Comprehensive Review and Systemization of the Product Features of Axial Flux Machines

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***Abstract*—With the increasing electrification of the powertrain across all mobility applications, the requirements for electric motors are becoming more and more diverse: Depending on the application, the requirements for power and torque vary greatly while at the same time keeping costs, weight and installation space must be kept to a minimum. While the radial flux design has established itself for electric traction drives in the market, axial flux motors also provide great potential for vehicles with high torque requirements and small installation space. The axial arrangement of the components within this topology allows many degrees of freedom in product design, which results in many sub-variants of axial flux motors. However, there is a lack of a uniform and consolidated categorization of these variating design features in both scientific literature and industrial practice. In this work, the different design features of axial flux motors were identified based on an extensive as well as systematic literature research and categorized according to uniform characteristics. As a result, the complex variety of different axial flux motor variants is systematized and standardized, which lays the foundation for a uniform categorization of this motor topology.**

Keywords—electric motor, electric motor production, axial flux motor, literature review, systemization, product, topology study, systematic review, categorization

I. Introduction

To date, electric traction drives have predominantly used electric motors with a radial flux design. This design is derived from the magnetic flux that runs radially to the direction of rotation between stator and rotor (RFM). The counterpart to this are electric motors with an axial flux design (AFM), in which the magnetic flux runs axially to the direction of rotation (Fig. 1).

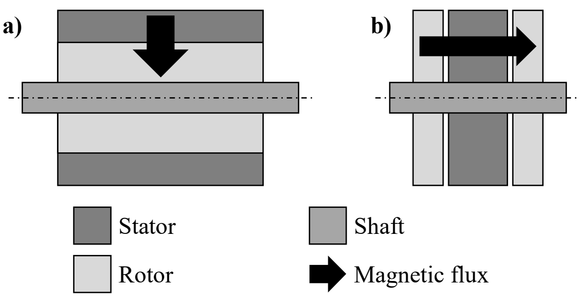

Fig. 1. Schematic comparison of a radial flux motor (RFM) (a) and an axial flux motor (AFM) (b)

The disk-shaped arrangement of rotor and stator also gives this design the name "disk motor". This arrangement enables a more efficient use of the installation space, which results in the following significant advantages, among others:

- **Compact design:** Due to their design, AFM can be built shorter in the axial direction. This offers more flexibility for integration in various applications.
- **Lower weight:** The specific design of AFM results in better utilization of the materials, especially the magnetic material, and thus in a lower weight and therefore an improved power density.
- **Efficient cooling:** The heat is distributed over a larger area of the electric motor and can therefore be dissipated more efficiently, making higher continuous outputs possible.

These advantages make this design interesting for the use in mobility applications, as the compact design offers a wide range of possibilities for space-saving integration. [1, 2]

Fig. 2 shows some examples of how AFM can be integrated into electric vehicles. The compact design of AFM allows it to be positioned close to the wheel with a differential or directly in the wheel. Compared to conventional electric drive axles, the space between the wheels can be used for additional battery capacity, for example. The electric motor on the crankshaft, between the combustion engine and the differential, enables particularly compact hybrid drives.

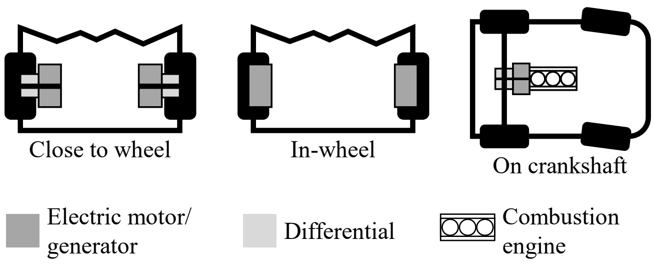

Fig. 2. Exemplary placement of AFM in passenger cars [3]

To date, there are many different design features of AFM. A uniform categorization of this multitude of features is still lacking. Such a categorization forms the basis for a generally understandable communication for the research and development of AFM. At the same time, standardization supports comparability and enables the classification of future technological developments.

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Several categorizations of AFM can already be found in the scientific literature. However, these do not come to a uniform conclusion and differ in the characteristics identified, so that they do not form a sufficient categorization as a basis for the development of AFM.

In their classification, GIERAS ET AL. focus in particular on the structural design of the stator. The design features that stand out are those of a slotted, a slotless and a salient-pole stator. In the case of the winding, they limit themselves exclusively to the distributed or concentrated winding design. [4] KAHOURZADE ET AL. and HABIB ET AL. show further variants of winding, which can be further subdivided into drum winding and ring winding. However, Habib et al. only consider these for coreless stators, whereas KAHOURZADE ET AL. distinguish between different designs for the stator core. [5, 6] HABIB ET AL. and GIERAS ET AL. discuss different geometric shapes of the magnets and their arrangements, although the results are not consistent. [4, 6]

However, all works are similar in the fact that a distinction is made at the top level according to the arrangement of rotor and stator. This involves, firstly single-stator single-rotor (SRSS) structure [7] respectively an axial arrangement of a stator facing a rotor. This configuration forms the basic structure for a double-sided AFM setup, where the machine can either consist of two rotors and one stator in between (DRSS) or the other way around (DSSR). Whereas the former is also named Torus, due to the internal rotor the latter is called AFIR. The Multi-staged structures (MSMR), in turn, are formed from the axial alignment of one or more Torus or AFIR topologies. [4–6, 8]

The SRSS structure offers both a high-power density and low total losses. However, its unbalanced axial attraction force that arises between the stator and rotor proves to be a drawback. This has negative effects on the bearings and can cause structural twisting, particularly under high rotor speeds. The double-sided AFM topology, AFIR or Torus, is mechanically stronger than the single-sided one due to the cancellation of the axial magnetic force and has a higher power density. While in the AFIR topology the stator windings only contribute to torque generation on one side, the Torus geometry uses the winding surface on both sides. As a result, the end windings in the Torus machine have a comparatively shorter length than in the AFIR geometry, which results in a higher motor efficiency and material utilization. [9, 10]

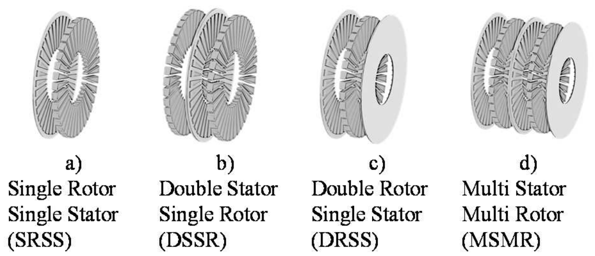

Fig. 3. Overview of the different axial flux motor topologies

An examination of these scientific studies shows that no uniform categorization of AFM exists to date. Therefore, a systematic literature research was chosen for this study to identify and summarize all known design characteristics of AFM and present them in a uniform categorization.

II. METHODOLOGY

The challenge of developing a comprehensive categorization of AFM is to ensure that as many variants of AFM as possible are recorded and included. To ensure this, a systematic literature search was carried out. The multi-stage procedure is shown in Fig. 4.

The first step was to identify articles from various scientific databases. The databases IEEE, scopus, ScienceDirect, JSTOR and WebOfScience were used. The search terms were divided into three groups and linked to each other using corresponding operators, as shown in Fig. 5. A total of 3.176 articles were identified.

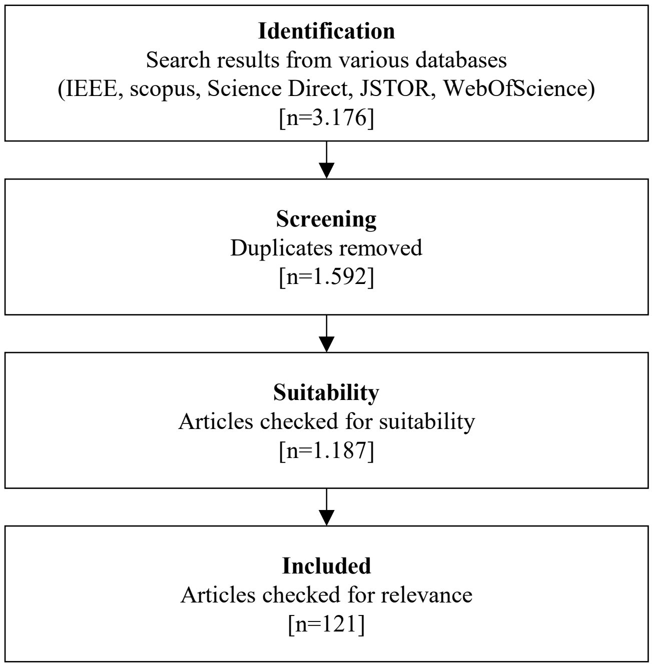

Fig. 4. Result of the systematic literature search

Duplicates were identified and removed during the screening phase. This allowed the article number to be reduced to 1,592. To determine the relevance of each article based on the title and keywords, articles containing less than 3 and more than 10 keywords were excluded. This measure further reduced the number of suitable articles to 1.187.

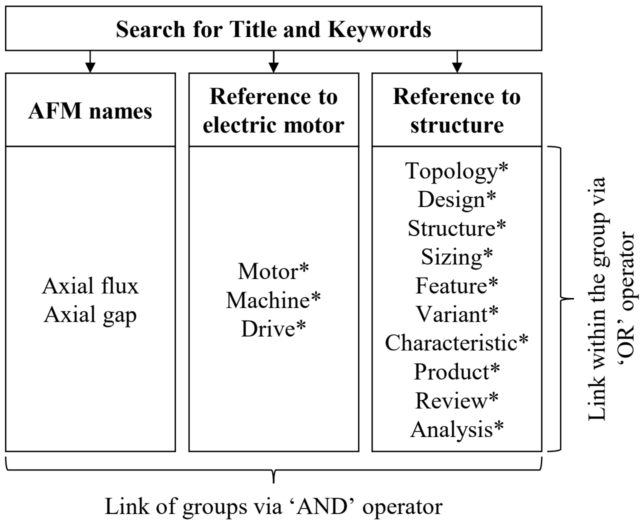

Fig. 5. Search terms and operators

Based on the title and keywords, the remaining articles were evaluated for their relevance to the categorization. This identified 121 articles, which were included in the final analysis. The last remaining articles were examined regarding design variables and variants of AFM. The variables and variants identified were included in the categorization of AFM. The result of this work is presented and described in the following section.

III. Results

A preliminary review of the research results has shown that the identified literature focuses primarily on permanently excited synchronous motors and that separately excited motors, asynchronous motors, or reluctance machines only play a minor role for the AFM. Based on this finding, the categorization described in the following subsections will be limited to permanently excited synchronous machines.

Firstly, the identified structures in relation to the stator and the winding will be discussed. Subsequently, the rotor and the different characteristics in relation to the magnets will be described. In addition, the different cooling methods for these four components will be explained. Finally, the components that have been discussed will be analysed in terms of the applied materials.

A. Stator topology

The structure of the stator can be categorised on a first level with regard to a ferromagnetic or non-ferromagnetic core. In a stator structure with the latter, also known as coreless or ironless, the magnetic stator core is replaced by a non-magnetisable polymer, such as soft magnetic composite, amorphous metal or charged polymers, results in a reduction of mass. Due to this the motor efficiency can be increased for the same motor torque. In addition, there are further advantages such as lower costs, no axial force on the stator in zero current state, no torque pulsations, no cogging torque as well as no hysteresis and eddy current losses. [4, 11] In addition, AFM with ironless structures, such as those proposed in Long et. al. [12], Halstead [13], Butterfield [14] and Greaves et. al. [15], can be produced in a simple and efficient manner. On the other hand, the absence of the magnetisable core leads to a lower magnetic flux density in the air gap, which in turn reduces the motor torque and power. [4, 9, 16] Due to these power limitations, ironless motors are usually not suitable for traction applications. These also include AFM with stators which are produced by printed circuit boards.

In case of ferromagnetic stator, the core is made of ferromagnetic materials and the structure can be differentiated between a slotted, unslotted, yokeless or salient pole design. In the case of a slotted structure, the stator is made with grooves in which the coil windings are accommodated. This structure results in a rigid stator design with a small air gap between rotor and stator. [7, 9] The main disadvantage of a slotted stator is the so-called cogging torque, which is caused by an interaction between the permanent magnets of the rotor and the stator slots in the area of the air gap. The interaction leads to a torque that depends on the rotor position and is therefore non-uniform. [17] In case of an unslotted stator, the coils are attached to the stator surface. This kind of structure decreases torque ripple but features a larger air gap to accommodate the windings. This leads to an increased use of copper and permanent magnet material to compensate the drop in air gap flux density. Further the unslotted structure features challenges in terms of fixing the winding to the stator and secure the position against forces occurring during operation. [7, 9]

A compromise between an iron core and an ironless design represents the yokeless structure. In this variant, the ferromagnetic core of the stator is broken down into separate individual segments [18, 19]. This is why the structure is also referred to as segmented [20]. The individual teeth of the stator are no longer connected via a magnetic back iron, but are instead fastened to a polymer ring, e.g., with the aid of screws, a clamp or by adhesive [17]. This arrangement also helps to reduce the stator weight and volume, its costs as well as the losses inside the core compared to conventional AFM structures [19–21].

AFM generally suffer from high torque ripples [22–24]. Some of the measures that can be taken in this regard are presented in the next section. For example, the slots in the stator can be arranged skewed. Skewing significantly reduces the torque ripple while increasing the magnetic flux at the same time. The skewing of the stator winding has a similar effect to that of the magnets, which will be described in a later section. Due to the simpler production of skewed magnets, however, skewed windings are rarely encountered and non-skewed windings are generally used here. [24, 25]

Letelier et. al proposes another approach based on an FEA simulation. Here, the stator coils are divided into two symmetrical rotor-stator sections. In both electromagnetic circuits, there is an interaction between the stator teeth and the rotor magnets. Based on an FEA calculation, the winding offset between the two stator windings could be optimised so that the maximum cogging torque value could be reduced by 50% compared to the initial situation. [26] This slot displacement technique can be used due to the symmetry in the SSDR structure. However, no real application of this proposal can be identified.

For the structure of a single tooth, a distinction can be made between a salient or non-salient pole in a final hierarchical level. Similar to the radial flux machine, stator teeth here have an overlap beyond the axial height of the coil. In the case of a non-salient structure, the stator teeth are axially flush with the coil. [4] The advantages of the salient over a non-salient structure lie in the effective conduction of the magnetic flux and a reduction in the need for rare earths.

B. Winding

About the winding, a differentiation is made between the selected conductor topology and the associated form of the winding.

1) Form

Depending on the motor design, the form of the individual coils and their orientation usually varies. A distinction can be made between drum and ring windings [5, 7, 9, 17, 27–29]. Drum windings are usually trapezoidal coils that are arranged in a circle on the stator. If these are embedded in slots in a slotted stator, they are also referred as tooth windings. Further those are usually connected in the circumferentially along the inner and/or outer radius and can be either non-overlapping, respectively concentrated, or overlapping, respectively distributed. [10, 30] The drum-winding can be used in combination with the SRSS, the AFIR as well as the Torus topology [6, 10].

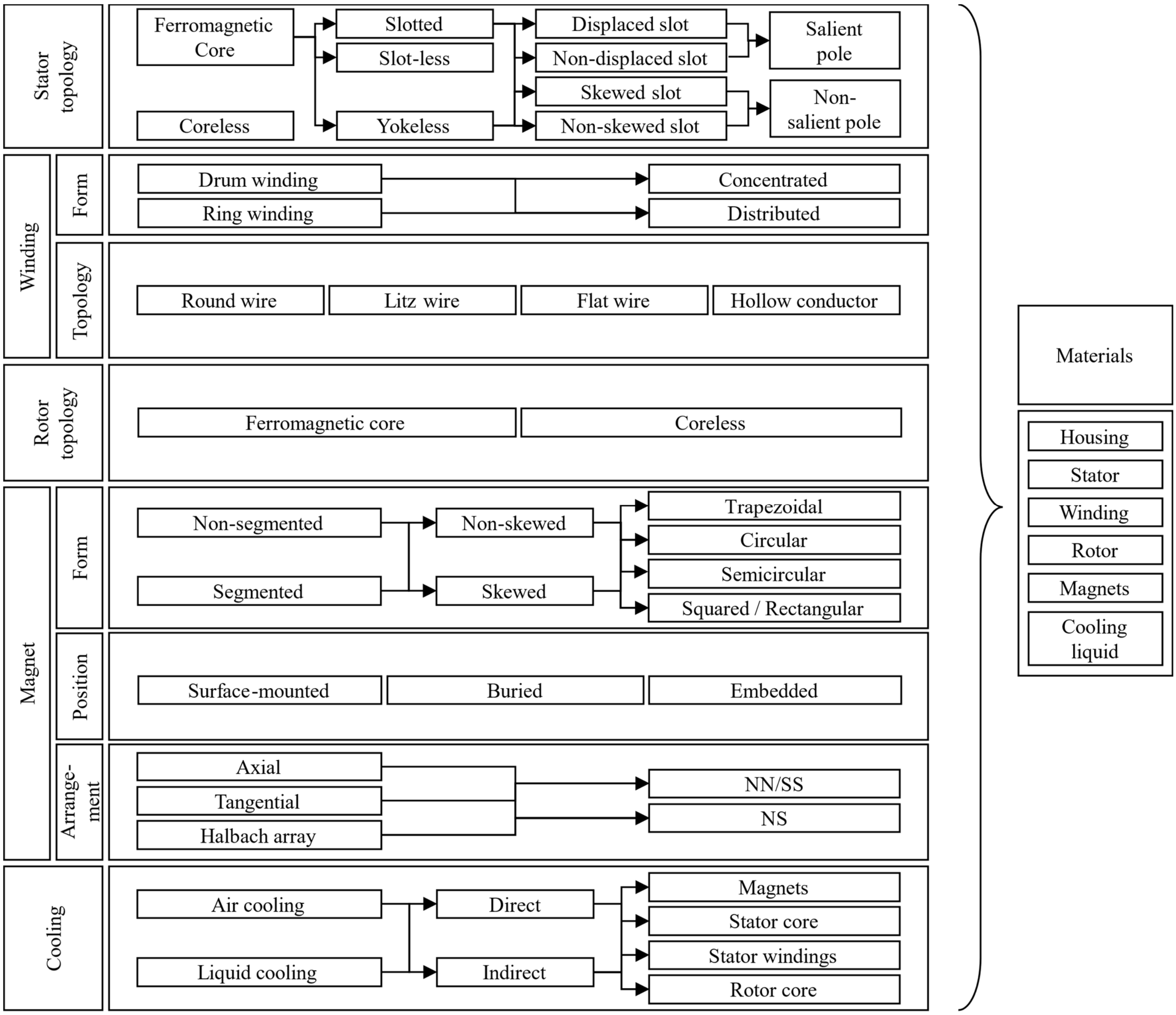

Fig. 6. Overview of the various superordinate AFM design features and their subordinate characteristics including associated possible combinations

Ring windings, which are also known as toroidal windings, are connected to each other by means of a joint placed axially on the inner or outer radius [10]. Those windings are used exclusively in NN Torus topology and are characterised by a short length as well as radial protrusion, simple connection and stator design. [4, 10]

Both winding forms can be either distributed or concentrated. In case of distributed drum windings two configurations are possible. Firstly, there is the option of arranging the drum winding in several layers with corresponding wiring (cf. Fig. 7left). In this case, the coil width of the drum winding is significantly larger compared to the concentrated winding. [31–34] To achieve the highest possible packing density in the case of an overlapping structure, the coils can be formed with offset bends on the inner and outer radius, to allow the coils to interlock. In addition, the coils can be made alternately larger or smaller in the radial direction. [4] Alternatively, the distributed winding can be formed over several meander-shaped conductors, which lie on top of each other in several layers. [32, 35, 36]

Concentrated, non-overlapping drum windings have shorter end-windings compared to overlapping windings and are therefore a more effective regarding the material consumption (cf. Fig. 7 middle) [37, 38]. Further those are characterized by low manufacturing costs [19, 30, 38] as well as a higher modularity [37]. These advantages of non-overlapping drum windings are offset by higher drag losses and periodic fluctuations in the motor torque, which are also known as torque ripple. Moreover non-overlapping windings have a lower winding factor, which causes a lower torque output compared to overlapping windings [33, 38]. Since the average electromagnetic torque is proportional to the winding factor, an electrical machine with low winding factor needs to compensate its lower torque with higher current density, which leads to higher Joule losses compared to a machine with a higher winding factor. [33] In addition, concentrated windings suffer from high assembly and contacting costs compared to meander-shaped distributed windings.

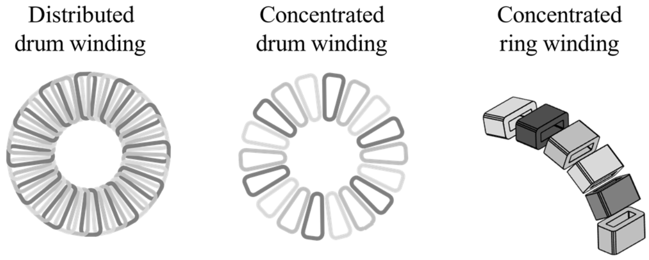

Fig. 7. Overview of the different winding forms. Distributed ring winding (left), concentrated drum winding (middle), concentrated ring winding (right)

The concentrated ring windings are exclusively applied in the Torus AFM topology and are wound directly onto the stator core or wound separately and then arranged alternately with the stator elements (cf. Fig. 7 right). In the latter case the stator has to be segmented to enable the coil assembly. Both the direct winding of the stator and the segmenting of the stator result in product- and process-related disadvantages compared to the use of drum windings, which is why the latter are used more often. [6, 10] Distributed ring windings can be manufactured productively with the aid of toroidal winding but this results in a lower fill factor, and therefore this technology and topology is also not widely used.

2) Topology

Concerning the conductor topologies used for the stator coils, round, flat and litz wires as well as hollow conductors can be identified, although the latter two are currently more of an exception in this application. Due to the higher fill factor that can be achieved with the flat wire compared to the round wire, the flat wire is used most frequently [17]. This high fill factor makes it possible to produce motors with a particularly high-power density. To reduce conductor losses due to the eddy currents, a trend towards even higher width-to-thickness ratios can be observed. This poses challenges for the bending processes used to form the coils. With regard to the application of round wire and flat wire in the different winding forms, it can be stated that drum winding are mostly wound from an insulated conductor with a round or rectangular cross-section [4]. In contrast to this ring windings are mostly wound from conductors with rectangular cross-section [17]

Instead of increasing the width-to-height ratio of the flat wire further and further, another way to reduce AC winding losses, especially at higher rotational speeds, is to use litz wires. [39–43] However, the reduced fill factor compared to flat wire and the associated reduced thermal conductivity result in higher DC losses. Litz wires are currently primarily used in motors with an ironless stator core. Due to the mechanical properties, however, shaping and ensuring exact positioning pose a challenge. [44]

With regard to the reduction of DC losses within the conductor, hollow wires can be used for axial flux motor coils [28, 42, 45]. The direct flow of coolant through the heat source can significantly lower the conductor temperature and thus reduce the associated joule losses. Compared to the use of flat wire, the structure of the hollow conductor results in a significantly reduced fill factor compared to flat wire. To compensate for this reduction in terms of current density and torque, the motor may need to be enlarged. [28]

C. Rotor topology

The rotor topology is differentiated with regard to the core material of the rotor and a distinction is made between a ferromagnetic core material and a non-ferromagnetic core or coreless setup. [4, 5, 46]

1) Ferromagnetic core

A ferromagnetic rotor core leads to a higher leakage flux in the magnets ends due to the fact they are surrounded by the ferromagnetic material. Also the overall thickness for ferromagnetic rotor discs is higher compared to non-ferromagnetic variants because the rotor disk must not only provide the mechanical stability but also cover the magnets over their entire height. [5] On the other hand the fixation of the magnets inside the rotor disc and protection from external hazards and corrosion is much easier compared to coreless rotor design. Also, the implementation of cooling systems directly inside the rotor disc is easier due to space available. [28, 47]

2) Coreless

Using a non-ferromagnetic core for the rotor offers the potential of reduced cogging torque and overall lower eddy current losses due to the lesser extend of magnetic material overall in the motor [4] A coreless rotor design also enables the use of non-magnetic materials for the rotor disc aside from conventional materials like aluminium or laminated steel. Doing so a significant reduction in weight, cost an overall increase in machine efficiency can be achieved. [16] Thus this comes like an effectively increased air gap due to the often used surface mounted magnet placement in combination with a coreless rotor. [6] To reduce this effect often special magnet arrangements are used which require increased amounts of magnet material for the rotor assembly. [16, 48]

D. Magnets

The magnets in the rotor are categorized according to the magnet shape, the magnet position in the rotor disc and the arrangement of the magnetic field. Within these superordinate categories, there is also a subdivided differentiation with regard to different characteristics and combinations of the respective characteristics. [4–6, 49] Aside from that there are also machine designs which are based on the switched reluctance effect and therefore use only a minimum amount of magnet material or none at all. [50, 51] Those designs offer a cost-advantage compared to permanent magnet machines and are overall easier to manufacture and assemble, especially for large machines. [51] But they also pose some challenges like the higher torque ripple, the parasitic airgap and the fixation of the rotor segments onto the rotor backplate [50, 51] However, since there are rather few publications on the topology of the reluctance axial flux machine compared to the permanent magnet machine, as mentioned previously this design is not considered in more detail in this paper.

1) Magnet form

The magnet form can be differentiated between an overall segmented or non-segmented magnet design. The magnet geometry itself can be either skewed or non-skewed and realized in different basic shapes like trapezoidal, circular, semicircular or rectangular / square like shown in Fig. 8. [4–6, 49, 52]

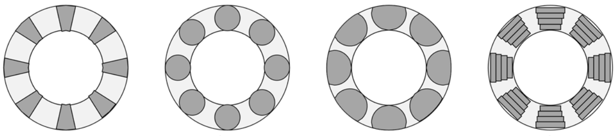

Fig. 8. Overview of typical magnet shapes applied to the rotor disk. a) Trapezoidal, b) Circular, c) Semi-circular and d) Squared / Rectangular [4, 53]

Using a segmented magnet design, the magnets for each pole are separated into multiple segments. In this case the magnets can be either separated in tangential direction or radial direction. [54, 55]. Depending on the size of the machine and therefore of the respective magnets needed, the eddy current path can be correspondingly long. To reduce these losses the magnets can be segmented. The more segments there are, the lower are the eddy current losses due to the blockage of the eddy current path and therefore the efficiency increases. The complexity of manufacturing the magnets on the other hand increases with an increasing number of segments. [55]

Non-segmented magnet designs consist of one magnet per pole and offer compared to segmented magnets a higher average air-gap flux density and a higher torque density with the cost of higher PM losses. [56] This leads to overall higher temperatures in non-segmented magnets which can result in a demagnetization. However, this downside can be compensated for by optimizing the machine design and also conventional sintered non-segments magnets are much more cheaper than segmented versions [56]

Both magnet designs, segmented and non-segmented can either have a skewed or non-skewed geometry, some examples are shown in Fig. 9. [49, 52, 57]

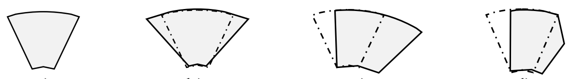

Fig. 9. An exemplary overview of different skewing designs. a) Fan-shaped, unskewed magnet, b) Parallel skewed magnet, c) Classic skew and d) Dual skew. [58]

Skewed magnet geometries offer the advantage of a reduced cogging torque; however, this effect is quite limited for AFM. To compensate for this the magnet geometry can be dual-skewed like for example in JIA, LIN ET AL. to increase this effect and make this design alternative attractive for the use in AFM. [49] The reduction in cogging torque is mostly dependent of the skewing angle and the cross position. Those two parameters are directly related to the wavelength of the cogging torque and therefore need to be optimized for the respective machine design. [59] If correctly optimized the magnet skewing can be used to reach very low levels of cogging torque in AFM. Regarding the basic geometry the skewing can be applied flexibly to squared / rectangular magnets, circular and semi-circular magnets. For the trapezoidal geometry the skewing leads to a significant reduction in the cogging torque but on the other hand also increases the leakage flux at the inner magnet radius und therefore decreases the overall average torque. [57]

Non-skewed magnet designs are easier to manufacture and offer the advantage of a slightly higher average torque. Also, for high-speed applications the torque ripple is usually filtered out by the inertia of the system. For these applications the cogging torque reduction from the skewing is negligible and therefore the use of non-skewed magnets overall more beneficial. [52]

The basic shape of the magnets can be either squared / rectangular, circular, semi-circular or trapezoidal. [4, 27, 60–62] The shape of the magnets affects the distribution of the magnetic field in the air gap and the total harmonic distortion. [4] If there are no specific requirements regarding the cogging torque distribution, the trapezoidal magnet shape is preferred due to the most uniform magnetic field distribution resulting from this geometry. If there are specific requirements regarding the maximum torque-output capability a circular magnet shape offers the best results. [62] Also, circular, and rectangular / square shaped magnets are a fixed type, easily available and have comparable low design costs. In a direct comparison the total harmonic distortion of low order harmonics is smaller for semi-circular magnets than for trapezoidal shaped magnets however for high order harmonics it is just the other way around. [27, 61]

2) Magnet position

The magnet position refers to the placement of the magnets in or onto the rotor disk. The magnets can either be buried, surface-mounted or embedded [5]. The positioning of the magnets is often related to the respective machine setup (the number of rotor and stators and the design of the stator). [4] For single-sided AFM the magnets can either be surface-mounted or embedded into the rotor disk, depending on the respective stator design. [4, 63] For dual-stator single rotor designs the magnets can either be surface-mounted, embedded or buried. In case of a slotless stator the magnet are mostly surface mounted, due to the large airgap between the rotor and the stator. [4] Having a dual stator single rotor setup in combination with a coreless rotor and stator a buried magnet positioning can be beneficial. [6]

The surface-mounted design offers the advantage of having a thin rotor disk, especially if using a non-ferromagnetic material for the rotor core and can be easily manufactured. [6, 63] However, the surface mounted design is limited for high-speed applications due to the associated forces. [64] Also due to the magnet permanence is almost identical to the air surrounding it, the effective airgap increases which leads to a larger magnetic flux source needed. [63] Using an embedded positioning for the magnets enables more stability especially for higher rotational speeds. However, the respective rotor disk is much thicker which results in an overall reduction of the machines power density. Also if using a ferromagnetic-core in combination with an embedded magnet positioning the leakage flux in the magnet ends is higher due to the surrounding ferromagnetic material. [6] Having a buried positioning, the magnets are covered from all sides, offering the most efficient fixation for high centrifugal forces as well as protection from corrosion which makes this setup especially attractive for high-speed applications. [63]

3) Magnet arrangement

Regarding the magnet arrangement it can be differentiated between the conventional array and the Halbach array. For the conventional array, the magnets are arranged with alternating poles. This can either be done in a tangential or radial direction. [65]. The Halbach array is a combination of the two conventional arrays with alternating tangential and radial poles. This arrangement leads to a strengthening of the filed on one side and the cancellation of the field on the other side. [65] The different array arrangements are shown in Fig. 10.

S	S	N	S	S	S	N
N	S	S	S	N	S	S

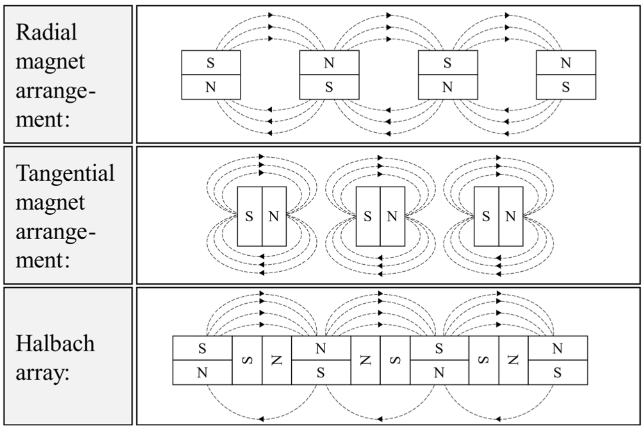

Fig. 10. Overview of the different magnet arrangements: Radial magnet arrangement (top), Tangential magnet arrangement (middle) and Halbach array (bottom) [65]

The radial arrangement of the magnets leads to an axial direction of the magnetic flux from the north to the south pole, like shown in Fig. 10. [16, 48] This can be combined with a surface mounted or embedded positioning of the magnets in the rotor disk. If combined with a surface mounted design, very thin rotors can be realized, especially if using a non-ferromagnetic rotor core material. [11] However, as explained in the section before, the magnets act in this case almost as air which increases the effective airgap. Embedding the magnets in the rotor disk can reduce this effect but increases the overall thickness of the rotor plate. [48]. Using a tangential arrangement of the magnets results in a tangential flux from the north to the south pole. [16, 48]. To realize this arrangement the magnets must be either embedded or buried in the rotor disk, which leads to a much thicker assembly and lowers the overall power density of the machine. [48] On top of that the other characteristics for the buried positioning apply, which were explained in the section before. Both arrangements lead to a square wave form of air-gap magnetic flux density which results in high-order harmonics in the air-gap flux density which will distort the back EMF when the air-gap depth is too small like outlined in HUANG, LIU ET AL. [66] Unsing a conventional arrangement compared to a Halbach array, a lower amount of magnetic material is required which leads to overall lower cost. [16]

The Halbach array leads to a combination of the magnetic flux of both conventional arrangements. (cf. Fig. 10). This also leads to a strengthening of the magnetic field on one side while reducing it on the other side. [16, 66] According to HUANG, LIU ET AL. the normal residual magnetization of Halbach-array magnets is not a square-waveform and also results in a lower tangential residual magnetization. [66] The Halbach-array arrangement is often used in combination with a non-ferromagnetic rotor core which offers the advantage of an overall lower mass and increase of machine efficiency. Due to the fact, that the Halbach-array magnetization vector rotates as a function of distance along the circumferential direction of the rotor and therefore a ferromagnetic rotor back iron leading the magnetic flux is no longer necessary. [4, 11] Another advantage is that there is no axial force on the stator in zero cogging state, no cogging torque and low hysteresis and eddy current losses. [4, 11, 16] Using a Halbach array in combination with a surface mounted positioning of the magnets the downside of the effectively bigger airgap is compensated due to the higher magnetic flux density which makes this arrangement especially advantageous for those topologies. [16] Regarding the disadvantages, the Halbach array requires a higher amount of magnetic material which leads to higher cost. Further the fixation and overall mechanical integrity of the magnet application is more challenging. [67] Due to the lower heat transfer of the magnetic material and the interference of the magnets with each other there is an increased risk of demagnetization. This can be compensated for using physical separators between the different magnets of the array. [67, 68]

Aside from the setup of the array, the magnet arrangement can be further categorized by the orientation of the magnetic poles to each other. [69] Hereby it is differentiated between the NN/ SS orientation or the NS orientation. N and S are referring the magnetic north and south pole. In case of the NN / SS arrangements the respective north and south poles are facing each other. The NS arrangement is the other way around and the respective north and south poles are opposite to each other. [16, 69] Using a NS arrangement, the flux path travels axially through the machine using a DRSS or DSSR setup and does no turn in in the circumferential direction. This offers the possibility to either eliminate the stator yoke and need for ferromagnetic material in the DRSS setup and the substitution of the rotor material in the DSSR setup. [16]

E. *Cooling*

One of the major challenges for the AFM topology is the cooling. Due to the high power density and the compact machine design, the thermal limits of the machine are often the restrictive factor. [28] In AFM there are typically three main sources of losses, magnet eddy losses, winding copper losses and in case of ferromagnetic cores, iron-core losses. [70]. Based on these losses the capabilities of the respective cooling system can be derived. On this level it can be differentiated based on the cooling media between air cooling and liquid cooling. Those two medias can be applied in different ways to the sub-assemblies of the stator like the rotor core, the magnets, the stator winding and the stator core.

For the rotor assembly either air-cooling or liquid cooling can be applied. Using air cooling for the rotor magnets and the respective core can be challenging due to the comparably low thermal properties of air as a cooling media. Also using air-cooling for the rotor assembly the cooling rate highly depends on the operating speed of the machine and the overall ambient conditions which makes quite challenging especially for machines with a low operational speed. [70] This can be compensated by using a forced convection to apply the air to the rotor, which on the other hand increases the overall complexity of the cooling system. [47] Based on the design of the rotor assembly and the overall machines there are several principles available to realize an airflow over the rotor disk surface like described by ELCRAT and NARAYANA AND RUDRAIAH [71, 72]. In any case, to set up an efficient rotor cooling using air, machine design specific optimization is necessary.

Alternative liquid cooling principles for the rotor assembly are mostly beneficial for high-performance applications and applications with an overall high-power density requirement. The cooling liquid can be applied either using a direct or indirect cooling method. For the indirect cooling the cooling of the rotor assembly can be realized using a cooling jacket around the rotor and stator assembly. However, due to the significant airgap between the rotor and the cooling jacket, there is a significant thermal resistance using this method for rotor cooling. [47] Other indirect cooling methods would be by cooling the rotor through the stator using for example cooling channels inside the stator core or hollow-wires to lead the coolant directly through the conductor or the centre of a litz-wire bundle. [42, 47, 73, 74] The direct cooling of the rotor can be realized using a spray-cooling setup. In this case this case the media is directly sprayed onto the rotor disks. To improve the cooling effect even further a refrigerant can be used to take advantage of the phase change. [47, 75] Another alternative would be to cool the rotor directly by pumping a dielectric cooling liquid into the rotor chamber of the housing. While this is has the best overall cooling effect, the drag of the rotor increases based on the coolant viscosity, density and the machines operating speed. [47]

Conduction cooling is a kind of special case. Here for example heat pipes filled with a special fluid are implemented into the rotor assembly. The fluid evaporates at high temperatures, moves to heat-exchange elements and condensates, and flows back. This implies an increased complexity of the rotor cooling and additional space requirements for the rotor assembly. There may also be interference with the electromagnetic function of the machine. [47, 76, 77] Alternatively a phase change material can be implemented in the rotor assembly near the magnets. This material absorbs heat until it is saturated and undergoes a phase change. When the system temperature subsequently drops, the absorbed heat is released, and the phase change takes place in reverse. Temperature peaks can be absorbed using this method. However, this method is only suitable for very short load peaks and there is no active cooling, only a delay in heating. Depending on the energy to be absorbed, the implementation of the phase change material in the required quantities in the rotor assembly also poses a significant challenge. [47]

For the cooling of the stator the available methods are versatile as described in JONES-JACKSON ET AL. Natural convection can be used as well as forced air, indirect liquid cooling using a cooling jacket setup or flow channels inside the stator core or directly inside the winding. [28, 42] Also direct cooling and heat pipe setups can be used. [28] The overall goal is to dissipate the heat as close as possible to the point of origin to avoid negative effects on the machine's performance and effectiveness. Regarding their basic principles of function, they are quite like the methods already explained for the rotor assembly. In general, each cooling method comes with advantages but also with challenges. Especially for high-power density motors thought the natural and forced air cooling is not sufficient for the stator assembly and therefore other principles must be used instead.

F. Materials

As in the area of radial flux motors, copper is primarily used as a conductor material for AFM due to its excellent electrical and thermal conductivity. However, alternative conductor materials are increasingly being sought, partly due to the high price of the material. In this context, the use of aluminium conductors is increasingly being investigated. Aluminium is characterized by a weight that is around three times lower, a lower price and lower price fluctuations. It also improves the recyclability of the motor and has a lower ecological footprint than copper. [78, 79] According to CAKAL ET AL. and RALLABANDI ET AL., aluminium can lead to better performance in terms of efficiency and losses, depending on the operating point. While aluminium is advantageous in the high-speed range due to the suppression of eddy current losses, copper is advantageous in the high-torque/current range due to the suppression of conduction losses. [80, 81] As a further alternative to copper with similar properties to aluminium, RALLABANDI ET AL. also proposes so-called carbon nanotubes [81].

There is a wide variety of different cooling materials used. A distinction can be made between synthetic oils, florin or paraffin-based oils, ethylene glycol mixtures or water. The choice depends on the type of cooling, i.e. direct or indirect, and the intended application profile. Different material properties, such as viscosity and its dependence on temperature, result in particularly suitable materials depending on the application. [28]

As described in KAMPKER, TREICHEL ET AL. there are a lot of material alternatives available for designs with iron cores as well as for ironless or coreless designs. The basic material used for ferromagnetic rotor back iron is iron and for the magnet holder, depending on the design of the machine, stainless steel. As an alternative to stainless steel soft magnetic composite materials (SMC) are possible. Aside from their advantages over laminated steel cores they can enable the realisation of mor complex motor design and can lead to overall more efficient machines but also have some boundary conditions and characteristics to consider. [16, 82] As an alternative also amorphous magnetic materials can be used especially for high-speed applications. [83]. Looking at ironless rotors, high-performance plastics can provide a suitable alternative to stainless steels. PEEK, PPS, PAI and PBI can be named as examples here. [84] The suitability of the respective plastic material is highly dependent of the thermal design of the machine and must be chosen accordingly. [16]

For the permanent magnets themselves, according to GIERAS, WANG ET AL. three different material classes are described. Alnicos (Al, Ni, Co, Fe), Ferritic ceramics (e.g. SrO x $6Fe_2O_3$), and Rare-earth materials such as NdFeB or SmCo. All of them offer different advantages and characteristics as well as boundary conditions for certain applications or operating fields. [4]

According to KAMPKER ET AL., several materials can also be considered for the structural components of the axial flux motor, especially the housing. In addition to conventional metals such as steel or aluminum, the use of plastics is also conceivable. However, only high-performance plastics (e.g. PEEK, PPS, PAI or PBI) can be considered due to the high forces involved and the required heat stability. The use of lightweight plastics also has the advantage of reducing the weight of AFM and thus improving the power density. The disadvantage compared to conventional metals is the high material and manufacturing costs. [16]

IV. Conclusion

Based on the literature research carried out, a comprehensive categorization of AFM was created. The categorization includes the main components (e.g. rotor, stator, etc.) of AFM as well as their possible characteristics. The results were presented in a tree structure that allows AFM to be clearly categorized. Categorization helps developers keep track of the variables in the development process by simplifying the complexity of AFM. Conversely, existing variants of AFM can be clearly assigned according to this categorization.

In the course of the work, further key findings were derived, which are briefly summarized below:

1. **Wide range of variants in the design of AFM**

   The large number of possible variables and characteristics in the design results in a wide range of possible AFM variants. The challenge in the development and design of AFM is therefore to find the best AFM variant for the underlying requirements of the application. The complexity and diversity of the variant drivers must be systematically narrowed by down during the development process by simulative comparison to develop the best AFM for the respective application.

2. **Production processes to exploit the advantages of AFM**

   The large number of variants of AFM results in many processes required for production. Furthermore, the high demands placed on the AFM components and assemblies to be produced result in technically sophisticated production processes that have not yet reached the necessary level of technical maturity. In order to fully exploit the potential of AFM, appropriate production processes must be developed.

3. **Implementation of cooling concepts**

   Cooling strategies are crucial for the performance and lifetime of AFM. The special design of AFM enables many possible cooling concepts (e.g. air, direct winding cooling, etc.). To ensure the success of AFM, further research is required to develop innovative cooling structures using materials with higher thermal conductivity. To exploit the advantages of installation space, the effectiveness of the cooling concepts must be precisely simulated and optimized with regard to space and weight requirements. The challenge of the producibility of the cooling concepts is also a decisive element.

V. References

[1] M. Trzesniowski, “Rennwagentechnik,” Wiesbaden, Springer Fachmedien Wiesbaden, 2014.

[2] Schäfer, Heinz (Hg.), 2019, “Elektrische Antriebstechnologie für Hybrid- und Elektrofahrzeuge,” : Tübingen, expert (Haus der Technik Fachbuch, 149). [Online]. Available: https://elibrary.utb.de /doi/book/10.5555/9783816984832.

[3] U. Knödel, F.-J. Stein and H. Schlenkermann, “Variantenvielfalt der Antriebskonzepte für Elektrofahrzeuge,” *ATZ Automobiltech Z,* vol. 113, no. 7-8, pp. 552-557, 2011.

[4] J. F. Gieras, R.-J. Wang and M. J. Kamper, “Axial Flux Permanent Magnet Brushless Machines,” Dordrecht, Springer Netherlands, 2008.

[5] S. Kahourzade, A. Mahmoudi, H. W. Ping et al., “A Comprehensive Review of Axial-Flux Permanent-Magnet Machines,” *Can. J. Electr. Comput. Eng.,* vol. 37, no. 1, pp. 19-33, 2014.

[6] A. Habib, M. A. A. Mohd Zainuri, H. S. Che et al., “A systematic review on current research and developments on coreless axial‐flux permanent‐magnet machines,” *IET Electric Power Appl,* vol. 16, no. 10, pp. 1095-1116, 2022.

[7] S. Amin, S. Khan and S. S. Hussain Bukhari, “A Comprehensive Review on Axial Flux Machines and Its Applications,”. *In: 2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET),* 30.01.2019 - 31.01.2019, Sukkur, Pakistan, 2019, pp. 1-7. [Online]. Available: https:// ieeexplore.ieee.org/abstract/document/8673422 (accessed: 2024/04/11).

[8] Z. Hao, Y. Ma, P. Wang et al., “A Review of Axial-Flux Permanent-Magnet Motors: Topological Structures, Design, Optimization and Control Techniques,” *Machines,* vol. 10, no. 12, pp. 1178, 2022.

[9] L. Shao, R. Navaratne, M. Popescu et al., “Design and Construction of Axial-Flux Permanent Magnet Motors for Electric Propulsion Applications—A Review,” *IEEE Access,* vol. 9, no., pp. 158998-159017, 2021.

[10] F. Giulii Capponi, G. de Donato and F. Caricchi, “Recent Advances in Axial-Flux Permanent-Magnet Machine Technology,” *IEEE Trans. on Ind. Applicat.,* vol. 48, no. 6, pp. 2190-2205, 2012.

[11] J. F. Gieras and I. A. Gieras, “Performance analysis of a coreless permanent magnet brushless motor,”. *In: Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No.02CH37344),* 13-18 Oct. 2002, Pittsburgh, PA, USA, 2002, pp. 2477-2482. [Online]. Available: https:// ieeexplore.ieee.org/abstract/document/1042794 (accessed: 2024/04/12).

[12] G. Long, B. Paden, M. Ricci et al., “Lightweight and efficient electrical machine and method of manufacture,” US10574110B2, filed: 2016/05/02. [Online]. Available: https://patents.google.com/ patent/US10574110B2/en?oq=US10574110B2 (accessed: 2024/04/12).

[13] R. Halstead, “Nested Serpentine Winding for an Axial Gap Electric Dynamo Machine,” US20090200889A1, filed: 2009/02/09. [Online]. Available: https://patentimages.storage.googleapis.com/ 62/ae/5d/5829581d646a04/US20090200889A1.pdf (accessed: 2024/04/12).

[14] P. Butterfield, “Optimized modular electrical machine using permanent magnets,” US7375449B2, filed: 2006/08/17. [Online]. Available: https://patentimages.storage.googleapis.com/fd/78/dc/ 0a23bbf62ef76e/US7375449.pdf (accessed: 2023/06/13).

[15] M. Greaves, B. Guymer and B. Walsh, “Winding arrangement for an electrical machine,” US8823238B2, filed: 2008/04/01. [Online]. Available: https://patentimages.storage.googleapis.com/b9/c9/0b/ 17afb0a31cc110/US8823238.pdf (accessed: 2024/04/12).

[16] A. Kampker, P. Treichel, K. Kreiskother et al., “Alternative Fabrication Strategies for the Production of Axial Flux Permanent Magnet Synchronous Motors for Enhanced Performance Characteristics,”. *In: 2018 8th International Electric Drives Production Conference (EDPC),* 04.12.2018 - 05.12.2018, Schweinfurt, Germany, 2018, pp. 1-7. [Online]. Available: https:// ieeexplore.ieee.org/document/8658341 (accessed: 2024/04/11).

[17] H. Vansompel, “Design of an energy efficient axial flux permanent magnet machine,” Dissertation, Ghent University, Ghent, filed: 2013.

[18] C. C. Chan, “Axial-field electrical machines with yokeless armature core,” Dissertation, Hongkong, filed: 01/1982.

[19] W. Geng, Y. Wang, J. Wang et al., “Comparative Study of Yokeless Stator Axial-Flux PM Machines Having Fractional Slot Concentrated and Integral Slot Distributed Windings for Electric Vehicle Traction Applications,” *IEEE Trans. Ind. Electron.,* vol. 70, no. 1, pp. 155-166, 2023.

[20] T. Woolmer and M. McCulloch, “Analysis of the Yokeless And Segmented Armature Machine,”. *In: 2007 IEEE International Electric Machines & Drives Conference,* 03.05.2007 - 05.05.2007, Antalya, Turkey, 2007, pp. 704-708. [Online]. Available: https:// ieeexplore.ieee.org/document/4270726 (accessed: 2024/04/13).

[21] G. Cakal and B. Sarlioglu, "Review of Advances in Cooling Schemes for Yokeless and Segmented Armature (YASA) Axial Flux Motors,". *In: 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe),* 04.09.2023 - 08.09.2023, Aalborg, Denmark, 2023, pp. 1-8. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10264667 (accessed: 2024/04/13).

[22] A. M. Ajamloo, M. N. Ibrahim and P. Sergeant, "Design, Modelling and Optimization of a High Power Density Axial Flux SRM with Reduced Torque Ripple for Electric Vehicles," *Machines,* vol. 11, no. 7, pp. 759, 2023.

[23] W. Zhao, T. A. Lipo and B.-I. Kwon, "A Novel Dual-Rotor, Axial Field, Fault-Tolerant Flux-Switching Permanent Magnet Machine With High-Torque Performance," *IEEE Trans. Magn.,* vol. 51, no. 11, pp. 1-4, 2015.

[24] M. Polat, A. Yildiz and R. Akinci, "Performance Analysis and Reduction of Torque Ripple of Axial Flux Permanent Magnet Synchronous Motor Manufactured for Electric Vehicles," *IEEE Trans. Magn.,* vol. 57, no. 7, pp. 1-9, 2021.

[25] M.-K. Hong, H.-J. Pyo, S.-W. Song et al., "A Study on the Improvement of Power Density of Axial Flux Motors for Collaborative Robot Joints through Same-Direction Skew," *Machines,* vol. 11, no. 6, pp. 591, 2023.

[26] A. B. Letelier, D. A. Gonzalez, J. A. Tapia et al., "Cogging Torque Reduction in an Axial Flux PM Machine via Stator Slot Displacement and Skewing," *IEEE Trans. on Ind. Applicat.,* vol. 43, no. 3, pp. 685-693, 2007.

[27] J. Zhao, X. Liu, S. Wang et al., "Review of Design and Control Optimization of Axial Flux PMSM in Renewable-energy Applications," *Chin. J. Mech. Eng.,* 2023, vol. 36, no. 1.

[28] C. Jenkins, S. Jones-Jackson, I. Zaher et al., "Innovations in Axial Flux Permanent Magnet Motor Thermal Management for High Power Density Applications," *IEEE Trans. Transp. Electrific.,* vol. 9, no. 3, pp. 4380-4405, 2023.

[29] F. N. Nishanth, J. van Verdeghem and E. L. Severson, "Recent Advances in Analysis and Design of Axial Flux Permanent Magnet Electric Machines,". *In: 2021 IEEE Energy Conversion Congress and Exposition (ECCE),* 10.10.2021 - 14.10.2021, Vancouver, BC, Canada, 2021, pp. 3745-3752. [Online]. Available: https://ieeexplore.ieee.org/document/9595085 (accessed: 2024/05/21).

[30] B. Zhang, "Soft Magnetic Composites in Novel Designs of Electrical Traction Machines," Dissertation, Karlsruher Institut für Technologie (KIT), Karlsruhe, filed: 2017.

[31] V. Rallabandi, N. Taran and D. M. Ionel, "Multilayer concentrated windings for axial flux PM machines,". *In: 2016 IEEE Conference on Electromagnetic Field Computation (CEFC),* 13.11.2016 - 16.11.2016, Miami, Florida, 2016, pp. 1. [Online]. Available: https://ieeexplore.ieee.org/document/7816369 (accessed: 2024/04/11).

[32] N. Taran, V. Rallabandi, G. Heins et al., "Coreless and Conventional Axial Flux Permanent Magnet Motors for Solar Cars," *IEEE Trans. on Ind. Applicat.,* vol. 54, no. 6, pp. 5907-5917, 2018.

[33] A. P. Ferreira, A. M. Silva and A. F. Costa, "Prototype of an axial flux permanent magnet generator for wind energy systems applications,". *In: 2007 European Conference on Power Electronics and Applications,* 02.09.2007 - 05.09.2007, Aalborg, Denmark, 2007, pp. 1-9. [Online]. Available: https://ieeexplore.ieee.org/document/4417748 (accessed: 2024/04/11).

[34] W.-S. Yao, M.-T. Cheng and J.-C. Yu, "Novel design of a coreless axial - flux permanent - magnet generator with three - layer winding coil for small wind turbines," *IET Renewable Power Generation,* vol. 14, no. 15, pp. 2924-2932, 2020.

[35] N. Taran, V. Rallabandi and D. M. Ionel, "WAVED: A Coreless Axial Flux PM Motor for Drive Systems with Constant Power Operation,". *In: 2019 IEEE Transportation Electrification Conference and Expo (ITEC),* 19.06.2019 - 21.06.2019, Detroit, MI, USA, 2019, pp. 1-6. [Online]. Available: https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1020&context=peik_facpub.

[36] V. Rallabandi, P. Han, M. G. Kesgin et al., "Axial-field Vernier-type Flux Modulation Machines for Low-speed Direct-drive Applications,". *In: 2019 IEEE Energy Conversion Congress and Exposition (ECCE),* 29.09.2019 - 03.10.2019, Baltimore, MD, USA, 2019, pp. 3123-3128. [Online]. Available: https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1013&context=peik_facpub (accessed: 2024/04/11).

[37] E. J. Echenique, O. Keysan and M. A. Mueller, "Rotor loss prediction in air-cored permanent magnet machines,". *In: 2013 International Electric Machines & Drives Conference,* 12.05.2013 - 15.05.2013, Chicago, IL, USA, 2013, pp. 303-310. [Online]. Available: https://ieeexplore.ieee.org/document/6556268 (accessed: 2024/04/11).

[38] M. J. Kamper, R.-J. Wang and F. G. Rossouw, "Analysis and Performance of Axial Flux Permanent-Magnet Machine With Air-Cored Nonoverlapping Concentrated Stator Windings," *IEEE Trans. on Ind. Applicat.,* vol. 44, no. 5, pp. 1495-1504, 2008.

[39] W. Geng and Z. Zhang, "Analysis and Implementation of New Ironless Stator Axial-Flux Permanent Magnet Machine With Concentrated Nonoverlapping Windings," *IEEE Trans. Energy Convers.,* vol. 33, no. 3, pp. 1274-1284, 2018.

[40] J. Ola Buoy, "Development of high efficiency Axial Flux Motor for Shell Eco-marathon," Master thesis, Norwegian University of Science and Technology, Trondheim, filed: 2013.

[41] M. G. Kesgin, P. Han, N. Taran et al., "Design Optimization of Coreless Axial-flux PM Machines with Litz Wire and PCB Stator Windings,". *In: 2020 IEEE Energy Conversion Congress and Exposition (ECCE),* 11.10.2020 - 15.10.2020, Detroit, MI, USA, 2020, pp. 22-26. [Online]. Available: https://ieeexplore.ieee.org/document/9236194 (accessed: 2024/04/12).

[42] P. Lindh, I. Petrov, A. Jaatinen-Varri et al., "Direct Liquid Cooling Method Verified With an Axial-Flux Permanent-Magnet Traction Machine Prototype," *IEEE Trans. Ind. Electron.,* vol. 64, no. 8, pp. 6086-6095, 2017.

[43] B. J. Chalmers and E. Spooner, "An axial-flux permanent-magnet generator for a gearless wind energy system," *IEEE Trans. Energy Convers.,* vol. 14, no. 2, pp. 251-257, 1999.

[44] F. Marcolini, G. de Donato, F. G. Capponi et al., "Design of a High Speed Printed Circuit Board Coreless Axial Flux Permanent Magnet Machine,". *In: 2021 IEEE Energy Conversion Congress and Exposition (ECCE),* 10.10.2021 - 14.10.2021, Vancouver, BC, Canada, 2021, pp. 4353-4360. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9595835 (accessed: 2024/04/12).

[45] P. M. Lindh, I. Petrov, R. S. Semken et al., "Direct Liquid Cooling in Low-Power Electrical Machines: Proof-of-Concept," *IEEE Trans. Energy Convers.,* vol. 31, no. 4, pp. 1257-1266, 2016.

[46] M. Valtonen, "Performance characteristics of an axial-flux solid-rotor-core induction motor," Lappeenranta, Lappeenrannan Teknillinen Yliopisto, 2007.

[47] W. Sixel, M. Liu and B. Sarlioglu, "Rotor Thermal Design for Electric Machines: Challenges and Opportunities,". *In: Rotor Thermal Design for Electric Machines: Challenges and Opportunities,* 13.06.2018 - 15.06.2018, Long Beach, CA, USA, 2018, pp. 821-826. [Online]. Available: https://ieeexplore.ieee.org/document/8450185 (accessed: 2024/05/21).

[48] A. Parviainen, "Design of axial-flux permanent-magnet low-speed machines and performance comparison between radial-flux and axial-flux machines," Lappeenranta, Lappeenrannan Teknillinen Yliopisto, 2005.

[49] L. Jia, M. Lin, W. Le et al., "Dual-Skew Magnet for Cogging Torque Minimization of Axial Flux PMSM With Segmented Stator," *IEEE Trans. Magn.,* vol. 56, no. 2, pp. 1-6, 2020.

[50] R. Madhavan and B. G. Fernandes, "Performance Improvement in the Axial Flux-Segmented Rotor-Switched Reluctance Motor," *IEEE Trans. Energy Convers.,* vol. 29, no. 3, pp. 641-651, 2014.

[51] H. Torkaman, A. Ghaheri and A. Keyhani, "Design of Rotor Excited Axial Flux-Switching Permanent Magnet Machine," *IEEE Trans. Energy Convers.,* vol. 33, no. 3, pp. 1175-1183, 2018.

[52] M. Aydin, Z. Q. Zhu, T. A. Lipo et al., "Minimization of Cogging Torque in Axial-Flux Permanent-Magnet Machines: Design Concepts," *IEEE Trans. Magn.,* vol. 43, no. 9, pp. 3614-3622, 2007.

[53] L. Xiao, J. Li, R. Qu et al., "Cogging Torque Analysis and Minimization of Axial Flux PM Machines With Combined

Rectangle-Shaped Magnet," *IEEE Trans. on Ind. Applicat.,* vol. 53, no. 2, pp. 1018-1027, 2017.

[54] Hanne Jussila, Pia Salminen, Asko Parviainen, Janne Nerg and Juha Pyrhönen, "Concentrated Winding Axial Flux Permanent Magnet Motor with Plastic Bonded Magnets and Sintered Segmented Magnets," Piscataway, NJ, IEEE, 2008.

[55] H. Zhang, H. Zhou and R. Pei, "Investigation of Axial-Flux Permanent Magnet Machine with Strap-Wire and Segmented Magnet for Logistics Electric Vehicle,". *In: 2021 IEEE International Magnetic Conference (INTERMAG),* 26.04.2021 - 30.04.2021, LYON, France, 2021, pp. 1-5. [Online]. Available: https:// ieeexplore.ieee.org/document/9579854 (accessed: 2024/05/21).

[56] G. de Donato, F. Giulii Capponi and F. Caricchi, "Fractional-Slot Concentrated-Winding Axial-Flux Permanent-Magnet Machine With Core-Wound Coils," *IEEE Trans. on Ind. Applicat.,* vol. 48, no. 2, pp. 630-641, 2012.

[57] S. Jamali Arand and M. Ardebili, "Cogging torque reduction in axial-flux permanent magnet wind generators with yokeless and segmented armature by radially segmented and peripherally shifted magnet pieces," *Renewable Energy,* vol. 99, no., pp. 95-106, 2016.

[58] M. Aydin and M. Gulec, "Reduction of Cogging Torque in Double-Rotor Axial-Flux Permanent-Magnet Disk Motors: A Review of Cost-Effective Magnet-Skewing Techniques With Experimental Verification," *IEEE Trans. Ind. Electron.,* vol. 61, no. 9, pp. 5025-5034, 2014.

[59] H. Xie, X. Wei, Y. Liu et al., "Research of Asymmetrical Bidirectional Magnet Skewing Technique in Modular Multi-Stage Axial Flux Permanent Magnet Synchronous Motor," *IEEE Trans. Magn.,* vol. 51, no. 3, pp. 1-5, 2015.

[60] A. Sani, B. M. R. Sinambela, R. Afdila et al., "The Influence of Rotor Shape and Air Gap Position on the Characteristics of the Three-phase Axial Flux Permanent Magnet Generator,". *In: 2021 5th International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM),* 15.09.2021 - 16.09.2021, Medan, Indonesia, 2021, pp. 164-167. [Online]. Available: https:// ieeexplore.ieee.org/document/9590127 (accessed: 2024/05/21).

[61] T. S. El-Hasan and P. C. K. Luk, "Magnet topology optimization to reduce harmonics in high-speed axial flux generators," *IEEE Trans. Magn.,* vol. 39, no. 5, pp. 3340-3342, 2003.

[62] L. Del Ferraro, R. Terrigi and F. G. Capponi, "Coil and Magnet Shape Optimization of an Ironless AFPM Machine by Means of 3D FEA,". *In: 2007 IEEE International Electric Machines & Drives Conference*, pp. 927-931. [Online]. Available: https:// ieeexplore.ieee.org/document/4270772 (accessed: 2024/05/21).

[63] O. Taqavi and S. M. Mirimani, "Design aspects, winding arrangements and applications of printed circuit board motors: a comprehensive review," *IET Electric Power Applications,* vol. 14, no. 9, pp. 1505-1518, 2020.

[64] M. Fuchslocher, T. Albrecht, M. Bargende et al., "Development of Alternative Magnetic Fixation Technologies for Axial Flux Machines,". *In: 2022 12th International Electric Drives Production Conference (EDPC),* 29.11.2022 - 30.11.2022, Regensburg, Germany, 2022, pp. 1-6. [Online]. Available: https:// ieeexplore.ieee.org/document/10019740 (accessed: 2024/05/21).

[65] A. Habib, H. S. Che, N. Abd Rahim et al., "A fully coreless Multi-Stator Multi-Rotor (MSMR) AFPM generator with combination of conventional and Halbach magnet arrays," *Alexandria Engineering Journal,* vol. 59, no. 2, pp. 589-600, 2020.

[66] R. Huang, C. Liu, Z. Song et al., "Design and Analysis of a Novel Axial-Radial Flux Permanent Magnet Machine with Halbach-Array Permanent Magnets," *Energies,* vol. 14, no. 12, pp. 3639, 2021.

[67] J. F. Gieras, "Permanent magnet motor technology," Boca Raton, CRC Press, 2010.

[68] M. Galea, L. Papini, H. Zhang et al., "Demagnetization Analysis for Halbach Array Configurations in Electrical Machines," *IEEE Trans. Magn.,* vol. 51, no. 9, pp. 1-9, 2015.

[69] T. Woolmer and M. McCulloch, "Axial flux permanent magnet machines: A new topology for high performance applications," *IET Hybrid Vehicle Conference,* 2006, vol. 12-13 December 2006, no.

[70] N. Taran, V. Rallabandi, G. Heins et al., "Systematically Exploring the Effects of Pole Count on the Performance and Cost Limits of UltraHigh Efficiency Fractional hp Axial Flux PM Machines," *IEEE Trans. on Ind. Applicat.,* vol. 56, no. 1, pp. 117-127, 2020.

[71] Alan R Elcrat, "On the swirling flow between rotating coaxial disks," *Journal of Differential Equations,* vol., no. Volume 18, Issue 2, pp. 423-430, July 1975.

[72] C. L. Narayana and N. Rudraiah, "On the steady flow between a rotating and a stationary disk with a uniform suction at the stationary disk," *Zeitschrift für angewandte Mathematik und Physik ZAMP,* vol. 23, no. 1, pp. 96-104, 1972.

[73] A. Nollau and D. Gerling, "A flux barrier cooling for traction motors in hybrid drives,". *In: 2015 IEEE International Electric Machines & Drives Conference (IEMDC),* 10.05.2015 - 13.05.2015, Coeur d'Alene, ID, 2015, pp. 1103-1108. [Online]. Available: https:// ieeexplore.ieee.org/abstract/document/7409199 (accessed: 2024/05/21).

[74] S. A. Semidey and J. R. Mayor, "Experimentation of an Electric Machine Technology Demonstrator Incorporating Direct Winding Heat Exchangers," *IEEE Trans. Ind. Electron.,* vol. 61, no. 10, pp. 5771-5778, 2014.

[75] H. Ding, Y. Li, S. G. Min et al., "Electromagnetic and thermodynamic design of a novel integrated flux-switching motor-compressor with airfoil-shaped rotor,". *In: 2017 IEEE Energy Conversion Congress and Exposition (ECCE),* 01.10.2017 - 05.10.2017, Cincinnati, OH, 2017, pp. 5409-5416. [Online]. Available: https://ieeexplore.ieee.org/document/8096905 (accessed: 2024/05/21).

[76] N. Putra and B. Ariantara, "Electric motor thermal management system using L-shaped flat heat pipes," *Applied Thermal Engineering,* vol. 126, no., pp. 1156-1163, 2017.

[77] M. Bradford, "The application of heat pipes to cooling rotating electrical machines - Electrical Machines and Drives, 1989., Fourth International Conference on," *1989 Fourth International Conference on Electrical Machines and Drives Conf. Publ. No. ??),* vol., no., pp. 145-149, 1989.

[78] J. van Damme, H. Vansompel and G. Crevecoeur, "Performance comparison of Axial Flux PM machine with Anodised Aluminium Foil and Round Copper Wire,". *In: 2022 International Conference on Electrical Machines (ICEM),* 05.09.2022 - 08.09.2022, Valencia, Spain, 2022, pp. 1397-1403. [Online]. Available: https:// ieeexplore.ieee.org/abstract/document/9910722?casa_token= KRXPQqoL8XQAAAAA:JMI5va9LAD1F2YtiN4IovlnFsFfzh3qq DEfMdXn8-zEuwhOTmuT5pnkp3cBLa-cfwY8rBkTz-A (accessed: 2024/04/13).

[79] J. van Damme, H. Vansompel and G. Crevecoeur, "Anodized Aluminum Foil Winding Axial Flux Machine for Direct-Drive Robotic Applications," *IEEE Trans. Ind. Electron.,* vol. 70, no. 10, pp. 10409-10419, 2023.

[80] G. Cakal and O. Keysan, "Flat winding made of aluminum or copper sheet for axial flux machines," *IET Electric Power Appl,* vol. 15, no. 4, pp. 429-440, 2021.

[81] V. Rallabandi, N. Taran, D. M. Ionel et al., "Coreless Multidisc Axial Flux PM Machine with Carbon Nanotube Windings," *IEEE Trans. Magn.,* vol. 53, no. 6, pp. 1-4, 2017.

[82] Y. Guo, J. G. Zhu, P. A. Watterson et al., "Comparative study of 3-D flux electrical machines with soft magnetic composite cores," *IEEE Trans. on Ind. Applicat.,* vol. 39, no. 6, pp. 1696-1703, 2003.

[83] N. Fernando and F. Hanin, "Magnetic materials for electrical machine design and future research directions: A review,". *In: 2017 IEEE International Electric Machines and Drives Conference (IEMDC),* 21.05.2017 - 24.05.2017, Miami, Florida, 2017, pp. 1-6. [Online]. Available: https://ieeexplore.ieee.org/document/8002412 (accessed: 2024/05/21).

[84] F. Profumo, F. Eastham, A. Tenconi et al., ""Plastic" electric motors: a viable solution for axial flux machines - Industrial Electronics, 2002. ISIE 2002. Proceedings of the 2002 IEEE International Symposium on,", 2002, vol. 1, no.