

A Novel Consequent Pole SPM Topology Using Grain-Oriented Steel for Reduced Rare-Earth Magnet Usage

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This paper proposes a novel grain-oriented consequent pole surface-mounted permanent magnet motor (GCSPM) designed to significantly reduce rare-earth magnet usage while maintaining acceptable electromagnetic performance. Conventional permanent magnet motors require large amounts of rare-earth materials, leading to high costs and supply chain risks. To address these challenges, the proposed GCSPM structure replaces part of the magnets with grain-oriented steel (GO), which exhibits superior magnetic properties along the rolling direction. By radially aligning the GO in regions where the magnetic flux flows consistently, the design seeks to minimize performance degradation despite the reduced use of magnets. In addition, torque ripple mitigation techniques such as magnet chamfering and skewing are applied to enhance torque smoothness. These improvements contribute to better drivability and operational stability. The performance of the proposed GCSPM, focusing on average torque and torque ripple characteristics, is evaluated through finite element analysis (FEM) by systematically varying skew angles, chamfering dimensions, and rotor design parameters to achieve optimized performance.

Index Terms— Consequent Pole, GCSPM, Grain-oriented Steel, Kickboard, Reduced Rare-Earth Magnet, Torque ripple reduction

I. INTRODUCTION

In recent years, the number of individuals owning vehicles has increased significantly, resulting in severe traffic congestion, particularly in densely populated urban areas. Additionally, the extensive use of fossil fuels due to the growing number of vehicles on the road has escalated environmental pollution concerns. To address these issues, the development of electric personal mobility devices, such as electric bikes, scooters, and kickboards, has gained substantial attention due to their convenience, affordability, and eco-friendly nature [1]-[2].

Among these options, the electric kickboard stands out as an efficient means of short-distance transportation in urban environments. Its compact size and lightweight frame allow for efficient maneuverability in crowded urban areas, providing a flexible transportation option. Moreover, electric kickboards offer a cost-effective solution with lower maintenance requirements compared to traditional vehicles, while also contributing to reduced carbon emissions.

Although electric kickboards are convenient and cost-effective, they depend heavily on the motor. High-performance motors rely on permanent magnets, significantly raising material costs [3]. Therefore, reducing material costs by minimizing the use of rare-earth magnets while maintaining high performance motor designs is essential.

This paper proposes a GCSPM that significantly reduces rare-earth magnet usage, while achieving acceptable performance retention compared to a conventional SPM motor. The proposed motor design utilizes GO materials within the south pole magnet regions to reduce the reliance on rare-earth magnets. The GO is shaped to resemble permanent magnets, contributing to maintaining electromagnetic performance despite the reduced use of rare-earth magnets.

II. GEOMETRY OF THE NOVEL GCSPM

Fig. 1 illustrates the geometry of the proposed GCSPM along with the B-H characteristics of the utilized NO and GO. In

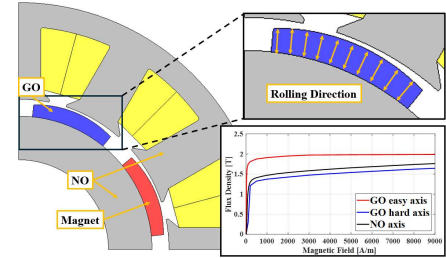


Fig. 1. Geometry of the GCSPM and B-H characteristic.

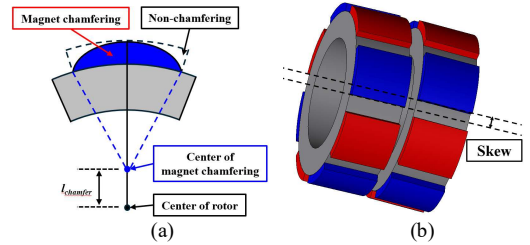


Fig. 2. Techniques of torque ripple reduction. (a) Magnet chamfering. (b) Skew.

contrast to conventional surface-mounted permanent magnet motors (SPM), the proposed structure replaces the south pole magnets with GO. The rolling direction of the applied GO is aligned radially, as illustrated in Fig. 1.

The GO exhibits superior B-H characteristics compared to NO when the magnetic flux flows along the rolling direction [4]. However, when the magnetic flux flows perpendicular to the rolling direction, the B-H characteristics decrease significantly. For this reason, it is crucial to apply GO at positions where the magnetic flux flows consistently along the rolling direction. As a result, GO is applied in the rotor south pole regions, where the magnetic flux generated by the stator flows in a relatively consistent direction along the rolling direction.

Consequently, the proposed topology reduces the use of permanent magnets by utilizing GO while maintaining high performance relative to the reduced magnet usage. Design Techniques Reducing torque ripple is essential to improve the driving safety and riding comfort of electric kickboards. In

SPM motors, torque ripple can be reduced by modifying the shape of the magnets. Therefore, torque ripple reduction is achieved by applying magnet chamfering to adjust the magnet shape. Additionally, skewing, a widely used technique for torque ripple reduction, is applied to reduce torque ripple.

A. Magnet Chamfering

The magnet chamfering is an effective way to reduce torque ripple, as illustrated in Fig. 2(a). In the case without magnet chamfering, as shown by the dotted line in Fig. 2(a), the magnet thickness remains constant across all regions. However, when magnet chamfering is applied, as indicated by the red region in Fig. 2(b), the magnet is thickest at the center and gradually decreases toward the edges. This magnet structure improves the air-gap flux density waveform, contributing to the reduction of cogging torque, back-EMF THD, and torque ripple [5].

B. Skew

Skew is another commonly used technique for torque ripple reduction. Skew can be applied in various forms, and in this study, a step skew is employed, as illustrated in Fig. 2(b). The applicable skew angle θ_{skew} for the entire model can be calculated using (1), and the skew slice angle θ_{skew_step} between slices can be determined using (2) [6].

$$\theta_{skew} = \frac{M-1}{M} \times \frac{360^\circ}{LCM(N_p, N_s)}. \quad (1)$$

Here, M represents the number of skew slices, while N_p and N_s denote the number of poles and slots, respectively.

$$\theta_{skew_step} = \frac{\theta_{skew}}{M-1}. \quad (2)$$

Applying skew reduces cogging torque and back-EMF THD, which ultimately contributes to torque ripple reduction [6].

III. ENHANCING THE DESIGN OF GCSPM BY INVESTIGATION

The initial geometries of the reference model and the proposed GCSPM are illustrated in Fig. 3, and their specifications are listed in Table I. The reference model in Fig. 3(a) is a conventional SPM, where the rotor is composed of magnets and NO. Meanwhile, the rotor of the proposed GCSPM in Fig. 3(b) consists of magnets, GO, and NO. Both models share the same stator design, electrical specifications and magnet shape.

The analysis results, as shown in Table II, show that the average torque and magnet usage of the GCSPM decreased by 13.25% and 50.00%, respectively, compared to the reference model, while the torque ripple increased by 1.60%. The reduction rate of the average torque is 26.50% relative to the reduction in magnetic usage. These results indicate that the proposed topology achieves a lower reduction in average torque compared to the reduction in magnet usage. In addition, a slight increase in torque ripple was observed. Therefore, in the full paper, further analysis will be conducted to reduce the torque ripple of the GCSPM by investigating the effects of skew angle,

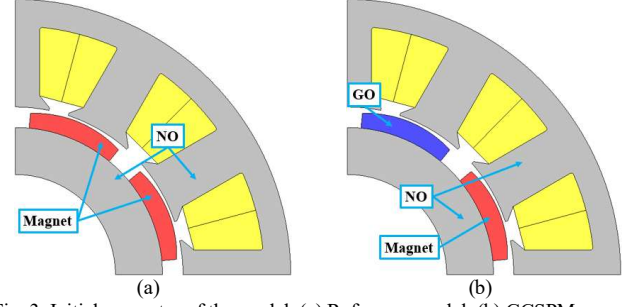


Fig. 3. Initial geometry of the model. (a) Reference model. (b) GCSPM.

TABLE I
SPECIFICATION OF REFERENCE MODEL AND GCSPM

Specification	Value
Pole / Slot	8 / 12
Stator outer [mm]	55
Rotor outer [mm]	33
Air gap [mm]	0.5
Stack length [mm]	40
Skew slice / angle [deg]	2 / 3.25
$l_{chamfer}$ [mm]	10

TABLE II
RESULT OF REFERENCE MODEL AND GCSPM

Model	Average torque [Nm]	Torque ripple [%]	Magnet usage [mm ³]
Reference	3.17	21.42	20129.52
GCSPM	2.75	23.02	10064.76
Difference	-13.25 %	+1.60 % _p	-50.00 %

magnet chamfering, and design variables related to the rotor geometry.

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