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A Survey on Axial Flux Induction Motors

***Abstract**. The induction motor with an axial air gap shows some performance characteristics that are superior to conventional induction machines. So it attracts the attention of the investigators to work on the performance prediction and design of these motors. In this paper a brief history of axial flux induction motors are presented and then the different structures of them are discussed. There are a lot of works on the design, performance prediction, analysis, and applications of these motors which are considered here.*

***Streszczenie.** Zbadano silnik indukcyjny z osiowymi szczelinami powietrznymi. Przedstawiono historię silników tego typu i różne jego rozwiązania. Przedstawiono przegląd stanu wiedzy w tej dziedzinie. (**Przegląd stanu wiedzy na temat silników indukcyjnych z osiowym strumieniem**)*

Keywords: Axial flux motor, different structures, application, and analysis
Słowa kluczowe: silniki indukcyjne, silniki z osiową szczeliną.

Introduction

Axial-field machines (AFMs) differ with conventional machines in that: (1) the air gap flux is in radial direction, while the effective conductors are radially positioned, and (2) the stator and rotor cores are of disc type [1]. Because the conductors in conventional radial flux motors (RFM) are axially arranged, the axial variation of the air-gap field may be neglected or it is taken into account by using the equivalent core length of the machine instead of the real stack length in the design. This assumption leads to a two-dimensional (2D) field problem, and hence the performance calculation may be greatly simplified. However, in AF motors, the conductors are radially arranged, and thereby the pole pitch and the tooth width will increase when increasing the core diameter. Therefore, the radial air-gap field distribution of AF motors is non-uniform, in the other words; it constitutes a (3D) field calculation [2].

Fig. 1 shows the configurations of a conventional and an axial-field machine. For the conventional machine, the main dimensions are the air gap diameter and the effective length while for the axial-field machine the main dimensions are the outer and inner diameters [1].

a) b)

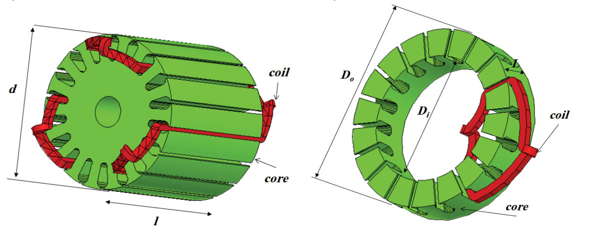

Fig. 1. Configurations of axial-field and radial-field machines, (a) Radial flux machine, (b) Axial flux machine

The history of electrical machines shows that the earliest machines were AFMs though they were replaced by RFM after a relatively short period of time. In 1821, Farady invented a primitive disc motor which was in the form of an AFM. However, since 1837, when Davenport claimed the first patent for a RFM, it became the accepted configuration for electrical machines. Exceptions to the rule are the printed circuit servomotor and the superconducting homopolar machine [1-3].

The classically built axial induction motor, as produced in the 1940's, has undergone a variety of modifications during the last several years. The derived modifications had to eliminate inherent deficiencies. In the 1960's, other special machines were developed including the axial synchronous alternator and different types of axial d.c. motors that had diverted the attention from axial induction motors [4].

Early in the 1900's, development trends were pushed by the materials and manufacturing methods available. Since 1980 the applicability of axial flux machines to low-speed, direct-drive electrical drive applications has been studied. For instance, for the realization of the Monospace™-lift designed by Kone Elevators an axial flux motor type solution is used [3].

The main reason for forgetting AF motors in production was the difficulty associated with production of their magnetic cores, in particular the stator and manufacturing cost [3-5]. Furthermore, the rotor construction of the machine has also been too weak to tolerate elevated rotational speeds [3]. On the other hand some manufacturing difficulty was created by the axial force acting on the rotor and bearings caused by one sided magnetic pull [1, 5]. However, this problem can be overcome by using some design considerations or using new materials, which will be discussed in the next parts of this paper. Furthermore one of the main limitations of conventional radial-field machines (RFMs) is the bottle-neck for the flux path at the root of the rotor tooth. There are other drawbacks such as cooling problems and inefficient utilization of the rotor core. These limitations cannot be conveniently removed unless there is an alteration in the geometry of the RFM [1-2].

Authors of the [5-6, 7-8] believe that the AFIM promises high utilization of the active materials and thus a favorable power density. Since the topology of the rotor's construction of an AFM can be readily varied, an AFIM may be designed to have a smaller or larger inertia [1]. So, one of the principal features of this motor type can be the relatively small inertia that promises a small mechanical time constant and makes it a suitable choice even for servo and high-speed applications [1, 6,8-9]. On the other hand, it is mentioned in [3] that a light construction and excellent mechanical and dynamical performance are properties that make the axial flux induction machine well adaptable to medium-speed (3000…15000 rpm) applications, too [1].

Since the axial-field machine possesses a greater diameter-to-length ratio and its inner diameter will usually be much greater than the shaft diameter, better ventilation and cooling can be achieved. The possible use of higher specific electric loading and higher specific magnetic loading will further reduce the size of the axial-field machines [1].

Meanwhile AFIMs may be, e.g., used in applications in which the short axial length of the machine is advantageous [7, 10-11]. On the other word this type of motor, because of its short axial length, can easily be adopted into the construction of various devices and has advantages in terms of size, appearance, and function. Another virtue is its increased economy in the use of raw materials for construction. According to Polard's theoretical considerations, the motor needs 13-14 percent less copper and 21.5-32.5 percent less iron than similar traditional motors producing equal power [5].

Generally, the use of high power variable speed electrical drives with solid-rotor-core induction motors is becoming increasingly popular, especially, in high pressure pumps, high speed compressor systems and in small energy conversion units, which normally require higher speed than it would be possible to reach by means of the network frequency [7, 10-11]. By using the machines, which are rotating at higher speeds than it would be possible to directly reach by means of the network frequency, it is possible to replace a mechanical gearbox by an electrical one and attach the load machinery directly on the motor shaft. This offers several advantages over the conventional low-speed electrical machines, e.g., the drive train efficiency is greater than that of a low-speed motor with gear because the losses due to the mechanical gearbox are avoided, a full speed control for the drive can be achieved and a size of the machine is smaller than the size of a low-speed motor of equal shaft motor [6].

Considering all of the advantages of the axial flux induction machines, new researchers show great attention on this topic. The literatures on the AFIMs are classified in five categories:

- Design and implementation of different structures
- Using new materials in the construction of AFIMs
- Modeling and performance prediction of the motor
- Using AFIMs in the different applications
- Analysis of the effects of the different motor parameters on the performance characteristics of AFIMs

In this paper authors try to review all above topics in brief.

Structure of Axial Flux Induction motors

As usual for induction motors, air gap length must be small and slotting effects must be controlled [12]. Therefore, there are different structures of the AFIMs. These structures can be categorized considering eight aspects.

A. The configuration of stator and rotor

Regarding the configuration of stator and rotor, there are three different arrangements:

- **Motors with one air gap**

This structure is the simplest and the oldest structure of the AFIMs and is named as single-sided motor [3, 7]. Generally, this structure is the most suitable choice for machines of low torque rating [3].

The main concern here is the bearing lifetime, which depends on the bearing load. However, there are several solutions, in which the bearings of the machinery are rigid enough to bear the axial force produced by the electrical machine [13]. Fig. 2(a) depicts a single-sided motor with a solid iron rotor; while a double-layer aluminum-solid iron rotor type is shown in Fig. 2(b) [13].

- **Motors with two air gaps**

In this category two air gaps may be both axial (double-sided motor) or one axial and one radial. The earlier one is able to reduce axial force and motor may be constructed from one rotor sandwiched between two stators (fig. 3(a) [13]) or one stator sandwiched between two rotors (fig. 3(b)).

Although in double-sided motor there are the benefits of high torque density and balanced axial forces [3], considering the cost of the machine, two stators are usually more expensive to manufacture, when compared with a single-sided equivalent, especially in the case of small machines. This is related to the amount of copper in the stator winding and also related to the time required to manufacture the winding. In machines with a higher torque rating, the difference in the manufacturing cost is smaller between single-sided and double-sided machines [3].

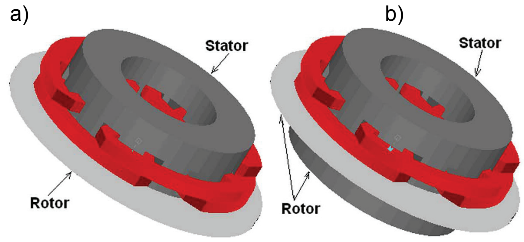

Fig. 2. Different configurations of single-sided axial air-gap induction motors a) with a solid iron rotor and b) with a double-layer aluminum- solid iron rotor [13].

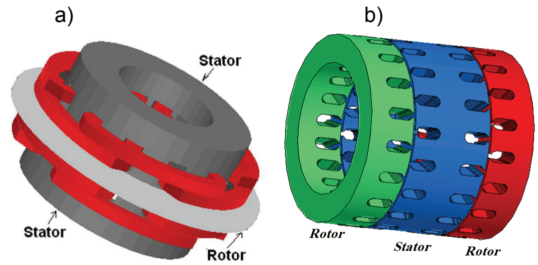

Fig. 3. Different configurations of double-sided axial air-gap induction motors (a) with one rotor sandwiched between two stators [13] (b) with one stator sandwiched between two rotors

Authors of [14] have proposed a new axial and radial-flux induction motor with high power density and efficiency. This motor has a single stator and a double rotor topology. The rotor has an axial and a radial-cage windings as illustrated in Fig. 4 [14].

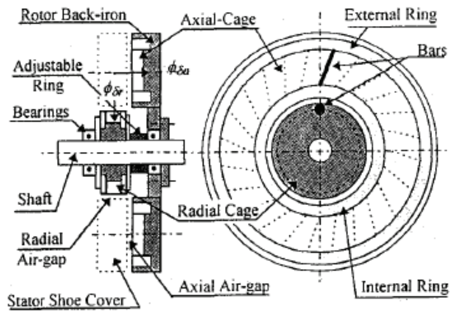

Fig. 4. Schematic views of the rotor the double air gap (Axial and radial air gap) motor [14]

- **Motor with multi air gaps**

Although double-sided structures have a good performance, multi-disk structure of axial flux motors may be the best choice for special applications such as high power machines.

B. The materials which are used in the Motor

The magnetic core of AFIMs can be built from iron [1-2], powder composite (magnetodielectrics) [5, 15], or Amorphous [54]. Superconductors are the other materials which are used to build AFIMs [16-20]. In this part these different types will be illustrated. It worth to notice that the magnetic core can be solid or laminated and the laminated core is usually made of a strip-wound circular core which is machined to form the slots.

- **Iron**

The conventional type of AFIMs uses the iron cores. As mentioned before the production of the iron magnetic core of stator in the AFIMs is difficult. The magnetic cores work under alternating magnetic flux and hence should have a laminated structure. Because of the axial direction of the magnetic flux in the air gap, the stator should be carefully insulated from the rotor pack. If traditional windings are used on the lateral surface of the stator and rotor, radial grooves should be formed of the stator. The manufacture of magnetic cores of such a configuration is difficult. Therefore, magnetic cores of current disk rotor induction motors are coiled from magnetic strips. Difficulty is encountered in the machining of the grooves, normally a milling or grinding process which both methods are costly and labor intensive [5].

- **Magnetodielectrics**

The problems described above justify the research aimed at finding an improved method of manufacturing these motors. Powder metallurgy and magnetically soft iron matrix composites offer advantages in the construction and manufacture of the magnetic cores. Whereas it is possible to build magnetic cores having simple or built- up structures, it may be impossible or at least very difficult to build them using traditional magnetic materials. In terms of magnetic properties, powder composites are not as efficient as magnetic strips or sheets. This fact may not significantly reduce the use of powder composites if the proper structure of magnetic core is chosen [5]. On the other word, these materials allow easier and less costly manufacturing of machine parts, and may reduce iron losses at very high electrical frequencies (~ 400-800 Hz) [21]. However, they do contribute to fringing in two aspects. Firstly, allowing the main flux in stator cores to stray in the third dimension, being isotropic in nature. Secondly, their low permeability strengthens these stray parts [22, 23].

- **Amorphous**

Amorphous metal tape having excellent magnetic properties have become available at about one-fourth the cost of conventional transformer steel used in electric machines. These tapes exhibit a core loss about one-fourth that of the conventional silicon iron and have very high permeability. The tape is made very thin (of from 0.0005 to 0.003 inch thick) and in widths of up to about two inches and has high resistivity resulting in superior high frequency properties. Good efficiency is then attainable even at high speeds [54].

- **Superconductors**

High temperature superconductors are being considered to replace the conventional material in electrical devices. The high currents in superconductors permit one to create the working magnetic field in an air core instead of in a heavy ferromagnetic one [20].

In the most of the superconducting core AFIMs only the rotor is superconducting while the stator is composed of conventional coils. But in [19], authors showed the superconducting stator windings for an axial flux air core motor. These windings are made of ceramic coils from machined YBCO bulks. They propose a design with the rotor of this motor made from a superconducting disk between two stators.

Although most of the superconducting AFIMs have employed YBCO due to its strong flux pinning, in [17] because of economically advantageous, a motor with Bi-2223 have been studied and in [16] a small axial type BSCCO motor immersed in liquid nitrogen is explained.

C. The existing of the stator slots

There are two types of AFIMs considering the existing of the stator slots. In the first type, the stator is slotted having conductors located in slots and requiring less magnetizing mmf than a slotless stator [12]. Manufacturing of this stator is difficult. The second type of stators is slotless stators having coils wound around a laminated, or composite, iron core [12]. In these configurations printed windings are preferred and the winding are fixed, mostly glued, to the lateral surface which has no grooves, and this increases the air gap. The effect of this increased air gap is a reduction of the energy coefficients (efficiency, power factor). This is particularly noticeable if more than one layer of printed windings is on the stator surface [5].

D. The magnetic core

Axial flux motors may have magnetic core or not. In the core less configurations, stator or rotor has air core. The air core stators require greater magnetizing mmf than stators with iron core [12]. On the other hand if the magnetic core is existed, it may be iron, magnetodielectrics, SMC core, or aluminum core (in rotor).

E. The source of the motor

Rotating field machines are designed to be operated by sinusoidal voltages and currents. But when an industrial application requires speed regulation, a simple and economic solution is to use of an A.C. motor supplied with a variable voltage-frequency source. So, considering the source of the motor, two types of the AFIMs are existed: sinusoidal source motors or inverter fed motors [24-25].

F. The number of the phases

Axial flux induction motors may be constructed as single phase, two or three phases.

G. The structure of the rotor

Rotor of the axial flux motors can be fabricated using solid or laminated steel. The laminations have to be shaped and arranged in such a way that unifies the lamination direction with the flux direction. These laminated sheets are used to reduce the eddy currents in the magnetic cores.

A normal laminated rotor cannot be used in high-speed machines because of its weakness and insufficient rigidness; one must be satisfied with a solid-rotor that in electromagnetic terms is notably weaker than a laminated one, the mechanical properties of which are yet superior [2, 12, 26].

H. The structure of the stator winding

There are various arrangements of the stator windings. They are categorized in single layer, double layer, and gramme [7, 27]. Fig 5 shows the single layer and gramme configurations [27-28].

Applications of Axial Flux Induction motors

The special features of the axial flux machines such as its planar and adjustable air gap, better power to weight and diameter to length ratio, compact construction, and better efficiency, especially in a machine with a large number of poles (more than 12), make them an attractive alternative over conventional machines in a number of applications, such as fans, wheels, pumps, domestic applications and electrical vehicles [8, 29]. Some of these applications are summarized below.

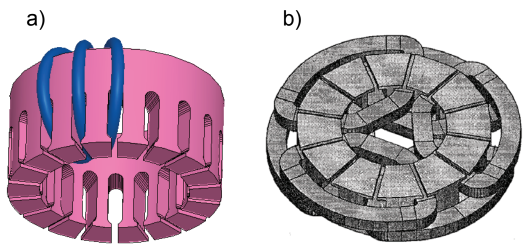

Fig. 5. The various arrangements of the stator windings, (a) gramme, (b) single layer configurations [27-28]

A. Electrical Vehicle

For an electric vehicle drive motor, the properties of high power and torque density, high efficiency and power factor, light structure, Optimal choice of system voltage to minimize inverter size, batteries weight, and system cost, and wide speed range are compulsory requirements [14, 30-32].

In recent years, axial-flux machines and new discoid topologies are becoming prime movers in electric vehicle propulsion systems, principally as wheel-direct coupling motors [14]. In [33] a pair of axial flux, poly-phase induction motors having their respective stator windings and also their magnetic circuits in series, with provision for 'out of balance' flux, arising due to differences in the two rotor speeds, to pass through a saturating magnetic shunt, is presented for omitting the mechanical differential of the vehicles.

B. Home apparatus

In the field of small power domestic applications, such as fans, pumps, food processors etc, single-phase axial-field induction motors may have distinct advantages [1, 35]. Firstly, the flat shape of AFM is a desirable configuration for the said applications. Secondly, the rotor may be integrated with the rotating part of mechanical load, e.g. the blades of fan, the impeller of pump, etc. The axial-force between stator and rotor is not so serious in small power range, thus it can be withstand by thrust bearing or by using ironless rotor disc and magnetic flux return path located at the opposite side of the rotor [1, 36]. Fig. 6 which copied from [1] shows the construction of an experimental axial-field squirrel cage induction motor for ceiling fan drives. Fig. 7 shows the comparison of the size of an axial-field induction motor with that of a conventional motor of the same power rating (150 W) [1].

C. High speed applications

The use of high power variable speed electrical drives with AF induction motors is becoming increasingly popular, especially, in high pressure pumps, high speed gas compression systems and in small energy conversion units, which normally require higher speed than it would be possible to reach by means of the network frequency. The idea of using high-speed machines is to replace a mechanical gearbox by an electrical one and attach the load machinery directly on the motor shaft. This offers several advantages over the conventional low-speed machines, e.g. the losses due to the mechanical gearbox are avoided and a full speed control for the drive can be achieved [37].

Reference [38] describes the problems of integrating an electrical machine with a diesel engine turbocharger. The actual choice of the motor in this application depends on a number of factors including type of bearing, operating speed, power rating, and ambient temperature (this can be in excess of 200°C during a hot-shutdown). So, again because of the high turbocharger speed, 130,000 rpm, and space restriction between the turbine and compressor an axial flux, solid rotor induction machine is an attractive motor option.

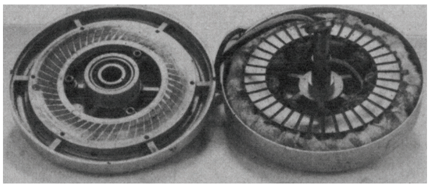

Fig. 6. Single-phase AFM for ceiling fan [1]

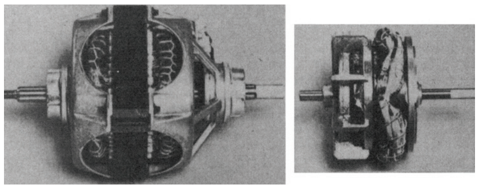

Fig. 7. Comparison of 150 W AF induction motor with a conventional induction motor [1]

Modeling and performance prediction of the motor

In this area there are two groups of papers. The first category is the papers which have modeled the motor using finite element analysis and the second group are the papers which analytically have modeled the motor.

A. Modeling with finite element analysis

The finite element solution of magnetic field problem was originally proposed by Silvester and Chari [39] and it may be done using two dimensional (2-D) or three dimensional (3-D) calculations. Both 2-D and 3-D analyses may be done using time stepping (transient), Magneto static or time harmonic (steady-state sinusoidal) solvers.

Disk-like structure of the stator and rotor causes the magnetic field to be non-uniformly distributed within the volume of the motor and it requires 3-D magnetic field calculations [8, 40, 49-50, 55]. Although modelling of the whole induction motor with 3-D time-stepping finite element method is too large a problem to modern computers [41], in [46, 28] various finite element formulations (in 3-D) for modeling plate or squirrel cage type AF machines are described.

Reference [8] discusses experience in applying time harmonic 3-D finite element method in analyzing an axial-flux solid-rotor induction motor and in [40-45] a correction factor is employed to modify the results of 2-D analysis of AFIM.

B. Theoretical Analysis

There are lots of works on the theoretical analysis of the axial flux induction motors. Most of them describe a 2-D numerical method for field calculations [27, 31, 47-48] and in [13] a quasi-three dimensional mathematical model based on the solution of field equations written in cylindrical coordinates is presented.

Analysis of the effects of the different motor parameters on the performance characteristics of AFIMs

There are some publications that discuss about the effect of the inverter switching frequency, air gap length, and number of rotor slots on the performance characteristics of axial-flux aluminum-cage solid-rotor core induction motors [24, 10, 6, 2, 51-53]. These references show that the additional losses are about inversely proportional to the switching frequency between 1 - 6 kHz and after that it is constant. On the other hand by increasing the air-gap length, the effects of air-gap harmonics can be reduced effectively. However, when the frequency converter supply was used and the length of the air-gap was increased, the efficiency of the motor was increased despite the fact that the stator copper losses increased. Furthermore, losses as a function of the number of rotor slots seem to decrease almost linearly.

Conclusions

In this paper a survey on the axial flux induction motors are presented. At first, the history of the construction of AFIMs and their opportunities and challenges comparing to conventional induction motors is discussed and then the different types of the AFIMs are categorized.

There are lots of papers which considered different aspects of AFIMs. These papers are divided in to five sets. The first set is devoted to the design and implementation of different structures, the next one discusses about using new materials in the construction of AFIMs. Modeling and performance prediction of the motor based on 2-D or 3-D finite element analysis, or analytical calculation is the third issue. Another important subject is using AFIMs in the different applications and finally the analysis of the effects of the different motor parameters on the performance characteristics of AFIMs is the last problem which is regarded in papers. Authors tried to summarize all these subjects in the paper.

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