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The Evolution of Axial-Field Electrical Machines

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***Abstract*: This paper is a review of axial-field electrical machines, which were at the origin of the invention of electrical machines such as the famous Faraday's disk. The different configurations of the axial-field machines are presented along with their advantageous key steady state characteristics such as high efficiency and high power to weight ratio. The differences between axial-field machines and conventional radial-field machines are discussed. The disc-type axial-field electrical machines with permanent magnet excitation seem to be among the best designs in terms of compactness, suitable shape, robustness, and electric characteristics. Axial-field machines are expected to be used in a large number of applications in the future owing to their special features and distinct advantages compared to conventional radial-field machines.**

***Keywords*: Axial-Field Electrical Machines**

1. Introduction

An electrical machine is an electromagnetic energy conversion device. It translates its input electrical power into an output mechanical power. Electrical machines have been available and working for nearly a century (Bose, 1986). During this period many extensive efforts have been made by researchers worldwide to develop and improve design, configuration and performance of electrical machines. Nowadays, electrical machines are found in various physical topologies. They may be categorized according to their conductor geometry and field orientation (see Figure 1) as:

1. Radial-field machine, where the conductor is axial and the air gap flux is radial.
2. Axial-field machine, where the conductor is radial and the air gap flux is axial.
3. Linear machine, where the mutually perpendicular flux and the conductors are arranged along a linear path.

The history of electrical machines shows that the earliest machines were of the axial-field type. Based on the principle of electromagnetic induction, Faraday invented the Faraday disk in 1832, which is also called the homopolar machine. Because of the strong magnetic force existing between the stator and the rotor, these machines were soon replaced by radial-field machines (Chan). These radial-field machines have been and are still used to a large extent. One example of a popular axial-field machine is the printed circuit servomotor (Chan, 1983 and Hanitsch, 1987). As mentioned above, one drawback of the axial-field design is the strong magnetic force between its stator and rotor. This problem may be alleviated by using a sandwich configuration with a stator placed between two rotors or a rotor sandwiched between two stators (see Figures 2b and 2c respectively). A study of axial-field machines reveals that high electrical power to weight ratios have been achieved as shown by the works of Chan (1983), Hanitsch (1987), Campbell (1974a), Spooner et. al. (1990a) and Spooner et. al. (1990b). There is reason to believe that axial-field machines will be used in the future in a large number of applications where their special features offer distinct advantages (Chan, 1983, Spooner et al, 1990a, Profumo et al, 1997, Caricchi et al, 1998b, 1997, Herdzak et al, 1996a, 1996b, 1997, 1998, Chalmers et al, 1999, Huang et al, 1999, Madlena et al, 1996, Panuza et al, 1996, Bailey et al, 1990, Eastman et al, 1995 and Rahman, 1995). Some potential applications of the axial-field machines include car heater blower, radiator cooling fan, auxiliary power unit, windpower generator, electric vehicle, high speed generator driven by a gas turbine, adjustable-speed pump drive, lawnmower motor, and others.

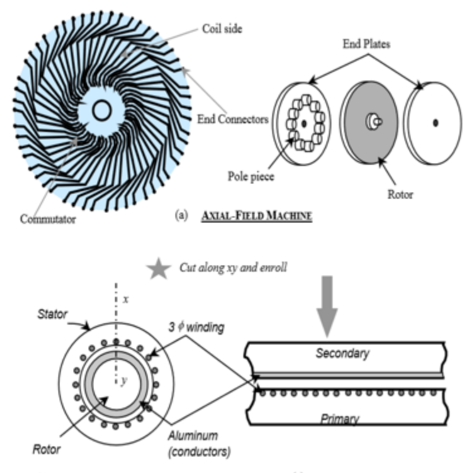

Fig. 1. Different types of electrical machines

This paper examines first the overall construction, development, and principle of operation of axial field machines, then compares the different configurations, steady state characteristics and applications of various axial field machines

2. Classification of Axial-Field Machines

In theory, each type of radial-field machine will have an analogous axial-field machine (Chan, 1983). Therefore, an axial-field machine can operate as a d.c. machine as well as an a.c. synchronous or induction machine. Figure 2 shows the topology of the magnetic circuit of the axial-field machine. These machines can be constructed in one of the following ways in correspondence with the design of the magnetic circuit:

1. Single stator and single rotor (one airgap), as shown in Figure 2(a).
2. Central-stator machine (double airgaps), as shown in Figure 2(b).
3. Central-rotor machine (double airgaps), as shown in Figure 2(c).
4. Multi-disc machine (multiple airgaps). Machines constructed using a single stator/rotor experience a strong magnetic pull between the stator and rotor and therefore, the sandwich configuration appears much more viable. Of the two types of sandwich construction available, the central-stator machine produces more torque per length of stator conductor, since both the working surfaces of the stator core are used. In axial-field machines, the electromagnetic torque is a function of the machine outer diameter (Spooner and Chalmers, 1992). The multi-stage arrangement is suited to overcome the restriction on the machine diameter and to meet the torque required at the machine shaft.

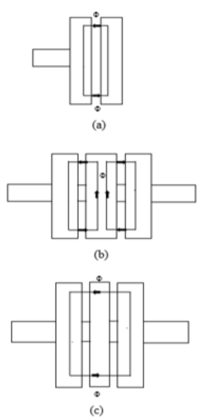

Fig. 2. Topology of the magnetic circuit of axial flux machine (ø is the flux)

3. Main Configurations of Axial-Field Machines

A. Faraday Disk

Based on the principle of electromagnetic induction, Faraday (1832) illustrated that if a copper disk is rotated in an axially magnetic field, with sliding contact and brushes mounted at the rim and at the center of the disk, a voltage will be present at the brushes. Such a machine is commonly known as the Faraday disk (Nasar, 1996) or the homopolar generator. The device is also capable of operating as a motor.

B. Printed Circuit Board Motors

In 1958, F. H. Raymond and J. Henry-Baudot invented the first printed-circuit-board (PCB) d.c. motor (Knights, 1975). The armature had a disk shape. The motor is lighter and shorter than a conventional type but slightly larger in diameter. It has a short time constant which results in a very fast response and low rotor inertia. These advantages derive mainly from the fact that the armature has no iron in it. The PCB armature (rotor) has conductors that are stamped from a sheet of copper, welded together and placed on a disc. The conductor segments are then joined with a commutator at the center of the disk. The disk armature is located between two sets of permanent magnets mounted on ferromagnetic end plates.

4. Applications of the Axial-Field Machines

Axial-field machines are particularly appropriate for the development of compact integrated designs owing to their disc-shape. Some potential applications of the axial- field machine include the following:

A. Auxiliary power units

Using the Torus configuration, a number of auxiliary power units for military applications have been developed in association with Dornier GmbH (Chalmers et al, 1997).

B. Wind-power generator

The Torus generator can be direct coupled to a wind turbine allowing the elimination of the gearbox. This brings about reduced nacelle weight and noise, and improved reliability and efficiency. These considerations led to the proposed use of direct-coupled Torus generators for small-scale stand-alone generating systems in remote areas. 10kW stand-alone wind/photovoltaic generating system prototypes have been constructed. The layout of a system that uses a wind turbine-driven permanent magnet machine and a photovoltaic array as power generating units (Stiebler and Okla, 1992, Caricchi et al, 1994a, Chalmers et al, 1996, 1999).

5. Conclusion

Axial-field machines have been presented and discussed. They offer an alternative to the conventional radial-field machines. Their main advantages over the conventional machines are:

- They can be designed (using permanent magnets) to possess a higher power-to-weight ratio.
- They have a larger diameter-to-length ratio.
- They have a planar and adjustable airgap.
- Their magnetic circuit topology can be easily varied so that many different types of axial field machines may be designed.

Axial-field electromagnetic differential induction motors are a promising solution for electrical cars because they can behave in the same way as an electro-magnetic differential supplied by a single set of inverters. The machines can have both higher efficiency and power density compared with two individual motors. Disc-type electrical machines with permanent-magnet excitation appear to be the best design in terms of compactness, suitability in shape, robustness, and superior electrical characteristics. Because the axial-field machines can be designed to possess high power to weight ratio, they are more suitable for use in aircrafts. Their relatively flat shape makes them also suitable for ceiling-fan motors, radiator cooling fans, etc…The possibility of using an ironless rotor in the axial-field machine makes it appropriate for applications with fast response and low inertia. Moreover, the prospect of separating the stator and the rotor makes the axial-field machine design suitable for sealed and screened machines, such as domestic pump motors and wheel-directly-coupled motors for electric vehicles. Finally, reductions in the cost of high-field permanent magnets are expected to open-up several applications for the axial-field machines.

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