*Progress In Electromagnetics Research Letters, Vol. 97, 69–76, 2021*

# Comparative Analysis of Electromagnetic Performance of Magnetic Gear

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**Abstract**—In order to investigate the influence of different magnetization modes on the electromagnetic performance of magnetic gear, four models of magnetic gear with different magnetization modes are established. The finite element method is used to simulate the four models and compare their performances. The distribution of magnetic flux lines, air gap magnetic field, harmonic distribution, static torque, and dynamic torque are calculated, respectively. The simulation results show that the coaxial magnet gear with Halbach array has larger air gap flux density amplitude, smaller air gap harmonic content, and higher output torque than the other three kinds of magnetic gears.

## 1. INTRODUCTION

With the progress of industrial technology and the development of new energy technology, the stable operation of electromechanical system has always been a very important issue. Mechanical gear has always been an important part of the transmission mechanism. However, mechanical gear has inherent defects, such as being easy to break teeth, needing frequent maintenance, and noise. So it is necessary to find a better gear to replace it. Magnetic gear is an electromagnetic device driven by non-contact magnetic force, which has the advantages of low noise, low vibration, maintenance free, and inherent overload protection [1–3]. At present, magnetic gears are used in many low-speed and high torque situations, especially in combination with permanent magnet motors, such as electric vehicles [4, 5], wind power generators [6, 7], and marine electric propulsion [8, 9].

The concept of magnetic gear can be traced back to 1913 and was put forward by B. Brukwici. However, scholars did not pay attention to this aspect, mainly due to the poor performance of magnetic materials at that time, low transmission efficiency, and low torque density. In [10], Atallah and Howe proposed the concentric magnetic gear topology for the first time, that is, the inner and outer rotors and the magnetic ring have a common center. The special structure is shown in Fig. 1. The torque density of the magnetic gear with this structure can reach $100\,\mathrm{kN{\cdot}m/m^3}$. Linear magnetic gear [11] and concentrated magnetic gear [12] have come out one after another. In 2007, a magnetic harmonic gear was proposed by a British professor, whose transmission ratio can be as high as 20 : 1 [13]. In [14], a superconducting material is proposed to replace the iron core on the magnetic ring, which greatly enhances the air gap magnetic flux density and improves the output torque of the magnetic gear. A magnetic gear with pole shape is proposed in [15]. The electromagnetic characteristics of the magnetic gear are analyzed and calculated by box-Behnken method, and the torque ripple is reduced by 1.27%. In [16], a systematic torque surface method is proposed, which decouples the average torque and torque ripple in the magnetic gear. The harmonic and torque pulsation in the average torque are derived, and the results are in good agreement with the finite element calculation results. In [17], the authors summarized the influence of polar logarithm on gear performance, introduced the new

*Received 15 March 2021, Accepted 2 April 2021, Scheduled 7 April 2021*

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pulsation coefficient, and explained why the design of non-integer gear ratio is often smaller than that of integer gear ratio. Although the output torque of magnetic gears with spoke structure and Halbach array structure is higher than that of conventional magnetic gears, the quantitative performance comparison of these structures is less. Therefore, it is necessary to study the magnetic gears with different magnetization directions.

In this paper, four kinds of magnetic gears with different magnetization modes are analyzed and compared. The four models are conventional radial magnetization, inner rotor spoke, outer rotor spoke, and Halbach array. The simulation software *ANSYS* is used to model and calculate the magnetic gear. The distribution of magnetic flux lines, the distribution of air gap magnetic field, and the harmonic content are compared, respectively, and the torques of four kinds of magnetic gears under static and dynamic torque are compared. The results show that magnetic gear with Halbach array can provide greater transmission torque.

## 2. BASIC THEORY AND MAGNETIC FIELD ANALYSIS

### 2.1. Basic Theory of MHG

As shown in Fig. 1, magnetic gear consists of the following 3 parts: inner rotor, outer rotor, stationary steel segment. The permanent magnet is installed on the inner and outer rotors and is radially magnetized. The inner rotor rotates at high speed and the outer rotor at low speed. The rotation speed of the two rotors is in accordance with a certain proportion. The number of magnetic stationary steel segments needs to meet the following relationship [11]:

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

where $n_s$ is the number of stationary steel segments, and $P_{in}$ and $P_{out}$ are the numbers of pole pairs of the inner and outer rotors, respectively.

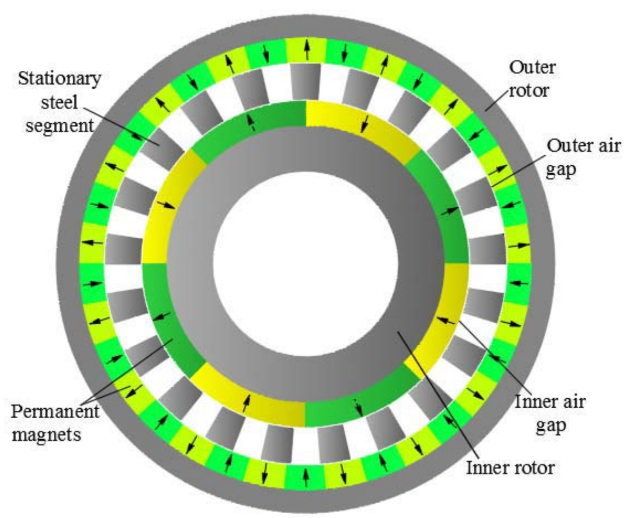



**Figure 1.** Conventional magnetic gear.

The inner rotor rotates at high speed and is connected with the input end, while the outer rotor rotates at low speed and is connected with the load. The stationary steel segment in the middle mainly plays the role of magnetic field modulation. The permanent magnet on the inner and outer rotors modulates many fixed harmonic components through the effect of the stationary steel segment, which affects the inner and outer air gap magnetic fields and makes the inner and outer rotors rotate. The magnetic field excited by the sub permanent magnet can effectively couple and generate the transfer torque. The harmonic components in the air gap have specific space pole pairs and rotational speeds, and the angular velocities of the harmonic components in the inner and outer air gaps are expressed as:

$$\Omega_{m,k} = \frac{mp}{mp + kn_s}\Omega_r + \frac{kn_s}{mp + kn_s}\Omega_s \tag{2}$$

where $m = 1, 3, 5, ..., \infty$; $k = 1, 2, 3, ..., \infty$; $p$ is the number of pole-pairs on permanent magnet rotor, $n_s$ the number of stationary steel segment, $\Omega_{m,k}$ the angular velocity of the space harmonic component, $\Omega_r$ the angular velocity of the inner and outer rotors, and $\Omega_s$ the angular velocity of the stationary steel segment.

For the transmission ratio of the magnetic gear, the stationary steel segment is usually fixed, and the inner and outer rotors are rotated at a certain speed. Therefore, the transmission ratio of the magnetic gear can be expressed as follows:

$$G_r = \frac{P_{out}}{P_{in}} \tag{3}$$

### 2.2. Topological Structure

Figure 2 shows the topological structure of the four kinds of magnetic gears to be analyzed, and the conventional radial magnetized magnetic gears are shown on the upper left. The upper right is the inner rotor spoke structure; the lower left is the Halbach array structure; and the lower right is the outer rotor spoke structure. They all have the same volume and the same number of permanent magnets. The material of each kind of magnetic gear is the same, which is composed of the same silicon steel sheet and permanent magnet. The inner rotor of each kind of magnetic gear has 4 pole pairs; the outer rotor has 17 pole pairs; and the number of stator segments is 21. The length of the inner and outer air gaps of the four kinds of magnetic gears is 1 mm, and the axial length is 40 mm. Their specific parameters are listed in Table 1.

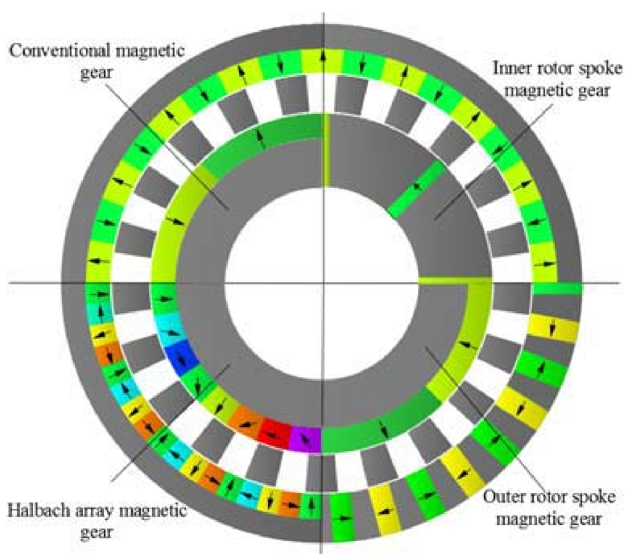
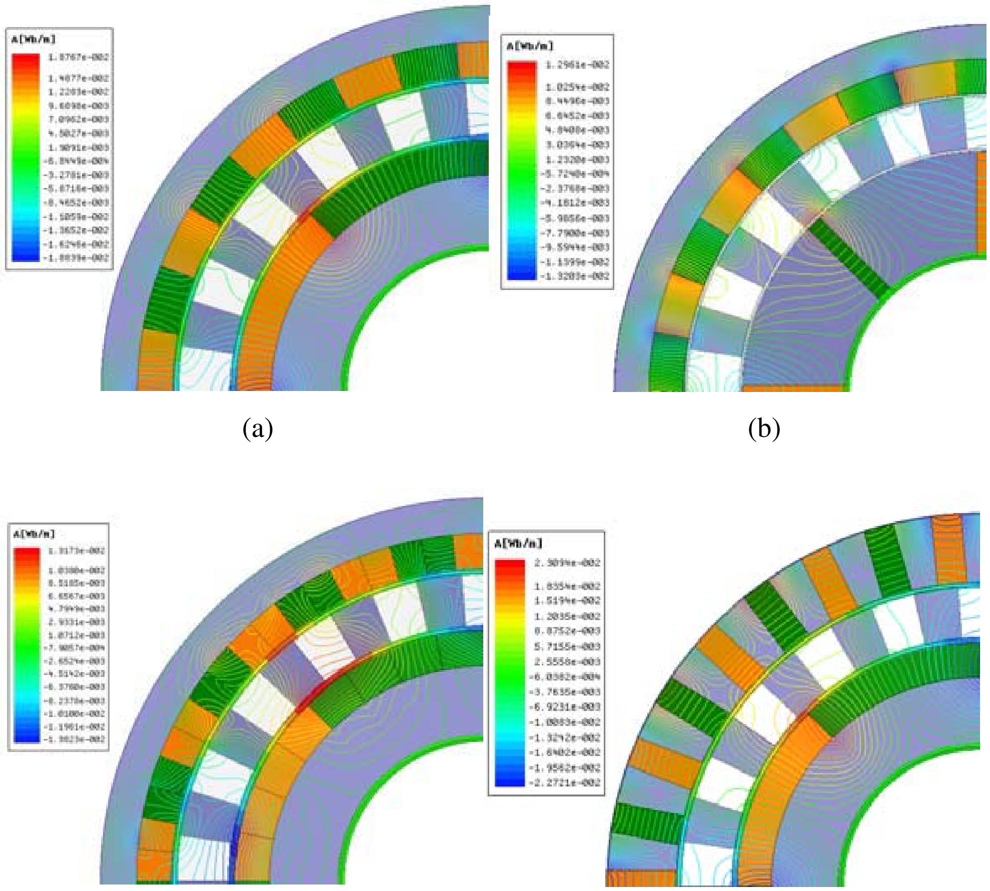



**Figure 2.** Four kinds of magnetic gears.

For the magnetic gear with Halbach array, each pole of the inner rotor is divided into four small pieces with a magnetization angle of 45°, and each pole of the outer rotor is divided into two small pieces with a corresponding angle of 90°.

## 3. MAGNETIC FIELD

In order to verify the electromagnetic characteristics of the four kinds of magnetic gears, four kinds of magnetic gear models are established by *Ansys* software. Fig. 3 shows the distribution of magnetic




(a) (b) (c) (d)

**Figure 3.** Flux line distributions. (a) Conventional; (b) Inner rotor spoke; (c) Halbach array; (d) Outer rotor spoke.

**Table 1.** Parameters of magnetic gear.

| Parameters | Values |
|---|---|
| Outer radius of stator yoke (mm) | 107 |
| Inner radius of stator yoke (mm) | 97 |
| Outer radius of low-speed rotor yoke (mm) | 97 |
| Inner radius of low-speed rotor yoke (mm) | 87 |
| Outer radius of the inner rotor yoke (mm) | 70 |
| Inner radius of the inner rotor yoke (mm) | 60 |
| Thickness of stationary steel segment (mm) | 15 |
| Thickness of the air gap (mm) | 1 |
| Pole pairs of the inner rotor | 4 |
| Pole pairs of the outer rotor | 17 |
| Remanence of NdFeB (T) | 1.2 |
| Relative permeability of NdFeB | 1 |
| Axial length (mm) | 40 |
| PMs material | NdFeB |

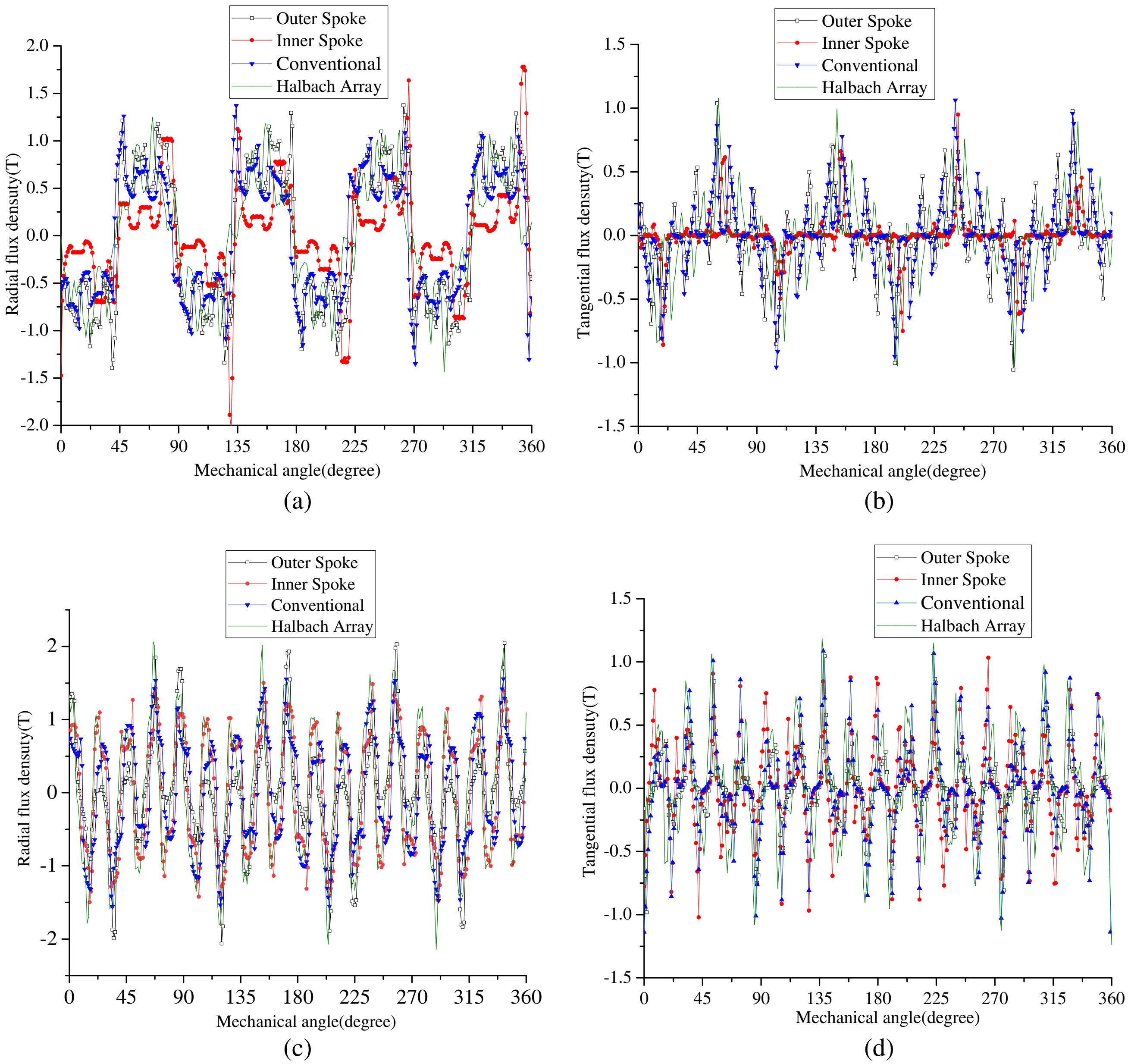



**Figure 4.** Flux density waveforms. (a) Radial component in inner air gap; (b) Tangential component in inner air gap; (c) Radial component in outer air gap; (d) Tangential component in outer air gap.

flux lines of four kinds of magnetic gear models. It can be seen that the magnetic flux lines of Halbach array model have little circulation on the yoke side of rotor, while the magnetic flux at the air gap side increases.

Figure 4 shows the radial and tangential magnetic flux density waveforms in the inner and outer air gaps calculated by finite element analysis. It is obvious that the magnetic flux densities of these four models are basically the same in waveform, so it is difficult to distinguish them graphically, so it is necessary to analyze their harmonics.

Figure 5 shows the harmonic spectrum of the air gap flux density of four kinds of magnetic gears.

As can be seen from Fig. 5(a), there are basic effective working harmonics in the air gap of the magnetic gear, and there are mainly 12th, 20th, 28th, 33th, 41th, and 46th harmonics in the conventional radial magnetization, inner rotor spoke, and outer rotor spoke. However, in the air gap magnetic field

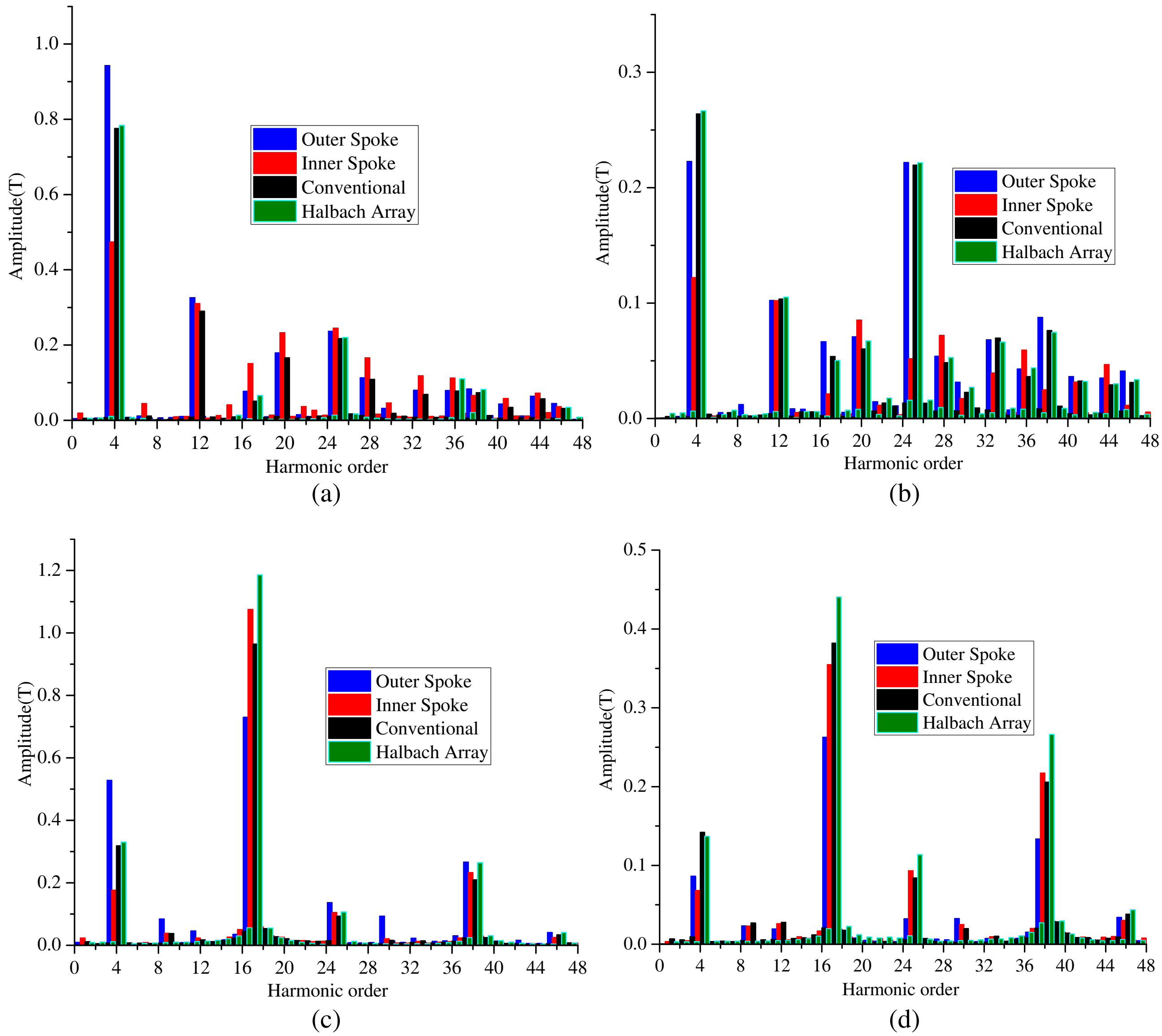



**Figure 5.** Harmonic spectrum of flux densities. (a) Radial component in the air gap; (b) Tangential component in inner air gap; (c) Radial component in outer air gap; (d) Tangential component in outer air gap.

of magnetic gear with Halbach array, these harmonics are greatly weakened. In Fig. 5(b), the change of harmonic spectrum of tangential flux density is relatively small. It can be seen from Fig. 5(c) and Fig. 5(d) that the amplitude of the outer air gap flux density of the magnetic gear with Halbach array is much larger than that of the other three kinds of flux density.

## 4. TORQUE

Static torque is one of the important properties of magnetic gear. Fig. 6 shows the variation of the torque which is exerted on the inner rotor while keeping the outer rotor and the modulating steel segment fixed. The inner rotor rotates with a phase angle $\psi_i$ varying from 0° to 90°.

It can be seen from Fig. 6 that the static torque waveforms of the four kinds of magnetic gears are sinusoidal, and the transmission ratio of the inner and outer rotors of the same magnetic gear ratio is 4.25 : 1. Among them, the magnetic gear with the inner spoke rotor has the smallest torque, and the

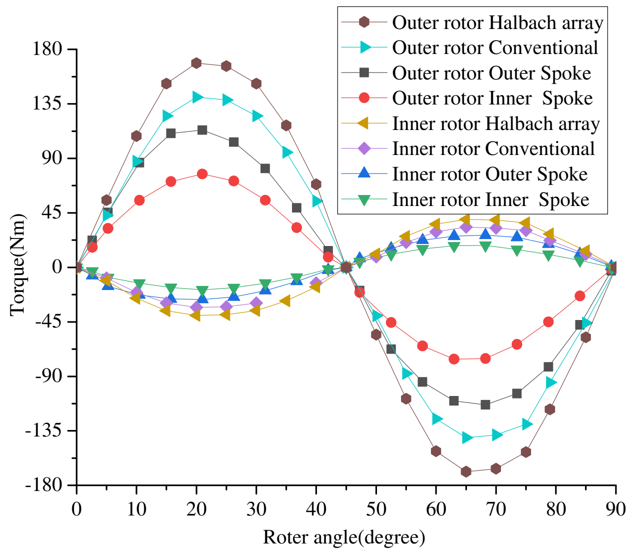



**Figure 6.** Static torque-angle curve.

torque of the outer rotor is 77.09 N·m. The magnetic gear with Halbach array can obtain the maximum electromagnetic torque, and the maximum torque of the outer rotor is 168.72 N·m. The torque values of the other two kinds of magnetic gears are between the two types.

In order to obtain the steady-state torque of the magnetic gear, the first step is to fix the modulating steel segment. The inner rotor rotates clockwise, and the outer rotor rotates counterclockwise. The ratio of their rotational speeds should conform to formula (3). Fig. 7 shows the steady-state torque curves of four kinds of magnetic gears, and the torque fluctuation of each type is very small. It can be seen that the output torques of magnetic gears with four different magnetization structures are quite different. Among them, the torque value of the magnetic gear with Halbach array is the largest, reaching 168.7 N·m, and there is no torque ripple. The torque value of magnetic gear with the inner spoke structure is the smallest, which is 77.1 N·m. For the same volume of magnetic gear, it is obvious that the magnetic gear with Halbach array will have greater torque density.

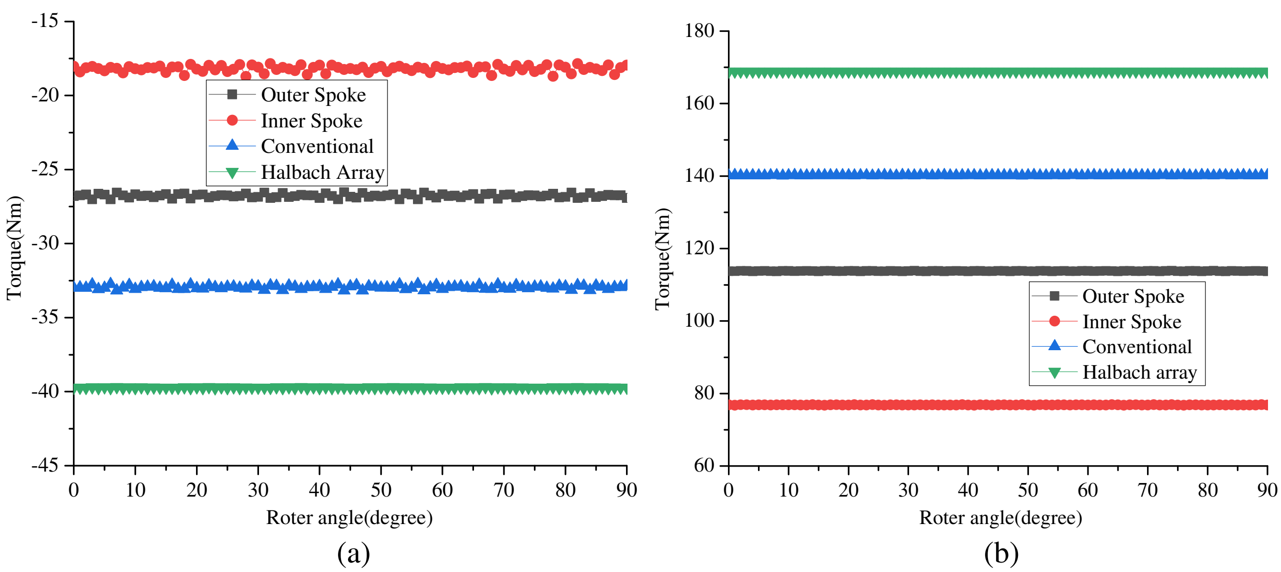



**Figure 7.** Electromagnetic torque. (a) Inner rotor; (b) Outer rotor.

## 5. CONCLUSION

In this paper, four kinds of magnetic gears with different magnetization structures are introduced, which are the conventional radial magnetization, the inner rotor spoke, the outer rotor spoke, and the inner and outer rotors are all Halbach array. The four kinds of magnetic gears have the same volume. By comparing the distribution of magnetic flux lines, the air gap flux density and the torque, it is found that the magnetic gear with Halbach array rotor structure has large torque and small torque ripple.

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