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Comparison and analysis of magnetic-geared permanent magnet electrical machine at no-load

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Abstract: Magnetic-geared permanent magnet (MGPM) electrical machine is a new type of machine by incorporating magnetic gear into PM electrical machine, and it may be in operation with low-speed, high-torque and direct-driven. In this paper, three types of MGPM machines are present, and a quantitative comparison among them is performed by finite element analysis (FEA). The magnetic field distribution, stable torque and back EMF are obtained at no-load. The results show that three types of MGPM machine are suitable for different application fields respectively according to their own advantages, such as high torque and back EMF, which form an important foundation for MGPM electrical machine research.

Key words: magnetic gear, MGPM electrical machine, quantitative comparison, finite element analysis, no load

1. Introduction

Gears and gearboxes are extensively used for speed regulation and torque transmission in some industrial applications. It is well known that the reliability of mechanical gear is high and the structure is simple, but it also suffers from some inherent problems such as contact friction, noise and heat, of which the vibration and reliability are of great concern. In contrast, magnetic gear (MG) has some advantages, such as low noise, easy maintenance, high reliability and overload protection due to the physical isolation between the input and output shafts [1, 2].

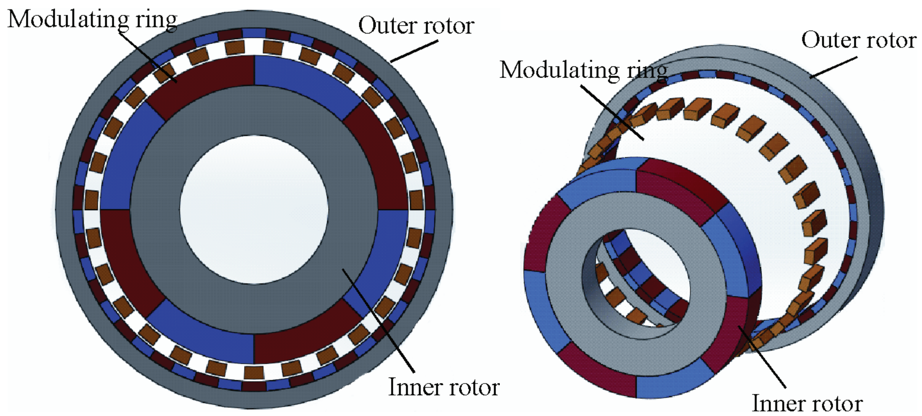
However, MGs has attracted little attention due to the poor torque density and complex structure for a long time. In 2001, the coaxial magnetic gear (CMG) was proposed [2-5], which has the higher torque transmission ratio and torque density. For obtaining the higher output torque at low speed and increasing the efficiency of electrical machine, the magnetic-geared permanent magnet (MGPM) electrical machine has been put forward by some specialists and scholars, which is a hybrid of PM electrical machine and MG [6, 7].

Recently, MGPM electrical machines have been applied in some fields, such as vehicle traction, wind power and aerospace [8-10]. In this paper, three types of MGPM electrical machines are compared to reveal their fundamental features and applications. The corresponding performances are calculated and compared by FEA at no-load, such as magnetic field distribution, torque and back EMF, etc.

2. Coaxial magnetic gear

CMG was proposed by Atallah and Howe as shown in Figure 1, which mainly includes an inner rotor, modulation ring and outer rotor. It can be found that the PMs on the inner rotor are less than that on the outer rotor. The modulation ring is composed of some irons with high-permeability. Owing to the modulation ring, the magnetic field produced by PMs can be modulated to match the number of space harmonic and the torque can be transmitted between its inner and outer rotor.

By adopting the coaxial topology, the utilization rate of PMs can be significantly improved. A higher torque density is obtained in CMG since all the PMs simultaneously contribute to torque transmission [3, 4].



a) 2D view b) 3D view

Fig. 1. Topology structure of CMG

By defining p_o, p_i as the pole pair number of outer and inner PMs, respectively, and n_s as the number of iron blocks in the modulation ring, which can be calculated by (1)

$$n_s = p_o + p_i . \tag{1}$$

Due to the magnetic field modulation function from the modulation rings, the speed and torque between the inner and outer rotor can be separately expressed as

$$T_i = -GT_o , \tag{2}$$

$$W_i = -GW_o , \tag{3}$$

$$G = \frac{p_o}{p_i}, \tag{4}$$

where W_o, W_i represent the outer rotor speed and inner rotor speed respectively, T_o, T_i represent torque of the outer and inner rotor respectively and G is the transmission ratio. The minus sign indicates that the two rotors rotate in opposite directions.

3. Topology structure of MGPM electrical machine

With the increasing demand for driving system, MGPM electrical machine becomes favorite since it has the higher torque density and transmission efficiency. It can be applied in wind power, electric vehicles, and electric ship propulsion, industrial robots and home appliances, etc. Recently, many MGPM electrical machines have been proposed and a large number of researches about the design, analysis and optimization have been carried.

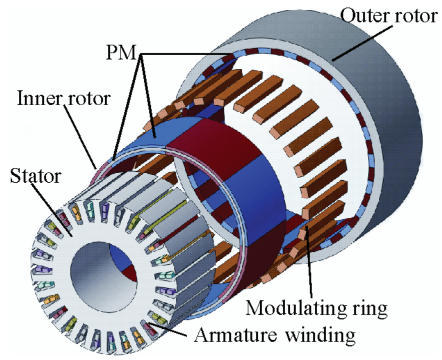
However, MGPM electrical machines have some disadvantages, such as complex mechanical structure, weak coupling between PM field and armature field. The existing MGPM electrical machines can be mainly classified as three types, outer-rotor MGPM machine (ORMGPM), Sandwiched Armature Stator MGPM machine (SASMGPM) and Two sets Armature windings MGPM machine (TAWMGPM), the 3-D views of which are shown in Figure 2.

Figure 2 (a) shows the structure of ORMGPM electrical machine, which is a simple combination of an outer-rotor PM machine with a CMG. The inner rotor could operate as the rotor of PM machine, as well as the inner rotor of CMG. The armature windings are placed in the stator slots and the modulation rings are fixed between the two rotors.

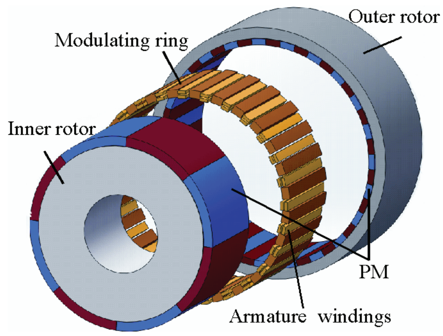
There are three layers of PMs mounted on the surface of rotor core. In this machine, the torque can be transmitted through the inner rotor and outer rotor based on magnetic field modulation, and the stable electromechanical energy conversion can be realized by the electromagnetic field from the PMs and armature windings. ORMGPM electrical machine incorporates the features of outer-rotor PM machine and magnetic gear, and also has the higher reliability than the other MGPM electrical machines. However, the mechanical construction of the machine is complex due to the two rotating parts and three air gaps in the machine.

In Figure 2 (b), the structure of Sandwiched Armature Stator MGPM (SASMGPM) electrical machine is much simpler than that of outer-rotor MGPM electrical machine. It consists of three main concentric components, the inner rotor with PMs mounted on its outer surface, the modulation ring with iron blocks and armature windings, and the outer rotor with PMs mounted on its inner surface. Different from the ORMGPM electrical machine, it has no independent stator, but the armature windings are sandwiched between the inner and outer rotor. That is, the armature windings are directly inserted in the modulating rings. Due to the two rotating parts and two air gaps of SASMGPM electrical machine, it can be divided into two machines and a MG. Under its operating condition, one machine works as an inner-rotor PM machine with high speed, while the MG is engaged to scale down its rotational speed, and the other machine can operate as an outer-rotor PM machine with low speed.

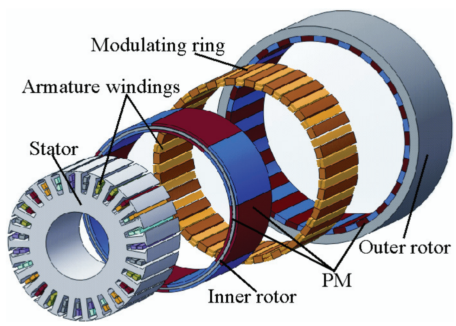
As shown in Figure 2 (c), the two sets armature windings MGPM (TAWMGPM) electrical machine has two sets of armature windings, which integrates the above mentioned MGPM machines. The structure of this machine is also complex, so that it can not be manufactured easily. However, the interior space of the machine and PM can be made full use to improve its power density.



a) ORMGPM



b) SASMGPM



c) TAWMGPM

Fig. 2. Topology structure of MGPM electrical machine

4. Performance comparison

Although the structure, operating principle, electromagnetic analysis and experimental measurement for the three types of MGPM machines have been presented, a quantitative of comparisons among them have not found in the existing literatures. The performance comparison of these machines can be obtained by FEA.

The simulation models with same specifications are built for fair comparison, such as the outer diameter, dosage of PM, rated speed and air gap length, etc. Table 1 gives some design parameters of the MGPM machines.

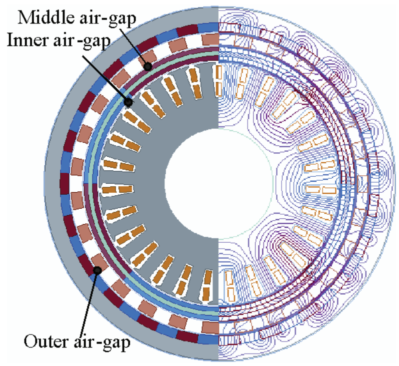
Table 1. Main design parameters of MGPM machines

MGPM machine type	ORMGPM	SASMGPM	TAWMGPM
Rated inner-rotor speed (rpm)	750		
Rated outer-rotor speed (rpm)	130		
Phase number	3		
Number of outer rotor pole-pairs	23		
Number of modulation rings	27		
Number of inner rotor pole-pairs	4		
Slot number of stator	27		27
Coil number of per phase	9	9	18
Overall outside diameter (mm)	160		
Thickness of modulating ring (mm)	5		
Inner air-gap length (mm)	1		1
Middle air-gap length (mm)	1	1	1
Outer air-gap length (mm)	1	1	1
PM material	NdFeB		

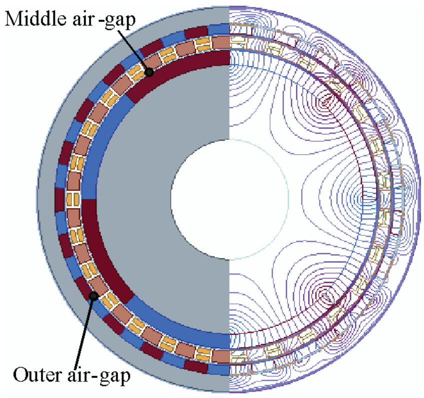
From Table 1, it can be found that the ORMGPM machine and TAWMGPM machine have the more complex construction since three air gaps are designed in these machines, while the SASMGPM machine has only two air gaps, as shown in Figure 3. According to Table 1 and Equation (3), the transmission ratios of all the machines are 5.75.

It should be attention that the mechanical structure of the three-air-gaps topology is much more complicated due to the three layers of PMs that mounting on two rotors, which undoubtedly increases the manufacturing cost.

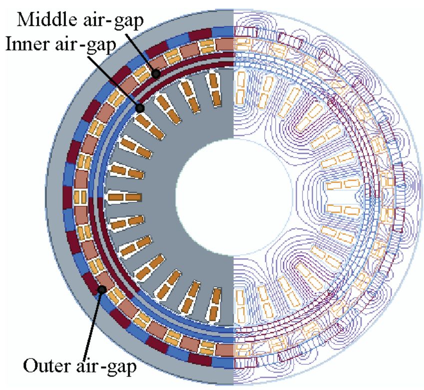
The static and transient analyses are carried out by Maxwell software for obtaining their electromagnetic property. In Figure 3, the left one shows 2D simulation models of MGPM machines and the right one shows its magnetic field distributions at no-load. As it can be seen, the magnetic circuit structures of ORMGPM machine and TAWMGPM machine are relatively complex compared with that of SASMGPM machine due to the three-air-gaps topology, which leading more stator core loss.



a) ORMGPM



b) SASMGPM



c) TAWMGPM

Fig. 3. 2D models and mgnetic field distribution at no-load

Figure 4 shows the middle air-gap flux density distributions of MGPM machines at no-load. It can be found that the flux density of SASMGPM electrical machine is much larger than the others. Because the magnetic flux in the middle air-gap produced by all the PMs in SASMGPM electrical machine, but only a part of magnetic flux produced by PMs in two other machines can pass middle air-gap due to their special structure of inner rotor. The difference of the structure between ORMGPM and TAWMGPM electrical machine is the number of armature winding, so the flux density distributions at no load are same.

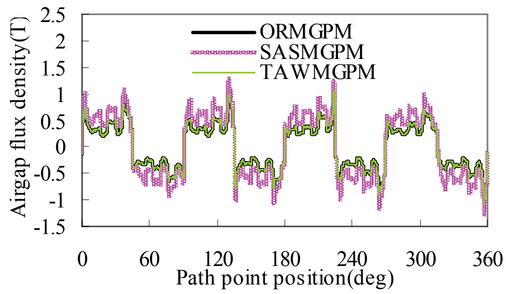


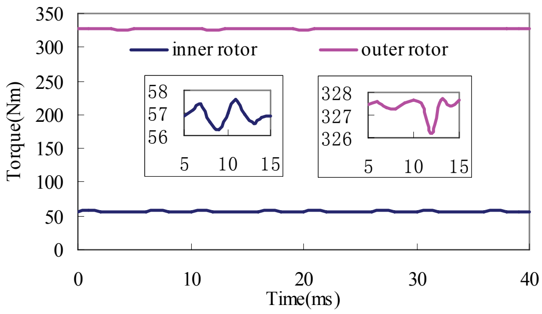
Fig. 4. Middle air-gap flux density distributions

The stable torque waveforms are given in Figure 5. The transmission ratio is about 5.751 from Equation (2), which is consistent with the theoretical expectation. The torque of inner rotor in SASMGPM electrical machine is approximately 89.5 Nm, but the value in the other machines is about 57 Nm. Owing to the modulation ring or magnetic gear, the output torque of outer rotor can be increased by 5.751 times compared to the torque of inner rotor. Therefore, the higher torque density can be obtained in SASMGPM electrical machine.

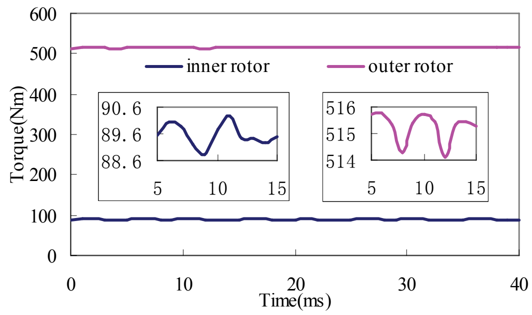
The no-load performance at the rated speed can be obtained from the armature windings. Figure 6 shows the winding flux linkage and the winding EMFs are given in Figure 7. It can be seen that the flux linkage and the back EMFs of TAWMGPM electrical machine is much larger than that of the others. Because of the space harmonic magnetic field produced by modulation method, their back EMFs also contains more harmonic components.

5. Conclusions

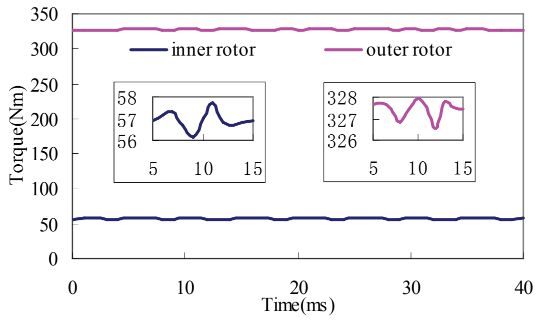
In this paper, a quantitative of comparisons for the three types of MGPM electrical machines are performed. The main electromagnetic performances at no load are analyzed and discussed, such as magnetic field distribution, stable torque characteristics and back EMF. Each MGPM electrical machine can be applied in a special case due to its advantages. For example, ORMGPM electrical machine is suitable for wind power and direct-driven electric vehicles owing to its higher reliability, and SASMGPM electrical machine is most suitable for the direct-driven applications with the low-speed and high-torque because of its high torque density and simple structure. TAWMGPM machine topology can be worked as a generator due to its high back EMF and power density.



a) ORMGPM



b) SASMGPM



c) TAWMGPM

Fig. 5. Stable torque characteristics

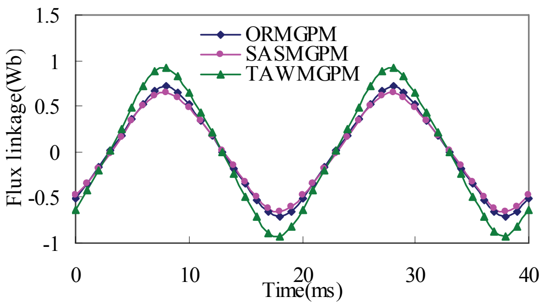
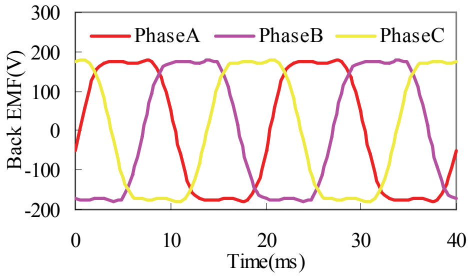
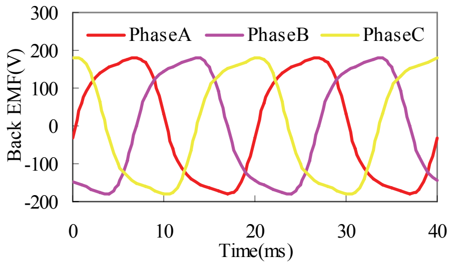


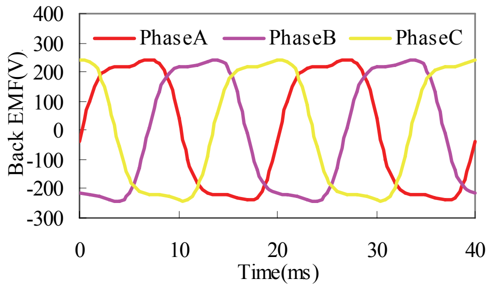
Fig. 6. Flux linkage waveforms of armature winding



a) ORMGPM



b) SASMGPM



c) TAWMGPM

Fig. 7. Back EMF waveforms at no load

Acknowledgements

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