operating temperatures and maximum currents must therefore be limited [12].

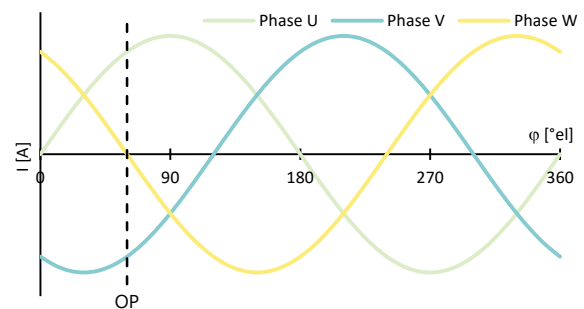


FIG 5: Current profile of rotating three-phase system

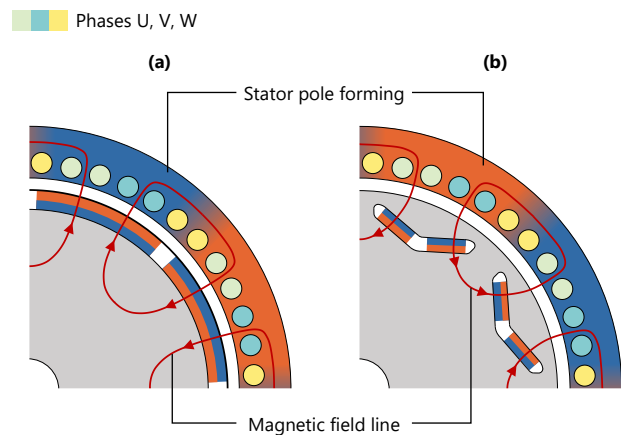


FIG 6: Magnetic field lines and stator pole forming of radial flux (a) surface and (b) interior PMSM for a specific operation point

Another configuration of the RFPMSM is the external rotor, which offers more space for the magnets around the circumference and requires fewer precautions to be taken with regard to mechanical stability [14]. Such high-pole systems also increase efficiency [10]. A special arrangement of the magnets is the Halbach array, whereby the magnetic field is strengthened on one side by forming large poles and weakened on the other by means of a magnetic short circuit. This leads to less leakage flux on the field weakening side [10]. FIG 7 shows this principle.

Distributed winding, as also used in FIG 6, is a common method for three-phase machines. The phases are distributed evenly across the slots [12]. Concentric winding, also known as toothed coil winding, is becoming

increasingly popular with PMSMs in particular. It is axially compact, the simple manufacturing can be fully automated and it offers a high gravimetric power density. However, the magnetic field in the air gap is distorted and a large number of harmonics occurs, which minimises efficiency and generates rotor oscillations and eddy currents in the PMs [12]. Distributed windings are therefore more suitable for high-speed applications. Innovative approaches, such as hairpins, can also be used to automate this type of winding and enable higher efficiency [12].

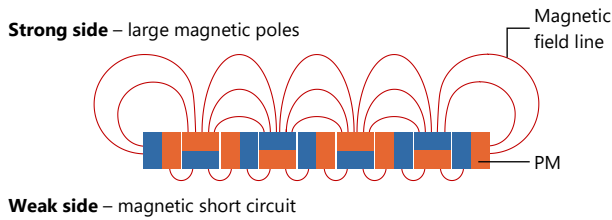


FIG 7: Principle of Halbach-Array

PMSMs are used where efficiency and weight have high priority. According to current research, RFPMSMs achieve high power densities through higher speeds. They offer high efficiency in the base speed range and a high torque density [19]. Furthermore, they have a low torque ripple, a high power factor, a medium control effort [16] and numerous cooling options due to the medium machine complexity [18]. Their safety suffers from the possible demagnetization of parts and reduced robustness [2]. Due to the PMs, the machines are also expensive to manufacture [2, 16, 20]. The current advanced technology readiness and its ongoing further development harbours great potential for a wide range of applications [1].

Propellers of a future electrified aircraft in a power class of 1-2 MW will probably require a speed of 2,500 rpm to 4,000 rpm [10]. According to Safran [9], regional aircraft will require even higher outputs in the future, which will tend to increase the size of the propellers and further minimize their speed. High-speed RFPMSMs run at a much higher speed in order to achieve high power densities. Despite decreasing safety, a gearbox is becoming essential in the drive train. Zhang *et al.* [10] emphasizes the probable usefulness of a gearbox. Investigations into new propeller configurations to enable gearless propulsion are being carried out in parallel, as by Brando *et al.* [21]. However, the counter-rotating system with integrated motor presented there requires an axial flux PMSM, which is considered in the next section.

Mechanical gearboxes have been used for many years in a wide variety of applications to adjust the torque-speed ratio. However, their installation increases the sources of error in the overall system. A backup lubrication system is also required for flight certification [22]. Such a gearbox causes vibrations and requires routine inspections and maintenance. Magnetic gearboxes, on the other hand, run without contact, with low noise and vibration and therefore

require significantly fewer maintenance intervals. In addition, simple slipping is possible in the event of an overload, which protects the drivetrain [22]. There has been little research into this type of gearbox, but it offers great potential in future drivetrains [22]. FIG 8 shows the principle of a coaxial magnetic gearbox with Halbach arrays and modulator ring. This type of gearbox is based on magnetic field modulation to vary the speed. Its mode of operation is explained in Bird [22]. 99 % efficiency appears to be possible [23]. The application of magnetic transmissions for electrified aviation is being investigated by NASA, among others, using prototypes [24]. In this context, the direct integration of such a gearbox into a motor is becoming attractive. Such geared motors have only been investigated in isolated cases, such as in Frandsen *et al.* [25]. Here, further development is necessary.

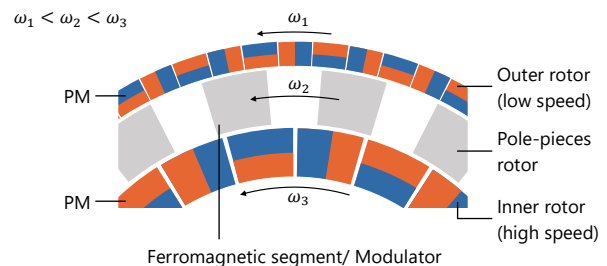


FIG 8: Principle of coaxial magnetic gear with Halbach-Arrays and pole-pieces rotor

RFPMSMs are becoming more popular in a variety of sectors due to their high power-to-weight ratio and efficiency. The IPMSM configuration is becoming increasingly important in the growing automotive industry. Well-known manufacturers such as Tesla and Lucid Motors rely on this topology [26]. A great deal of research is also being conducted in the aviation sector. Siemens has developed an air-oil-cooled direct drive with 260 kW continuous power [27]. The *SP260D-0* machine, which operates at 2,500 rpm, is based on the principle of an internal rotor SPMSM with a Halbach array configuration and was tested with a specific power of 5.2 kW/kg. Its further development, the *SP260D-A*, is even expected to achieve 5.9 kW/kg, although this still needs to be validated [27]. Another concept is the *SP2000D* with an output of 2 MW. The liquid-cooled motor is operated at 6,500 rpm and, according to current data, should achieve 7.7 kW/kg [27]. The prototype investigated by Sanchez *et al.* [28] at the University of Illinois [5] is an external rotor SPMSM with a Halbach array configuration. The continuous power of 1 MW is achieved with a speed of 15,000 rpm. Due to the carbon fibre ring on the outer skin of the rotor, a tip speed of 264.8 m/s is possible. This machine, which is entirely cooled by forced convection, achieves a mass-specific power of 15 kW/kg [28].

2.2.2. Axial flux permanently excited machine

Another form of PMSMs is the axial flux PMSM (AFPMSM). In contrast to the RFPMSM, the magnetic flux between the rotor and stator is axial. Theoretically, axial flux designs are possible for all topologies, but in practice only the PMSM is relevant [14]. Axial flux machines have gained popularity in recent years due to their high power and torque density, low moment of inertia and better winding utilisation than RFPMSM [1, 10, 29]. They are increasingly finding a wide range of applications as direct drives with high efficiency, low torque ripple and high power factor [29–31].

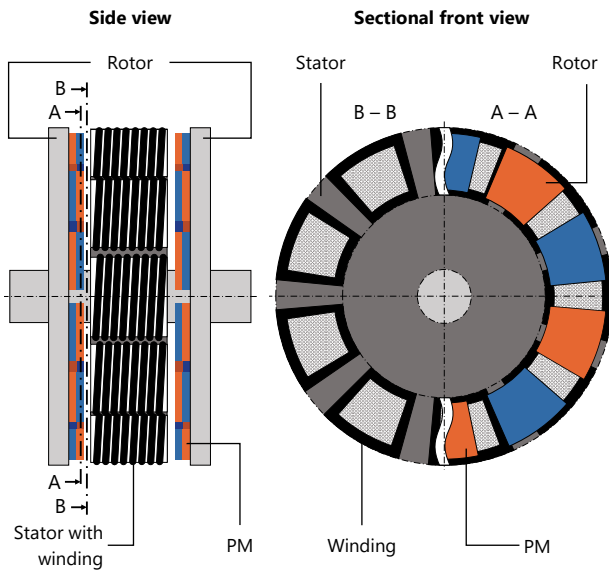


FIG 9: Axial flux permanently excited synchronous machine in AFOR-configuration

AFPMSMs offer a large variation in geometry with dependent machine complexity. Single-side (one air gap), double-side (two air gaps) and multidisc configurations (>2 air gaps) are possible. Double-side AFPMSMs are also divided into axial flux internal rotor (AFIR) and axial flux external rotor (AFOR) [32]. FIG 9 shows the schematic structure of an AFPMSM in AFOR configuration.

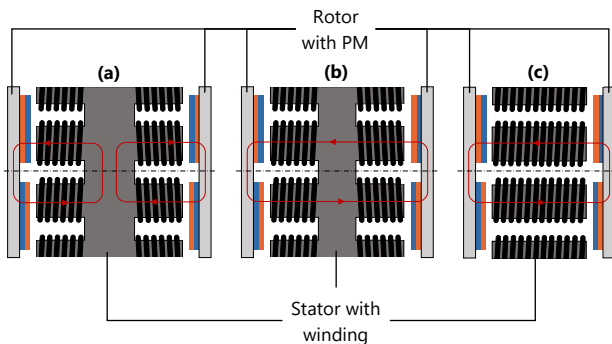


FIG 10: Structures of: (a) AFOR N-N type, (b) AFOR N-S type and (c) yokeless AFOR type (YASA)

Single-side AFPMSMs are the simplest configuration and are very short axially. Due to the asymmetry, large axial forces are generated on the bearings [32]. The other configurations become increasingly relevant when several rotors/stators are arranged in series to maximize torque without increasing the diameter. The AFOR-PMSM has two external rotors with PMs. Either a continuous magnetic flux (N-S type) or two magnetic fluxes decoupled from each other (N-N type) are formed, which are presented in FIG 10 (a) and (b) respectively. A special form of the N-S type is the YASA design (yokeless and segmented armature), displayed in FIG 10 (c), in which the stator yoke is also removed to reduce iron losses and axial length. This is mainly used in industry [32].

In turn, the stator yokes of the AFIR configuration cannot be eliminated, which leads to higher losses, increased axial length and results in a reduced number of applications [33]. AFOR-PMSMs achieve high power densities with high current density and low electrical load. AFIR, on the other hand, achieve high power at low current density and high electrical load [34]. Cascading in the multidisc configuration ensures a further increase in power for the same diameter. At the same time, however, the complexity also increases. The stators can be operated magnetically and electrically decoupled from each other, which leads to redundancy effects [32].

In contrast to single-side AFPMSMs, double-side and multidisc configurations have a symmetrical design and therefore low axial forces on the bearings [35]. However, a rotor tilt effect can occur in all variants due to eccentricity and, in addition to possible partial demagnetization and low robustness, reduces the safety of the machine [1]. In order to minimize harmonics, it is possible to rotate these in relation to each other in a multi-stator variant. Wang *et al.* [36] demonstrate the extensive elimination of the 4th harmonic using this method. The torque ripple can be reduced by a slotless design, as presented by Mahmoudi *et al.* [34]. In contrast to RFPMSMs, the windings do not taper due to the planar structure, which enables greater stator flux and thus comparatively more rotational thrust [33]. Habib *et al.* [37], Nishanth *et al.* [38] and Hong *et al.* [39] point to the use of Halbach arrays to further increase performance, reduce mass and inertia and minimize flux leakage on external rotors.

AFPMSMs have a high torque yield in relation to the active material used [33], require medium control effort and offer numerous cooling options. They have a larger operating range with high efficiency than their analogue radial flux design [40]. The difference in power density compared to the radial counterpart raises with increasing power class [29]. The high-pole machines have a high PM requirement and are therefore expensive, but offer the possibility of direct drive due to the high specific torque [32]. Single-side AFPMSMs are currently rarely used. They are utilized at higher speeds due to their compactness and simpler

mechanical structure compared to the other AFPMSMs. Double-sided machines currently have the widest range of applications and are becoming increasingly attractive in the automotive industry, aviation and the marine sector. Multidisc configurations offer potential for low-speed high-torque applications, such as the marine sector [32].

AFPMSMs are increasingly being used in the automotive industry, such as by Mercedes-Benz in the all-electric *Vision One-Eleven* concept [41] and by Ferrari in the *SF90 Stradale* as a hybrid drive [42]. In the aviation sector, H3X is presenting the *HPDM-1500* concept with a continuous output of 1.5 MW and a maximum of 2,500 rpm [43]. The liquid-cooled motor is supplied with up to 900 VDC and should achieve over 10 kW/kg in nominal operation. The electrical supply runs via eight decoupled sectors. The motors can be axially stacked up to 9 MW [43]. Evolito is presenting its *D1500 2x3* motor for low-speed high-torque aerospace applications alongside its high-speed and mid-speed solutions [44]. The torque machine delivers up to 280 kW at 1,900 rpm in continuous operation. The 7 kW/kg motor is fed via 2x3 phases [44].

2.2.3. Transverse flux permanently excited machine

Like the AFPMSM, the transverse flux PMSM (TFPMSM) is used as a direct drive. Due to the high-pole system, it achieves a multiple of the force density and torque compared to other topologies. Nevertheless, this machine is currently a niche product due to its complexity of structure and magnetic flux control [13, 14].

As with the AFPMSM, the TFPMSM enables a wide range of geometry variations. Internal and external rotor, single and double-sided configurations as well as all variations at component level are possible. A wide variety of topologies in transverse flux design is also conceivable, such as machines with reluctance rotor, reluctance rotor and supporting PM stator excitation, permanent and externally excited rotors and induction machines [45]. FIG 11 shows the schematic structure of a single-sided internal rotor TFPMSM.

The stator consists of a support material, salient poles and a characteristic ring winding. Surface-mounted PMs are located on the rotor in two axially offset planes, which are connected via a flux carrier material. The rotor support material holds the arrangement in position. As shown in FIG 12, the magnetic flux for torque generation runs radially via the stator pole onto the rotor, then axially via the support material and finally, radially back onto the stator. FIG 12 shows the direction of rotation resulting from the resulting torque. As shown in Kaiser and Parspour [45], the PMs can also be installed in a flux-concentrated or axially magnetised arrangement. The flux routing changes accordingly. The U-core stator pole shown in FIG 11 can also be manufactured in U-, C-, CP-, E- or Z-core configuration,

as shown in Kaiser and Parspour [45].

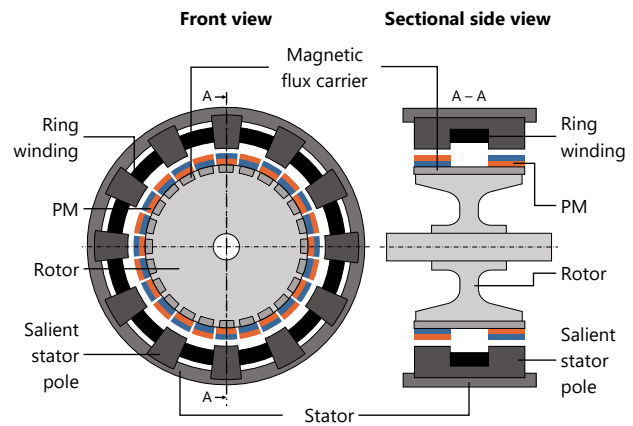


FIG 11: Transverse flux permanently excited synchronous machine in single-side configuration

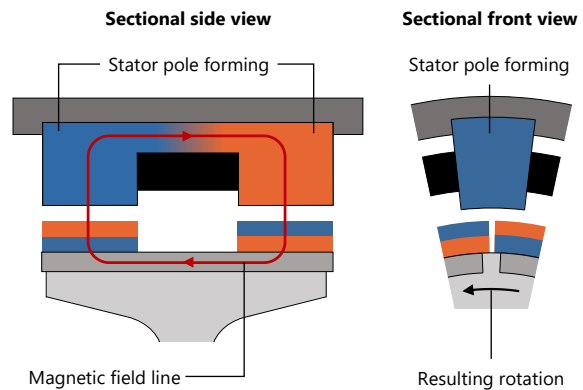


FIG 12: Magnetic field line, stator pole forming and resulting rotation of TFPMSM

The concentric winding is fed by a pulsed alternating current. To maintain rotation and to minimize the high torque ripple, two or more transverse flux units and thus phase systems with twisting are lined up axially. This is done magnetically coupled or separated, whereby a large axial air gap is required in the separated case. There are no winding ends, which means less copper mass and losses as well as the possibility of direct conductor cooling [13]. Two air-cooled topologies are analyzed in Baker and Jordan [46]. The independence of the phases results in simple manufacturing, power scaling and ideal space utilisation through spatial distribution [45]. A decisive advantage of the TFPMSM compared to the radial flux and axial flux design is the resolution of the geometric limitation in the formation of the magnetic and electrical circuit [13] and thus the possibility of separate dimensioning and design of high-pole systems for low-speed high-torque applications [35]. With TFPMSMs, the current limit is less restricted by the high temperatures but more by the possible partial demagnetization of the PMs [13].

To increase the fault tolerance and simultaneously maximize the torque, the significantly more complex

double-sided configuration, as shown in FIG 13, can be used. In this case, there is an additional magnetic flux concentration on the rotor due to radial cross-section reduction and thus the amplifying effect of the PMs [13]. The spatial separation of the phases in the TFPMSM generally also reduces the risk of short-circuiting between them [45].

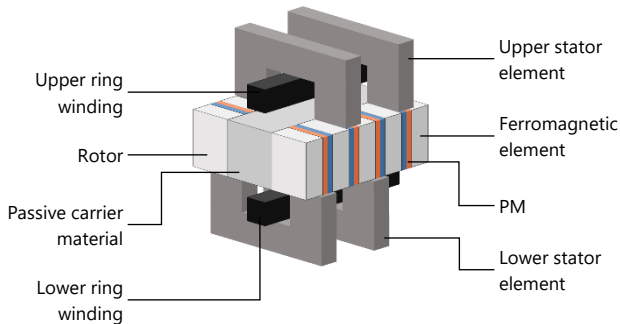


FIG 13: Principle of structure of double-side TFPMSM

In addition to their complexity and cost-intensive manufacturing [14], TFPMSMs have a high torque ripple and, in contrast to RFPMSMs, a power factor that is strongly dependent on the operating point. Due to the complex flux routing, there is increased leakage flux, particularly at high torques, which leads to increasing reactive power [45]. The torque ripple can be minimized by means of the control strategy and/or mechanically, by the number of phases and relative rotation of the stators. In Zhao and Niu [47], a claw pole (CP-core) TFPMSM is investigated in this regard. In Kulan *et al.* [48], the challenges in the complex production of a 4-single-phase machine are considered. In addition to the complex mechanical bearing of the machine [35], saturation effects occur early on due to the high electrical charge in TFPMSMs. AFPMSMs and RFPMSMs have a significantly larger torque-speed range and AFPMSMs have the widest range of high efficiency overall [45].

The great potential of the TFPMSM is limited by the challenges listed above. The machine is currently only used sporadically in small performance classes. It has not yet been implemented in industry. Among other things, the topology is being investigated as a potential drive unit in rail, bus, e-bike, automotive and aviation sectors [45].

Rolls-Royce presents its *150 kW EPU* for urban air mobility [49]. The air-cooled drive unit is operated at 1,100 rpm, supplied with up to 900 VDC by two modular inverters and has a specific output of 3 kW/kg [49].

2.2.4. Electronically commutated machine

A special form of PMSMs is the electronically commutated machine (ECM). This is also known as Brushless Direct Current Machine (BLDC), whereby DC stands for the intermittent energization of the stator coils per interval and not for the permanent supply.

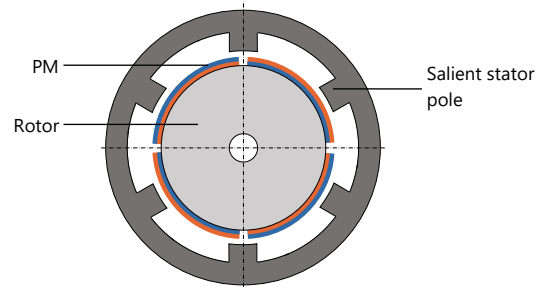


FIG 14: Electronically commutated machine

FIG 14 shows the basic structure of an ECM. As with the RFPMSM, the rotor is permanently excited and rotates synchronously with the rotating excitation field. This is generated by energizing the concentric stator windings by means of a pulsed, rectangular current waveform instead of the usual sinusoidal current. Commutation is dependent on the rotor position, whereby in the case of a three-phase system, two phases per interval have opposite polarity and the third phase is always de-energized [14]. This principle is illustrated in FIG 15. In practice, the current ramps are limited due to the inductance. Large machines therefore offer slower reaction times than small ones. High-pole machines have the same effect due to the increasing frequency [50]. FIG 16 shows the stator current flow with the resulting polarity for each pole and the associated rotor position.

Due to the PMs on the rotor, a rectangular waveform of the magnetic flux density is created in the entire air gap [51]. Compared to RFPMSMs an improved stator core utilization that is achieved due to the characteristic energization also leads to a torque density that is up to 15 % higher [52, 53]. Internal rotors are characterized by their low inertia and better heat dissipation via the housing. External rotors, on the other hand, generate a higher torque and lower cogging torque, whereby the internal coils are further away from the environment and require a more complex thermal management [16].

The high torque ripple and voltage distortion are significant challenges of the ECM for use in high power classes [50]. Current research shows that increasing the number of phases leads to higher torque, increased efficiency and minimisation of torque ripple. Smaller stator currents are also possible at the same voltage. The problem of the increasing complexity of the required PE can be minimized using DSP controllers [54]. Alternatives for minimizing the torque ripple include adaptations of the modulation strategy and the DC-side circuit [52]. In Liu *et al.* [55], sensorless position detection is described with the help of the back electromotive force due to its complicated installation, low reliability and high costs. Difficulties arise here at low speeds and unavoidable commutation errors can occur.

ECMs are currently primarily used in low-power applications such as CPU fans, fans for air conditioning systems and compressor pumps [16]. Due to their advantages, their field

of application is increasingly expanding. The companies MGM COMPRO and Rotex Electric are jointly developing ECMs for aviation applications up to 70 kW continuous power [56, 57]. These include light sports aircraft, drones and multirotor configurations. Their *REB90* motor delivers up to 80 kW maximum power, is operated from 1,500 rpm up to 4,000 rpm and can be used as a direct drive with a specific power of 2.3 kW/kg [56, 57].

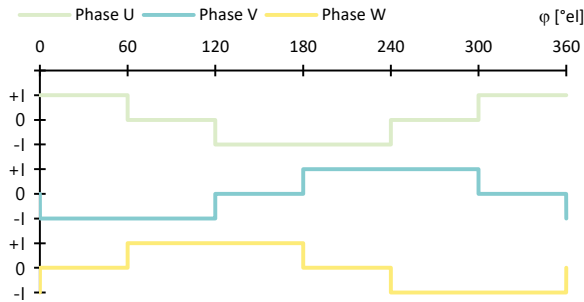


FIG 15: Current profile of switched three-phase system for ECM

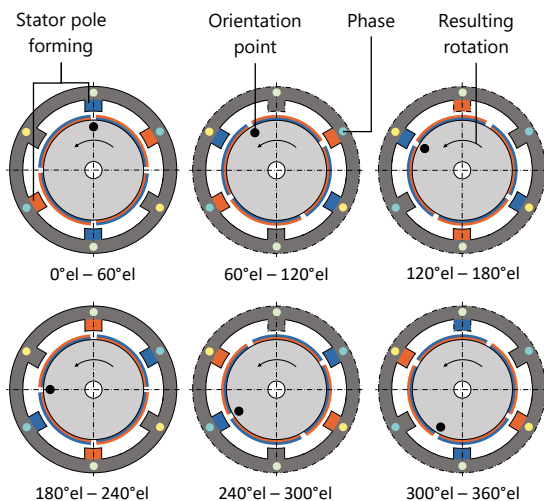


FIG 16: Process of stator pole excitation and rotor position of ECM

2.2.5. Externally excited machine

The non-capability of rotor field adjustment and deenergizing, which are disadvantages of PMSMs, are possible with externally excited synchronous machines. Here, the stator rotating field is formed analogue to the PMSM, whereby the rotor field is generated by DC-fed rotor windings and can be adjusted depending on the speed and load [12]. The rotor windings are either wound around salient poles or run axially, embedded in the rotor. This results in the following configurations: Salient Pole Synchronous Machine, which is also known as: Wound Field Synchronous Machine (WFSM), and Cylindrical Pole Synchronous Machine (CPSM) [13]. The structure of both types is shown schematically in FIG 17.

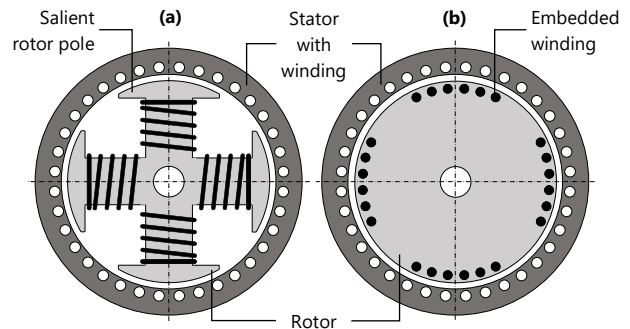


FIG 17: (a) Wound field and (b) cylindrical pole synchronous machine

The rotor can be excited via brushes and slip rings in a similar way to DCMs in externally excited machines, which on the one hand leads to better dynamic performance, but also to significantly lower reliability, safety and more frequent maintenance [10, 20, 50]. Brushless excitation can be achieved by an exciter machine using the transformer principle by means of a co-rotating three-phase bridge circuit consisting of diodes [12, 13]. In both cases of rotor excitation, the additional unit increases the manufacturing costs of the machine [1, 20].

CPSMs are solid steel rollers and are mainly used as turbo generators in very high power classes [13]. The excitation windings of the very long rotors with comparatively small diameters cause a staircase-shaped field curve, which leads to the formation of numerous harmonics [13]. The further development of intensive cooling technologies, such as direct H₂-cooling or liquid cooling using waveguides, demonstrates the technological progress in electrical engineering [13].

In contrast, WFSMs seem to be the far more interesting variant as a potential propulsor drive [1, 10, 50, 58]. Due to their salient poles, they have a large reluctance component, which leads to better behaviour in the event of field weakening [16]. FIG 18 shows the principle magnetic fluxes of both machines. The rotor poles differ by 90°el in view of the positioning in FIG 17. WFSMs have a high, adjustable power factor, a high magnetic charge and medium robustness for high speeds [10]. They allow a wide design space to minimize weight and losses. For increasing specific outputs, the machines are smaller and operated at high speeds [50]. The importance of versatile cooling is increasing [10, 59]. WFSMs have a medium power density, medium efficiency and low torque ripple [20]. The separate excitation offers the advantage for use in aviation of being able to isolate the field coils in the event of failure and to stop the power output immediately [13]. WFSMs are also easy to control and offer good overload capacity due to their thermal inertia [1, 20]. The complex rotor design leads to mechanical and thermal limitation of the speed and the rotor excitation requires more effort than with other topologies [1, 59].

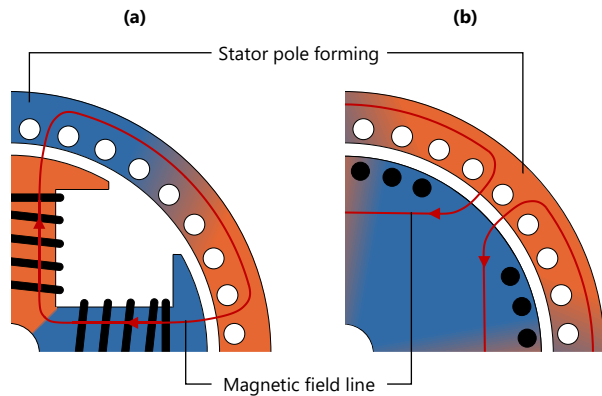


FIG 18: Magnetic field lines and stator pole forming of (a) WFSM and (b) CPSM

WFSMs are technologically mature and are already in use as generators in aviation [20]. Such machines usually consist of a pilot pre-exciter, a main exciter and the WFSM. PMs rotating on the same shaft induce a voltage on the stator, which is rectified and used to re-induce voltage on the rotor. After further rectification on the rotor, the armature windings of the WFSM are supplied with DC. By externally driving the unit, the WFSM ultimately generates electrical power according to the generator principle [20]. Honeywell presents its aerospace-grade 1 MW turbogenerator with a power density of 7.9 kW/kg [60]. This is operated with a 2x3 phase system at 19,000 rpm and an efficiency of up to 98 %. The combination of oil and spray cooling enables such specific outputs [61].

Unlike a generator, a traction machine is operated over a much wider range in motor mode, which shifts the design point considerably. NASA Glenn Research Center [62] is investigating their High Efficiency Megawatt Motor (HEMM) with a target of 1.4 MW output, 16 kW/kg power density, 99 % efficiency at a speed of 6,800 rpm [5]. The WFSM has an integrated cryocooler for the superconductors on the rotor. This eliminates the need for an external, complex cooling system. The rotor is also located in a vacuum in order to minimize heat transfer to the high-performance stator [62].

Superconductors are alternative winding materials and have almost no electrical resistance below their threshold temperature, which makes them interesting for future high power density technologies [18]. A distinction is made between superconductors and high-temperature superconductors (HTS). Currently applied HTS are used at approximately 70 K and pose considerable challenges for cooling [18]. Their technology readiness level is very low, which is why the short-term implementation of such complex systems, as proposed by the authorities [3], will not be possible for the time being [22]. Zhang *et al.* [10] speak of a period of 20 – 30 years for a high technology readiness. Promising studies [63–66] show the great potential of superconductivity. Due to the low level of technology

readiness, no assessment is made in the context of this paper.

2.2.6. Reluctance machine

In contrast to other topologies, reluctance machines (RM) do not generate their torque through the interaction of two magnetic fields, but by resistance variation of the magnetic flux. A high reluctance force is achieved if the ratio of the inductances in the d- (flux direction) and q-axis (reverse direction) is as large as possible. This is achieved in Synchronous RMs (SynRMs) by means of internal flux barriers and in Switched RMs (SRMs) by means of external flux barriers [16]. RMs have become increasingly popular in recent years, as they are simple, cost-effective and safe due to missing PMs and windings on the rotor [10, 18, 50]. FIG 19 shows the schematic design of both variants.

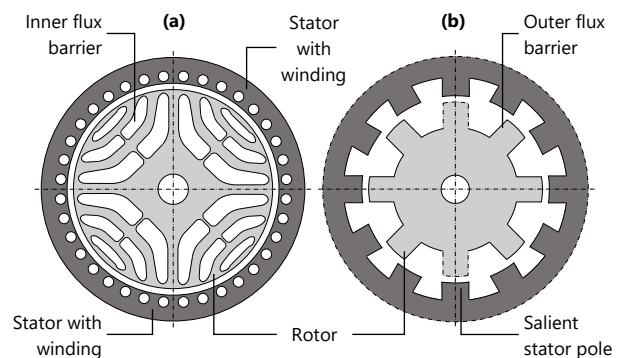


FIG 19: (a) Synchronous and (b) switched reluctance machine

SynRMs are energized in the same way as PMSMs and therefore by the identical inverter. FIG 20 shows a magnetic field line of such a machine. The power density is lower compared to the PMSM, which is why the machines are usually larger. The topology is increasingly being used in industry with a single operating point and is replacing the widely used induction machine due to its higher efficiency, lower manufacturing costs and other advantages in many areas of application [16]. Furthermore, it is becoming increasingly attractive in combination with embedded PMs in the form of IPMSM in traction applications [12].

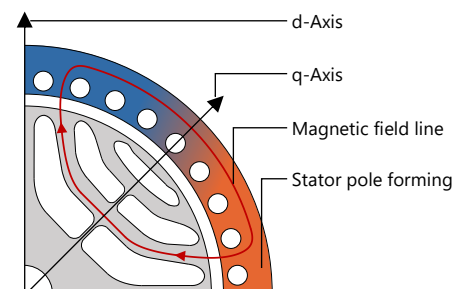


FIG 20: Magnetic field line and stator pole forming of SynRM

The SRM is more in vogue for aviation applications [2, 18, 20, 50]. It is characterized by its salient poles on the rotor and stator and is mostly used in high-speed applications due to its robustness and low thermal rotor limitation [67]. The concentrated winding of the SRM is supplied by means of pulsed current, similar to the ECM in FIG 15, which increases the control effort [16], but nevertheless favours the simplification of power electronic filters and the heat dissipation of the short winding ends [40, 50]. A distinction is made between single-phase and two-phase supply, with the latter leading to magnetic phase coupling, but also to higher torque [68, 69]. When one phase is interrupted, it is possible to continue running at a lower torque [16]. FIG 21 shows the different field lines, whereby a distinction is also made between short flux path (SFP) and long flux path (LFP) for two-phase supply. In addition to the good short-circuit behaviour, there is also no voltage induction in the event of a power failure, which increases safety [20]. The power factor is comparatively low due to the required magnetization reactive current [35]. The salient teeth on the rotor result in large, fluctuating radial forces and thus cause vibrations, noise and high bearing forces [40, 50], which can be minimized by increasing the number of poles and using a suitable control method [16]. The rotor poles also cause a pulsating torque and high wind losses, which can be reduced by using a sleeve or by filling the free spaces with non-magnetic material [20, 50]. The rotors have good dynamic behaviour and require little cooling [16].

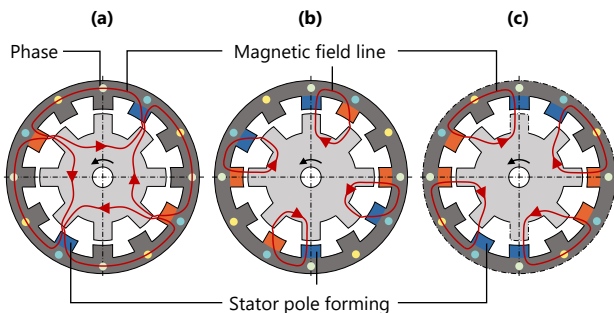


FIG 21: Magnetic field lines and stator pole forming of SRM in (a) one-phase, (b) SFP two-phase and (c) LFP two-phase configuration

Novel SRM designs, such as rotor and stator segmentation to shorten the magnetic flux, hybrid stator excitation and double stator/ double rotor configurations to increase power density and axial twisting of the stator/ rotor teeth to minimize torque ripple, are presented in Diao *et al.* [70]. Sayed *et al.* [20] also discuss the performance enhancement by bevelled and segmented rotor teeth and modular rotors. Additionally, the addition of stator PMs as a hybrid excitation to maximize torque is highlighted. An exemplary configuration for this is the Flux-Switching Permanent Magnet Machine (FSPMM), which offers great potential for aviation due to its high torque and power density, fault tolerance and robust rotor [71]. The position of the PMs on

the stator favours its cooling and minimizes the risk of partial demagnetization [72]. FIG 22 shows the according schematic structure. PMs magnetised in the circumferential direction are integrated within the fractional-slot concentrated winding, which additionally directs and amplifies the flux and segments the stator. The complexity of the topology increases [72].

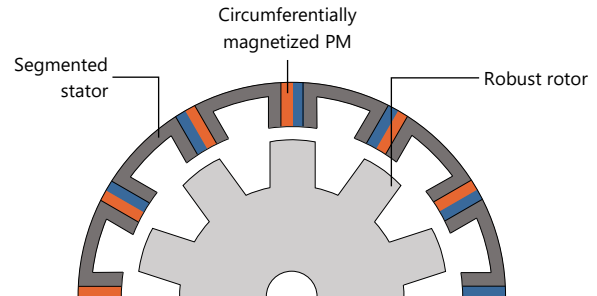


FIG 22: Flux-switching permanent magnet machine

In Sanabria-Walter [71], a 600 kW ring-type direct-drive FSPMM for the main rotor of a helicopter is investigated. Here, a Halbach array is used to increase performance. The prototype achieves 6 kW/kg. In Abdollahi *et al.* [73], a 70 kW SRM is considered as a direct drive for a Light Sport Aircraft. The potential replacement of the existing RFPMSM is analyzed. SRMs have been used as starter/ generators (S/G) in aviation for many years, such as in the *Lockheed Martin F-22* [74]. Although the SRM is suitable for high speeds, it is becoming increasingly attractive for aviation as a direct drive and is being further researched with the aid of prototypes [75, 76]. They have a lower level of experience compared to other topologies, but offer great potential for future applications due to their robustness, simplicity, safety and reliability as well as novel configurations [2, 18, 70, 77].

2.3. Asynchronous machine

Rotors of asynchronous machines lag behind the stator field. This so-called slip is essential for generating torque [14]. This machine topology also known as the induction machine (IM) is characterized by its simplicity, robustness, high reliability and favourable manufacturability compared to the PMSM [2, 18]. It is the most widely used electrical machine in industry [16]. Its basic structure is shown in FIG 23.

The stator of an IM is identically designed as a synchronous machine, whereby the rotor is designed in a squirrel-cage or slip ring configuration. The former consists of aluminium or rarely of copper bars [10, 78]. Those bars are short-circuited at the end faces by means of rings in the form of a cage. As shown in FIG 23, the rotor bars are fixed by the sheet package. They are manufactured either by die casting or by mechanical hammering [12]. In turn, a slip ring IM has rotor windings that are guided to external resistors via brushes in order to limit the high starting currents of the

machine. In nominal operation, the windings are also short-circuited or supplied with an additional voltage [14]. Due to the slip and thus the relative movement, there is a continuous voltage induction on the rotor. A magnetic field forms on the rotor, which causes the torque through interaction with the stator field [35]. The slip s results from the speed of the rotating field n_D and the rotor speed n_R according to the equation:

$$s = \frac{n_D - n_R}{n_D} \quad (2.3)$$

Depending on the load, the slip occurs until the maximum torque, the so-called breakdown torque, is reached and consequently no longer rotates with the stator rotating field.

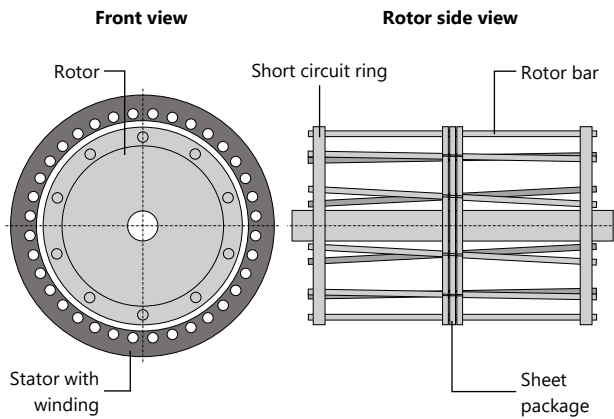


FIG 23: Induction machine in squirrel-cage configuration

The torque-speed characteristic of an IM hardly differs from that of a synchronous machine when operated with an inverter. However, this depends heavily on the geometry of the rotor bars [16]. In comparison, IMs have a lower efficiency, power density and power factor. This results from the high reactive power requirement, which is necessary to magnetise the rotor [16, 18, 74]. In the field weakening range, however, IMs are very efficient in comparison and are mainly used in high-speed applications due to their high overload capacity and low thermal rotor limitation [10, 35]. The sudden switch-off of the power supply does not cause any continuous voltage induction and drag torques, as the rotor field also disappears. Torque ripples are largely minimized by the axial rotation of the rotor bars, as illustrated in FIG 23 [35]. The non-high-pole machines have phase coupling due to the distributed winding, which leads to a reduction in fault tolerance. Multiphase systems can counteract this [2, 20].

Double-fed IMs are currently en vogue. The rotor in slip ring configuration is controlled by an inverter instead of resistors, which regulates the phases, the strength of the rotor excitation and the frequency. This variant is interesting for S/G systems, as the output voltage can be kept constant without additional components [16, 20]. Elbuluk and Kankam [79] also discuss a squirrel-cage rotor for this

application. Various IM-based S/G systems are presented by Bu *et al.* [78]. Furthermore, Smith *et al.* [80] investigate a 250 kW IM rim motor for a boundary-layer-ingestion fan. The advantages of IMs at high speeds can be utilized here. The Ohio State University [5] is developing a ring IM with variable cross-section wet coil stator cooling. By widening the conductor strip to reduce resistance and direct liquid cooling outside the active area, a high current density in the stator is possible. The aim of that work is to integrate a 10 MW machine with a diameter of one metre into a turbofan, which rotates at 5,000 rpm. Machines in the 300 kW, 1 MW and 2.6 MW power classes are initially being investigated as prototypes. Ultimately, 13 kW/kg with over 96 % efficiency should be achieved [5, 81].

IMs have been in use for many years. They are being replaced by PMSMs and reluctance machines in many areas, but still have their reason for existence in the field weakening sector [16]. They offer advantages due to their simple control, high-speed capability, low mechanical and thermal limitations as well as high reliability and safety. Nevertheless, IMs have a comparatively reduced efficiency, lower power density and complex rotor cooling [16, 20, 35].

3. EVALUATION

3.1. Methodology

In order to compare the listed machine topologies for suitability as a potential drive system for an electrified aircraft, a specific evaluation method is applied. Such methods simplify decision-making processes in the entire product development process, ensure traceability and early risk identification and resolve subjective tendencies by means of an objective approach [82]. In order to be able to achieve a high level of objectivity, people from different technical areas are required for the evaluation [83]. Depending on the progress in the product development process and the available time, different methods are suitable, which can be simple, elaborate and complex [82]. The weighted point evaluation method is used for the assessment considered here. In analogy to Sadraey [7] and Kazula [84], evaluation criteria are derived from the aviation-specific requirements for electric machines, which are then weighted according to their importance using a pairwise comparison. Exclusion criteria filter out the obviously less suitable topologies in advance. A basic understanding of the candidates under consideration is essential for the application of evaluation methods. This is provided by the previous explanations of the individual topologies.

3.2. Criteria

Individual criteria are identified from aviation-specific requirements for electric machines. Dependencies between some of them cannot completely be avoided. Some of them are also dependent on each other. For example, the use of high-performance materials to achieve high flux densities results in high manufacturing costs. The use of permanent magnets means that rotor excitation is not necessary in order to increase efficiency, but reduces safety in the event of partial demagnetization during failure. The most important criteria for evaluating the machine topologies can be summarized as follows: performance and mass, ease of integration, safety, reliability and life cycle costs as well as technology readiness.

Performance and mass (P)

In addition to the required power of an electrical machine, its gravimetric power density is of great importance for use in aviation. This depends on the volume and density of the materials used as well as the additional components required for operation, cooling and safety aspects. For future electric machines, specific outputs of over 10 kW/kg or, according to NASA, even over 13 kW/kg are required [1, 10, 11]. The performance evaluation also includes parameters such as efficiency and torque ripple, which are decisive for the suitability of use in the drivetrain. The poorer the efficiency, the more energy is required for the same output. In addition, a more complex thermal management is required, which leads to more mass.

Ease of integration (I)

The machine can be easily integrated into the drive train and its installation space if it requires low-effort cooling and control, emits little vibrations, is electromagnetically compatible and generally requires as little complex additional equipment and precautions for installation as possible. In the event of high waste heat, fire walls, detection devices and extinguishing systems may be necessary in the vicinity of highly flammable liquids. The electrical machine must be grounded and, conversely, also protected from the effects of surrounding components. The consideration of the necessity of a gearbox is neglected at this point, as the specific configuration of the topology is decisive and no general statement can be made in this regard.

Safety (S)

System safety is of great importance in aviation applications. Machine complexity, robustness and behaviour in the event of failure are included in the evaluation. Due to functional dependencies and the resulting cascading error chains, safety-critical effects are possible with high machine complexity. The safety of machines is reduced, for example, by possible partial demagnetization of permanent magnets, unimpeded, retroactively induced voltages in the PEs, non-redundant

phase systems and complex magnetic flux. Another safety risk is the risk of fire due to external influences, but also due to inadequate internal cooling or incorrect component design and the resulting consequences. The latter is exemplified by the effect of partial discharge in the windings via the insulation and its gradual damage.

Reliability and life cycle costs (R)

Reliability and life cycle costs are closely linked to the complexity of the machine, which results from the number of parts, their own complexity and additional auxiliary components required. High-performance materials are essential for achieving high flux densities to increase the power density. These are sometimes pushed to their limits electrically, magnetically, thermally and mechanically. The selection of materials and the design of the overall system for various operating conditions form the basis of the manufacturing costs, the achievable service life and the resulting life cycle costs of a machine. Compared to the automotive sector, a significantly longer service life is required in the aviation industry.

Technology readiness (T)

The technology readiness of a machine for use as a propulsor drive is mainly determined by the TRL and the experience gained in the aviation sector with the respective topology. Comparatively new types, such as the AFPMSMs, still have a lower TRL, but offer great potential for the future. Developments, investigations and tests are still required for all machine types across all topologies, as future requirements, such as outputs above 1 MW [10] with power densities above 10 kW/kg [1], will set new standards. When developing such innovative machines, attention must be paid to the interaction of the preceding evaluation criteria, which is becoming a challenge for current research.

Criteria weighting

To weight the evaluation criteria, a pairwise comparison is conducted as follows [82]. If one criterion appears to be more important, it is rated with the value „2“ and the correspondingly less important criterion is rated „0“. If they are equal, both criteria are given the value „1“. As soon as all criteria i have been evaluated, they have a total sum value x_i . By dividing the sum of all assigned values X , the weighting w_i of each criterion is calculated according to:

$$w_i = \frac{x_i}{X} \quad (2.4)$$

The criteria evaluation was carried out by five independent engineers and was compared with the literature [7]. The results are shown in TAB 1. Power and mass as well as safety are the highest rated criteria for the use of an electric machine as a propulsor drive.

TAB 1: Criteria weighting via pairwise comparison

	P	I	S	R	T	w_i
Performance and mass (P)		2	1	2	2	0.35
Ease of integration (I)	0		0	1	1	0.10
Safety (S)	1	2		2	2	0.35
Reliability and life cycle costs (R)	0	1	0		2	0.15
Technology readiness (T)	0	1	0	0		0.05

Values: row criterion is more important than column criterion (2), equally important (1), less important (0)

3.3. Rating

3.3.1. Preselection

Before the topologies are evaluated on the basis of the previously established criteria, they are analyzed with regard to immediate exclusion criteria.

Due to the wear-prone commutator with essential routine inspections and maintenance as well as the resulting costs, the risk of arcing and the comparatively low efficiency and power density, DCMs are not a potential candidate for propulsion systems in aviation [2, 58]. RFPMSMs and AFPMSMs, on the other hand, show great potential, which has been emphasized by previous investigations, concepts and prototypes [1, 5, 20, 43]. TFPMSMs have high torque and power densities, but also a high level of complexity and reduced reliability [13, 14]. They are currently only used sporadically and have not yet been implemented in industry. Their use as a potential drive unit is still being investigated [45]. Hence, they are excluded in this medium-term investigation. A detailed evaluation of the ECM is also not carried out due to its torque ripple and voltage distortion [50]. In comparison, the RFPMSM is the better solution here due to the potential for higher power densities. CPSMs are increasingly being used as turbo generators, but are less suitable for high-performance drives with high power outputs [13]. However, promising investigations [1, 2, 20, 40, 50, 58, 85] are awakening interest in the WFSM as well as in the SRM and IM. The SynRM continues to find its way into industrial applications with the most constant possible operating point [16]. However, the SynRM is not being considered as a potential propulsor drive due to its low power density.

3.3.2. Weighted Point Rating

Consequently, the RFPMSM, AFPMSM, WFSM as well as SRM and IM are evaluated based on the established criteria. Qi *et al.* [16] points out the strong dependence of the specific topology configuration in the evaluation. For example, RFPMSMs in IPM and SPM or internal and external rotor configuration, as well as single-side, double-side and multidisc AFPMSMs each have their own characteristic features, which is why a superordinate topology evaluation

is not considered definitive, but should always be seen as an orientation and serves to highlight the potentials of current research results. In TAB 4 in the appendix, the characteristic features of the analyzed topologies are listed [1, 2, 16, 18, 20, 58]. The characteristics are used to evaluate each topology for each criterion. The degree of concretisation is chosen in view of the general validity of the evaluation. For the same reason and due to the strong dependence on the application, no specific values are given in TAB 4. The evaluation is carried out using the symbols/points from TAB 2. The results are summarized in TAB 3.

TAB 2: Values for evaluation of topology characteristics

Symbol	Points	Criteria fulfilment
++	4	Very good
+	3	Good
o	2	Moderate
-	1	Bad
--	0	Very bad

Based on the individual evaluation $m_{i,j}$, the normalized and weighted evaluation factor r_j is calculated for each topology according to equation 2.5 using the criteria weighting w_i from TAB 1. In this context, k stands for the number of criteria.

$$r_j = \sum_{i=1}^k \frac{w_i \cdot m_{i,j}}{4} \quad (2.5)$$

The result of the topology evaluation in TAB 3 shows the great potential of AFPMSMs and RFPMSMs. Due to the good properties of the SRM in terms of safety, reliability and life cycle costs, their evaluation is also very positive. TAB 3 also clearly shows that no machine fulfilled a criterion very poorly. This is an indication of a suitable topology preselection.

TAB 3: Summarized evaluation of relevant electric machine topologies

	P	I	S	R	T	r_j
RFPMSM	+	+	+	o	+	0.71
AFPMSM	++	++	+	-	o	0.78
WFSM	o	+	+	-	+	0.59
SRM	-	+	++	+	o	0.65
IM	-	+	+	o	+	0.54

Values: very good („++“ = 4), good („+“ = 3), moderate („o“ = 2), bad („-“ = 1), very bad („--“ = 0)

FIG 24 shows the utility plots of the machine topology evaluations. The width of the bars symbolises the weighting of the respective criterion. The weighted, but not normalized, evaluation factor also results from the area of all the bars of a topology.

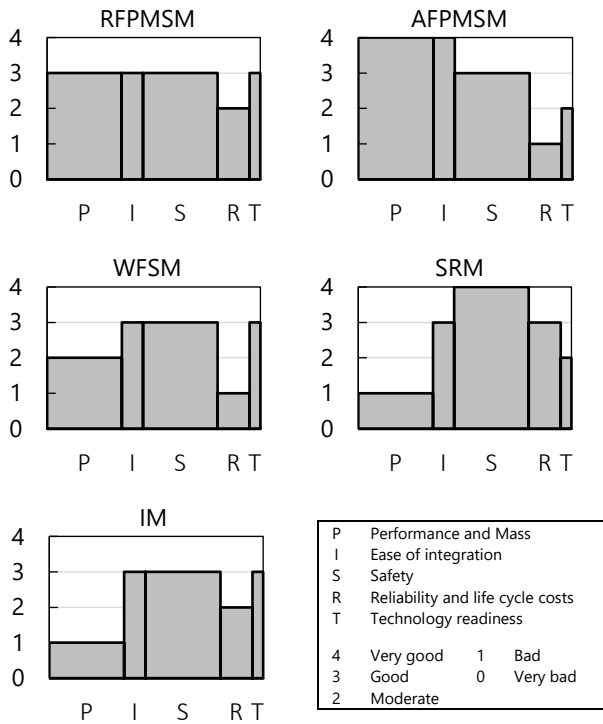


FIG 24: Utility plots of evaluation of relevant electric machine topologies

3.4. Potentials and challenges

The evaluation factors from TAB 3 reflect a tendency of the potential of the respective topologies. PMSMs are potential candidates for future propulsion systems in aviation due to their high power density and efficiency [1]. The AFPMSM in particular has been positively emphasized in current studies [40]. The risk of partial demagnetization of the PMs of a PMSM and the permanent rotor excitation have a disadvantageous effect in the event of a malfunction. In addition, there is the strong dependence on individual nations for the procurement of rare earths [86]. SRMs are characterized by high reliability and safety with low machine complexity. The non-necessity of PMs and rotor windings makes them a cost-effective alternative [18, 20]. Increasing their average gravimetric power density through novel concepts are current research issues [71, 73, 87]. Although the WFSM and IM were rated comparatively less favourably in the present evaluation, they are being studied and tested in detail by the Glenn Research Center [62] and the Ohio State University [81] for future electrified aircraft propulsion systems. This discrepancy results from the non-consideration of superconductivity in this article as well as from the generalized topology evaluation. For an evaluation with a high degree of concretisation, the exact use case is essential. For example, different EMs may be more suitable for different drive train architectures. A holistic view of the powertrain is necessary for its design due to the mutual dependencies of the components [35].

The listed concepts and prototypes of the individual topologies show current trends. For example, RFPMSMs tend to achieve high specific power at high speeds, as per the logic in Equation 2.1 [28]. According to the current concept of H3X [43], AFPMSMs can be operated as direct drives with a high gravimetric power density. The NASA Glenn Research Center [62] demonstrates the great potential of superconductivity in the context of a WFSM for future EMs. Sanabria-Walter [71] presents a novel concept of an SRM for a low-speed high-torque application with a high specific power-to-weight ratio. According to the Ohio State University [5], IMs can also be very suitable for specific applications. The comparison of the mass-specific performance between the topologies based on the concepts and prototypes presented must be viewed critically in that the output variables of the drive train must be identical for actual comparability. This means that an additional gearbox is required for high-speed machines and therefore reduces the gravimetric power density, whereas a direct drive machine does not require this. Furthermore, it is not clear from every power density specification which masses have actually been taken into account. Overall, the choice of cooling technology is concatenated with the area of application of the EM. For example, intensive cooling methods, such as liquid cooling [27, 43], tend to be used for low-speed machines in high performance classes, while less complex technologies, such as forced convection [5], are used for high-speed applications. Superconductivity is becoming increasingly attractive for high efficiency at high power and power density [5]. Furthermore, the endeavour of redundancy and segregation to increase safety is becoming apparent. For example, mutually decoupled multiphase systems are used [43, 88] and the possibility of axial stacking of motors to achieve redundant high-power machines [43] is created.

However, the average values of the topology evaluation factors also show the need for further investigations, tests and subsequent improvements. Although electric machines have been in versatile use for years, aviation harbours new challenges. Weight, efficiency, safety and reliability at variable altitude, temperature and air pressure are becoming more important and open up new research questions for future electrified air transport.

4. CONCLUSION

In this article, the most common topologies of electric machines, such as the direct current machine, the permanently excited and externally excited synchronous machine, the reluctance machine and the induction machine, as well as their topology variations were considered. Their design, mode of operation, characteristic features and areas of application were described. Evaluation criteria were identified on the basis of aviation-specific requirements and weighted by means of a pairwise comparison. After a pre-selection with the help of exclusion

criteria, selected topologies were evaluated with regard to the established criteria. The results show the high potential of RF- and AFPMSMs due to their high power density and efficiency. The SRM was also rated highly due to the non-necessity of PMs and windings on the rotor and the resulting low complexity, high safety and reliability. During the evaluation, the strong dependence on the specific application becomes apparent. In contrast to ground applications, the challenges in aviation become clear across all topologies. These include the variation of altitude, temperature and air pressure, taking into account high efficiency and power-to-weight ratio with high reliability and system safety. Despite the advanced technology readiness, the average values of the evaluation factors emphasise investigations, tests and improvements. More in-depth analyses and developments can support the use of EMs as a propulsor drive and thus contribute to even safer, more climate-friendly and more sustainable aviation.

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NOMENCLATURE

Acronyms

AEA	All-Electric Aircraft
AFIR	Axial Flux Inner Rotor
AFOR	Axial Flux Outer Rotor
AFPMSM	Axial Flux Permanent Magnet Synchronous Machine
BLDC	Brushless Direct Current Machine
CPSM	Cylindrical Pole Synchronous Machine
DC	Direct Current
DCM	Direct Current Machine
ECM	Electronically Commutated Machine
EM	Electric Machine
FSPMM	Flux-Switching Permanent Magnet Machine
FOC	Field Oriented Control
HTS	High Temperature Superconductor
IPMSM	Interior Permanent Magnet Synchronous Machine
LFP	Long Flux Path
PE	Power Electronic
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Machine
RFPMMSM	Radial Flux Permanent Magnet Synchronous Machine
RM	Reluctance Machine

S/G	Starter/Generator
SFP	Short Flux Path
SPMSM	Surface Permanent Magnet Synchronous Machine
SRM	Switched Reluctance Machine
SynRM	Synchronous Reluctance Machine
TFPMSM	Transverse Flux Permanent Magnet Synchronous Machine
TRL	Technology Readiness Level
WFSM	Wound Field Synchronous Machine
YASA	Yokeless and Segmented Armature

Symbols

A	Current Coating	$[A/m]$
B	Flux Density	$[T]$
d	Diameter	$[m]$
l	Length	$[m]$
M	Torque	$[Nm]$
$m_{i,j}$	Criteria Fulfilment	$[-]$
n	Rotational Speed	$[rpm]$
P	Power	$[W]$
r_j	Evaluation Factor	$[-]$
s	Slip	$[%]$
w_i	Weighting Factor	$[-]$
V	Volume	$[m^3]$
λ	Power Factor	$[-]$
ω	Angular Velocity	$[s^{-1}]$

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APPENDIX

TAB 4: Detailed evaluation of relevant electric machine topologies

Criteria		RFPMSM	AFPMSM	WFSM	SRM	IM
Performance and mass (P)	$(w_1 = 0.35)$	+ High Power Density + High Efficiency + Torque Ripple + Power Factor	+ High Power and Torque Density + High Efficiency + Torque Ripple + Power Factor	+ Medium Power Density + Medium Efficiency + Torque Ripple + Adjustable Power Factor (Variable Rotor Excitation)	+ Medium Power Density + Medium Efficiency + Dynamic Behavior - Torque Ripple (Salient Rotor Teeth and Switched Control) - Power Factor (Rotor Excitation by Stator Field)	+ Medium Efficiency + Torque Ripple - Low Power Density - Power Factor (Rotor Excitation by Stator Field)
		+	++	o	-	-
Ease of integration (I)	$(w_2 = 0.10)$	+ Medium Controllability + Cooling Complexity + Magnetic Field Alignment (Halbach Array) + Noise Emission - Thermal Rotorlimitation (PMs)	+ Medium Controllability + Cooling Complexity + Magnetic Field Alignment (Halbach-Array) + Axial Length/ Stackable + Noise Emission - Thermal Rotorlimitation (PMs)	+ High Controllability + Cooling Complexity + Noise Emission - Thermal Rotorlimitation (Windings) - Exciter Machine or Slip Rings for Rotor Excitation	+ Cooling Complexity + Thermal Rotorlimitation (Solid Rotor) - Low Controllability (Switched Control) - Noise Emission (High Radial Forces)	+ High Controllability + Thermal Rotorlimitation (Rotor Bars) + Noise Emission - Cooling Complexity
		+	++	+	+	+
Safety (S)	$(w_3 = 0.35)$	+ Medium Machine Complexity (Interior or Surface PMs, Bandage if necessary) - Robustness (Interior or Surface PMs)	+ Medium Machine Complexity (Axial Discs with Windings and PMs) - Robustness (Axial Discs with Windings and PMs)	+ Deactivation of Counter-Induction by Switching Off Rotor Excitation) - High Machine Complexity (Rotor Windings, Rotor Exciter System)	+ Robustness (Solid Rotor) + Very Low Machine Complexity (Solid Rotor with no Windings or PMs) + Short-Circuit Behavior	+ Robustness (Rotor Bars in Sheet Package) + Low Machine Complexity (Rotor Bars in Sheet Package)

Values: very good („+“ = 4), good („+“ = 3), moderate („o“ = 2), bad („-“ = 1), very bad („--“ = 0)

(Continued)

TAB 4: Detailed evaluation of relevant electric machine topologies (Continued)

Criteria		RFPMSM	AFPMSM	WFSM	SRM	IM
Safety (S)	(w ₃ = 0.35)	- PM-Partial Demagnetization - Permanent Counter-Induction through PMs	- PM-Partial Demagnetization - Permanent Counter-Induction through PMs - Rotor Dynamics (Tilt-Effects of Rotor and Stator Discs)	- Robustness (Rotor Windings on Salient Poles, Rotor Exciter System)	+ No Counter-Induction (No Rotor Self-Excitation)	+ Short-Circuit Behavior + No Counter-Induction (No Rotor Self-Excitation)
		+	+	+	++	+
Reliability and life cycle costs (R)	(w ₄ = 0.15)	+ Medium Machine Complexity (Interior or Surface PMs, Bandage if necessary) - Expensive (PMs)	+ Medium Machine Complexity (Axial Discs with Windings and PMs) + Expensive (PMs, Complex Structure)	- High Machine Complexity (Rotor Windings, Rotor Exciter System) - Expensive (Rotor Windings, Rotor Exciter System)	+ Very Low Machine Complexity (Solid Rotor with no Windings or PMs) + Inexpensive (No Rotor Windings or PMs)	+ Low Machine Complexity (Rotor Bars in Sheet Package) + Medium Inexpensive (Rotor Bars)
		+	-	-	+	o
Technology readiness (T)	(w ₅ = 0.05)	+ Broad Experience in Ground Applications + Growing Application as Traction Motor + Research as High Power-to-Mass Ratio Configuration by NASA [89] + Research as Mid Power-to-Mass Ratio Configuration by Siemens [27]	+ Growing Experience through Prototypes, Mid-Power Motors + Growing Application as Traction Motor + Growing Number of Companies with Mid and High Power Aircraft Application [43, 88, 90–92]	+ Broad Experience in Ground Applications + Growing Application as Traction Motor + Experience in Aviation as Generator + Research as High-Efficient, High Power-to-Mass Ratio Configuration by NASA [62]	+ Growing Experience through Prototypes + Growing Application as Low-Power Mass-Produced Articles + Experience in Aviation as Mid-Power S/G + Research as Mid Power-to-Mass Ratio Configuration by Sanabria-Walter [71]	+ Broad Experience in Ground Applications + Most used Industrial Motor + Research High Power-to-Mass Ratio Configuration by NASA [81]
		+	o	+	o	+

Values: very good („++“ = 4), good („+“ = 3), moderate („o“ = 2), bad („-“ = 1), very bad („--“ = 0)