Electromagnetic performance analysis of the umbrella shaping inner rotor coaxial magnetic gear with dual modulation rings

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Abstract
The coaxial magnetic gear is a new type of noncontact transmission mechanism, which avoids the inherent defects of the mechanical gearbox due to gear meshing transmission. To study a coaxial magnetic gear (CMG) with high torque density and low torque ripple to replace the mechanical gear in the semidirect drive wind turbine, a novel umbrella shaping inner rotor CMG (US-CMG) with an auxiliary modulation ring is proposed in this paper. The novel structure adopts a CMG with a dual modulated ring to increase the electromagnetic torque. In addition, the magnetic block of the poled inner rotor is divided into three pieces magnetized by Halbach arrays, and the middle piece is umbrella-shaped to reduce torque ripple. Based on the topology of the US-CMG and the principle of the magnetic field modulation, the operation mechanism of the US-CMG is analyzed. A contrastive analysis among the US-CMG, Halbach magnetized dual-modulator CMG (HM-CMG), and surface-mounted CMG (SM-CMG) is established to identify the performance of the US-CMG. Compared with the SM-CMG, the results show that the electromagnetic torque of the US-CMG has increased by 65.46%, and the torque ripple of the US-CMG is 57.6% of that of the SM-CMG.

KEYWORDS
auxiliary modulation ring, electromagnetic torque, torque ripple, umbrella shaping

1 | INTRODUCTION

Wind energy is the kinetic energy formed by the flow of air on the surface of the earth. It is a kind of abundant, widely distributed, pollution-free, and safe green energy, and wind turbines are a key technology that can convert wind energy into electrical energy. The semidirect drive wind turbines are equipped with a reduction box between the generator and the impeller to reduce loss and avoid excessive volume, as shown in Figure 1. Coaxial magnetic gear as a transmission system has the advantages of small size, high efficiency, and reduced loss, and will be extremely competitive in the future market. However, the traditional mechanical gearbox has inherent defects, such as friction loss, tooth deformation, noise, and deformation, which causes the generator to cause additional energy loss, shorter service life, and a higher failure rate. Therefore, the magnetic
gear that transmits torque through magnetic field coupling has attracted the attention of many scholars. Atallah and Howe proposed a coaxial magnetic gear (CMG),\textsuperscript{10} which can achieve two-way modulation of the inner and external magnetic fields, thereby achieving low-speed and high-torque output. In addition, the coaxial magnetic gear is a noncontact transmission device, which has the advantages of no friction loss, no fatigue, no lubrication, and overload protection.\textsuperscript{11–13} Gouda et al.\textsuperscript{14} and Nakamura et al.\textsuperscript{15} compare the performance of CMG and mechanical gears. After a series of performance comparisons, it can be found that the magnetic gears can also work in the same way as mechanical planetary gears. In addition, the magnetic gears have comparable or even better performance than mechanical ones with the obvious benefits of avoiding many mechanical fixation defects. Therefore, semidirect drive wind turbines use coaxial magnetic gears to obtain a lower failure rate and higher reliability than traditional mechanical gearboxes.

To improve the electromagnetic performance of coaxial magnetic gears, some scholars have done many research. Chen et al.\textsuperscript{16} compare the electromagnetic performance of CMG with different permanent magnet (PM) materials, and it can be found that under the same volume structure, the rare earth permanent magnets have better performance and lower prices. In addition, the electromagnetic performance of CMG is also related to the consumption of permanent magnets, the position of the magnetized block, the array of permanent magnets, and the shape of the magnet block.\textsuperscript{17,18} However, these coaxial magnetic gears still cannot meet the needs of the industry. Jing et al.\textsuperscript{18} introduced a new structure for CMG, which adopts a new structure of the inner rotor a slotted spoke external PM rotor to increase the torque density. However, this structure will also increase the torque ripple. Wang et al.\textsuperscript{19,20} proposed a sinusoidal PM pole shaping to obtain a nearly sinusoidal flux density distribution and reduced the harmonic distortion rate (THD), which could suppress torque ripple. However, the PM pole shaping weakened the air-gap flux density distribution, which would affect the torque density. Jing et al.\textsuperscript{21} presented a CMG with a high-temperature superconductor (HTS) magnetic ring, a novel inner rotor, and Halbach arrays. The novel inner rotor adopted the PM pole-trimmed to form the eccentric structure, which was used to obtain an approximately sinusoidal flux density distribution to suppress torque ripple. Moreover, the use of the HTS modulation ring could improve the modulation effect, so that the torque density is improved. However, the cost of the HTS modulator is so high that the structure is not ideal. A novel CMG using eccentric inner rotor and Halbach arrays was proposed in Jing et al.\textsuperscript{22} The inner rotor of the novel CMG adopts a method similar to PM pole trimmed and Halbach arrays, which can suppress torque ripple. However, the PM of the surface-mount CMG may fall off when the gear rotates. In addition, the external rotor of the surface-mounted CMG has flux leakages, resulting in low torque density of CMG.\textsuperscript{23} Uppalapati and Bird\textsuperscript{24} presented a spoke CMG that can achieve flux focusing. The structure embeds pole-shoes between the PMs of the external rotor and tangential magnetization of the external PM, which can achieve the effect of magnetic flux focusing. The flux focusing CMG makes the torque density 25% higher than that of the traditional surface-mount CMG. Li et al.\textsuperscript{25} show the comparison between the torque density of the spoke CMG with different magnetization directions. It could be found that the spoke CMG with tangentially magnetized had the highest torque density. However, the flux leakages still existed outside the spoke-type PMs. To suppress the flux leakages of the spoke CMG, Zhang et al.\textsuperscript{26} proposed a dual-flux-modulator CMG. This CMG introduced an auxiliary modulation ring located outside of the spoke external rotor, which could suppress the magnetic flux leakages and enhance the torque density. However, the dual-modulator CMG increases the air gap magnetic density, thereby increasing the cogging torque and greatly improving the torque ripple, which is not conducive to the stability of the gear transmission. It can be seen that the dual-modulator CMG is not suitable for semidirect drive wind turbines. Therefore, it is necessary to study a CMG with high torque density and
low torque ripple to improve the performance of semidirect drive wind turbines. The structure of traditional CMG used in a semidirect drive wind turbines is shown in Figure 1.27

To improve the electromagnetic performance of CMG and replace the mechanical gearbox in the semidirect drive wind turbines, an umbrella-shaped inner rotor CMG with double modulators (US-CMG) is proposed in the paper, as shown. The double magnetization ring and spoke-type external rotor can enhance the magnetic field modulation effect to increase the torque density. In addition, the umbrella-shaped inner rotor with Halbach magnetization can suppress torque pulsation. Section 2 introduces the topological structure and the working mechanism of US-CMG to enhance torque density and suppress torque ripple. In Section 3, a quantitative comparison of the electromagnetic performance of the US-CMG, Halbach magnetized dual-modulation-ring CMG (HM-CMG) and surface-mounted CMG (SM-CMG) is obtained by using two-dimensional finite element, and the improvement effect of US-CMG on the electromagnetic performance is analyzed. Finally, Section 4 draws the conclusions. It can be found that the new US-CMG has a lower torque ripple and higher torque density than traditional CMG, so it is more suitable for replacing mechanical gearboxes in semi-direct drive wind turbines.

2 TOPOLOGY AND OPERATION MECHANISM OF US-CMG

This section first introduces the topology of the proposed new US-CMG and shows the specific structure of the new eccentric umbrella shaping inner rotor and auxiliary modulation ring. Then, the mechanism by which US-CMG can suppress the torque ripple and enhance the electromagnetic torque is explained.

2.1 Topology of US-CMG

The topology of US-CMG with the auxiliary modulation ring and the umbrella shaping inner PM rotor is shown in Figure 2A. The US-CMG adopts a tangentially magnetized spoke external rotor, and a static auxiliary modulation ring is added on the outermost side of the US-CMG. The inner rotor is deformed by the PM pole trimmed, and then each PM pole is divided into three eccentric blocks magnetized by Halbach arrays.

Figure 2B shows the relative position of two modulation rings in US-CMG, and the auxiliary modulation ring is slotted. To ensure that the auxiliary modulation ring and the main modulation ring have similar modulation effects, the slots number on the auxiliary modulation ring \(nt\) must be the same as the pole-pieces number on the main modulation ring \(np\). Moreover, as shown in the figure, the pole-piece angles \(\beta\) and \(\alpha\) of the two modulation rings should be kept equal. The pole-piece axis distance between the main and auxiliary modulation ring should be \(\theta_p (\theta_p = 180°/n_p)\) to make the modulation ring achieve the best modulation effect.26

Figure 2C shows a specific structure of the umbrella shaping inner rotor. It can be found that the arc \(|EB|\) and arc \(|FB|\) have the center of \(O\), the eccentricity of \(|OO'|\),
and the radius of $R'$. Furthermore, each pole of the inner rotor is divided into three blocks with a middle umbrella-shaped block, and two PM blocks on the left and right are attached to the middle piece. The arc $|ABC|$ has the center of $O''$, the eccentricity of $|OO''|$, and the radius of $R''$. To obtain a better curvature effect and to compensate for the flux leakage between PM poles, a reserved structure is conducive to obtaining a more sine flux density distribution by PM pole-trimmed to suppress torque ripple. As shown in Figure 2C, the middle PM piece is radial magnetization, and the left block and the right block are magnetized at an angle of $\gamma$ and $-\gamma$, respectively. According to the Jing et al., the Halbach magnetization angle $\gamma$ is 45 degrees in this paper.

The magnetization directions of the PMs rotors are shown in Figure 2C, and the expression of the magnetization intensity $M$ of the magnetic poles on PM rotors is as follows:

$$M = M_r \hat{r} + M_\theta \hat{\theta},$$  \hspace{1cm} (1)

where $M$ is a vector, $M_r$, and $M_\theta$ are calculated as follows:

$$M_r = \sum_{n=1,3,5, \ldots} M_{rn}(n) \cos \{np(\theta - \theta_0)\},$$  \hspace{1cm} (2)

$$M_\theta = \sum_{n=1,3,5, \ldots} M_{\theta n}(n) \sin \{np(\theta - \theta_0)\},$$  \hspace{1cm} (3)

where $M_{rn}$ and $M_{\theta n}$ are calculated as follows:

$$M_{rn}(n) = \frac{4B_0}{\mu \pi n} \sin \left(\frac{n\pi}{2a}\right) \left\{1 + \sum_{k=2}^{m} \cos \left[\frac{(k-1)n\pi}{a}\right] \cos \left[\frac{(k-1)n\pi}{a}\right]\right\},$$  \hspace{1cm} (4)

$$M_{\theta n}(n) = \frac{4B_0}{\mu \pi n} \sin \left(\frac{n\pi}{2a}\right) \left\{1 + \sum_{k=2}^{m} \sin \left[\frac{(k-1)n\pi}{a}\right] \sin \left[\frac{(k-1)n\pi}{a}\right]\right\},$$  \hspace{1cm} (5)

where $a$ is the block number on each PM pole, $k$ represents the $k$th block on each pole, $\theta_0$ represents the angle between the initial position of $R$-axis and PM center line, $B_0$ represents PM remanence, and $\mu$ represents the vacuum permeability.

The magnetization intensity of each pole on the PM rotors can be calculated by (1)–(5) to clarify the magnetic field distribution. According to the magnetic field distribution of the inner and external PM pole, it can obtain the key factors that determine the performance of the CMG, such as the torque density and magnetic flux distribution.

Table 1 shows the main parameters of the proposed US-CMG. To analyze the specific effect of inner rotor deformation on the improvement of CMG performance, a CMG with Halbach magnetization inner rotor and auxiliary modulation ring (HM-CMG) is presented. Each inner PM pole of HM-CMG is divided into three equal pieces magnetized by Halbach, and the rest of the structure and material consumption are the same as US-CMG. Figure 3 shows the specific topology of HM-CMG.

Figure 4 shows the conventional SM-CMG and spoke-type CMG (ST-CMG). The SM-CMG is mainly composed of two rotating rotors and a stationary modulation ring. There are PMs on the surfaces of the two rotors, and the stationary modulation ring is between the two rotors with air gaps. Furthermore, the ST-CMG forms a flux focusing effect by embedding pole-shoes between tangentially magnetized external rotor PMs. The mainstream magnetic gear is mainly SM-CMG and ST-CMG and compared with SM-CMG, the torque of spoke-type CMG is increased by 25%.

**TABLE 1** Main design specifications of US-CMG

| Quality                                      | Value  |
|----------------------------------------------|--------|
| inner iron yoke thickness                    | 20 mm  |
| inner rotor PM thickness                     | 5 mm   |
| $R'$                                         | 40 mm  |
| $R''$                                        | 30.17 mm |
| External rotor PM thickness                  | 10 mm  |
| Angle of external PM                         | 3.913° |
| Air-gaps thickness                           | 1 mm   |
| Pole-piece thickness main modulation ring    | 8 mm   |
| Pole-piece angle of the main modulation ring | 6.67°  |
| Iron yoke thickness of auxiliary modulation ring | 6 mm |
| Outer radius of the auxiliary modulation ring | 100 mm |
| Axial length                                 | 65 mm  |
| $\gamma$                                     | 45°    |
| External rotor pole pairs                    | 23     |
| inner rotor pole pairs                       | 4      |
| PM material                                  | NFeB   |
| Pole-pieces of the main modulation ring      | 27     |
2.2 | Operation mechanism of US-CMG

2.2.1 | The principle of the US-CMG is to enhance electromagnetic torque

Due to the existence of the pole-shoes and the auxiliary modulation ring, the modulation effect of US-CMG is different from the traditional SM-CMG. In this part, the working mechanism of dual modulators is analyzed, and the principle of the spoke outer rotor and auxiliary modulation ring to enhance torque density and cogging torque is explained. Torque density is related to the flux density distribution of the air gaps, and torque ripple is related to the cogging torque. Therefore, this paper analyzes the change of torque ripple by cogging torque and analyzes that of the electromagnetic torque by magnetic density distribution, thus determining the influence of adding auxiliary modulation ring and pole-shoes on the electromagnetic performance of CMG.

According to the Zhang et al., Without the modulation effect of the main modulation ring, pole-pieces, and auxiliary modulation, the influence of the tangential and radial flux density of any rotor at the distance \( r \) is expressed as follows:

\[
B_{\phi 1} = \sum_{x=1,3,5}^{+\infty} b_{\phi x}^0 (r) \cos [x(\theta - \omega_s t) + x\phi_1],
\]

\[
B_{\theta 1} = \sum_{x=1,3,5}^{+\infty} b_{\theta x}^0 (r) \cos [x(\theta - \omega_s t) + x\phi_2],
\]

where \( x \) represents the harmonics number, \( p \) represents the number of PM pole-pairs, \( \omega_s \) is the rotor speed, \( b_{\phi x}^0 \) and \( b_{\theta x}^0 \) are Fourier coefficients, \( \phi_1 \) and \( \phi_2 \) respectively represent the initial radial angle and tangential angle of the magnetic flux.

The main and auxiliary modulation rings can modulate the magnetic field of the air gap, which can be expressed as an air-gap permeability function. Since the pole-pieces number of the main flux modulator \( n_t \) is equal to the slots number of the auxiliary modulator \( n_p \), the flux modulation effect of the two modulators can be formulated by the air-gap permeability functions:

\[
\lambda_{\phi p} (r) = \lambda_{\phi p}^0 (r) + \sum_{j=1}^{+\infty} \lambda_{\phi p}^j (r) \cos [jn_p (\theta - \omega_p t)] + jn_p \phi_{\theta p} \]

\[
\lambda_{\theta p} (r) = \lambda_{\theta p}^0 (r) + \sum_{j=1}^{+\infty} \lambda_{\theta p}^j (r) \sin [jn_p (\theta - \omega_p t)] + jn_p \phi_{\theta p} \]

where \( j \) represents the harmonics number, \( \omega_p \) represents the modulation ring speed, \( \phi_{\theta p} \) and \( \phi_{\theta p} \) respectively represent the initial radial and tangential angles of modulation ring, \( \lambda_{\phi p}^0, \lambda_{\phi p}^1, \lambda_{\phi p}^j, \lambda_{\theta p}^0, \lambda_{\theta p}^1, \lambda_{\theta p}^j \) represent Fourier coefficients.

The pole-shoes are embedded in the adjacent PMs of the spoke outer rotor to support each other, and the PMs

![FIGURE 3 Topology of HM-CMG](image)

![FIGURE 4 (A) The topological structure of SM-CMG and (B) the topological structure of ST-CMG.](image)
and pole-shoes are distributed along the circumference. Therefore, the pole-shoes and the modulation rings have a similar modulation effect. The specific expression is as follows:

\[ \lambda_n(r) = \frac{\lambda_0^n(r)}{2} + \sum_{k=1}^{\infty} \lambda_k^n(r) \cos[kn_t(\theta - \omega_t) + kn_r \varphi_{rn}], \]  
\[ \lambda_{\phi_s}(r) = \frac{\lambda_0^n(r)}{2} + \sum_{k=1}^{\infty} \lambda_k^n(r) \sin[kn_t(\theta - \omega_t) + kn_r \varphi_{rn}], \]  
(11)

where \( k \) represents the harmonics number, \( n_s \) represents the pole-shoes number, \( \omega_s \) is the pole-shoes speed, \( \varphi_{rn} \) and \( \varphi_{rn} \) respectively represent the initial radial and tangential angles of the pole-shoes, \( \lambda_0^n, \lambda_1^n, \lambda_2^n, \) and \( \lambda_3^n \) and \( \lambda_4^n \) represent Fourier coefficients.

According to the functions of the pole-shoes and the two modulation rings, the radial magnetic flux distribution produced by any rotor is calculated as follows:

\[ B_r(r) = \sum_{j=0, \pm 1, \pm 2}^{\infty} \sum_{k=0, \pm 1, \pm 2}^{\infty} \sum_{a=1,3,5}^{\infty} b_r^{j,k,a}(r) \times \cos \left( \frac{pa + jn_p + kn_s}{\omega_s} \right) \times \left( \theta - \frac{pa \omega_r + jn_p \omega_p + kn_s \omega_s}{pa + jn_p + kn_s} + t \right) + pa \phi_r \n + jn_p \phi_{rp} + kn_s \phi_{rs} \]  
(12)

where \( b_r^{j,k,a} \) represents Fourier coefficients.

The tangential magnetic flux distribution produced by any rotor is calculated as follows:

\[ B_{\phi}(r) = \sum_{j=0, \pm 1, \pm 2}^{\infty} \sum_{k=0, \pm 1, \pm 2}^{\infty} \sum_{a=1,3,5}^{\infty} b_r^{j,k,a}(r) \times \sin \left( \frac{pa + jn_p + kn_s}{\omega_s} \right) \times \left( \theta - \frac{pa \omega_r + jn_p \omega_p + kn_s \omega_s}{pa + jn_p + kn_s} + t \right) + pa \phi \n + jn_p \phi_{\phi p} + kn_s \phi_{\phi s} \]  
(12)

where \( b_r^{j,k,a} \) represents Fourier coefficients.

The number of space harmonic pole pairs of US-CMG should satisfy the following relationship:

\[ p_{j,k,m} = |pa + jn_p + kn_s|, \]  
(14)

where \( a = 1, 3, 5, \ldots, \infty, \)

\[ j = 0, \pm 1, \pm 2, \pm 3, \ldots, \pm \infty \]

\[ k = 0, \pm 1, \pm 2, \pm 3, \ldots, \pm \infty \]

According to the operation principle of CMG in Atallah and Howe, the modulated pole-pieces number and PM pole-pairs should be satisfied as (15).

\[ n_p = p_i + p_o, \]  
(15)

where the \( n_p \) represents the modulated pole-pieces number, \( p_i \) and \( p_o \) respectively represent pole-pair numbers of the inner and external rotor.

The inner and external PM rotors should satisfy the (16) to ensure that the CMG can transmit stable torque.

\[ G_r = \frac{\omega_i}{\omega_o} = \frac{p_o}{p_i}, \]  
(16)

where \( G_r \) is the gear ratio, \( \omega_i \) represents the inner rotor speed, and \( \omega_o \) represents external rotor speed. The negative sign represents that the rotation directions of the two PM rotors are opposite.

Because of the effect of the pole-shoes, the pole-shoes and inner rotor will generate \( p_i + n_s \) pole-pairs harmonics. Similarly, the modulated pieces and external rotor will produce \( p_o + n_p \) pole-pairs harmonics. It should satisfy the (17).

\[ p_i + n_s = p_o + n_p. \]  
(17)

The Fourier expansion of the magnetic field intensity at a certain spatial position is shown as follows:

\[ \begin{aligned}
B_\theta &= \sum_k B_{\theta k} \cos(k \alpha - \alpha_{\theta k}), \\
B_r &= \sum_k B_{rk} \cos(k \alpha - \alpha_{rk}),
\end{aligned} \]  
(18)

where \( B_r \) represents the radial magnetic field component and \( B_\theta \) represents the tangential magnetic field component. \( B_{rk} \) and \( B_{\theta k} \) respectively represent the kth Fourier coefficients of the radial and tangential components. \( \alpha_{rk} \) and \( \alpha_{\theta k} \) are the kth phase angles at that position. Then the kth harmonic torque can be obtained according to the Maxwell tensor method as (19).

\[ T_k = \frac{\pi r^2 \mu_o}{\mu_o} B_{rk} B_{\theta k} \cos(\alpha_{rk} - \alpha_{\theta k}), \]  
(19)
where \( r \) represents the air-gap radius, \( \mu_0 \) represents the vacuum permeability, and \( L_{ef} \) represents the axis length.

The cogging torque is generated by the interaction of the regulating ring and the PMs during the magnetic field modulation of the air-gap magnetic field. When using Maxwell software to calculate the cogging torque in this paper, the cogging torque formed by the interaction between the inner PM rotor and the modulation ring is only considered. The cogging torque of the CMG is the main factor to produce torque ripple. According to (19), the harmonic torque generated by the \( k \)th harmonic can be calculated, and the cogging torque at a certain position can be obtained by superimposing each harmonic torque.

\[
T_{cog} = \sum_{k=1}^{\infty} T_k. \tag{20}
\]

As shown in Figure 5, a comparison between the cogging torque waveforms of the traditional SM-CMG and the dual-flux-modulator CMG (dual-modulator CMG) is given. It can be found that the cogging torque of SM-CMG is lower than that of Dual-modulator CMG. Therefore, it can be found that the spoke external rotor and auxiliary modulator can enhance the flux density and cogging torque of the CMG.

In summary, because of the effect of the pole-shoes, the Dual-modulator CMG has \( pl + ps \) and \( po + np \) pole-pairs harmonics between the pole-shoes and the PM, which has a higher flux density distribution and cogging torque than the CM-CMG. Therefore, the spoke-type external rotor and the auxiliary modulation ring enhance the torque density, and the structure also increases the cogging torque to enhance torque ripple. It is necessary to do further research on suppressing the torque ripple of the dual-flux-modulator CMG.

### 2.3 The operating principle of the pole shaping inner rotor to reduce torque ripple

The magnetic flux starts from the N pole on the PM rotor, passes through the air gap and the stator in turn, and finally reaches the S pole of the rotor. Therefore, the magnetic flux line crosses the air gap twice in the whole process. Figure 6 is a schematic diagram of the magnetic circuit of one pole pair.

As shown in Figure 6, the total air-gap thickness and PM thickness at any position is a certain value \( l \), and \( B_l \) is the remanence of PMs, \( B_{g(\alpha)} \) represents the flux density and should be calculated as follows:

\[
B_{g(\alpha)} = \frac{B_l}{l} \times l_m(\alpha). \tag{21}
\]

This paper proposes a US-CMG inner rotor based on the principle of pole shaping to adjust the magnetic flux density. Figure 7 shows the model of the pole-trimmed inner rotor and the umbrella-shaped inner rotor.

As shown in Figure 7, the edge of the permanent magnet has a reserved thickness \( m \), which is beneficial to suppress the harmonic content as much as possible by pole shaping. The PM thickness \( l_m(\alpha) \) is changed at

![Figure 5: The cogging torque of SM-CMG and Dual-modulator CMG.](image-url)
different position angles, the sum of the PM thickness and the effective air gap length at each position $l$ is a constant value, and the maximum thickness of the PM pole $k$ remains unchanged. According to (21), the obtained $B_g(\alpha)$ changes with the $l_m(\alpha)$, so the $B_g(\alpha)$ will be sinusoidal. Therefore, a magnetic flux density distribution closer to a sinusoidal distribution can be obtained. The $m/k = 0.5$ in the paper.

It has $l_m(\alpha) \leq l$ after PM pole shaping, resulting in a decrease of $B_g(\alpha)$. The magnetic flux density distribution can be weakened by PM pole shaping, and the cogging torque can be reduced to suppress the torque ripple. Next, according to the characteristics of the Halbach array, the inner rotor of the US-CMG can increase the magnetic field intensity outside the inner rotor to enhance the torque density. In addition, a closer sinusoidal flux density distribution can be obtained, which can reduce torque ripple.\(^{19}\)

Figure 8 shows the radial flux density waveform of the umbrella shaping (umbrella) and pole shaping (pole shaping). Figure 9 shows a comparison diagram of the harmonic amplitudes between the Umbrella and Pole shaping.

The sinusoidal characteristics of the flux density are related to the THD,\(^{29}\) which is calculated as follows:

$$\text{THD} = \sqrt{\sum_{e} B_{e}^{2} / B_{1}^{2}} \times 100\%,$$

where $B_f$ represents the fundamental harmonic amplitude, $B_e$ represents each harmonic amplitude ($e = 1, 2, 3, ...$).

The THD of the umbrella and pole shaping can be calculated as shown in Table 2.

It can be seen from Table 2 that the THD of the Umbrella is lower than that of Pole-trimmed, so the flux density distribution of the Umbrella is closer to the sinusoidal waveform, which suppressed the torque ripple. In addition, the radial flux component range of the Umbrella structure is $-0.9564$–$0.9104$ T, and the range of the Pole shaping is $-0.9412$–$0.8701$ t. It can be found that the umbrella shape with Halbach magnetization can increase the flux density to enhance the torque density.

### 3 COMPARATIVE ANALYSIS OF CMGS

The finite element method is used to calculate the electromagnetic performance of HM-CMG, US-CMG, and SM-CMG in this section. According to the comparative analysis of the electromagnetic performances of the three CMGs, it can be shown that the umbrella shaping with Halbach arrays’ inner rotor of the US-CMG can improve the electromagnetic performance. Furthermore, the flux lines distribution of US-CMG and CMG without an auxiliary modulation ring are compared in this part, and the changes in the flux lines distribution caused by the additional auxiliary modulation ring are analyzed.

#### 3.1 The influence of the auxiliary modulation ring on the magnetic field

The effect of the auxiliary modulation ring increases the flux density, which can enhance the cogging torque and torque density. To analyze the influence of the outermost...
auxiliary modulation ring on the magnetic field, the magnetic lines distribution of the US-CMG and the CMG without an auxiliary modulation ring are compared in this part. Figure 10 shows the flux lines distribution.

Without the auxiliary modulation, there are some lines of magnetic flux between the pole-shoes and the external PM as Line 2 in Figure 10A, which can cause harmonics to be generated in the external air gap of the spoke CMG. As shown by Line 3 in Figure 10A, a part of the magnetic flux lines crosses the air gap several times to generate the harmonics, resulting in a high harmonic reluctance and poor flux modulation. Furthermore, there are flux leakages as Line 1 in Figure 10A, which will not have an effect on the electromagnetic torque and reduce the PM utilization. The pole shoes of the outer rotor are arranged along the circumference to modulate the magnetic field, which generates \(|p_o - n_s|\) pair harmonics with the outer rotor in the air gap. Similarly, the outer rotor and the pole pieces will generate \(p_o + n_p\) and \(|p_o - n_p|\) pole pairs harmonics. In addition, the inner rotor, pole shoes, and pole pieces will generate \(p_i + n_s\) and \(|p_i - n_p|\) pole pairs harmonics.

Figure 10B shows the magnetic lines distribution of US-CMG. As shown in the figure, there are some magnetic flux leakages on the outermost side of the spoke external rotor, such as Line 1 in Figure 10B. The flux leakages are guided by an auxiliary modulation ring to circulate between the auxiliary modulation ring and the external PM rotor. Therefore, the useless leakages are turned into useful harmonics to increase the electromagnetic torque of the CMG. Furthermore, the auxiliary modulation ring provides a less reluctance path and guides more flux lines to travel through the path, such as Line 3 in Figure 10B, so that the auxiliary modulator can enhance the flux modulation effect in three air gaps. The magnetic flux leakages are guided into the air gap because of the effect of the auxiliary modulation ring, which can increase the flux density to enhance the electromagnetic torque. Compared to the magnet gear
without an auxiliary modulation ring, the auxiliary modulation ring generates $p_o + n_l$ and $|p_o - n_l|$ pole pair harmonics with the outer rotor; and it generates $|p_i - n_l|$ pole pair harmonics with the inner rotor. These harmonics enrich the magnetic density in the air gap to enhance the torque capability.

### 3.2 Comparative analysis of the harmonics

The schematic magnetic flux distributions of US-CMG, HM-CMG, and SM-CMG can be obtained based on the control variables method. Figure 11 shows the magnetic flux line distribution diagrams of the three structures obtained by simulation.

Figure 12 shows the inner air gap magnetic flux density diagram, where Figure 12A is the radial distribution and Figure 12B is the tangential distribution. As shown in the figures, the PM pole shaping inner rotor weakens the flux density, which leads to the radial amplitude of the US-CMG being the lowest among the three CMGs, thereby decreasing the cogging torque to suppress the torque ripple.

The radial and tangential harmonic spectra of the inner air gap are shown separately in Figure 13A and 13B. As shown in the figure, compared with HM-CMG and SM-CMG, the 20th, 28th, 31st, 36th, 44th, and 51st pole-pair harmonics of US-CMG are greatly suppressed. This proposed structure can suppress the higher harmonics to suppress the torque ripple. In addition, the pole-pairs harmonics of HM-CMG are also suppressed, but it is not as significant as that of US-CMG. As shown in the figure, the umbrella shaping inner rotor with Halbach magnetization can enhance the magnetic field intensity outside of the inner rotor, and the working harmonics of the US-CMG are higher than that of the HM-CMG. Therefore, compared with HM-CMG, the US-CMG structure can suppress torque ripple more effectively, and the torque density is higher than that of HM-CM.

In addition, the torque ripple is related to the THD. Table 3 shows the THD of the three CMGs calculated by the formula (22). It can be found that the THD of the US-CMG is 36.05%, which is lower than the 43.81% of the HM-CMG and 61.71% of the SM-CMG. Therefore, the US-CMG can effectively suppress the torque ripple of CMG.

Similarly, Figure 14A,B show the external air-gap magnetic flux distribution. Since the HM-CMG and US-CMG have the same outer rotor, the magnetic density distribution of the two structures almost coincides. The radial flux density of the US-CMG outer rotor ranges from $-2.0886$ to $1.7821$ T, the radial

![Figure 10](image1.png) The magnetic lines distribution, (A) the CMG without auxiliary modulation ring and (B) the US-CMG.

![Figure 11](image2.png) Magnetic line distribution of three CMGs (A) US-CMG, (B) HM-CMG, and (C) SM-CMG.
The flux density of the HM-CMG ranges from $-1.9748$ to $1.7695$ T, and the radial flux density of the SM-CMG ranges from $-1.4611$ to $1.4635$ T. Therefore, it can be found that the auxiliary modulation ring and spoke external rotor could enhance the flux density to increase the electromagnetic torque.

**FIGURE 12** The flux density distribution of inner air gap

**FIGURE 13** The harmonic spectrum of the inner air gap. (A) Radial harmonic and (B) tangential harmonic.

**TABLE 3** THD of US-CMG, HM-CMG and SM-CMG.

| Type                    | THD (%) |
|-------------------------|---------|
| US-CMG inner gap        | 36.05   |
| HM-CMG inner air gap    | 43.81   |
| SM-CMG inner air gap    | 61.71   |

flux density of the HM-CMG ranges from $-1.9748$ to $1.7695$ T, and the radial flux density of the SM-CMG ranges from $-1.4611$ to $1.4635$ T. Therefore, it can be found that the auxiliary modulation ring and spoke external rotor could enhance the flux density to increase the electromagnetic torque.
The radial and tangential harmonic spectra of the external air gap are shown in Figure 15A,B. Due to the influence of the auxiliary modulation ring, the 23rd and 50th pole pairs of US-CMG and HM-CMG are suppressed. The auxiliary modulation ring provides a path with less reluctance for magnetic lines of the external PM rotor, and the magnetic field lines circulating between the main modulated pole-pieces and external rotor are reduced, resulting in weakened magnetic flux density. Moreover, the 4th and 6th pole-pairs harmonics have been enhanced, which have a great contribution to the increase of torque density, so

**FIGURE 14** The flux distribution of external air gap. (A) Radial distribution and (B) tangential distribution.

**FIGURE 15** The harmonic spectrum of the external air gap. (A) Radial harmonic and (B) tangential harmonic.
it can be seen that the electromagnetic torque has also been enhanced.

### 3.3 Comparative analysis of the electromagnetic performance

The static torque of CMG is a very important indicator of electromagnetic performance. When the load torque exceeds the peak static torque, the inner and outer rotors of the magnetic gear will no longer drive according to the established ratio. Therefore, the static torque of the magnetic gear directly determines the load capacity. Based on the Maxwell tensor method, the static torque is related to the product of the tangential and the radial magnetic flux density when the shaft length is a fixed value. The static torque of the magnetic gear can be obtained by the Maxwell tensor method as (23).

\[
T_{em} = \frac{L_{ef} R_e^2}{\mu_0} \int_0^{2\pi} B_r B_\theta \, d\alpha,
\]

where \( L_{ef} \) represents the shaft length of CMG, \( R_e \) represents the air-gap radius, \( B_r \) and \( B_\theta \) represent the radial and tangential components of the flux distribution, respectively.

Due to the gear ratio \( G_r = p_{in}/p_{out} \), \( p_{in} = 4 \) represents the pole-pairs number of the inner PM, and \( p_{out} = 23 \) represents the pole-pairs number of the external PM. Therefore, the transmission ratio \( G_r = 5.75 \) can be obtained.

In this part, two modulation rings and external rotor are kept stationary, while the inner rotor speed is maintained at 575 r/min, and then the static torques of the PM rotors can be obtained. Figure 16A,B, respectively show the inner static torque and external static torque of the three CMGs. Since the PMs of the three CMGs have the same volume, the ratio of torque density is equal to the ratio of torque. As shown in the static torque diagram, the static torque waveforms of the three CMGs are sinusoidal. The peak torques of the PM rotors can be obtained when the rotation angle reaches 90 degrees, and the torques of the US-CMG are higher than the HM-CMG and SM-CMG. The specific peak torques are shown in Table 4.

Table 4 shows the maximum torque and gear ratio of the three structures. It can be seen that the US-CMG structure and the theoretical transmission ratio are both 5.75:1, which indicates that the US-CMG structure has better transmission stability. Moreover, the external static torque of the US-CMG is 68.73% higher than the SM-CMG and 4.89% higher than the HM-CMG, and the inner static torque of the US-CMG is 65.46% higher than the SM-CMG and 4.09% higher than the HM-CMG. According to the torque comparison of the three structures, it can be found that the umbrella shaping inner rotor can enhance the electromagnetic torque of the CMG.

![Figure 16](image-url) The static torque of three CMGs. (A) Inner torque and (B) external torque.

| Type          | Torque (Nm) | Gear ratio |
|---------------|-------------|------------|
| SM-CMG external rotor | 102.33      | 5.64:1     |
| SM-CMG inner rotor    | 18.15       |            |
| HM-CMG external rotor | 164.61      | 5.71:1     |
| HM-CMG inner rotor    | 28.85       |            |
| US-CMG external rotor | 172.66      | 5.75:1     |
| US-CMG inner rotor    | 30.03       |            |
CMG. US-CMG and SM-CMG have the same outer rotor diameter; the axial lengths are both 65 mm; US-CMG has an outer diameter of 100 mm, and SM-CMG has an outer diameter of 90 mm. The maximum torque of US-CMG is 172.66 Nm, and the maximum torque of SM-CMG is 102.33 Nm; the torque density $D$ is equal to the ratio of the output torque and the magnetogear volume. Therefore, the torque densities of the US-CMG and SM-CMG can be calculated as $D_{US-CMG} = 84.55 \text{KNm/m}^3$ and $D_{SM-CMG} = 61.87 \text{KNm/m}^3$, respectively. It can be found that the torque density of US-CMG is 36.66% higher than that of SM-CMG.

In this paper, the cogging torque is calculated using Maxwell software, the cogging torque formed by the interaction between the inner PM rotor and the modulation ring is only considered. The comparison of the cogging torques between the three CMGs is shown in Figure 17. As shown in the figure, the cogging torque of SM-CMG is the largest, while the cogging torque of US-CMG is much smaller than that of the other two structures. Therefore, it can be found that the HM-CMG has little effect on the reduction of cogging torque, and the US-CMG can effectively weaken the cogging torque to suppress the torque ripple of the CMG.

Similarly, keeping the modulation ring stationary, the inner rotor speed is 575 r/min, the external rotor speed is 100 r/min, and the two rotors rotate in opposite directions. Therefore, the steady-state torque waveforms of the three CMGs can be obtained. As shown in Figure 18, the torque ripple of the US-CMG is much lower than that of the SM-CMG and HM-CMG, so the US-CMG has better transmission stability than the other CMGs. Due to the three-layer air gap caused by the auxiliary flux modulator, the static torque is different from the steady-state
torque, but the torque of US-CMG is still the highest among the three CMGs.

The coefficient $K_p$ represents the torque ripple on each rotor of the CMG, $K_p$ is defined as (24).

$$K_p = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}} \times 100\%,$$  \hspace{1cm} (24)

where $T_{\text{max}}$ represents the maximum torque of CMG, $T_{\text{min}}$ represents the minimum torque of CMG, and $T_{\text{avg}}$ represents the average torque of CMG.

Table 5 shows the torque ripple of the three CMGs. It can be seen that the average torque of US-CMG is the highest among the three CMGs. The external torque ripple of SM-CMG is 2.73%, and the inner torque ripple is 17.52%, so the torque ripple of SM-CMG is relatively large. The external torque ripple of the HM-CMG is 3.45%, which is the largest of the three CMGs. The inner torque ripple of HM-CMG is 12.82%, which is lower than SM-CMG and higher than US-CMG. According to the comparative analysis of harmonics, it can be seen that the auxiliary modulation ring can enhance the electromagnetic torque, but it also greatly increases the torque ripple of CMG. The Halbach array can not effectively suppress the torque ripple of the dual-flux modulator CMG. Therefore, this paper proposes an umbrella-shaped shaped inner rotor CMG, which can make the flux density closer to the sine wave. Therefore, the structure can effectively weaken the cogging torque to suppress the torque ripple and enhance the electromagnetic torque.

![Table 5: The torque ripple](image)

| Type       | Maximum (Nm) | Minimum (Nm) | Average (Nm) | Torque ripple (%) |
|------------|--------------|--------------|--------------|------------------|
| Outer rotor|              |              |              |                  |
| SM-CMG     | 103.90       | 101.10       | 102.56       | 2.73             |
| HM-CMG     | 121.48       | 117.37       | 119.21       | 3.45             |
| US-CMG     | 125.44       | 123.53       | 124.53       | 1.53             |
| Inner rotor|              |              |              |                  |
| SM-CMG     | 20.09        | 16.89        | 18.27        | 17.52            |
| HM-CMG     | 22.16        | 19.49        | 20.83        | 12.82            |
| US-CMG     | 21.74        | 21.52        | 51.64        | 1.01             |

4 | CONCLUSION

In this paper, the theoretical calculation and analysis of the magnetic gear are carried out, and then the finite element analysis is used to verify it. According to a large number of references, the finite element analysis method is credible.26,30

The finite element method was used to simulate US-CMG, HM-CMG, and SM-CMG, and the electromagnetic performances of the three CMGs are also theoretically analyzed. The results show that the torque density of US-CMG is the highest and the torque ripple is the lowest among the three CMGs. The electromagnetic torque of US-CMG is at least 4.09% higher than the HM-CMG, and the torque ripple of US-CMG is reduced to 1.01%, which is 57.6% of SM-CMG and 78.0% of HM-CMG. According to the harmonic analysis, the auxiliary modulation ring guides the flux leakages to circulate between the pole-shoes and the external PMs, which can enhance torque density. However, the cogging torque is increased to enhance the torque ripple when the magnetic flux density is increased. In addition, according to the quantitative comparison, it can be seen that the Halbach arrays have little effect on the reduction of the torque ripple of the dual flux modulator CMG. An umbrella-shaped shaped inner rotor CMG is proposed, which can make the flux density closer to the sine wave. Therefore, the structure can effectively weaken the cogging torque to suppress the torque ripple and enhance the electromagnetic torque. Compared with the SM-CMG, the US-CMG improves the utilization efficiency of the PMs to enhance the electromagnetic torque and significantly suppresses torque ripple. The electromagnetic torque of the US-CMG is at least 65.46% higher than the SM-CMG, and the torque ripple is 57.6% of the SM-CMG. Therefore, the US-CMG can better replace mechanical gearboxes in semi-direct drive wind turbines and provide more stable output and higher electromagnetic torque.

ACKNOWLEDGMENT

This study was supported by the National Natural Science Foundation of China (Grant no. 51765020), and the Natural Science Foundation of Jiangxi Province (Grant no. 20161BAB206153).
CONFLICT OF INTEREST
The authors declare no conflict of interest.

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How to cite this article: Wang J-g, Zhang B, Qian L-q, Xu S-r. Electromagnetic performance analysis of the umbrella shaping inner rotor coaxial magnetic gear with dual modulation rings. Energy Sci Eng. 2022;10:3138-3153. doi:10.1002/ese3.1207