A New Method for Reducing Cogging Torque in Modular Permanent Magnet Motors (Postprint)

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Abstract

To reduce the cogging torque of modular permanent magnet motors, a novel stator structure with leftward and rightward slot openings along the circumferential direction is proposed and discussed, combining the slot opening shift method for permanent magnet motors. Due to the mechanical displacement of the stator slot openings, the generated cogging torque components also shift to the right and left. Therefore, for an appropriate shift angle, half of the cogging torque components and the other half can be shifted by 180°, which causes the cogging torque components to cancel each other out, thereby weakening the total resultant cogging torque. By employing a method that regards the total cogging torque of a motor as being superimposed from the cogging torques of two motors, the analysis approach becomes simpler and more comprehensible, and the expression for slot opening shift is derived. Experimental simulations demonstrate that this method can effectively weaken the cogging torque of modular permanent magnet motors and keep the torque ripple below 2% of the rated torque.

Full Text

A Novel Method for Weakening Cogging Torque in Modular Permanent Magnet Motors

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Abstract

To reduce the cogging torque of modular permanent magnet motors, this paper proposes and discusses a novel stator structure that incorporates leftward and rightward slot openings along the circumferential direction, building upon the slot-opening shift method for permanent magnet motors. Due to the mechanical displacement of the stator slot openings, the resulting cogging torque components are correspondingly shifted to the right and left. Therefore, with an appropriate shifting angle, half of the cogging torque components can be shifted by 180° relative to the other half, enabling mutual cancellation and thereby weakening the total resultant cogging torque. By regarding the total cogging torque of a single motor as the superposition of cogging torques from two separate motors, the analysis method becomes simpler and more intuitive, and the expression for slot-opening shift is derived. Experimental simulations demonstrate that this method can effectively weaken the cogging torque of modular permanent magnet motors while keeping torque ripple below 2% of the rated torque.

Keywords: Modular permanent magnet motor, slot-opening shift, cogging torque, torque ripple, finite element analysis **Classification:** TM464; V44

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1 Introduction

Modular Permanent Magnet Machines (MPMM) represent a novel topological structure characterized by multiple pole pairs, low-speed operation, and high output torque [1-3]. According to the relationship n = 60f, increasing the number of pole pairs can reduce motor speed for a given frequency, making MPMMs well-suited for these requirements. With numerous poles and low speed, MPMMs deliver substantial output torque, enabling low-speed, high-torque operation without reduction gears. The primary distinction between MPMMs and conventional motors lies in their modular stator construction, where phase windings are wound on separate, continuous stator teeth, eliminating cross-phase windings. This design not only simplifies manufacturing but also achieves a high winding distribution factor, leading to high efficiency and reduced manufacturing complexity. For a given pole number, only a small slot count is required.

Current research on MPMMs primarily focuses on analyzing cogging torque, back EMF, load torque, and iron losses, yet no effective method has been proposed to specifically weaken cogging torque in modular permanent magnet motors. To address this gap and further enhance MPMM performance, this paper presents a novel cogging torque reduction method. Unlike conventional approaches, this method reduces total cogging torque by canceling out slot-induced cogging torque components.

Cogging torque arises from the interaction between permanent magnets and the iron core when the motor windings are unenergized, caused by tangential components of the interaction forces between permanent magnets and armature teeth. The presence of cogging torque significantly degrades motor stability, generating vibration and acoustic noise. Consequently, cogging torque reduction is a critical consideration in permanent magnet motor design. However, focusing solely on cogging torque is insufficient; torque ripple must also be considered during the reduction process. This paper designs a novel stator that weakens cogging torque while simultaneously maintaining low torque ripple.

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2 Theoretical Analysis

The effectiveness of this approach depends on Nc (the least common multiple of slot and pole numbers). A larger period number yields higher cogging torque frequency and smaller amplitude, making this method suitable for appropriate pole-slot combinations. When the period number becomes excessively large, the cogging torque peak approaches zero; such cases are not considered in this study. Therefore, a 10-pole 12-slot motor is selected as the model for analysis.

As mentioned in literature [5], motor cogging torque can be viewed as the superposition of contributions from each individual pole. Accordingly, this paper divides the motor into two substructures, as illustrated in [Figure 1: see original paper]. Each substructure consists of six stator slots, with their combination forming the complete stator. The motor' s cogging torque can thus be expressed as:

$$T_{cog} = T_I + T_{II}$$

where the expressions for T_I and T_{II} are given as:

$$T_I = \sum_{n=1,2,3,\ldots} T^{I}_{Nc,n} \sin(N_c\theta)$$

$$T_{II} = \sum_{n=1,2,3,\ldots} T^{II}_{Nc,n} \sin(N_c\theta)$$

In these equations, $T^{I}_{Nc,n}$ and $T^{II}_{Nc,n}$ represent the amplitudes of the nth harmonic cogging torque for part I and part II, respectively; θ denotes the mechanical angle between the stator and rotor.

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3 Novel Stator Design

Cogging torque is generated by the interaction between permanent magnets and the stator iron core when motor windings are unenergized, making the permanent magnets and stator the primary factors affecting cogging torque magnitude. Numerous studies have investigated this phenomenon [6-13], but existing methods have limitations. For instance, skewing can reduce cogging torque to some extent but fails to address cogging torque generated between permanent magnet ends and stator core ends. Auxiliary slots, while effective, complicate the manufacturing process and increase production costs. This paper proposes a simple solution that reduces cogging torque without affecting other motor performance characteristics or manufacturing processes, based on a compensation principle.

As shown in [Figure 2: see original paper], conventional stator teeth have uniform slot openings. When permanent magnets rotate with the rotor, changes in magnetic field energy produce cogging torque. In the shifted stator design, the slot openings are displaced by an angle relative to conventional stator slot openings, as depicted in [Figure 3: see original paper]. Similar to conventional motors, slot-opening shifts do not affect the amplitude of cogging torque but only alter its phase angle. This raises the possibility of shifting the slot openings of part I and part II by appropriate angles to achieve mutual cancellation of their respective cogging torques, thereby achieving reduction. [Figure 4: see original paper] illustrates this novel stator structure.

According to literature [4], the general expression for cogging torque is:

$$T_{cog} = \sum_{n=1,2,3,\dots} T_{c,n} \sin(nN_c\alpha)$$

where $T_{c,n}$ is the amplitude of the nth harmonic cogging torque, N_c is the least common multiple of the slot number Q_s and pole number $2p$, and α is the mechanical angle between stator and rotor.

In the novel structure shown in [Figure 4: see original paper], the slot openings of part I are shifted rightward by angle , while those of part II are shifted leftward by angle . The cogging torque after shifting can be expressed as:

$$T_I = \sum_{n=1,2,3,\dots} T_{Nc,n} \sin[N_c(\alpha - \beta)]$$

$$T_{II} = \sum_{n=1,2,3,\dots} T_{Nc,n} \sin[N_c(\alpha + \beta)]$$

Since parts I and II are essentially identical substructures differing only in permanent magnet polarity, we can assume $T^{I}_{Nc,n} = T^{II}_{Nc,n} = T_{Nc,n}$. The total motor cogging torque becomes:

$$T_{cog} = \sum_{n=1,2,3,\ldots} T_{Nc,n} \sin[N_c(\alpha - \beta)] + \sum_{n=1,2,3,\ldots} T_{Nc,n} \sin[N_c(\alpha + \beta)]$$

$$= 2 \sum_{n=1,2,3,\ldots} T_{Nc,n} \sin(N_c\alpha) \cos(N_c\beta)$$

According to this expression, to eliminate the cogging torque component produced by the nN_cth torque harmonic, the following condition must be satisfied:

$$\cos(nN_c\beta) = 0$$

which yields:

$$\beta = \frac{\pi}{2nN_c}$$

For the model 10-pole 12-slot motor ($n = 1$, $N_c = 60$), the slot-opening shift angle is:

$$\beta = \frac{180°}{2 \times 60} = 1.5°$$

as shown in [Figure 5: see original paper].

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4 Finite Element Simulation

The main motor parameters are listed in the table below.

[TABLE:N] Motor Major Parameters

Parameter	Value
Permanent magnet inner diameter (mm)	
Permanent magnet outer diameter (mm)	
Stator inner diameter (mm)	
Stator outer diameter (mm)	
Air gap (mm)	
Core axial length (mm)	
Pole pairs p	
Remanence Br (T)	
Load current If (A)	
Rated torque T (Nm)	
Speed n (rpm)	

[Figure 5: see original paper] shows the cross-section of the motor with the new stator design. [Figure 6: see original paper] presents the no-load magnetic field distribution of the novel stator motor. [Figure 7: see original paper] compares the radial air-gap flux density waveforms between the novel and conventional stator motors, revealing that slot-opening shifting does not affect the amplitude of radial flux density but changes its angular position. [Figure 8: see original paper] provides harmonic analysis of the radial flux density, clearly showing that the fundamental amplitude of the novel stator motor is essentially consistent with that of the conventional design, while its harmonic amplitudes are slightly lower. The Total Harmonic Distortion (THD) of radial flux density is 46.3% for the conventional stator motor and 43.2% for the novel design, indicating improved sinusoidal characteristics of the air-gap flux density.

[Figure 9: see original paper] compares the cogging torque waveforms of the novel and conventional stator motors. In the conventional design, cogging torque reaches 0.55 N · m, which is substantial for practical applications. In contrast, the novel stator design significantly reduces cogging torque to less than 0.15 N · m at the optimal shift angle. Furthermore, [Figure 10: see original paper] shows the output torque waveforms under maximum load for both designs. For a load current If = 100 A and rated torque of 12 N · m, the torque ripple in the novel stator motor is approximately 1.5% of rated torque, compared to approximately 5.8% for the conventional design.

5 Conclusion

This paper proposes and investigates a novel stator design for weakening cogging torque in modular permanent magnet motors. Through an asymmetric slot-opening structure, cogging torque components are reduced by shifting slot openings left and right from their original positions, causing corresponding phase shifts in the cogging torque waveform. With an appropriate shift angle, the total cogging torque is significantly reduced. Additionally, the new stator design effectively decreases torque ripple. Compared to other methods, the proposed stator design offers a simpler and more cost-effective manufacturing process.

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Note: Figure translations are in progress. See original paper for figures.