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AXIAL FLUX PERMANENT MAGNET DISC MACHINES: A REVIEW

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Abstract

Axial flux permanent magnet (PM) machines are being developed for many applications due to their attractive features. An extensive literature exists concerning the design of a variety of types of axial flux PM machines. An overview of axial flux, slotless and slotted various PM machines are presented in this paper. Machine structures, advantages and features of the Axial Flux PM machine (AFM) are clarified. Several interesting novel axial flux machine structures are also covered from a variety of perspectives.

1. INTRODUCTION

PM machines are increasingly becoming dominant machines with the cost competitiveness of high energy permanent magnets. These machines offer many unique features. They are usually more efficient because of the fact that field excitation losses are eliminated resulting in significant rotor loss reduction. Thus, the motor efficiency is greatly improved and higher power density is achieved. Moreover, PM motors have small magnetic thickness which results in small magnetic dimensions. As for the axial flux PM machines, they have a number of distinct advantages over radial flux machines (RFM). They can be designed to have a higher power-to-weight ratio resulting in less core material. Moreover, they have planar and easily adjustable airgaps. The noise and vibration levels are less than the conventional machines. Also, the direction of the main air gap flux can be varied and many discrete topologies can be derived. These benefits present the AFMs with certain advantages over conventional RFMs in various applications.

The objective of this paper is to examine the AFMs covered in the literature and investigate several new and promising AFM structures. Axial flux surface magnet PM machines including slotless and slotted topologies with different number of rotor and stators are extensively reviewed. A general look at the AFMs other than surface magnet PM structures is also presented. Sizing and design approach is briefly summarized as well. Some flux weakening PM topologies from a machine design point of view are also reviewed.

2. RADIAL FLUX SURFACE MOUNTED PM MACHINES

Conventional radial flux PM machines have now been used extensively for decades. Many papers exist in the literature concerning the RFM machine, the most common type of PM machine used in industry. These machines are well known to have higher torque capability than the more common induction machine (IM). The efficiency is also higher than an IM due to the lack of rotor windings have higher power density and higher torque per ampere ratio. However, an important manufacturing disadvantage of the RFM is that magnet maintenance must be carefully implemented so that the rotor does not fly apart.

The non-slotted version of the conventional radial flux PM machine has also been analyzed in the literature. The two major differences between the slotted and non-slotted versions of the radial flux PM machine are the existence of slots and the type of polyphase winding. The stator structure is non-slotted and consists of a stack of laminated steel. Back-to-back connected polyphase windings are wrapped around the stator in a toroidal fashion and termed airgap windings since the windings are not placed into slots. The places in between the windings are filled with epoxy resin to increase robustness and provide better conductor heat transfer. The rotor structure is formed by surface mounted NdFeB magnets, rotor core and shaft.

It should be noted that only the windings facing the rotor PMs are used for torque production in RFMs. The portions of the windings on the outside surface of the stator and the portions on both sides are considered to be end windings in this topology. Therefore, this topology has long end windings when the aspect ratio D/L (diameter over axial length) is small. In that case, small aspect ratio could result in high copper loss. Besides, the flux density is reduced due to the large airgap. However, one important advantage of this machine is that the structure transfers the heat from the stator frame very easily. Therefore, machine electrical loading can be relatively high.

3. SIZING APPROACH FOR AXIAL FLUX PM MACHINES

A general purpose sizing equation for axial flux machines has been provided by the authors in the previous literature [1-3]. The general purpose sizing equations have the following form for axial flux machines:

$$P_R = \begin{cases} \dfrac{1}{1+K_\phi}\dfrac{m}{m_1}\dfrac{\pi}{2}K_e K_i K_p K_L \eta B_g A \dfrac{f}{p}(1-\lambda^2)\dfrac{1+\lambda}{2}D_o^2 L_e \\ \dfrac{1}{1+K_\phi}\dfrac{m}{m_1}\dfrac{\pi}{2}K_e K_i K_p \eta B_g A \dfrac{f}{p}(1-\lambda^2)\dfrac{1+\lambda}{2}D_o^3 \end{cases} \quad (1)$$

where P_R is the rated output power of the machine, m and m_1 are the number of machine phases and each stator, K_i, K_p, are the current and electrical power waveform factors respectively, η is the machine efficiency, B_g is the airgap flux density, A is the total electrical loading, D_o,D_g ,D_i are machine diameters at the outer surface, air-gap surface and inner surface, $K_\phi=A_r/A_s$ is the electrical loading ratio and $K_L=D_o/L_e$ is the aspect ratio coefficient for AFM and λ is the diameter ratio. A procedure must be developed to determine K_L pertinent to a specific machine structure. This procedure must incorporate the effects of temperature rise, losses, and efficiency requirements on the design.

In practice, the lengths L_s and L_r depend upon the stator equivalent electrical loading, current density, slot fill factor, and flux densities in different parts of the machine. The length L_{PM} depends on the air gap flux density and air gap length. Some optimization and design examples using general purpose sizing equations are presented in the literature [36-37], [49].

In AFMs, the diameter ratio λ is the foremost design parameter which has a significant effect on the machine characteristics. To optimize machine performance, the value of λ must be carefully chosen. In practice, the optimal value of λ is different depending upon the optimization goal. Furthermore, for given electrical loading and flux density values, the optimal λ differs for different rated power, pole pairs, converter frequency etc. Further, if different materials or different structures are involved, the optimal λ will have a significantly different value.

4. AXIAL FLUX SURFACE MOUNTED PM MACHINES

The first work focused on PM disc machines was performed in late 70s and early 80s [4-14]. Disc type axial flux PM machines have found growing interests in the last decade especially in the 90s and have been increasingly used in both naval and domestic applications as an alternative to conventional radial flux machines [14-82].

As briefly mentioned earlier, AFMs have some distinct advantages over RFMs. First, they can be designed to have a higher power-to-weight ratio resulting in less core material and higher efficiency. Secondly, they are smaller in size than their radial flux counterparts and have disc shaped rotor and stator structures. This is an important feature of axial flux machines because suitable shape and size to match the space limitation is crucial for some applications such as electric vehicle. Thirdly, they have planar and adjustable airgaps, which radial flux machines do not. Moreover, the direction of the main airgap flux can be varied and many discrete topologies can be derived. For instance, while the main flux traveling axially through the air gap and stator core creates an external-rotor-internal-stator topology, the main air gap flux traveling axially through the airgap and both axially and radially in the stator core creates a second external-rotor-internal-stator topology. These features provide the AFMs with certain advantages over conventional RFMs in some applications. [72-79]

Both radial and axial flux machines can be constructed in many ways as seen in Figure 1. They can be constructed in single-stator-single-rotor form or multiple-stator-multiple-rotor form.

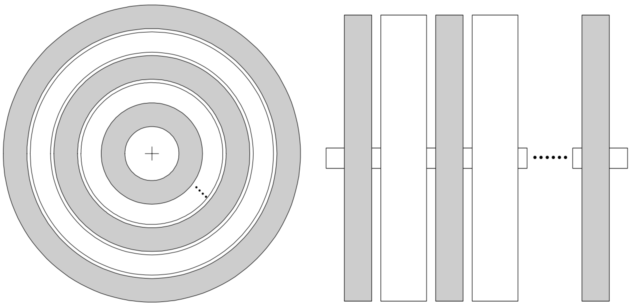


Figure 1. Radial and axial flux machines in multi stage form

Axial flux machines are classified based on the rotor structure. It is termed an axial flux induction machine if the rotor structure is a squirrel cage; an axial flux surface mounted permanent magnet machine if the rotor is formed by surface mounted permanent magnets; and an axial flux interior PM machine if the rotor has an interior magnet structure. In this paper, the focus will be on axial flux surface mounted PM machines with different rotor configurations but there will be a short review of some other type of AFMs and applications as well.

The basic and simplest axial flux structure is the single-rotor-single-stator structure as it is seen in Figure 2. The stator consists of a ring type winding embedded in epoxy-like material and an iron disc which is manufactured from a simple tape wound iron core. The rotor is formed from a solid steel disc on which the magnets are embedded.

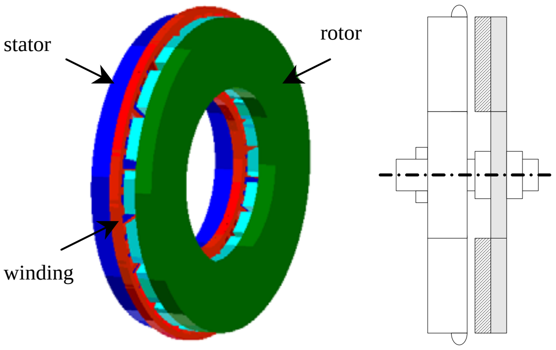


Figure 2. Single-rotor-single-stator axial flux PM machine structure

AFMs forms thin disc structures with the biggest effective torque producing portions. As a consequence, torque-per-unit-volume and torque-per-unit-weight are both significantly better than RFMs.

The main hurdle to overcome in axial flux designs including the single-stage structure is the large axial force exerted on the stator by the rotor magnets. This magnet force could twist the structure very easily. The axial force is less severe if the stator teeth are removed since this force is exerted on the iron not the copper windings.

Non-slotted TORUS machine (TORUS-NS) is a typical double-rotor-single-stator, axial flux, PM, slotless, disc-type structure [15-29]. An idealized version of the machine structure is shown in Figure 3. The machine has a single stator sandwiched between two PM rotor discs. The stator of the machine is realized by tape wound core with polyphase AC airgap windings which are wrapped around the stator core with a back-to-back connection.

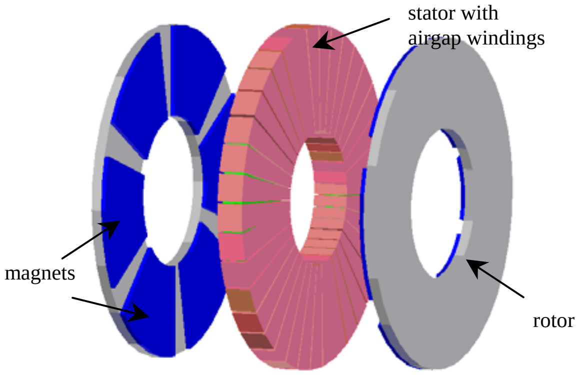


Figure 3. Axial flux TORUS type non-slotted surface mounted PM motor configuration (TORUS-NS)

The rotor structure is formed by arch-shaped surface mounted NdFeB magnets, rotor core and shaft. The two disc shaped rotors carry the axially magnetized NdFeB magnets mounted axially on the inner surfaces of the two rotor discs. Detailed views of the stator and rotor structures are also given in Figure 4 and Figure 5. The active conductor portions are the radial portions of the toroidal windings facing the two rotor structures.

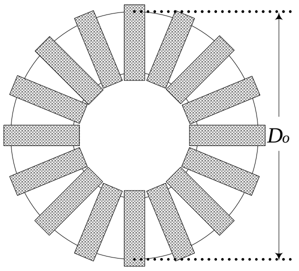


Figure 4. Stator structure of slotless TORUS machine (TORUS-NS) with airgap windings

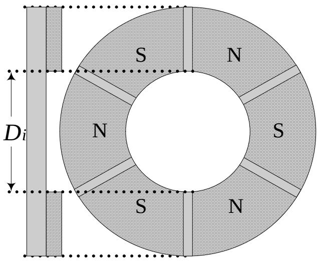


Figure 5. Rotor structure of slotless TORUS machine (TORUS-NS)

The basic flux paths of the TORUS-NS machine at the average diameter in 2D and in 3D are also shown in Figure 6 and Figure 7. As can be seen from the figures, the N magnets drive flux through the two airgaps into the stator core. The flux then travels circumferentially along the stator core, returns across the airgaps and then enters the rotor core through the opposite pole (S pole) of the permanent magnets. Therefore, it can be expected that the axial length of the stator core would be quite long because of the summation of the flux entering the stator from both rotors. Also, it should be mentioned that this machine could be thought to be the combination of two independent halves due to the direction of the flux.

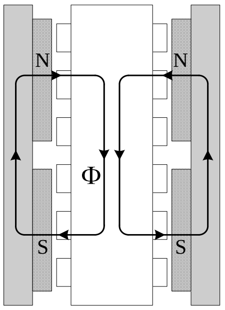


Figure 6. 2D Flux directions of the TORUS–NS machine

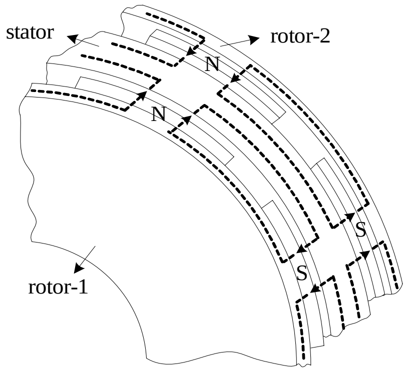


Figure 7. 3D Flux directions of the TORUS–NS machine

The slotless TORUS topology has a high power-to-weight or torque-to-weight ratio because of its short axial length. The portions between the airgap windings are assumed to be filled with epoxy resin as in all non-slotted structures in order to increase the robustness and provide better conductor heat dissipation. Moreover, in the TORUS topology, the windings in the airgap are used for the torque production. The end windings are quite short which results in making the copper loss of the TORUS-NS machine smaller, efficiency higher and the conductor heat transfer easier. The non-slotted airgap windings provide lower values of leakage and mutual inductances. Effects resulting from the slots such as flux ripple, cogging torque, high frequency rotor loss, and saturation on stator tooth are eliminated and this feature leads to a low noise machine. Moreover, the demagnetization effect of the magnets is quite small due to the large effective airgap since achieving high airgap flux density using NdFeB magnets is not an issue as seen in Figure 8. In additioin, another important feature of this machine is that the self-inductance is smaller.

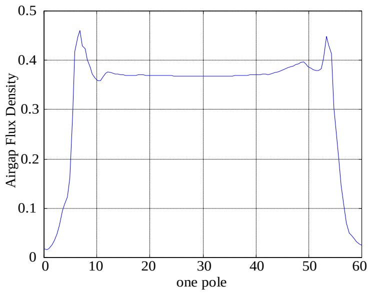


Figure 8. No load airgap flux density variation over one for the slotless TORUS–NS machine by finite element analysis

A 3D picture of the slotted TORUS (NN type) permanent magnet motor structure is given in Figure 9 [30-39]. The machine has a single stator and two surface mounted PM rotor discs as in a slotless TORUS machine. The stator has a slotted structure with strip wound stator steel. Evenly distributed back-to-back connected windings are placed into back-to-back slots. The rotor structure is exactly the same as that of the TORUS-NS machine rotor. The disc shaped rotors carry the axially magnetized magnets which are mounted axially on the inner surfaces of the rotor discs. The windings in radial direction are used for torque production. Therefore, the end windings are quite short, which leads to lower copper loss and higher efficiency for this topology. A back-to-back winding configuration, which is used both in slotless and slotted structures is also illustrated in Figure 10.

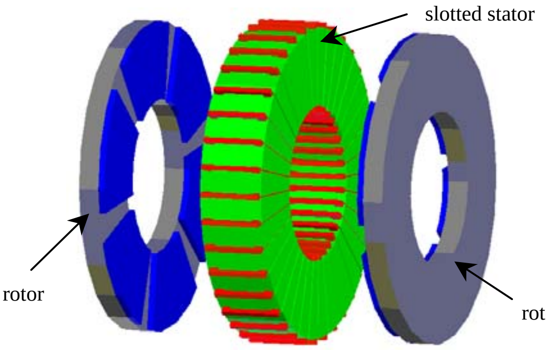


Figure 9. Axial flux TORUS type slotted surface mounted PM motor configuration (TORUS-S)

The flux paths of the NN type TORUS-S machine are shown in Figure 11 and Figure 7. The principle of the machine is the same as that of slotless TORUS topology. As can be seen from the two figures, the magnet driven flux enters the airgap and then to the stator core. The flux travels along the stator yoke, as in the case of the slotless TORUS topology, and closes its path through an opposite polarity of permanent magnet and rotor core.

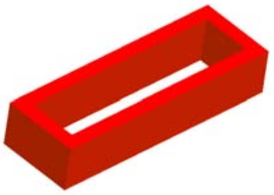


Figure 10. Back-to-back (or gramme type) winding configuration used in slotless machines and NN type axial flux slotted PM machine

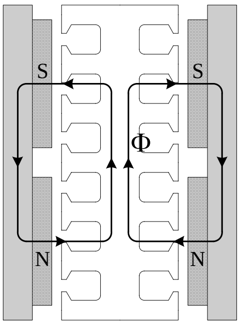


Figure 11. 2D Flux directions of the NN type TORUS–S machine

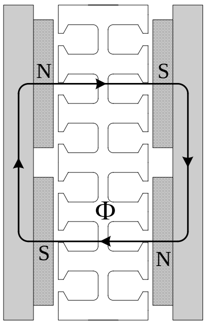


Figure 12. 2D Flux directions of the NS type TORUS–S machine

By looking at the NN type TORUS machine, one can easily derive the NS type TORUS topology by simply modifying the flux directions. The second type is the one in which flux travels axially along the stator of the machine. In other words, the magnet flux passes through both airgaps and the stator without traveling circumferentially in the stator yoke. NS type of the TORUS-S machine, which is displayed in Figure 13, has the same physical structure as the NN type TORUS-S machine except for the fact that the stator yoke is eliminated or reduced significantly compared to the first type of the TORUS-S machine. It has two disc shaped rotors carrying axially magnetized magnets mounted on the inner surfaces of the rotor discs. The stator structure is also the same as that of the first type. The only difference is the magnetization direction of the permanent magnets and the flux path. The 3D and 2D illustration of the flux directions of the NN type TORUS-S machine are shown in Figure 12 and Figure 14 respectively.

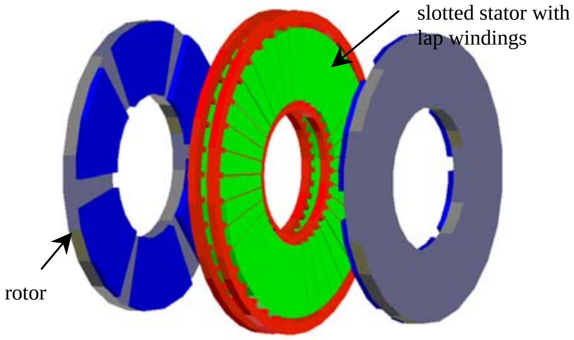


Figure 13. Axial flux TORUS type NS type slotted surface mounted PM motor configuration

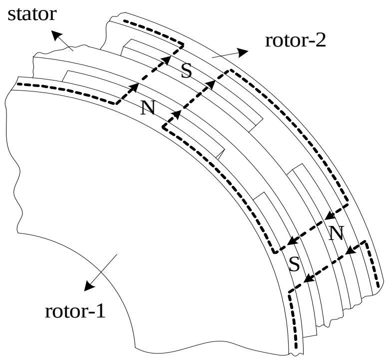


Figure 14. 3D Flux directions of the NS type TORUS–S machine

Since the flux passes through the stator and does not travel circumferentially, the axial thickness of the stator can be less than that of the NN type TORUS-S machine. This important feature results in less weight, less iron loss, and consequently higher efficiency than the NN type TORUS machine. In theory, there is no need for the stator yoke by any means. However, there must be a small yoke because of mechanical constraints. One other difference between the two TORUS topologies is the winding type. Either back-to-back connected windings or lap windings can be used in the NN type. However, only 3 phase lap winding coils can be used in the NS type in order to produce torque. Airgap flux directions and no load flux density distribution of a typical NN type slotted TORUS machine over one pole section is illustrated in Figure 15.

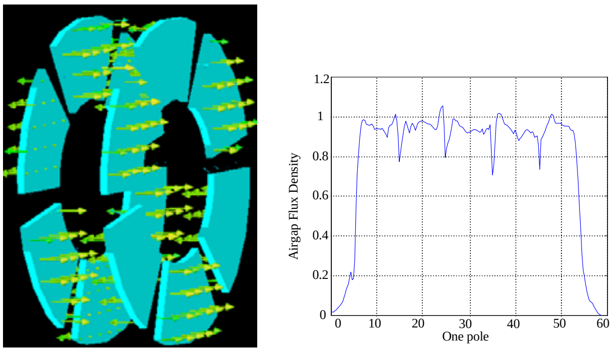


Figure 15. No load airgap flux density variation over one pole and direction of the slotted TORUS machine

Another NS type TORUS machine is also known as coreless (or yokeless) machines in small and medium powers since there is no need for the stator core or yoke. The rotor of the machine has surface magnets with rotor disc as in other axial flux PM machines. However, the stator structure comprises only windings unlike TORUS machine stator with core. 2 Pole machine picture is illustrated in Figure 16. This type of coreless axial flux machines is appeared in the literature less frequently than other TORUS type machines [36-37]. The main idea behind the coreless machines is that since the main flux travels from one rotor to another and does not travel in the stator core, stator structure can be eliminated.

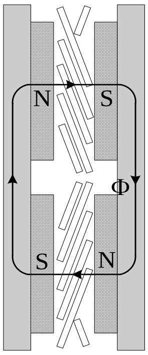


Figure 16. NS type axial flux coreless (or yokeless) TORUS machine

In addition to the axial flux internal-stator-external-rotor TORUS type PM machines, there exists non-slotted axial flux internal-rotor-external-stator (AFIR-NS) and slotted axial flux internal-rotor-external-stator (AFIR-S) disc type PM machines investigated in the literature [49], [74-76].

AFIR-NS permanent magnet motor structures are external stator internal rotor type structures illustrated in Figure 17. The structure has two stators and one PM rotor disc. The stators are non-slotted structures with strip wound stator steel. Distributed back-to-back connected windings are placed around the stator core. A nonmagnetic material such as epoxy resin is again used to fill the spaces of stator windings to increase the robustness and provide better conductor heat transfer as in all non-slotted structures.

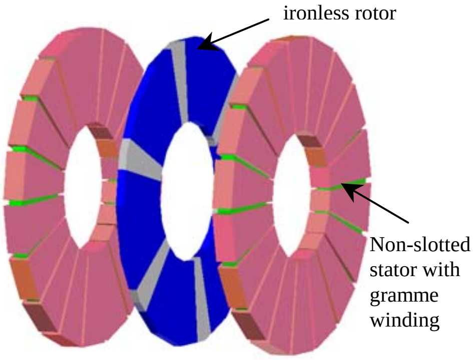


Figure 17. Axial flux AFIR type non-slotted surface mounted PM motor configuration (AFIR-NS)

The rotor structure is slightly different from the rotors of the TORUS topologies. In the AFIR topologies, the steel disk is not used in the rotor structure simply because the main flux does not travel in the rotor. The rotor is formed only by the axially magnetized fan shaped NdFeB permanent magnets and a shaft. A nonmagnetic material, on the other hand, is used to fill the spaces between the magnets and form a rigid structure since there is no need for a magnetic rotor disc to hold the magnets. This raises an important feature of inner rotor PM disc machines which is to have very high power to inertia ratio due to the lack of iron in the rotor. This feature makes the AFIR structures very attractive for applications which require small inertia. The machine rotor is illustrated in Figure 19. Either aluminum or non-magnetic steel could be used to form the rigid rotor structure. Slotless AFIR stator and rotor structures are shown in Figure 18 and Figure 19 for better illustration.

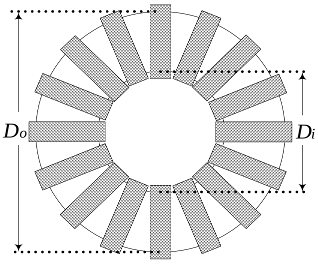


Figure 18. Stator structure of the AFIR-NS topology

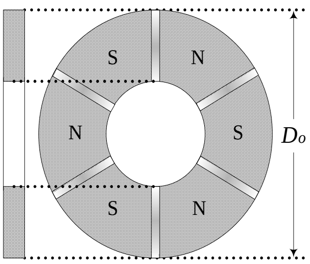


Figure 19. Rotor structure of the AFIR-NS and AFIR-S topologies

The winding parts used for the torque production is on the inner sides of the stator facing the rotor. Therefore, the end windings are again relatively long in the AFIR-NS topology which provides higher copper loss and lower efficiency. Furthermore, it should be mentioned that AFIR-NS machines have larger inductance than equivalent TORUS type machines have. Besides, leakage flux from the back sides (non torque producing sides) of the AFIR-NS topology could link iron parts not associated with the machine proper.

Both 3D and 2D illustrations of the flux paths of the slotless AFIR machine are shown in Figure 20 and Figure 21 respectively. As it is seen from the 2D 2-pole section, the N polarity permanent magnets drive flux across the airgap into the stator core. The flux then travels circumferentially along the stator core, returns to the airgap, and then enters the stator core through the S pole of the magnets and closes its path through the airgap.

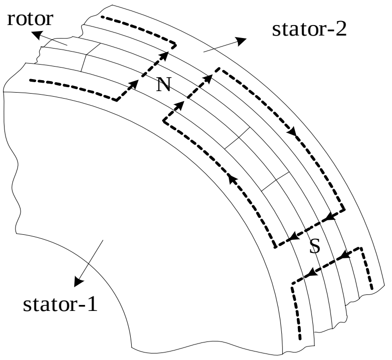


Figure 20. 3D Flux directions of the AFIR–NS machine

The slotted AFIR type disc machine is another axial flux type surface mounted PM motor which is illustrated in Figure 23 [46-55]. The machine is realized by two slotted stators and a single PM rotor. The slotted stator cores of the machine are again realized by a tape wound core with a lap type polyphase AC winding located in the punched stator slots. The rotor structure of the AFIR-S machine, which is the same as AFIR-NS machine rotor, is formed only by the axially magnetized NdFeB magnets where epoxy resin or aluminum is used in between the magnets to form a solid rotor structure.

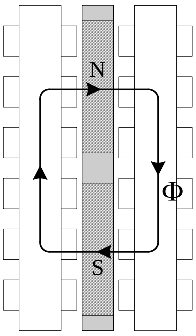


Figure 21. Flux directions and structure of AFIR-NS topology

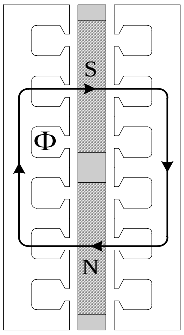


Figure 22. 2D illustration of flux directions and structure of slotted AFIR type machine

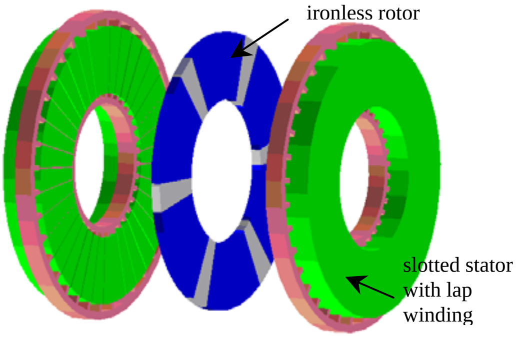


Figure 23. Axial flux AFIR type slotted surface mounted PM motor configuration (AFIR-S) with two sets of lap windings in each stator

The basic flux path of the AFIR-S machine is the same as that of the AFIR-NS machine. (See Figure 20 for 3D flux path picture). The 2D flux path over two poles at the average diameter is also shown in Figure 22. It should be noted that end windings are relatively short in the AFIR-S topology because of the short-pitched winding used, which results in lower copper loss and better efficiency compared to its slotless counterpart.

Electromagnetic torque is a function of the outer diameter in axial flux machines. If the machine is to be designed for small outer diameter, the required torque can be achieved by using multi-stage arrangements. This type of multi disc or multi stage axial flux machine structures has not found enough attention in the literature [56-63]. Multi stage machines are very competitive because of easier assembly and even better torque and power densities. The reason is that the airgap surface in RFMs get smaller as going into the inner rotors while the airgap surface stays the same in AFMs which makes the power or torque density higher than RFMs and makes the machine assembly much easier.

Both TORUS and AFIR type machines mentioned earlier as well as radial flux machines can be constructed in multi stage versions [56-63]. In general, the multi stage machine structure has N stator and N+1 rotor discs where N is the number of the stages or stators. The rotors share the same mechanical shaft. The stator windings of the N stator can be connected either in parallel or series. The rotor core used only for the outer rotor and has to be chosen carefully since they provide the main flux path.

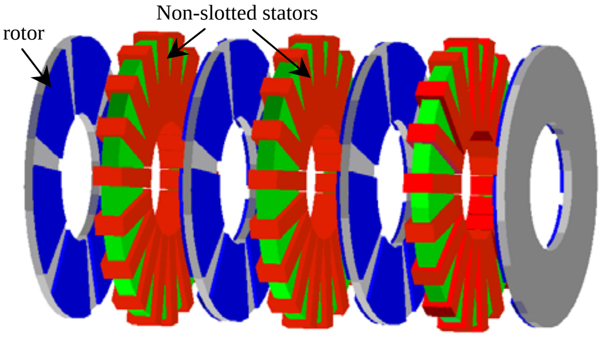


Figure 24.3D view of the slotless MULTI stage PM machine for N=3

A sketch of the slotless axial flux multi stage topology (MULTI-NS) for N=3 is shown in Figure 24. The stators are formed by non-slotted strip wound stator steel. Back-to-back connected gramme type airgap windings are again placed around the stator core. The outer rotor discs are formed by both rotor cores and axially magnetized surface mounted magnets as in other TORUS type topologies. The inner rotors are formed by rotor discs with permanent magnets on both sides of the rotor core. The winding parts used for the torque production is the parts on the inner sides of the stators facing the rotors. Therefore, the end windings are quite short in MULTI-NS topology resulting in low copper loss and high efficiency. Also, since the motor is longer than the single stage axial flux machines, there is more stator frame surface area to transfer the heat generated.

The flux path of the MULTI-NS machines is basically the same as that of either TORUS or AFIR type structures. As can be seen in Figure 25 (a) and Figure 25 (b), flux either travels from one outer rotor to the other outer rotor through N stator, N+1 coreless rotor and 2N airgaps or travels in each of the rotor and stator structures.

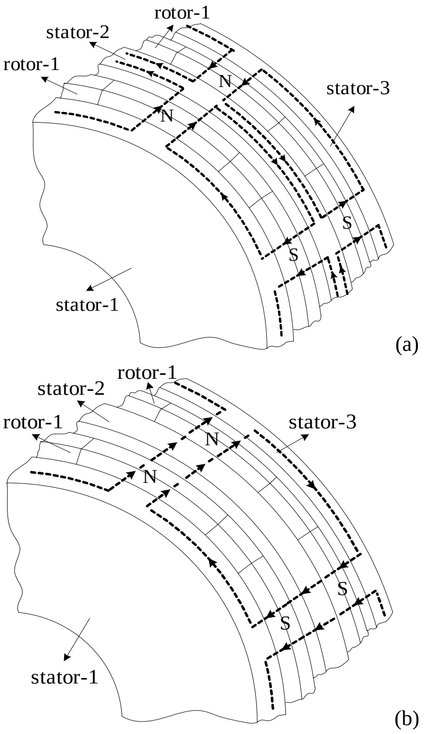


Figure 25. 3D illustration of flux directions and paths of the MULTI stage topologies (3 stator - 2 rotor version) (a) NN type and (b) NS type

Slotted MULTI stage (MULTI-S) machine structure has N stator and N+1 rotors like the MULTI-NS topology. Two different MULTI-S machine structures can again be considered here. The NN type topology (MULTI-S NN type) is the one in which the main flux travels circumferentially in the stator. Therefore, back iron is needed in each stator. The motor structure is illustrated in Figure 26. The NS type topology (MULTI-S NS type) is the one where the main flux travels in axial direction. Since the flux does not travel in the stator core, there is no need for stator back iron and the stator structures can be designed in such a manner that they are comprised of a number of stator teeth only. The teeth are distributed to form a circle and held together in position by one end plate which is made of magnetic material. In addition, very small back iron could be used in the stator structure to form a solid structure.

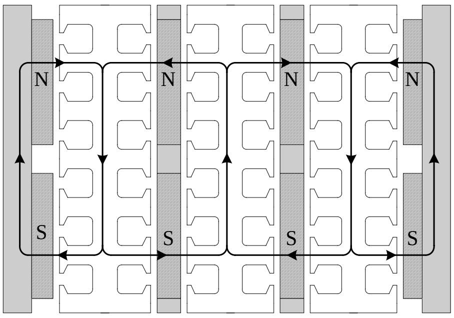


Figure 26. NN type slotted MULTI stage machine for N=3

The stators of NN type MULTI-S are formed by slotted strip wound stator steel. The slotted stator cores of the machine are realized by tape wound core with sinusoidally distributed back-to-back connected windings in the stator slots. The rotor structures of both MULTI-S machines are the same as that of the MULTI-NS machine. A nonmagnetic material such as epoxy or non-magnetic steel is used to increase the robustness of the rotor structure.

The advantage of using NS type MULTI machine, which is displayed in Figure 27, is similar to NS type TORUS machines. The size of the machine is smaller than NN type MULTI stage machines since no back iron is used in the stator structures of NS type MULTI machines, then efficiency and power density are higher than the NN type MULTI stage machines. In addition, there exists no waste of core material since slots are not cut from the lamination for slotless topologies.

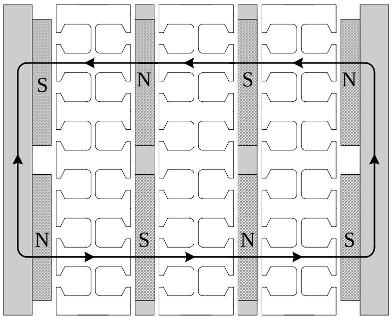


Figure 27. NS type MULTI-S machine topologies for N=3

Another version of multiple stage axial flux machine is the one with ironless stator [40-45]. This type of machine can be built with multiple rotors and ironless armature windings. The magnet flux passes through the machine from one end to the other as can be observed from Figure 28.

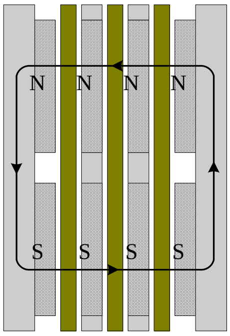
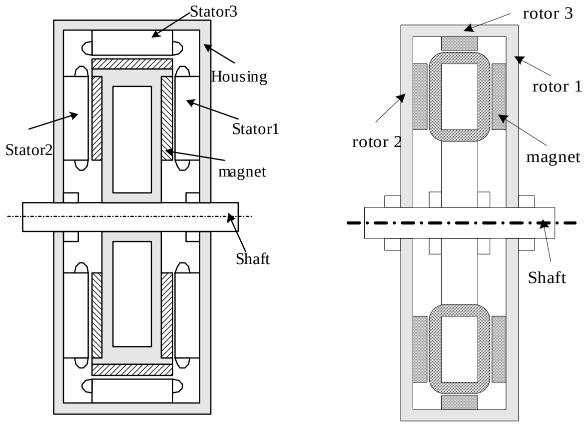


Figure 28. Multiple disc ironless stator PM machine

In addition to disc rotor PM motors, there exist a small number of double-sided hybrid PM motor structures appeared in the literature [83-84]. An attractive hybrid motor is proposed by Dr Hsu and the machine is illustrated in Figure 29 (a). This motor includes 3 sets of magnets and 3 sets of corresponding stators which are tied to the frame. One rotor disc carries two sets of magnets and operated across the axial airgap. The third sets of magnets are placed on top of the rotor disc and operate across the radial airgap with a surrounding stator as in radial flux PM machines. In other words, all the surfaces of the rotor structure have magnets and are used in the torque production. The machine offers a high power density since the entire rotor surface is used in the torque production. Another double-sided hybrid PM motor is shown in Figure 29 (b). The magnets embrace the stator and armature windings from three sides and only the inner sides of the stator windings do not produce any torque. The slotted version of this structure is also possible.

However, this motor structure does not have the necessary robustness.



(a) (b)

Figure 29. Double- sided hybrid motors with both axial and radial airgap

IV. OTHER AXIAL FLUX PM MACHINES

There exist few other axial flux disc type machines covered in the literature. Axial flux interior PM (AFIPM) machine structure over two poles [64-69] is illustrated in Figure 30. The structure is realized by two interior PM rotors and a strip wound stator. Two sets of polyphase windings are mounted in the slots. The rotor has arc shaped steel poles, tangentially magnetized square shaped magnets and a steel disc to hold the poles and magnets.

AFIPM machine have some attractive features for traction applications: One of the important features of this machine is to be able to obtain the required torque value at the field weakening region by designing the stator inductances (L_q and L_d) since the effective machine airgap is small. Secondly, the AFIPM machine has quite robust structure since the magnets are buried in between the iron poles as well as the stator windings are located inside the iron structure. Therefore, this structure can be used in high speed applications.

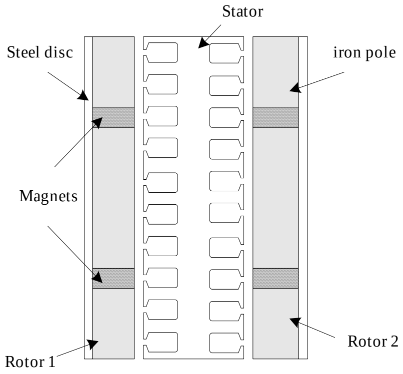


Figure 30. Axial Flux Interior PM (AFIPM) machine

One other axial flux PM machine structure is axial flux doubly salient PM (AFDSPM) machine which is displayed in Figure 31 [85-86]. The machine utilizes ferrite magnets and flux poles in the rotor and salient poles with concentrated windings in the stator. The concept of axial flux operation guaranties the electromagnetic balance of the windings of the machine. In addition, the machine utilizes a doubly salient structure that enhances the PM flux concentration effect. As the AFDSPM machine and its radial counterpart is compared AFDSPM machine is simpler mechanical structure and better cooling abilities than not only RFDSPM machine but most of the radial flux machines as well.

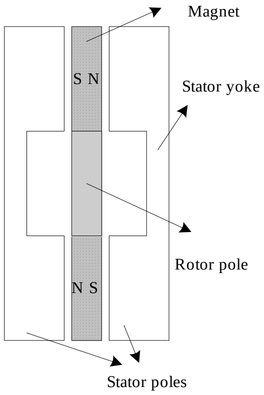


Figure 31. Structure of Axial Flux Doubly Salient PM (AFDSPM) machine

A majority of variable speed applications do not require field-weakening applications. However, there exist some applications such as traction drives, washing machines and spindle drives that necessitate field-weakening operation [68], [70-72]. The means to realize field weakening in PM machines by eliminating the effects of d-axis current injection has been a great interest in machine designers and new machine structures are of great importance at this point. There exist several alternative solutions in order to eliminate this problem in conventional PM machines. In particular, advances in materials technology such as PMs and magnetic steel allow the researchers to propose new machine configurations.

One of the few axial flux machines for flux weakening operation has been developed by Profumo et.al. [66-67]. The machine structure over two poles is displayed in Figure 32. This research deals with the design of a new axial flux interior PM (AFIPM) machine with flux weakening operation by the use of soft magnetic materials.

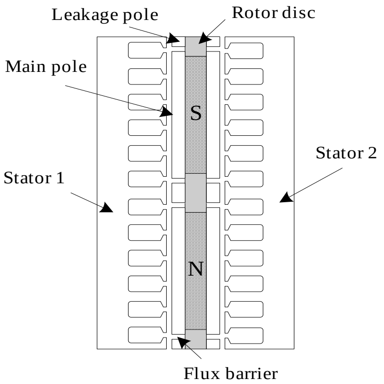


Figure 32. Axial flux interior PM synchronous motor realized with powdered soft magnetic materials

The machine is composed of two slotted stators and a single rotor. The one side slotted stators have tape wound core with series connected stator windings. The rotor structure has axially magnetized magnets, rotor disc and main and leakage poles. There exist two flux barriers in between the leakage and main poles. The position and size of the flux barriers can be designed in such a manner that d-axis and q-axis stator inductances can satisfy the required torque in the flux weakening region.

Recently, a new axial flux PM machine topology with a DC field winding in order to accomplish easy and inexpensive control has been introduced at the University of Wisconsin-Madison [80-82]. This new field controlled axial flux surface mounted PM (FCAFPM) machine concept is proposed not only to overcome the drawback associated with current injection but also to improve the features of the conventional PM machines by introducing a new axial flux machine concept with flux weakening capability. One derivation of the new concept, which is called double-rotor-single-stator NS type AFPM machine and used as an example to describe the structure, is illustrated in Figure 33.

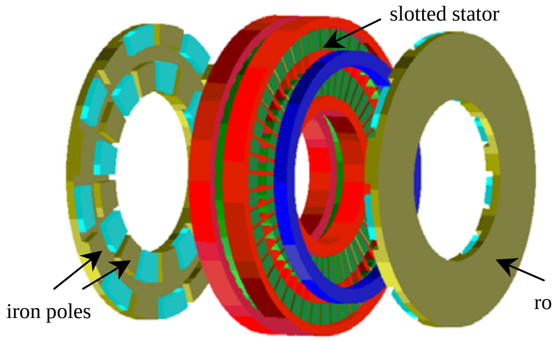
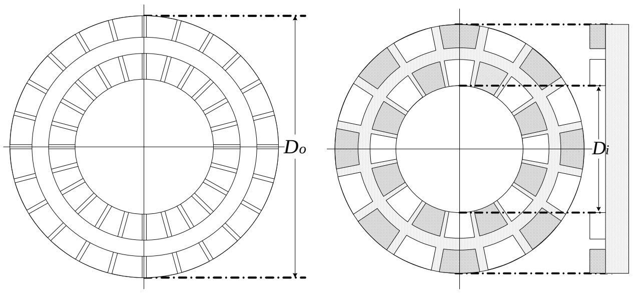


Figure 33. Field Controlled Axial Flux surface magnet PM (FCAFPM) machine structure

The new structure is composed of two part tape wound disc type slotted stator structure one incorporated into another, two rotor discs with axially magnetized surface magnets and iron pieces, two sets of 3 phase AC stator windings and a DC field winding which is the main difference between the axial flux PM machine and the new concept FCAFPM machine. In other words, there exist two sources in the machine: constant magnet excitation and variable DC field excitation. The detailed machine structure is shown in Figure 34. Excitation of the DC coil of one polarity tends to increase the consequent poles on both inner and outer portions of the rotor thus strengthening the field. Excitation of the DC coil with opposite polarity decreases the field in the consequent poles in both inner and outer portions of the rotor disc thereby weakening the airgap flux. This topology eliminates the demagnetization risk of the magnets since the DC field A-turns do not directly oppose the magnet A-turns. And airgap flux can be controlled in a wide range with the use of FCAFPM machine.



(a) (b)

Figure 34. 2D view of the FCAFPM machine stator (a) and rotor (b). The stator has two pieces for NN type topologies and one piece for NS type

5. CONCLUSIONS

Axial flux PM machines reported in the literature and several new and promising AFM structures have been reviewed in this paper. Machine structures, principles, main differences, features and some advantages of the AFM are clarified. Some of the attractive axial flux PM novel machine structures are examined from a variety of perspectives. Finally, a detailed and complete reference section has been provided.

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