A State of Art on Different Configurations of Permanent Magnet Brushless Machines

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The highest efficiency, fast dynamic response and high power density of permanent magnet brushless (PMBL) machines are resulting in their wide spread applications. There are various type of these machines including permanent magnet synchronous motors (PMSM), permanent magnet brushless dc motors (PMBLDM) and hybrid doubly salient motors. This paper presents a comprehensive review of different configurations of PMBL machines, their rotor geometries and application potential, state of art and recent trends in PMBL machines. A classified list of more than one hundred research publications on the subject is appended for quick reference.

Keywords : Permanent magnet; Axial flux; Radial flux; Rotor geometries; Classification of PMBL machines

INTRODUCTION

Permanent magnet brushless (PMBL) machines are achieving increasing popularity due to advancement in geometries and design innovations. PMBL machines are best suited for position control and medium size industrial drive due to their excellent dynamic capability, reduced losses and high torque/weight ratio[1-28]. These machines are becoming popular due to availability of cost effective rare earth PM materials like Sm-Co and Nd-Fe-B. Availability of these high energy density PM materials not only enhances the performance of PMBLM drive but also reduces the size and losses in these machines. The PM excitation has been used in place of dc excitation in different PMBL machines to get brushless construction with reduced maintenance cost and increased life[29-39]. The various configurations of PMBL machines include PMSM, PMBLDC motors, axial flux permanent magnet (AFPM) machines, PM alternators and torous alternators[40-80]. The different rotor geometries include surface type, interior type, radial and axial field machines. Permanent magnet machines have found wide range applications in various fields such as domestic equipments, automobiles, transportation, aerospace equipment, power tools, toys, vision and sound equipments and healthcare equipments ranging from microwatt to megawatts. With the advancement in power electronics and PM material technology it is possible to design PM generators for power generation board on ships, aircraft, hybrid electric cars and buses, with the saving in generator weight, size and their higher payload capacity for the complete vehicle. Recent developments in PM machines technology include availability of improved PM material, varying construction for motor and generators such as axial field, radial field, two phase, three phase, higher phases with different rotor geometries, hybrid configuration, rectangular fed motor, sinusoidal fed motor, improved sensor technology, fast semiconductor modules, low cost high performance microelectronics devices. New control approaches have been proven to use these machines suitable for position control in machine tools, robotics and high precision servos, speed control and torque control in various industrial drives and process control applications. In spite of being most promising nature of these machines they have faced many hurdles to come to their present stage in terms of cost, torque ripple, noise, vibration, reduce reliability due to large number of components, operational constraints such as temperature rise *etc*[81-113]. Due to their unmatched advantages and wide range of applications of these PMBL machines, new finding in design, cost optimization and development are reported in new books and recent publications. Therefore, it is considered a timely attempt to present a broad perspective on the status of PMBL machines technology.

This paper deals with an exhaustive review of PMBL machines consisting an state of art on various PM materials, different types of constructions and various rotor configurations. The application potential[114-126] and futuristic trends are also presented in brief alongwith conclusive remarks.

DIFFERENT PERMANENT MAGNET MATERIALS

The properties of PM materials are having great influence on the performance of PMBL machines. These are used for excitation in machines for the application ranging from robotics to standard commercial drive to energy generating systems. PMAC machines have various advantages such as high efficiency and power factor, high torque to weight ratio, brushless construction etc.

It is equally important to know that which type of design and configuration is used in an electrical machine. The application requirement decides the type of PM material used due to cost, size and weight. It is very important to consider operating temperature range, external demagnetizing field, weight constraint and space limitation at design stage itself. PM motors of commercial characteristics use ceramic or polymer-bonded neodymium-iron-boron magnets. For high performance motors, where the size and weight constraints are present, there sintered rare earth magnets are used. In applications, where the motor is exposed to extreme environment, Alnico is preferred in these machines. The use of Nd-Fe-B based PM material makes it possible to design and develop an electrical machine of any size excited by fully or partially by these

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Table 1 Different permanent magnetic materials

Name of Material	Type of Magnet	Br, T	Hc, kA/m	(BH)max KJ/m^3
Alnico-5	Alnico	1.28	50.90	43.76
Alnico-8	Alnico	0.92	127.30	47.76
Ceramic-5	Ceramic	0.38	183.00	27.85
Mn-Al-C	Ceramic	0.56	238.70	59.68
Co-17- R-2	Sm-Co rare earth	1.1	397.88	238.73
NdFeB, Vacodym (633HR)	Nd-Fe-B rare earth	1.3	1000.00	330.00

permanent magnets. Table 1 enlists a few available PM materials used in electrical rotating machines. Alnico magnets can carry flux densities equivalent to soft magnetic irons but they are easily demagnetized due to lower values of coercive force as compared to ceramic magnets. Ceramic magnets are cheap but limited by low maximum energy density product. It is due to lower values of retentivity. Rare earth PM materials such as samarium cobalt alloys have relatively more desirable magnetic properties, but these are expensive. Except the polymer bonded rare earth magnets, ferrites and cobalt based metallic magnets are physically hard and brittle. It is application specific to select the particular PM material but recent trends are to use Nd-Fe-B rare earth magnets due to its highest energy density and residual flux density amongst available PM materials[29-39].

DIFFERENT CONFIGURATIONS OF PM BRUSHLESS MACHINES

PM machines can be classified into two broad categories of brushed and brushless construction. These PMBL machines can be further subdivided according to various criteria including mode of operation *ie*, motor or generator, direction of the magnetic field *ie*, axial or radial field machines, type of rotor, *ie*, different rotor geometries, rating of machines such as fractional kilowatts or high power machines, sensorless or with sensors. The PMBL motors can be further categorized as PM brushless dc Motors (PMBLDCM) and PM synchronous motors (PMSM). Among all of these configurations of PMBL motors, PMBLDCM and PMSM are most popular form of PMBL motors used in various applications. These different classifications of PMBL machines are shown in Figure 1 and various rotor geometries for radial field PM machines are given in Figures 2-24. Figures 25-28 show four schematics of axial field PM machines.

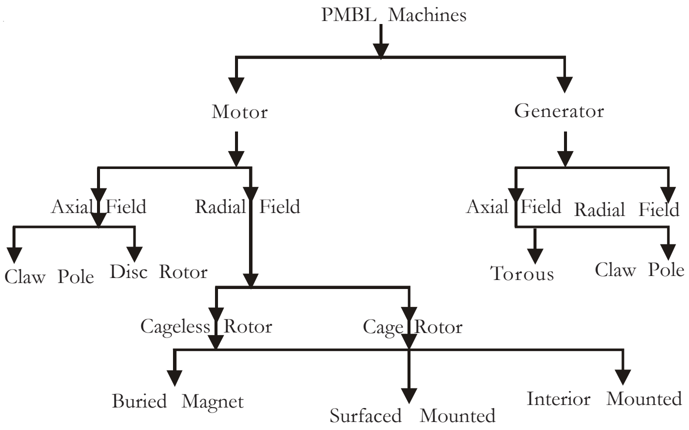

Figure 1 Classification of PM machines

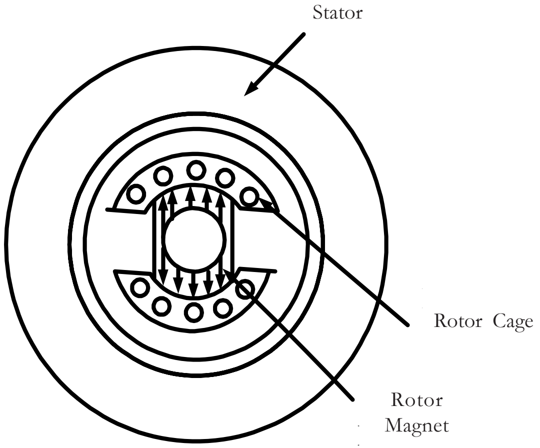

Figure 2 Classical configuration of embedded magnet rotor type PM machine

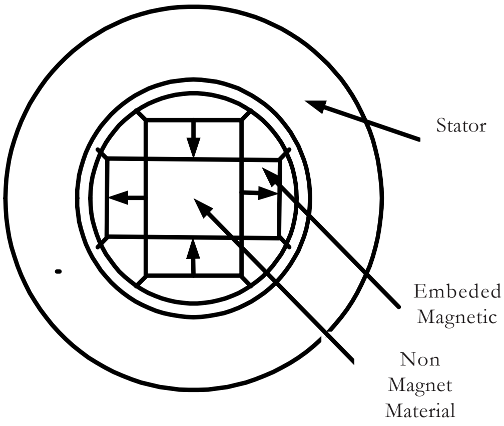

Figure 3 Buried magnet rotor type PM machine

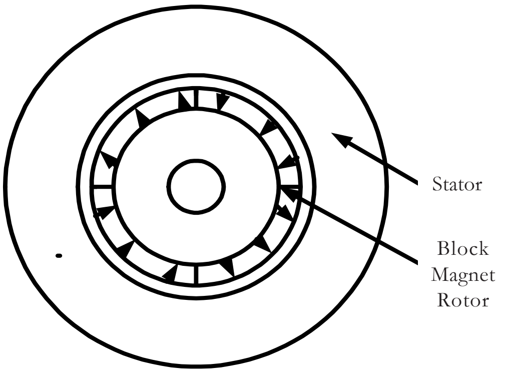

Figure 4 Bonded ring magnet rotor type PM machine

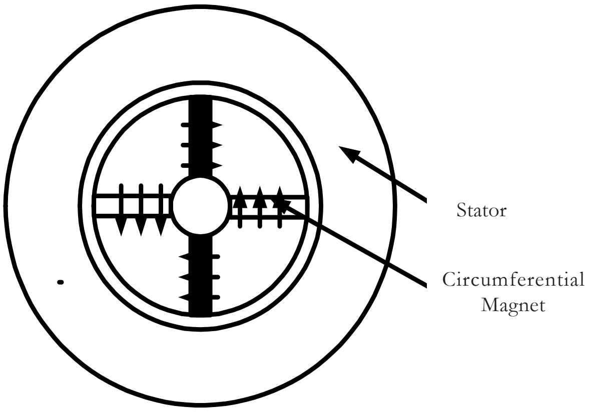

Figure 5 Circumferential magnet rotor type PM machine

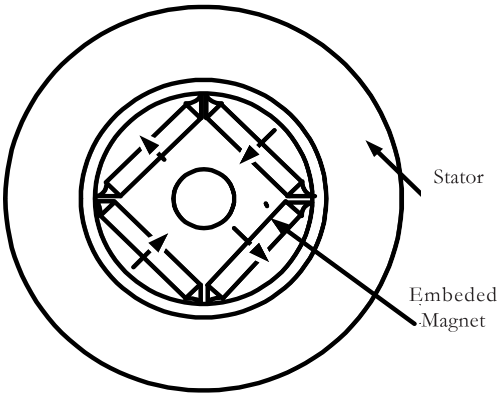

Figure 6 Embeded magnet rotor type PM machine

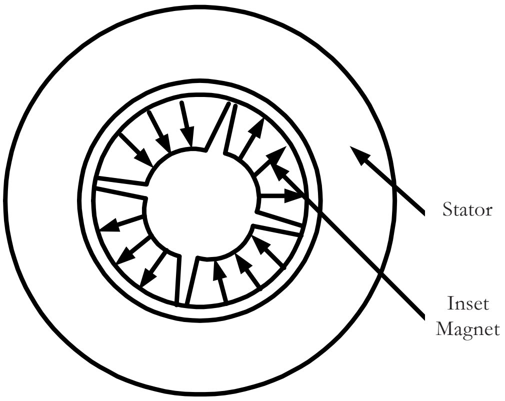

Figure 7 Inset magnet rotor type PM machine

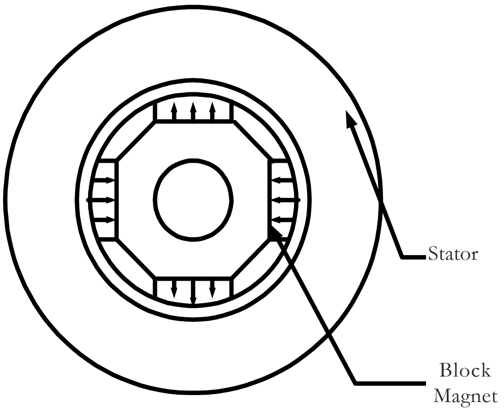

Figure 8 Block magnet rotor type PM machine

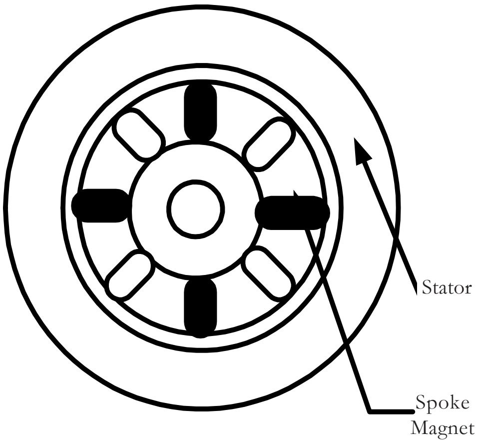

Figure 9 Spoke magnet rotor type PM machine

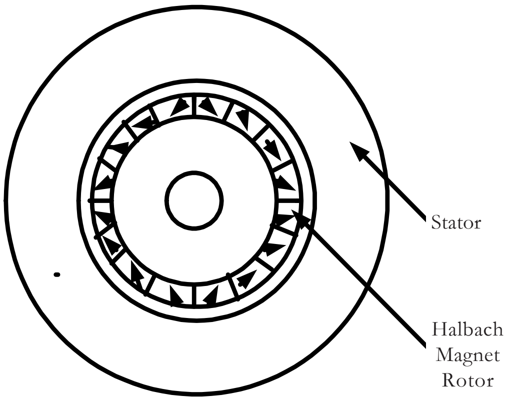

Figure 10 Halbach magnetized rotor type PM machine

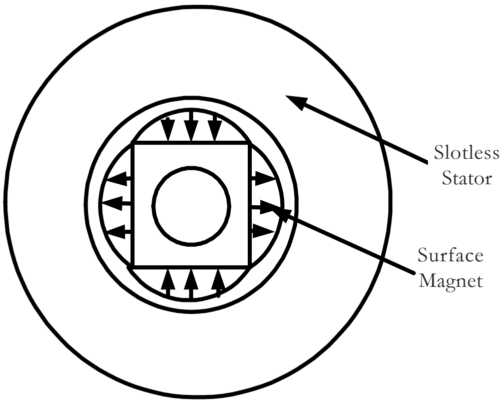

Figure 11 Slotless stator type PM machine

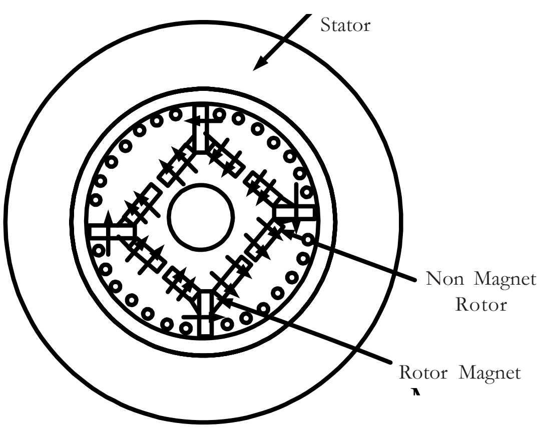

Figure 12 New design inset magnet rotor type PM machine

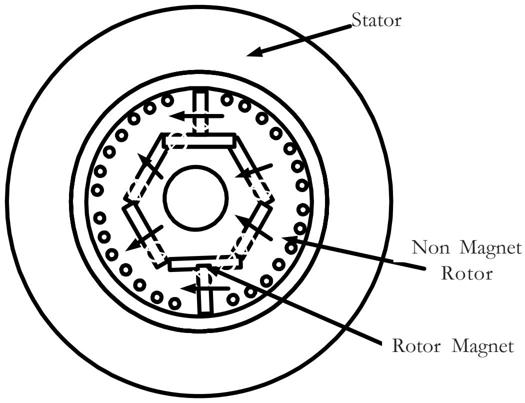

Figure 13 Specially direction magnetized rotor with cage type PM machine

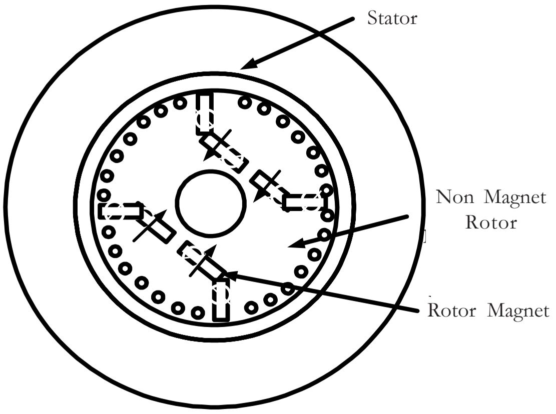

Figure 14 Inset magnet with damper bar rotor type PM machine

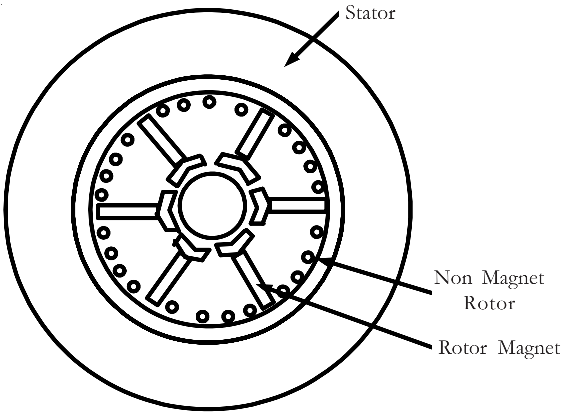

Figure 15 Radially magnetized rotor type PM machine

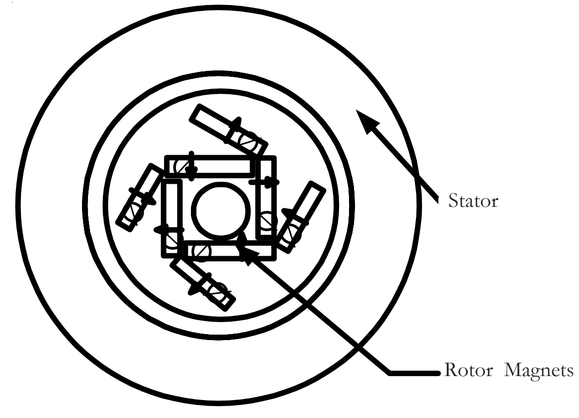

Figure 16 Special direction magnetized rotor type PM machine

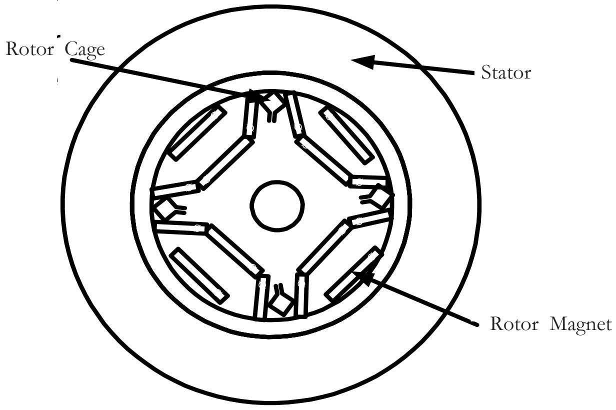

Figure 17 Interior double layer PM rotor type PM machine

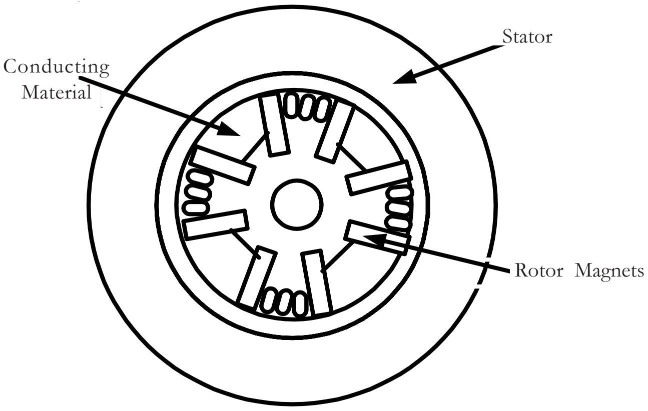

Figure 18 New design of PM rotor type PM machine

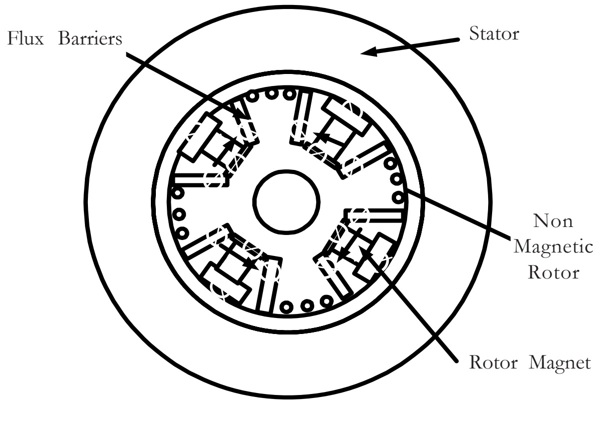

Figure 19 Hybrid magnetized rotor type PM machine

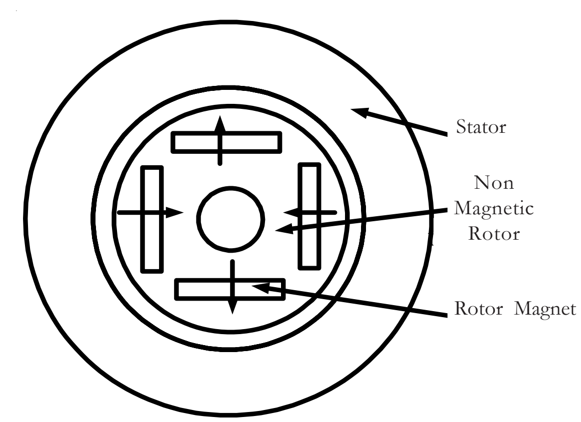

Figure 20 Classical configuration rotor type PM machine

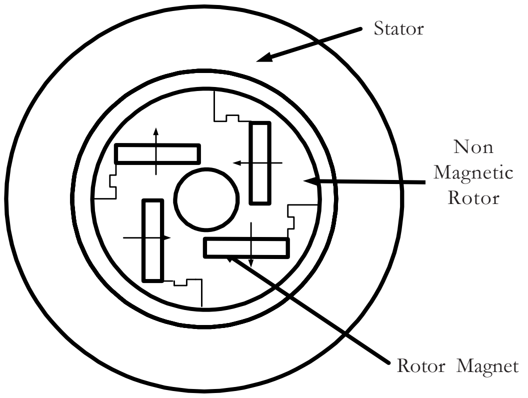

Figure 21 Rotor with buried magnets asymmetrically distributed rotor type PM machine

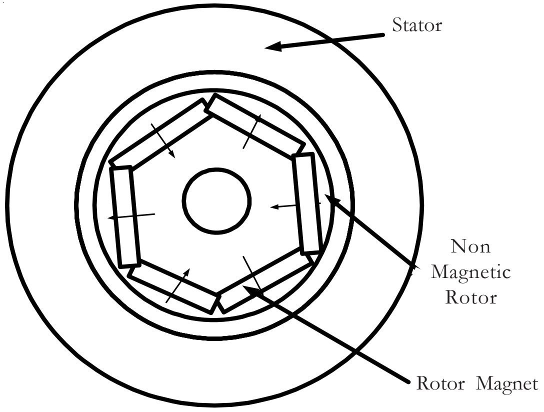

Figure 22 Interior six-pole magnet type rotor type PM machine

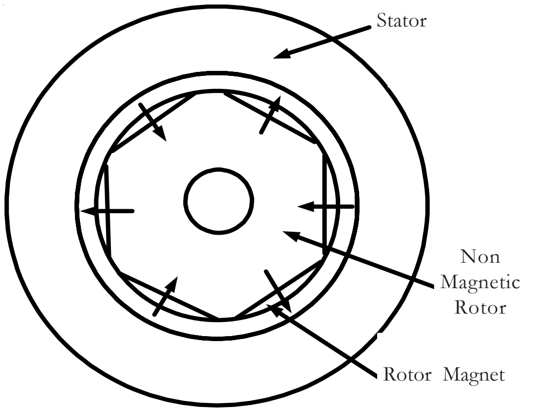

Figure 23 Bread loaf magnets rotor type PM machine

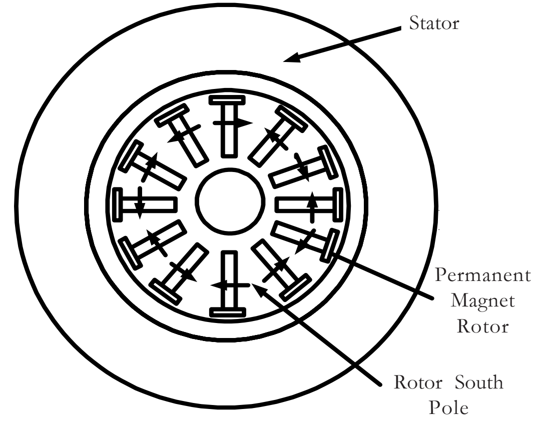

Figure 24 Tangentially magnetized rotor type PM machine

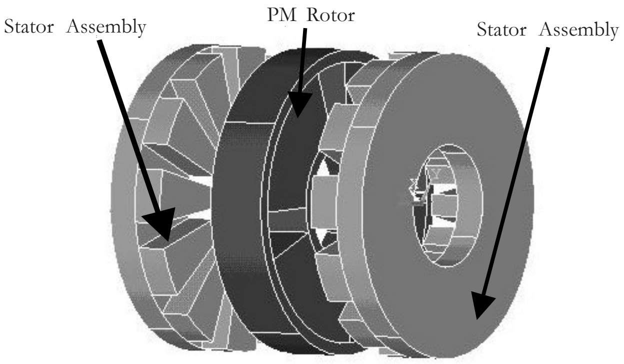

Figure 25 Axial field double stator PM synchronous motor

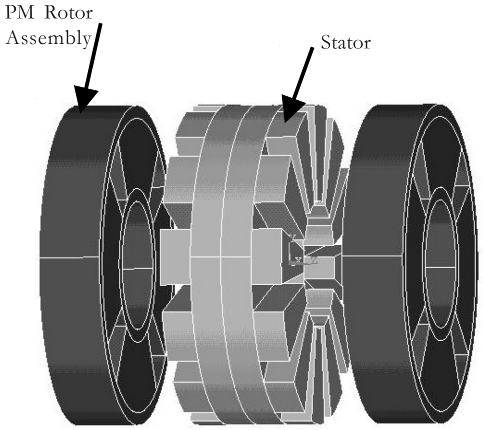

Figure 26 Axial field double rotor PM synchronous motor

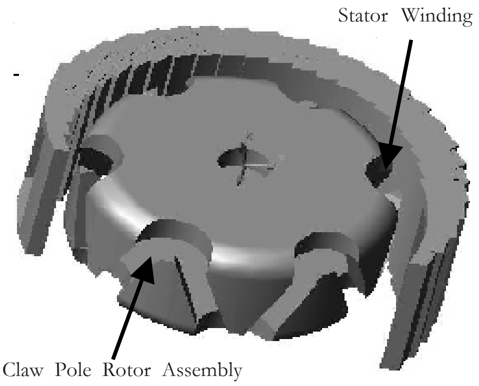

Figure 27 Claw pole rotor type PM axial flux alternator

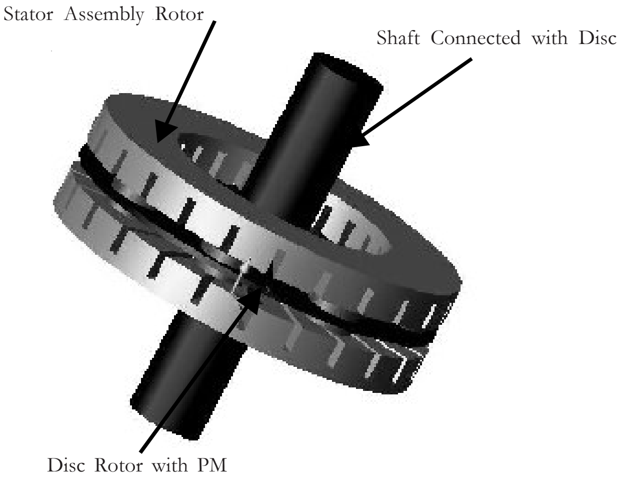

Figure 28 Disk rotor type PM axial flux alternator

The stator of PM synchronous motor is very similar to that of a polyphase induction motor. In last decade various geometries of PM synchronous motors have been used. They are usually based on the further improvements of power density and efficiency by adopting flux enhancement, armature reaction reduction and high-speed operation. Two main configurations of PM synchronous motors are surface magnet type where magnet are mounted on the outer surface of the rotor, and the buried magnet type where the magnets are mounted inside the magnetic structure of the rotor. Mountings the magnets to the surface of the rotor are the simplest and cheapest method for construction of PMBL motor. Surface mounted magnets are typically glued to the shaft and sometimes bonded with a non-conductive material. This surface mounting design tends to yield a small rotor diameter with small inertia, which is suitable for fast dynamic performance. Another type of surface magnet is the inset magnet motor. This machine has magnets that span less than one pole pitch mounted to the surface of the rotor, with an iron rotor tooth, filling the space between magnets. This design of a machine with a much higher reactance than one without the rotor tooth, has X_q larger than X_d. In this machine the saliency provides a significant reluctance torque as well as the magnet torque. The high reactance ratio makes it possible the flux weakening operation of PM synchronous motor and also helps to reduce harmonic copper losses in the motor. Another method for mounting the magnet on the surface of the rotor is to imbed them in the interior of the rotor. Interior design provides mechanical robustness and smaller air gap, which results in a component of reluctance torque in addition to the developed torque due to PM excitation.

Surface and interior magnet mounted designs are radially magnetized, therefore no-load flux density is limited to magnet flux density. If higher air gap flux density is required, the interior magnet design may be employed where the magnets are magnetized in the circumferential direction with the poles in opposition to concentrate the flux at the pole compared to magnet surface. The various type of PM rotor geometries include the permasyn motor[41], siemosyn motor[6], isosyn motor[41], Binns PM rotor geometry configuration[41] and GE design PM rotor[6]. Another type of PMBL machine is axial field machine in which direction of the magnetic field is axial instead of the radial field. The claw pole PM machines used in automobiles alternator and disk rotor machine with very low rotor inertia, are the example of axial flux machines. The various configurations of axial field PMBL machine include single stator and single rotor, single stator sandwiched between two rotors (double air gaps), single rotor sandwiched between two stators (double air gaps) and a variety of multiple stators and rotors (multiple air gaps)[88-104]. These different configurations of the PM machines are summarized in the Table 2. In this table different PM rotor geometries are compared on the basis of their advantages, limitations, power rating and field of applications.

APPLICATION POTENTIALS AND FUTURISTIC TRENDS

In the field of PMBL machines technology the current research include search of high energy density PM materials, application of new rotor geometries for effective utilization of the magnet flux. The recent trends in PMBL machines are in the area of improvement in the design and manufacturing techniques, reduction and elimination of torque ripple and cogging torque by employing appropriate rotor geometry. The PM materials ranging from ferrite to alnico and rare earth magnets have gradually changed the cost and size of these PMBL machines[1-39]. Various types of PMBL machines include the PMSM and PMBLDC motor[40-80]. Application of finite element analysis (FEA) is used for the magnetic field computation and analysis of performance of PMBL machines with different rotor configurations. FEA is a useful tool for improving the existing design of PMBL machines towards the performance improvement and design optimization of theses machines. The resulting PMBL machines are quite accurate and verifiable versus laboratory test data on these machines[105-113].

For high performance applications, torque smoothness is essential. It is very important to consider torque ripple minimization by design improvement or by using appropriate rotor geometry. The PMSM have great potential for both ripple torque and cogging torque minimization by adopting fractional slot pitch windings or skewing of the rotor magnet. Whereas PMBLDC motor requires controller based techniques for minimizing pulsating torque by means of active cancellation algorithm[81-87].

Axial flux permanent magnet (AFPM) machines are having ability to produce high torque. The PMBL machines have great potential for diverse applications ranging from high performance servo drive needed for precise tool manufacturing to energy efficient drive for various consumer product and industrial applications. Axial flux permanent magnet brushless motors develop high torque even in the low speed range with high power density and efficiency. The axial flux motor is used as a wheel to an electric motorbike and its characteristics are very promising for use in electric vehicles (EV's) applications[118-121]. In the aerospace applications PMBL generators are best suited due to its high specific output power (output power/ volume), which helps in substantial fuel economy and improvements in payload capability of aircraft. Another application of PMBL machines are in ship where these machines are used for power generation and ship propulsion[114-126].

CONCLUSION

An exhaustive review of different configurations of PMBL machines has been presented, which includes use of new PM materials, different rotor geometries and their construction and optimization. The present status of permanent magnet machines has revealed that these machines have great potential for use in a number of applications. The latest manufacturing techniques, intelligent closed loop control, sensorless operation and field weakening have resulted in wide range applications and provided a broad prospective to these machines.

Table 2 Comparison of different PM rotor geometries

Sr No	Name of the Rotor Configuration	Advantages	Limitations	Power Rating	Application	Figure No
1.	Embedded magnet rotor	Line start, radial field compact magnet	Rotor cage bars	Small, medium	Pump, fan, irrigation, transport machines	2,6
2.	Buried magnet rotor	Less chances for demagnetization	Difficult to fabricate	Small, medium	High speed applications	3,21
3.	Bonded ring magnet rotor	Compact magnet, easy to magnetize, reduce cogging torque	Magnets are epoxied or bonded to steel yoke	Medium	Used in low rating motor	4
4.	Circumferential magnet rotor	Line start, Cost effective, low energy density magnets, less cogging	Fluxes are collected and concentrated by soft iron pieces	Medium and large	Pump, molding machines, compressor	5
5.	Inset magnet rotor	High torque/inertia ratio	Expensive to wind	Large rating upto 5MW	Servo system and industrial drive	7,12
6.	Block or arc magnet rotor	Rugged construction, reluctance torque, excellent torque linearity	Consequent pole configuration is used	Medium and large	High performance drives servo drive, spindle tool	8
7.	Spoke magnet rotor	Low cost design, good saliency, best suited to sine fed motor	Higher inertia of the rotor assembly	Medium and high	Spindle tool variable speed drive	9
8.	Halbach magnetized rotor	Ripple free torque, very high speed operation, higher air gap flux density	Special techniques are needed to magnetized the rotor	Small and medium	Used in high speed applications	10
9.	Slotless stator type PM rotor	Zero cogging torque	Costly, difficult to fabricate	Small and medium	Used for high speed turbo application	11
10.	Specially direction magnetized with cage	Line start capability	Braking torque during starting	Medium power rating	Used in compressor and pump drive	13
11.	Inset magnet with damper bar rotor	High torque/inertia ratio	Expensive to wind	Large rating upto 5MW	Industrial drive	14
12.	Radially magnetized rotor	Easy to construct, and less costly	Poor utilization of PM flux	For medium and high	Used in industrial drive	15
13.	Specially direction magnetized rotor	Higher flux density in air gap	Expensive technique	For medium power rating	Medium power rating drives	16
14.	Interior magnet rotor	Reluctance torque, firmly placed magnets	Difficult to fabricate	Small and medium	High speed and higher torque applications.	17, 22
15.	New design of PM Rotor	Higher air gap magnetic field is produced	Intricate construction, requires special production techniques	Medium and large power rating	Wide range of frame size motors efficient integral horse-power drives	18
16.	Hybrid magnetized rotor	Line start capability	Rotor cage bars are needed	Medium and high	Compressors and fans	19
17.	Classical configuration buried PM rotor	Suitable for rapid acceleration and deceleration	Require high energy density magnets	Large rating upto 5MW	High speed drive, servo application	20
18.	Bread loaf magnets type rotor	Lower cost	Special geometry is needed	Small and medium	Low speed drives	23
19.	Tangentially magnetized rotor	Less cogging torque	Difficult to fabricate	Small and medium	High performance servo drives	24
20.	Axial flux PM rotor	Easily magnetized, low cost and zero cogging torque	Iron losses increases with higher speed	Medium	Medium speed, medium power application	25,26
21.	Claw pole machines	Use concentrated winding for high torque	Generally use with single phase system	Low and medium	Timer circuit, car alternators	27
22.	Disc motor	Low cost, smooth rotation with zero cogging	Excessive eddy current losses in the stator above 1000 rpm	Low and medium	Record players, VCR players, CD players and floppy disc drives	28

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