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A New Structure for the Magnetic Gear

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ABSTRACT In this paper, a new structure for increasing the magnetic gear torque is proposed, which has high torque density and high mechanical properties. The permanent magnets (PMs) of the outer rotor are spoked and magnetized along the tangential direction. The PMs of inner rotor are the surface-mount type and magnetized in the radial direction. The PMs are fixed in the inner and outer rotors' iron yoke that the aim is to keep the PMs from falling off during the rotation. In order to reduce the amount of iron, it is considered to slot on the outer rotor. The two-dimensional finite element method is used for simulating the proposed model. The magnetic field and electromagnetic torque of the magnetic gear are calculated. Compared with the conventional magnetic gear, the results show that the torque transmission capability of the proposed magnetic gear can be substantially improved.

INDEX TERMS Magnetic gear, permanent magnets (PMs), magnetic field, electromagnetic torque, finite element method.

I. INTRODUCTION

With the development of new energy, electric vehicles and wind turbines have attracted much attention from research institutes and the outside world [1], [2]. Among them, mechanical gear is very important in power transmission. However, noise, vibration and other factors restrict the further development of mechanical gears. Magnetic gears based on permanent magnetic materials have the advantages of low noise, low vibration, maintenance-free and inherent overload protection [3]–[5], and were once considered the most likely to replace mechanical gears as the main force of torque transmission. Although magnetic gears have many advantages, the utilization rate of permanent magnetic materials is very low due to the influence of parallel shaft topology structure in the early stage, resulting in very low torque density of magnetic gears.

In recent years, the coaxial magnetic gear (CMG) has been put forward, and the utilization ratio of permanent magnet has been obviously improved. Many types of magnetic gears, such as linear, axial, harmonic and planetary magnetic gears, are proposed based on the principle of magnetic field modulation [6]–[10]. At the same time, Halbach array application pushes the torque capability of magnetic gears to a commanding height [11], and can greatly reduce torque ripple. For the next time, the research on magnetic gear mainly focuses on improving torque density and practicability. From changing the shape of the magnetic ring to optimizing the parameters of the magnetic gear has become a hot spot in this field [12]–[15], aiming at improving the torque density of the magnetic gear. In order to make the magnetic gears no longer confine themselves to fixed ratios, the magnetic gears with variable transmission ratios are proposed in literature [16] to make them more suitable for variable speed electric vehicles and wind turbines, thus increasing the practicability of magnetic gears. On the other hand, the use of high-performance permanent magnet materials has a positive effect on the torque of magnetic gears, for different properties of permanent magnet materials, the quality, volume and performance of magnetic gears are quite different [17]–[19]. At present, the combination of magnetic gear and motor has many advantages [20], so it is necessary to study the magnetic gear with light weight, small volume and high torque density.

In this paper, a magnetic gear topology modified by magnetic flux focusing effect is proposed. The PMs of inner rotor are the surface-mount type and magnetized in the radial direction. The permanent magnets (PMs) of the outer rotor are spoked and magnetized along the tangential direction. There are some slots in the outer rotor. The magnetic field and output torque of the model are calculated by the finite element method, and the harmonic content of the air gap magnetic field was analyzed.

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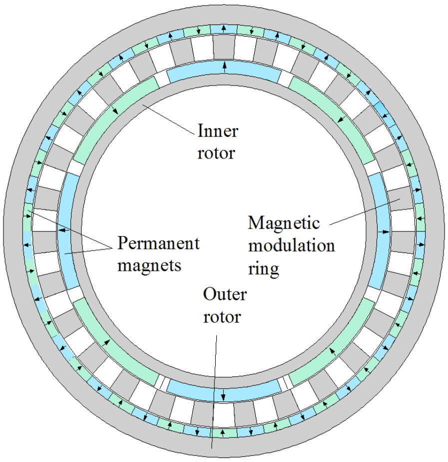

FIGURE 1. A conventional CMG.

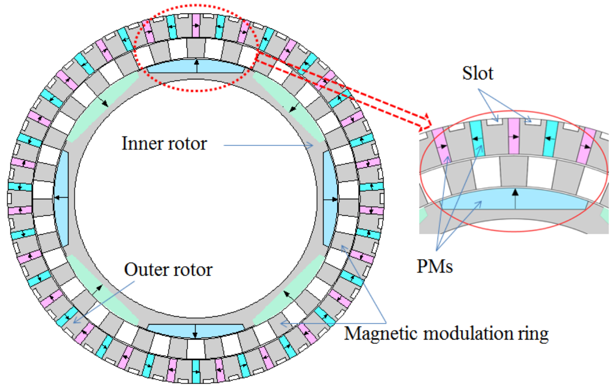

FIGURE 2. A improved model.

TABLE 1. Parameters for analyzed CMG.

Parameter	Value
Radius of the outer rotor (mm)	67.25
Thickness of the outer rotor (mm)	5.9
Thickness of the PMs on the outer rotor (mm)	2.7
Air-gaps (mm)	0.4
Thickness of the ferromagnetic segments (mm)	7.25
Thickness of the PMs on the inner rotor (mm)	4
Thickness of the inner rotor (mm)	3.4
Axial length (mm)	60
PMs	NdFeB
Remanence of PMs	1.1T
Pole pairs of the outer rotor	23
Pole pairs of the inner rotor	4
Arc coefficient	0.9

II. BASIC THEORY OF MAGNETIC GEAR

Fig. 1 is the structure of the conventional CMG established by Ansoft Maxwell software. Its basic parameters are listed in Table 1. It consists of two rotors and a magnetic modulation ring, which plays an important role in the modulation of the inner and outer air-gap. The number of ferromagnetic pole-pieces and permanent magnets satisfies the following relationship,

$$N_s = P_{in} + P_{out} \tag{1}$$

where P_{in} and P_{out} are the number of the inner and outer rotor permanent magnets pairs, respectively; N_s is the number of ferromagnetic pole-pieces.

The magnetic modulation ring mainly affects the inner and outer air-gap magnetic fields, so that the magnetic field excited by the internal and external permanent magnets can be effectively coupled to realize the torque transfer. The harmonic logarithm of the magnetic gear air-gap magnetic field is

$$p_{m,k} = |mp + kn_s| \tag{2}$$

where $m = 1, 3, 5 \ldots, \infty$, $k = 0, \pm 1, \pm 2, \ldots, \infty$.

The harmonic components in the air-gap have a specific number of spatial pole pairs and rotational speed. The angular velocity of the harmonic components of the inner and outer air-gap space is

$$\Omega_{m,k} = \frac{mp}{mp + kn_s}\Omega_r + \frac{kn_s}{mp + kn_s}\Omega_s \tag{3}$$

where $\Omega_{m,k}$ is the angular velocity of the spatial harmonic component, Ω_r and Ω_s are the rotation speed of the rotors and magnetic modulation ring, respectively.

When $k = 0$, there is no magnetic modulation ring, the angular velocity of a harmonic magnetic field is equal to the angular velocity of the inner and outer rotor. When $k \neq 0$, the angular velocity of a harmonic magnetic field is different. When $m = 1$, $k = -1$, the harmonic magnetic field is the most important harmonic except the fundamental wave. From equation (3), the angular velocity of the harmonic component is

$$\Omega_{1,-1} = \frac{p}{p - n_s}\Omega_r - \frac{n_s}{p - n_s}\Omega_s \tag{4}$$

In fact, due to the magnetic gear strength and stiffness constraints, the modulation ring is generally fixed. So, the gear ratio (G_r) of the CMG is

$$G_r = \frac{p_{out}}{p_{in}} \tag{5}$$

The improved magnetic gear is shown as in Fig. 2.

The inner rotor is the same as the conventional model which has one layer of permanent magnets with the arrangement of N-pole-S-pole-N-pole. The outer rotor permanent magnets are embedded into the outer rotor yoke and adopted a parallel magnetization method. The magnetic modulation ring acts as regulating the magnetic field inside and outside the air gap so that the output torques of the inner and outer rotors meets the transmission ratio. Considering the middle part of the outer yoke of the rotor does not affect the transmission of torque, on the premise of inner and outer rotor torque, the slotted yoke central, one hand to reduce the amount of iron. On the other hand, it also reduced the whole weight of the magnetic gear, and the mass density of the magnetic gear can be improved.

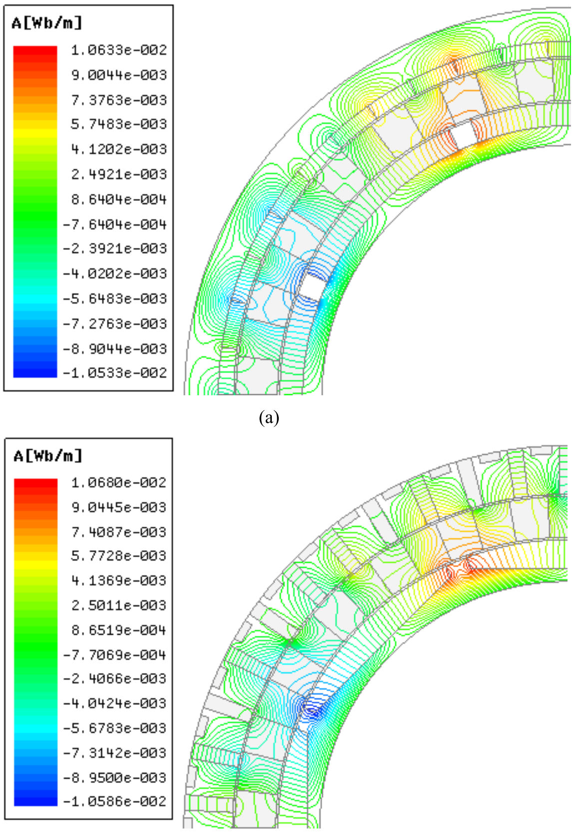

FIGURE 3. **Flux distributions. (a) Conventional model; (b) Improved model.**

III. SIMULATION ANALYSIS

In order to make the conventional model and the improved model comparability, the basic parameters of the two are guaranteed to be the same. Through modeling and finite element calculation, we compare the conventional and the improved model in terms of magnetic force line distribution, air-gap magnetic field, harmonic content and torque.

A. MAGNETIC FIELD ANALYSIS

Fig. 3 shows the magnetic field distribution of two different structures of magnetic gear. Most of the magnetic lines pass through the iron of the modulation ring to transmit torque, but there is also a part of the magnetic flux leakage. Fig. 3 is a local magnetic field map with no slotting and slotting. From Fig. 3(a), magnetic yoke part of the outer rotor is not through, therefore, in Fig. 3(b) for slotting and the transfer will not affect the torque transmission. After slotting, the amount of iron is reduced and the quality of the magnetic gear is reduced.

Fig. 4 is a comparison diagram of the internal and outer air-gap flux density. It is obvious that the air gap flux density of the improved model is larger than that of the conventional model. Of course, there is not only the fundamental component, but also a number of harmonics, and the harmonic spectrums of flux density are shown in Fig. 5 and Fig. 6.

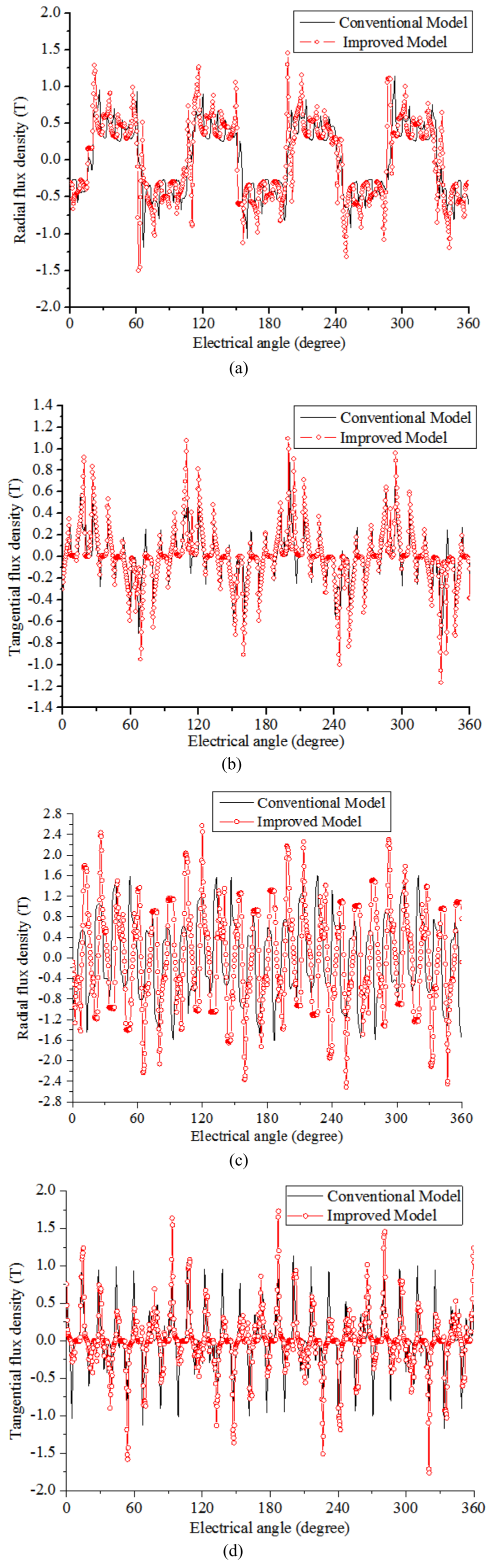

FIGURE 4. **Comparison of flux density waveforms. (a) Radial component in inner air-gap; (b) Tangential component in inner air-gap; (c) Radial component in outer air-gap; (d) Tangential component in outer air-gap.**

Fig. 5 is the magnetic density harmonic distribution maps of the inner air-gap. It can be observed that a large number of harmonics are introduced under the action of the

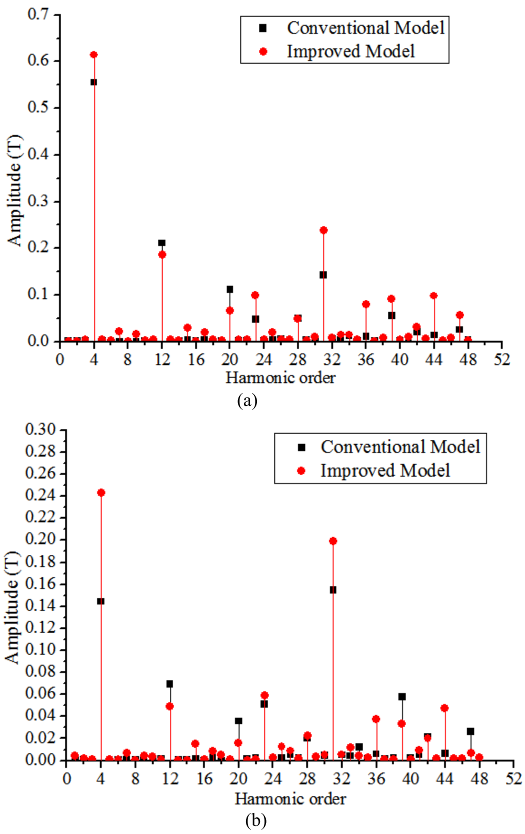

FIGURE 5. Harmonic spectra of flux density in inner air-gap. (a) Radial component; (b) Tangential component.

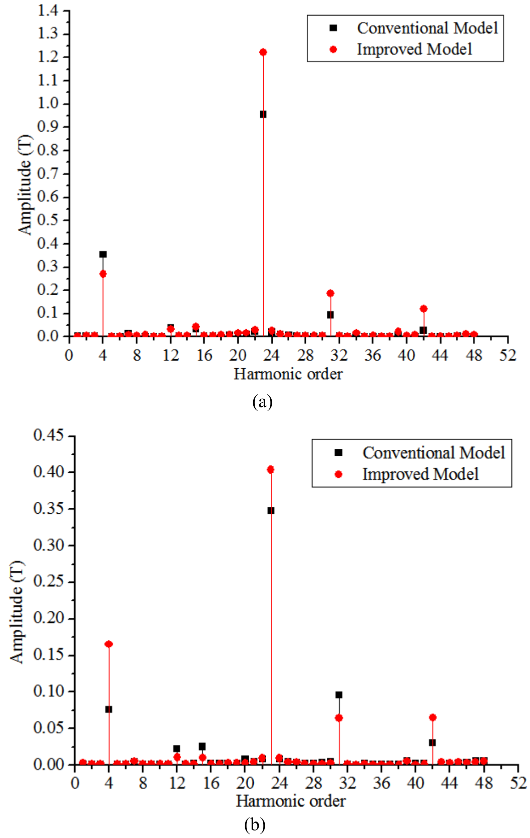

FIGURE 6. Harmonic spectra of flux density in outer air-gap. (a) Radial component; (b) Tangential component.

modulation ring. The main harmonics are 4, 12, 20, 23, 28, 31, 36, 39 and 44. The largest amplitude is 4 harmonic, and it is the highest harmonic generation of torque. As can be seen from Fig. 5, the improved model enlarges the amplitude of the fundamental wave, and the difference of the other harmonic values is not much.

Fig. 6 is the magnetic density harmonic distribution maps of the outer air-gap. It can be observed that the change of harmonic in the outer air-gap is not very big, and it mainly contains 4, 23 and 31 harmonics. The amplitude of the 23 harmonic is the largest, which is the basic harmonic in the outer air-gap. In the same way, the improved model improves the amplitude of the 23 harmonic, and it is helpful to increase the output torque of the outer rotor.

B. TORQUE-ANGLE CURVE

Static torque is an important parameter to measure the performance of the magnetic gear. The torque-angle curve of the conventional model and the improved model is shown in Fig. 7. It is obvious that the torque-angle curve is sinusoidal. When the electric angle is 90°, the static torque reaches the maximum value. The inner rotor torque of the conventional and improved model are 12.96N·m and 24.39N·m respectively. The outer rotor torque of the conventional and improved model are 74.52N·m and 140.40N·m, respectively. The torque is twice times closer to the original value. At the same time, the ratio of inner and outer torque is equal to the ratio of permanent magnet pole pairs for 1:5.75.

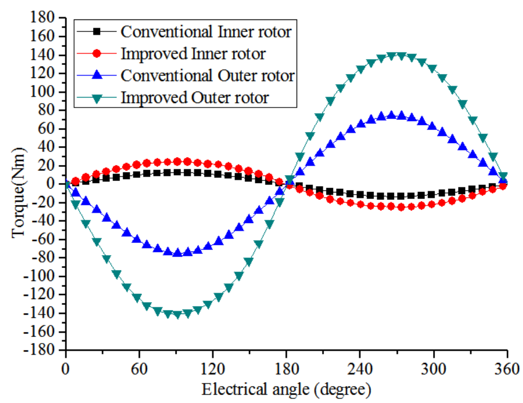

FIGURE 7. Static torque-angle curve.

Fig. 8 is the steady state torque of the two models, the inner rotor speed is 690r/min, and the outer rotor rotates in the opposite direction by 120r/min. The simulation shows that the inner torque of the conventional model and the improved model fluctuate within the range of 12.879N·m to 13.041N·m and 24.14N·m to 25.01N·m respectively, and the outer torque fluctuates within 74.472N·m to 74.63N·m and 140.31N·m to 140.48N·m respectively. Since the inner rotor has fewer poles

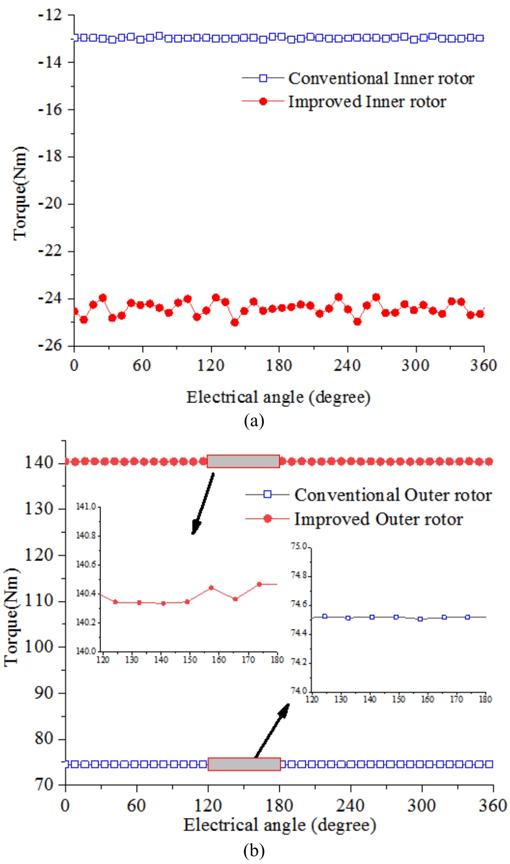

FIGURE 8. **Dynamic torque curve. (a) Inner rotor; (b) Outer rotor.**

TABLE 2. **Quantitative comparison among two MGs.**

	Conventional Model	Improved Model
PMs Weight (kg)	0.968	0.5967
MG volume(m^3)	8.65*10^-4	
Outer torque (N·m)	74.519	140.397
Torque density (kN·m/m^3)	86.14	162.31

than the outer rotor, the inner torque ripple is larger than that of the outer rotor but still within the control range.

C. TORQUE DENSITY

The improved model shows increased the inner and outer rotor torque by raising the inner and outer air gap flux density. Compared with the conventional model in terms of the amount of permanent magnets, the quantity of the improved model permanent magnets is significantly reduced. The torque density of the magnetic gear is greatly increased due to change the inner permanent magnet shape of the magnetic gear and the magnetization of the outer permanent magnet. The volume, mass and torque density of the permanent magnet of the magnetic gears is calculated, as showed in Table 2.

According to the calculation, the permanent magnet dosage of the conventional model and the improved model is 0.968kg and 0.5967kg respectively and the mass of the permanent magnet is reduced by 38.36%. Moreover, the torque density is also increased from 86.14kN·m/m^3 to 162.31kN·m/m^3.

IV. CONCLUSION

In this paper, we improved the conventional model for the problem of low torque density and low mechanical strength of the magnetic gear. By changing the shape of the inner permanent magnet and the magnetization of the outer permanent magnet, the two models are simulated by two dimensional finite element method and the electromagnetic field and torque of the magnetic gear are calculated. Simulation results show that the improved model can improve the air gap flux. The inner rotor torque is increased from 12.96N·m to 24.39N·m, and the outer rotor torque increased from 74.52N·m to 140.40N·m. In addition, the improved model reduces the quality of the permanent magnets and helps to improve the utilization of the permanent magnets. It can be observed that the improved model is helpful to improve the torque density, and can be used for reference for the design of magnetic gear.

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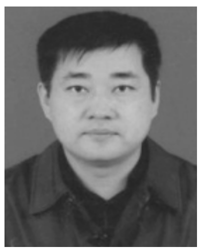

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