

Article

Torque Ripple Reduction and Power Density Improvement of a Slotless Motor Design for Rack-Type Electrical Power Steering

Dong-Youn Shin ¹, Do-Hyeon Choi ¹ , Hyung-Sub Han ¹ , Deepak Dubal ² and Won-Ho Kim ^{3,*} 

¹ Department of Next-Generation Smart Energy System Convergence, Gachon University, Seongnam-si 13120, Republic of Korea; tlsehdbs97@gachon.ac.kr (D.-Y.S.); brosubi@naver.com (H.-S.H.)

² Department of Chemistry & Physics, Queensland University of Technology, Brisbane, QLD 4000, Australia; deepak.dubal@qut.edu.au

³ Department of Electrical Engineering, Gachon University, Seongnam-si 13120, Republic of Korea

* Correspondence: wh15@gachon.ac.kr

Abstract

Electric power steering (EPS) systems have become the dominant steering solution in modern vehicles due to their advantages in energy efficiency and driving convenience. Among EPS configurations, rack-type EPS (R-EPS) is widely adopted in mid-to-large vehicles for its direct and responsive steering characteristics. However, conventional slotted motors used in R-EPS suffer from cogging torque and torque ripple caused by periodic reluctance variation in the stator tooth structure, resulting in vibration and noise directly perceived by the driver. This article proposes a slotless Surface Permanent Magnet Synchronous Motor (SPMSM) employing a Bar-Type magnet with a double-bridge rotor structure for R-EPS applications. By eliminating stator teeth, the proposed design achieves a uniform reluctance distribution during rotor rotation, theoretically reducing cogging torque to zero. The absence of stator tooth magnetic saturation further enables the use of high-remanence permanent magnets, improving gravimetric power density and enabling motor miniaturization. The proposed motor was designed and verified through finite element analysis (FEA). Compared to the conventional Arc-Type motor, the optimized design achieves a torque ripple reduction of 64.7% (from 5.07% to 1.79%) through Bar-Type magnet shaping combined with a 5 mm edge filet. The optimized design achieved an output power of 359.9 W, a gravimetric power density of 276.85 W/kg based on an active part weight of 1.30 kg, and a structural safety factor of 1146, demonstrating the effectiveness of the proposed double-bridge slotless motor for R-EPS applications.

Keywords: cogging torque; electric power steering; rack-type EPS; slotless PMSM; torque ripple



Academic Editor: Zafer Bingul

Received: 16 May 2026

Revised: 17 June 2026

Accepted: 19 June 2026

Published: 2 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

Electric power steering (EPS) systems have become the dominant steering solution in modern vehicles, replacing conventional hydraulic systems owing to their advantages in energy efficiency and compatibility with advanced driver-assistance systems [1,2]. Among EPS configurations, rack-type EPS (R-EPS) is widely adopted in mid-to-large class vehicles due to its direct mechanical linkage between the assist motor and the steering rack, which enables high steering force with precise responsiveness [3]. Because this direct-drive architecture transmits motor-side torque disturbances almost unattenuated to the steering wheel, the motors used in R-EPS must satisfy stringent requirements for low cogging torque, low torque ripple, and high gravimetric power density.

Surface-mounted permanent magnet synchronous motors (SPMSM) are the preferred topology for R-EPS applications owing to their high torque-to-weight ratio and ease of control [4–6]. However, conventional slotted SPMSM designs inherently generate cogging torque and torque ripple due to the periodic reluctance variation caused by the stator tooth-slot structure [7]. Various mitigation techniques have been proposed, including stator skewing, tooth-tip shaping, and fractional-slot winding configurations, but these approaches involve geometric trade-offs that limit overall effectiveness or increase manufacturing complexity [8–13]. Slotless motor architectures eliminate stator teeth entirely, yielding a theoretically zero cogging torque and removing tooth magnetic saturation constraints, which allows for greater utilization of high-remanence permanent magnets and improved power density [14–17]. Despite these advantages, existing slotless studies have largely focused on cogging torque elimination and high-speed operation, while three critical aspects of R-EPS-oriented slotless design remain insufficiently addressed. First, systematic magnet-shaping methodologies that simultaneously suppress back-EMF harmonics and high-order torque ripple, rather than only the dominant cogging component, are rarely reported. Second, lightweight rotor structures that reduce active-part weight without sacrificing the structural integrity required under centrifugal loading have received limited attention in the slotless context. Third, design procedures tailored to the 48 V system architecture and the stringent NVH requirements of R-EPS applications are sparsely documented in the literature. This study addresses these gaps by integrating Bar-Type magnet shaping with edge filing for harmonic suppression, a double-bridge lightweight rotor verified by structural analysis, and a complete FEA-based design procedure under a fixed 48 V slotless stator configuration.

This paper proposes a slotless SPMSM employing a Bar-Type permanent magnet with a double-bridge lightweight rotor topology for 48 V R-EPS applications. A Bar-Type magnet geometry introduces a non-uniform air-gap profile that enables flux shaping, effectively suppressing high-order harmonics in the back-EMF and reducing torque ripple without additional stator-side modifications. The double-bridge rotor topology reduces active part weight while maintaining structural integrity under centrifugal loading, as verified by finite element analysis (FEA). The remainder of this paper is organized as follows: Section 2 defines the conventional motor and design constraints; Section 3 presents the magnet optimization, lightweight rotor design, structural analysis, and FFT-based torque ripple evaluation; Section 4 summarizes the conclusions.

2. Conventional Motor and Design Constraints

For rack-type EPS(R-EPS) motors, the radial flux type surface-mounted permanent magnet synchronous motor (SPMSM) is commonly employed. The uniform air-gap flux density distribution of the SPMSM enables precise torque control, which is highly advantageous for motor miniaturization and weight reduction compared to the interior permanent magnet synchronous motor (IPMSM). Furthermore, the absence of stator tooth magnetic saturation in slotless SPMSM configurations allows for greater utilization of permanent magnet flux, making the slotless architecture particularly suitable for high-power-density and low-noise EPS applications.

A conventional slotless R-EPS motor was selected as the baseline, as shown in Figure 1, Red and blue represent the north (N) and south (S) poles of the magnets, respectively. to establish the performance and size requirements for the proposed design. As illustrated in the exploded view of Figure 1a and the assembled view of Figure 1b, the motor consists of an inner rotor carrying surface-mounted permanent magnets, an air-gap winding wound directly without stator teeth, and a slotless cylindrical stator back-yoke that provides the magnetic return path; these components are enclosed by the housing and end brackets

supported on the shaft and bearings. The labeled exploded view further identifies the rotor core, permanent magnets, plastic mold, molded coil, and stator back-yoke, which constitute the main electromagnetic and mechanical support components of the baseline slotless R-EPS motor. In operation, the permanent magnets establish a radial air-gap field, and three-phase currents in the air-gap winding interact with this field to produce torque. Because the slotless stator presents a smooth bore with no teeth, the air-gap reluctance remains constant during rotor rotation, so cogging torque is theoretically eliminated, and the back-EMF waveform is governed primarily by the magnet shape rather than by tooth-slot geometry. The conventional motor operates at a rated speed of 1000 rpm with a rated torque of 3.41 Nm, delivering an output power of 355 W and a gravimetric power density of 259.17 W/kg with an active part weight of 1.37 kg. Detailed specifications of the conventional motor are summarized in Table 1.

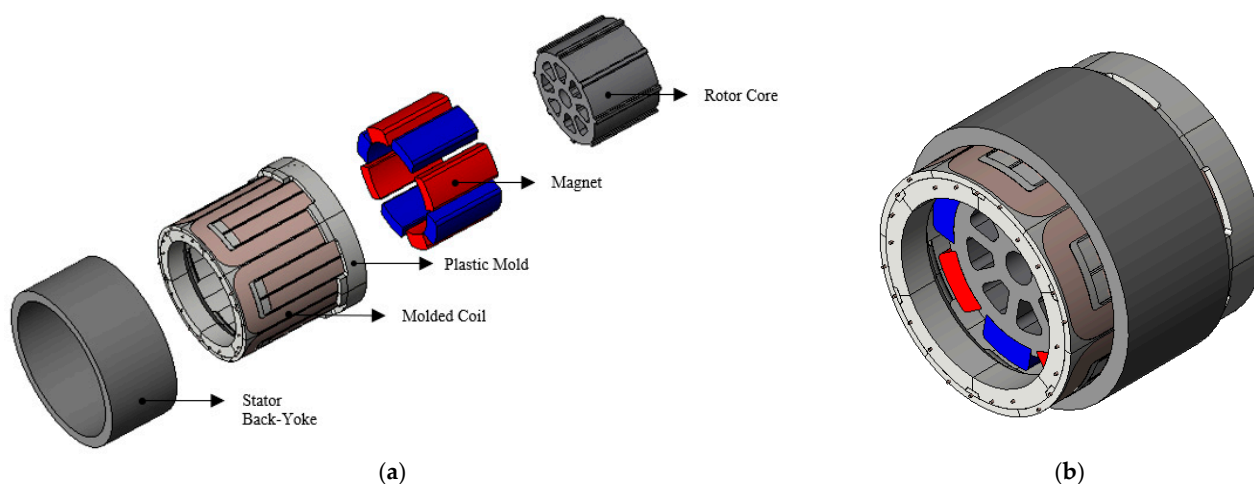


Figure 1. Conventional slotless R-EPS motor: (a) exploded view, (b) assembled view.

Table 1. Specifications of the Conventional Motor.

Parameter		Value	Unit
Size	Poles/Slots	8/24	-
	Stator Diameter	84.9	mm
	Rotor Diameter	67.5	mm
	Airgap	0.5	mm
	Stack Length	38	mm
Winding	Coil Diameter	0.65(0.8)	mm
	Number of Turns	36	-
	Number of Parallels	4	-
Materials	Magnet	1.43/1109 Nd	T/ka/m
	Coil	Copper	-
	Core	50PN470	-

To ensure equivalent or superior output performance while achieving meaningful reductions in cogging torque, torque ripple, and active part weight, the proposed slotless motor was designed based on the specifications of the conventional motor. The design targets include maximizing gravimetric power density and minimizing electromagnetic vibration sources within the given spatial constraints of the R-EPS installation environment. The detailed design methodology and resulting specifications of the proposed motor are presented in the following section.

In this study, the stator outer diameter and coil specifications of the conventional slotless R-EPS motor were fixed in accordance with the requirements of the manufacturing

partner. Therefore, the design variables available for optimization were limited to the permanent magnet shape parameters. As illustrated in Figure 2, the red hatched region represents the actual coil winding area, while the yellow highlighted region on the right indicates the curved lower section of the winding. A detailed verification of the coil turn validity within the innermost winding region was beyond the scope of this study, as the primary objectives are to improve power density and torque performance through THD minimization under a fixed stator configuration. Within these constraints, the permanent magnet geometry was optimized to maximize no-load back-EMF while minimizing total harmonic distortion (THD) of the phase voltage, which directly influences cogging torque and torque ripple in slotless motors.

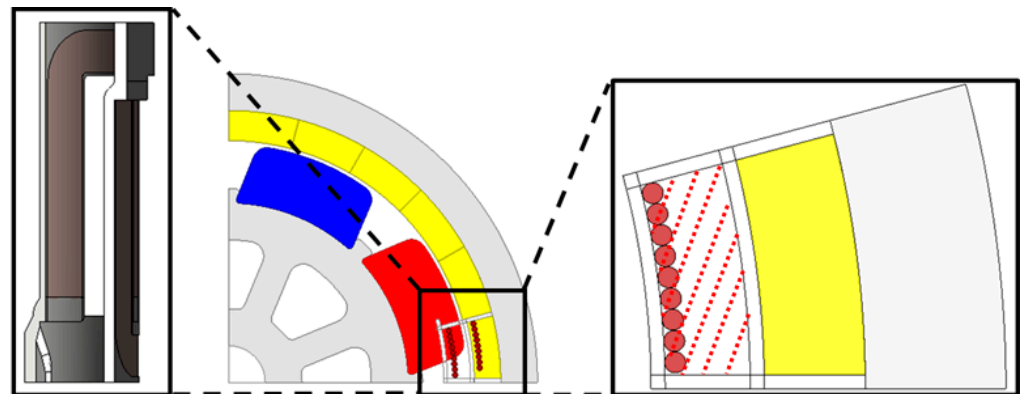


Figure 2. Two-dimensional finite element analysis (FEA) model of the conventional slotless R-EPS motor. Cross-sectional view of the motor illustrating the rotor core, stator core, permanent magnets, coil winding region, and stator back yoke. Gray, red, blue, and yellow represent the rotor core and stator core, north (N) pole, south (S) pole, and coil winding region, respectively.

3. Proposed Motor Design and Optimization

As shown in Figure 3, the Arc-Type permanent magnet is designed such that its inner and outer curvatures conform to the rotor core and stator, maintaining a constant air-gap along the rotational direction θ .

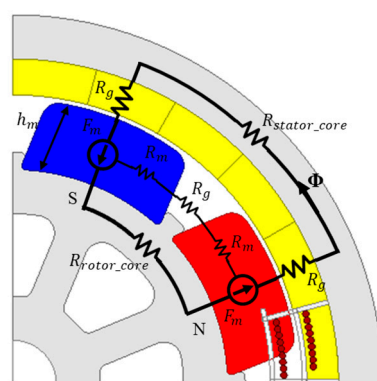


Figure 3. Magnetic equivalent circuit (MEC) model of the conventional Arc-Type magnet.

In the Arc-Type structure, since the magnet thickness h_m and the air-gap thickness δ is uniform across the entire magnetic pole area, the parameters of the magnetic circuit are treated as constants. The total reluctance of the magnetic circuit R_{total} is defined as follows

$$R_{total} = R_m + R_g + R_{core} \approx \frac{h_m}{\mu_0 \mu_r A_m} + \frac{\delta}{\mu_0 A_g} \quad (1)$$

R_m is the internal reluctance of the magnet, and R_g is the air-gap reluctance. The reluctance of the iron core, R_{core} can be neglected by assuming infinite permeability. Because the Magnetomotive Force (MMF) source is constant and the magnetic reluctance is uniform regardless of position, the air-gap flux density $B_g(\theta)$ theoretically forms a square wave distribution within the range of the pole arc angle a_g .

$$\delta_\theta = \sqrt{(R_m + R_g)^2 + (R_r \sin \theta)^2} - R_r \cos \theta \quad (2)$$

This square wave distribution, when decomposed via the Fourier series, contains substantial high-order harmonic components that directly elevate the total harmonic distortion (THD) of the back-EMF, contributing to cogging torque and torque ripple.

3.1. Bar-Type Permanent Magnet Optimization

In contrast to the conventional Arc-Type geometry, the Bar-Type magnet configuration features a non-uniform air-gap $\delta(\theta)$ that varies with angular position [18]. This enables flux shaping, in which the magnetic equivalent circuit (MEC) parameters are tailored to improve the harmonic profile of the back-EMF [19].

The air-gap reluctance $R_g(\theta)$ and the resulting air-gap flux density $B_g(\theta)$ for a Bar-Type structure can be defined as Equations (3) and (4).

$$R_g(\theta) = \frac{\delta(\theta)}{\mu_0 A_g(\theta)} \quad (3)$$

$$B_g(\theta) \approx \frac{B_r}{1 + \mu_r \frac{\delta(\theta)}{\mu_0 h_m(\theta)}} \quad (4)$$

By substituting the position-dependent air-gap function $\delta(\theta)$ into Equation (4), it is evident that the air-gap flux density $B_g(\theta)$ is no longer constant across the pole arc. Since the air-gap length $\delta(\theta)$ increases as the angular position moves from the center toward the pole edges, the flux density naturally attenuates at the magnet peripheries. This physical characteristic transforms the conventional square wave distribution into a more sinusoidal profile, effectively suppressing high-order harmonics that contribute to Total Harmonic Distortion (THD).

An additional degree of freedom is introduced through a side-cut geometry at the magnet edges, as shown in Figure 4 [20]. By tuning the side-cut angle, the effective pole arc and the flux density transition slope can be precisely controlled, enabling targeted suppression of specific harmonic components in the back-EMF. Parametric simulations confirm that an optimized side-cut angle can reduce the THD to below 1%, which is essential for EPS applications requiring smooth torque delivery and minimal vibration.

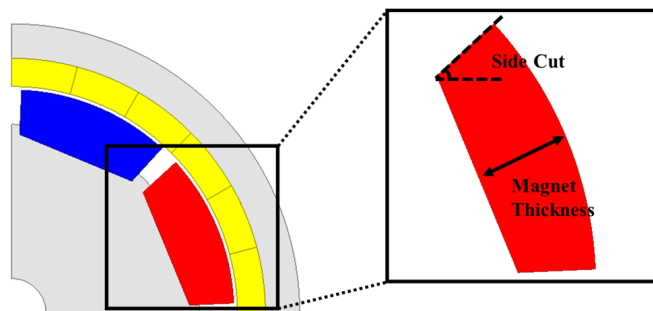


Figure 4. Analysis model of the Bar-Type magnet geometry.

However, an excessive side-cut reduces the fundamental flux density component, which may compromise average torque output. Therefore, the magnet thickness and side-cut angle were selected through an iterative optimization process to satisfy both torque density and NVH requirements simultaneously, as illustrated in Figure 5.

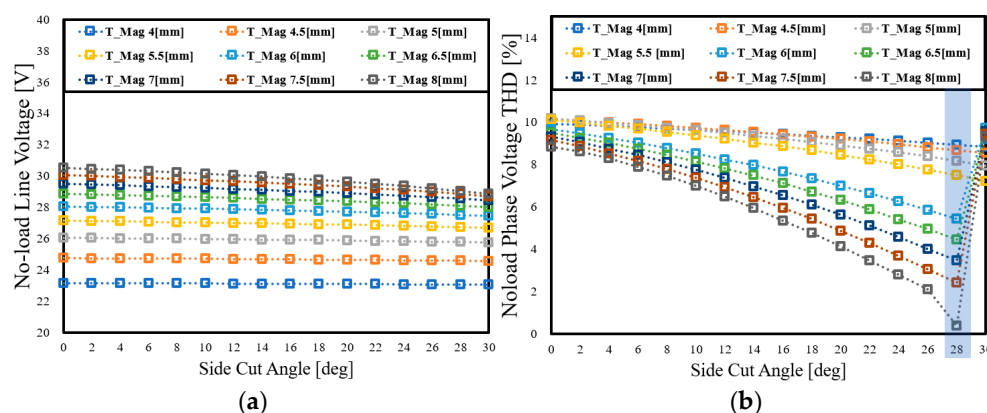


Figure 5. Parametric analysis of no-load characteristics according to magnet thickness and side-cut angle: (a) No-load line-to-line back-EMF; (b) No-load phase voltage THD.

Based on the comprehensive parametric analysis, a magnet thickness of 8.0 mm and a side-cut angle of 28° were selected as the final design parameters for the 48 V EPS motor. This configuration achieves a no-load line-to-line back-EMF of 30.05 Vrms and a minimum phase voltage THD of 0.38%. Furthermore, a performance comparison was conducted through load analysis to verify the operational characteristics of the optimized design, with the load magnetic field distribution of the proposed Bar-Type model shown in Figure 6, and the results are summarized in Table 2. The optimized design meets the required torque and efficiency targets under rated operating conditions.

Table 2. Comparison of Performance of Arc-Type Model and Bar-Type Model.

Performance		Arc-Type	Bar-Type	Unit
No-Load	Resistance	0.42		Ohm
	BEMF	17.52	18.03	V _{rms}
	L2L BEMF	25.11	25.88	V _{max}
Load	Torque	3.42	3.52	Nm
	Torque Ripple	5.07	3.36	%
	L2L Max	36.93	37.27	V _{max}
	Speed	1000		rpm
	Current	11.8		A _{rms}
	Current Density	17.78		A _{rms} /mm ²
	Copper Loss	175.44		W
	Core Loss	2.45	1.69	W
	Output Power	355.69	380.54	W
	Efficiency	66.66	68.10	%
Output	Weight	1.34	1.58	kg
	Power Density	258.64	240.51	W/kg

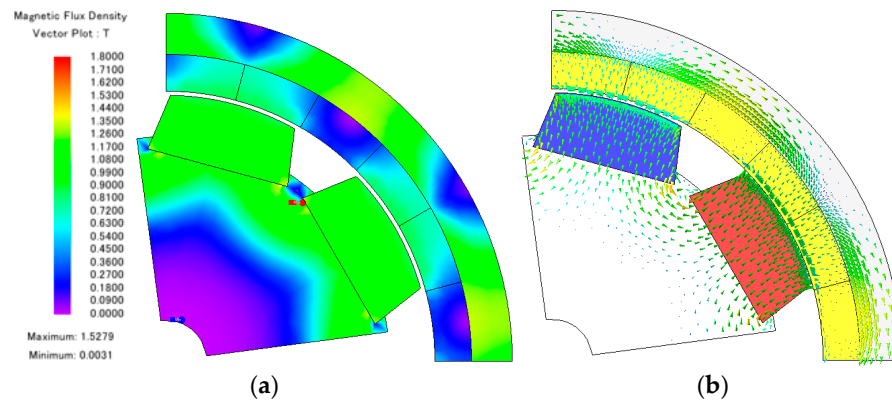


Figure 6. Load magnetic field distribution of the proposed Bar-Type model (a) Magnetic flux density contour plot; (b) Magnetic flux density vector plot.

3.2. Double-Bridge Lightweight Rotor Design

The analysis results in Table 2 confirm improvements in no-load back-EMF, torque and output power. However, because the rotor lightweight design has not yet been implemented, the total weight is 0.24 kg higher, resulting in a power density that is 18.13 W/kg lower than the conventional motor. Consequently, a rotor lightweight design is conducted on the proposed model to address this deficiency. As illustrated in Figure 7, both Polygon-type and Bridge-type topologies are proposed. The optimal rotor geometry is derived by observing the trends in magnetic flux density saturation relative to various bridge thicknesses and angles, with the saturation analysis for the polygon-type rotor presented in Figure 8.

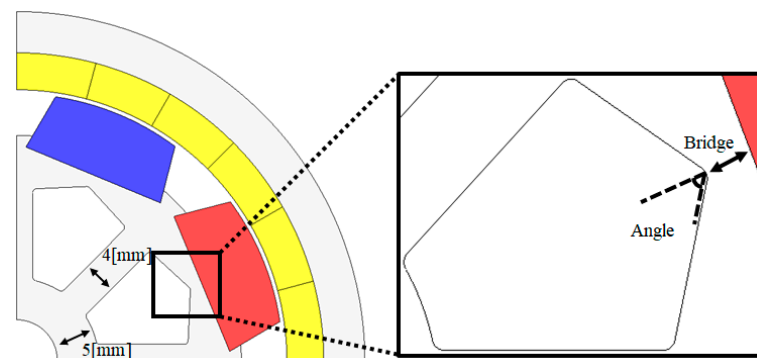


Figure 7. Polygon-type lightweight rotor topology.

The analysis results revealed that for the polygon-type configuration, magnetic saturation exceeding 1.8 Tesla occurred in the rotor back-yoke region due to the thin bridge thickness. Consequently, a dual-bridge rotor lightweight topology, featuring an iron core inserted into the center of the polygon rotor shape, is presented in Figure 9. Similarly, Figure 10 illustrates the magnetic flux density saturation trends at various angles for a bridge thickness of 2 mm.

The analysis results indicated that for the double-bridge rotor configuration, some magnetic flux leakage occurred due to the insertion of the central iron core; however, this modification effectively reduced the magnetic saturation level in the back-yoke region. Consequently, the trends in torque and weight based on this analysis model are illustrated in Figure 11, and model (d) in Figure 10 was selected as the final design as it satisfies the saturation limit of under 1.8 Tesla without compromising electromagnetic performance.

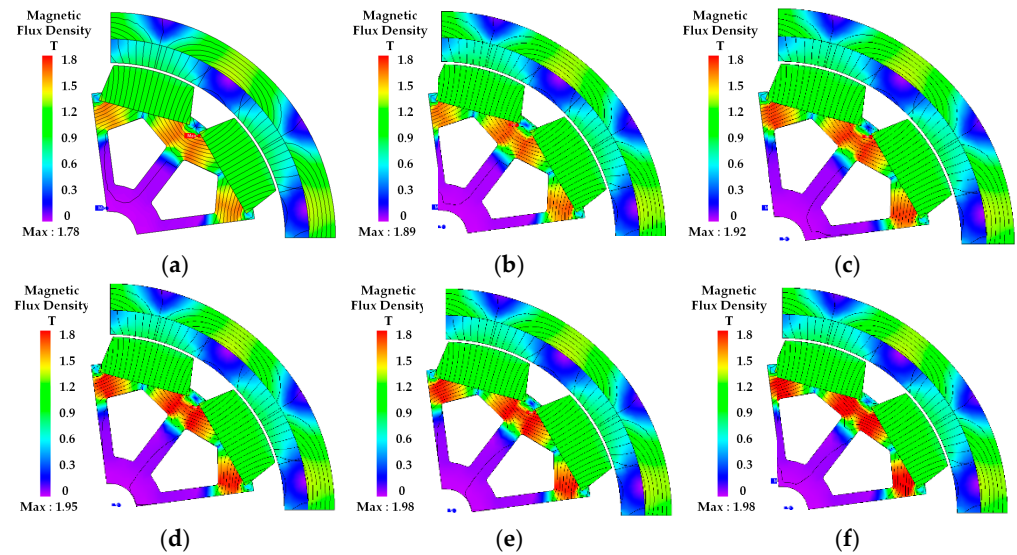


Figure 8. The magnetic flux density saturation analysis for the proposed polygon-type rotor as a function of bridge thickness and rib angles. (a) 55°; (b) 57°; (c) 59°; (d) 61°; (e) 63°; (f) 65° (bridge thickness: 2 mm).

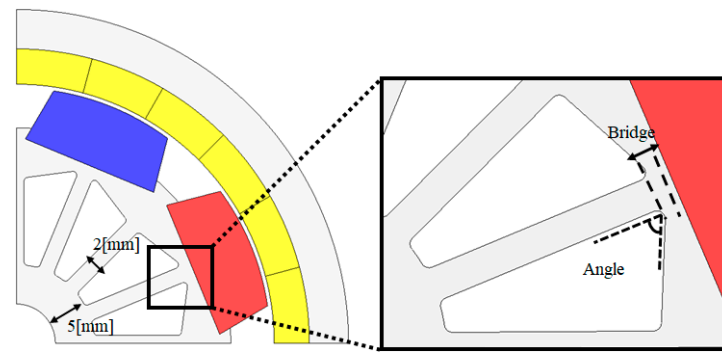


Figure 9. Double-bridge lightweight rotor topology.

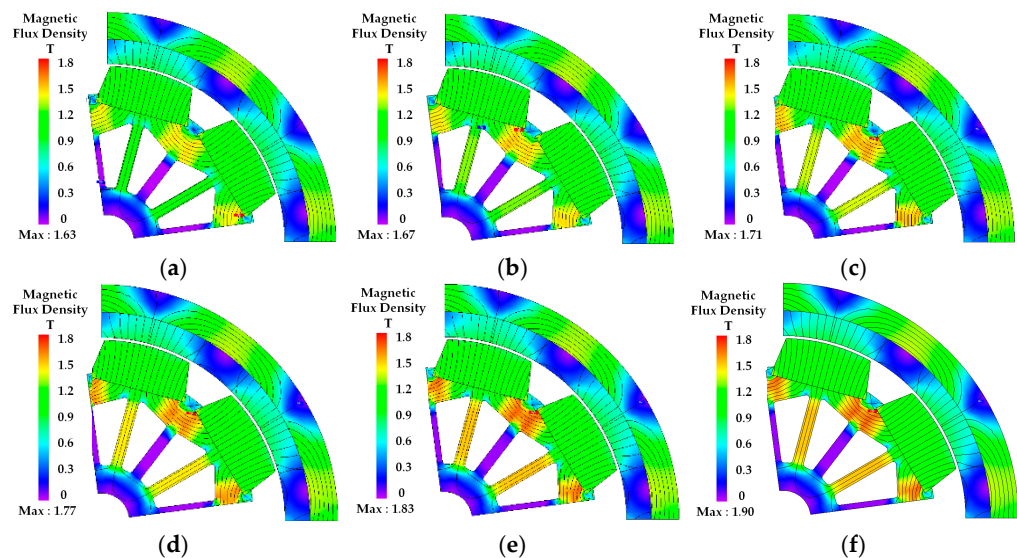


Figure 10. The magnetic flux density saturation analysis for the proposed bridge-type rotor as a function of bridge thickness and rib angles. (a) 55°; (b) 57°; (c) 59°; (d) 61°; (e) 63°; (f) 65° (bridge thickness: 2 mm).

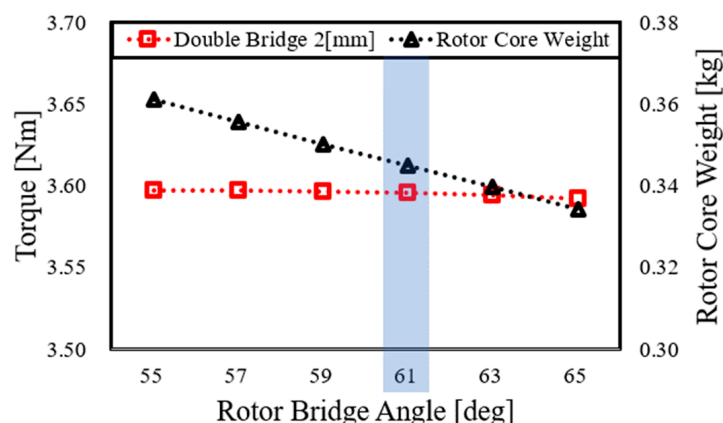


Figure 11. Variation in output torque and rotor core weight as a function of the rotor bridge angle.

3.3. Structural Integrity Analysis

To ensure the mechanical reliability of the proposed Double Bridge lightweight rotor, a structural integrity analysis was performed using Finite Element Analysis (FEA) [21]. While the primary goal of the “Polygon” and “Double Bridge” topologies was to enhance power density through weight reduction, it is critical to verify that the reduced bridge thickness can withstand the centrifugal forces generated at maximum operating speeds. The analysis was conducted under the maximum rated speed of the EPS motor. The material properties of the rotor core (electrical steel) were defined with a Yield Strength σ_{yield} of 275 MPa. The main objective was to ensure that both the induced stress and radial deformation remain within safe limits to prevent structural failure or air-gap interference.

The distribution of von Mises stress and the resulting radial displacement across the rotor cross-section are illustrated in Figure 12. The mechanical stress distribution is shown in Figure 12a. The maximum von Mises stress σ_{Max} occurs at the inner edges of the bridge, reaching a value of 0.24 MPa. This stress level is concentrated at the sharp corners of the bridge and rib areas, which act as the primary mechanical supports for the permanent magnets against centrifugal load. The radial displacement distribution is illustrated in Figure 12b. The maximum displacement is recorded as 7.51×10^{-4} mm, occurring at the outermost sections of the permanent magnets. This negligible deformation indicates that the structural rigidity of the optimized rotor is sufficient to maintain a consistent air-gap clearance, ensuring magnetic stability and preventing any physical contact between the rotor and stator during operation.

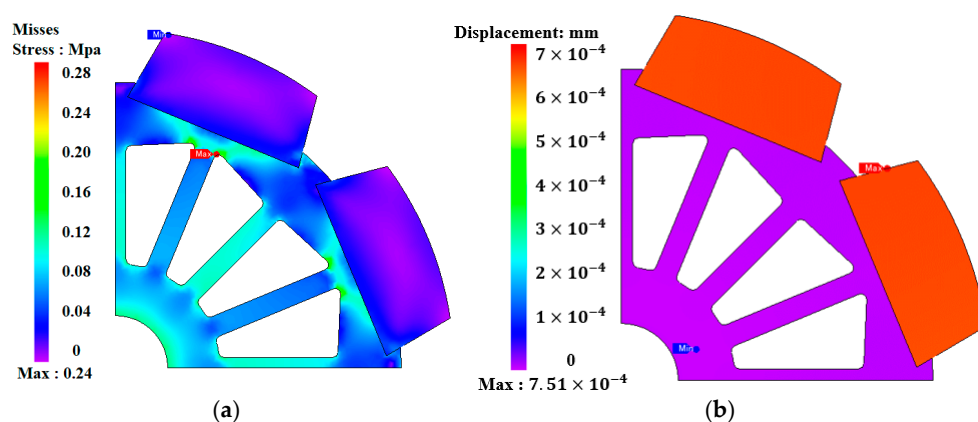


Figure 12. Structural analysis results (a) von Mises stress; (b) radial displacement.

To quantitatively evaluate the structural reliability, the Safety Factor (SF) was calculated using the following Equation (5).

$$F \approx \frac{\sigma_{yield}}{\sigma_{max}} \quad (5)$$

Given the yield strength of 275 MPa and a maximum induced stress of 0.24 MPa, the calculated safety factor is approximately 1146. In general mechanical design, a safety factor between 1.5 and 2.0 is considered sufficient for reliable operation. The calculated safety factor of 1146 far exceeds this threshold, confirming that the proposed double-bridge rotor maintains structural robustness despite the significant weight reduction.

3.4. Electromagnetic Performance Comparison

With the structural integrity of the double-bridge rotor confirmed, this section presents a comparative analysis of the electromagnetic performance between the conventional Arc-Type and the optimized Bar-Type rotor models. The key performance metrics, including back-EMF, torque output, core loss, and efficiency, are evaluated based on finite element analysis (FEA) results and summarized in Table 3.

Table 3. Performance comparison between the conventional Arc-Type and the Bar-Type rotor models.

Performance		Arc-Type	Bar-Type	Unit
No-Load	Resistance	0.42		Ohm
	BEMF	17.52	18.40	V _{rms}
	L2L BEMF	25.11	26.4	V _{max}
Load	Torque	3.42	3.59	Nm
	Torque Ripple	5.07	3.87	%
	L2L Max	36.93	37.39	V _{max}
	Speed	1000		rpm
	Current	11.8		A _{rms}
	Current Density	17.78		A _{rms} /mm ²
	Copper Loss	175.44		W
	Core Loss	2.45	1.72	W
	Output Power	355.69	374.22	W
	Efficiency	66.66	67.87	%
Output	Weight	1.34	1.33	kg
	Power Density	258.64	281.37	W/kg

The FEA results show that the proposed Bar-Type model outperforms the conventional Arc-Type motor in several key areas. The no-load line-to-line back-EMF increased from 25.11 V_{rms} to 26.4 V_{rms}, which directly contributed to a 4.97% increase in output torque (from 3.42 Nm to 3.59 Nm). Furthermore, the core loss was significantly reduced from 2.45 W to 1.72 W, representing a 29.8% reduction [22,23]. This improvement in the electromagnetic loss profile, combined with the higher torque output, resulted in an overall efficiency enhancement from 66.66% to 67.87%. To address torque ripple reduction, Section 3.5 performs a comparative FFT analysis of the torque produced by existing Arc-Type and Bar-Type motor designs.

3.5. Torque Harmonic Analysis and Magnet Edge Filet Optimization

This section examines the torque ripple characteristics of the conventional Arc-Type rotor and the optimized Bar-Type rotor. To investigate the specific frequency components contributing to torque fluctuation, a Fast Fourier Transform (FFT) analysis was performed, with the results illustrated in Figure 13. Although the time-domain waveforms are sim-

ilar owing to the slotless structure, the harmonic spectra provide a more sensitive and quantitative indication of the effect of magnet shaping.

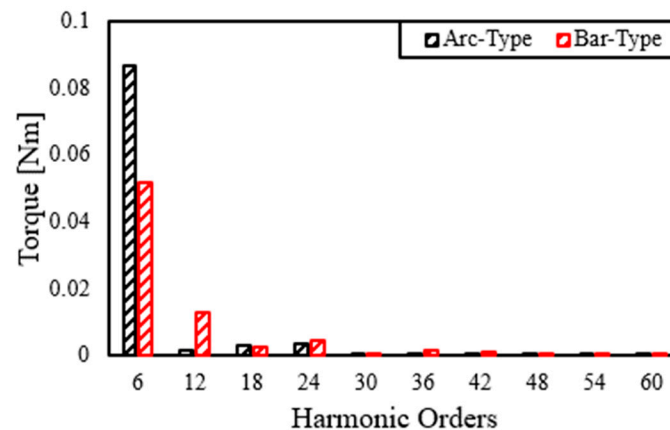


Figure 13. Fast Fourier Transform (FFT) analysis results.

As shown in Figure 13, the Bar-Type rotor significantly reduces the dominant 6th-order harmonic compared with the Arc-Type rotor, whereas some higher-order components, such as the 12th, 24th, 36th, and 42nd harmonics, are relatively increased. This harmonic redistribution arises because part of the energy suppressed at the dominant 6th-order component is transferred to higher-order multiples due to the geometric saliency and sharp flux-transition points of the Bar-Type topology [24–26]. Although these high-order harmonics are small in absolute magnitude, they may still affect steering NVH performance by inducing high-frequency vibration components [27].

To mitigate these harmonic risks while maintaining the high average torque characteristic of the Bar-Type design, a fillet geometry was implemented at the magnet extremities. Figure 14. presents the proposed magnet edge filing intended to smooth the air-gap flux density distribution, and Figure 15. analyzes the resulting reduction in dominant torque harmonics as a function of the fillet radius.

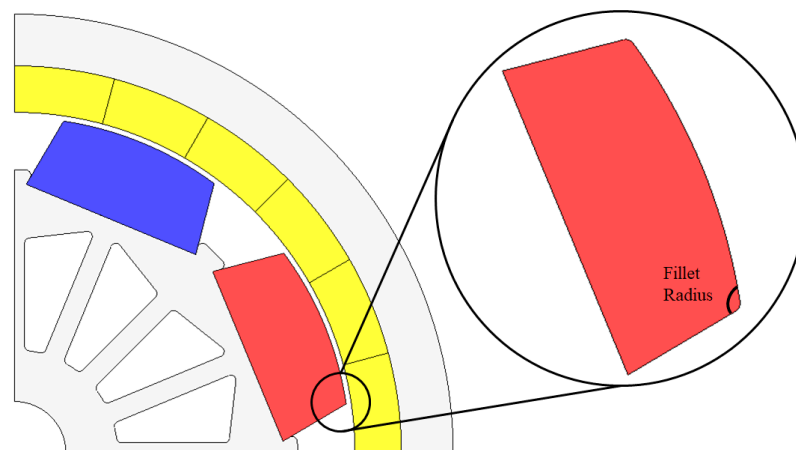


Figure 14. Proposed magnet edge filing for torque ripple and THD reduction.

The analysis in Figure 15a demonstrates that while the average torque of the Bar-Type rotor decreases as the fillet radius increases, it remains above the Arc-Type baseline of 3.42 Nm up to a 5 mm fillet radius. Furthermore, as shown in Figure 15b, increasing the fillet radius effectively attenuates the torque harmonics across major orders. In particular, the 5 mm fillet was identified as the optimal design point, offering the most significant suppression of high-order harmonic components while maintaining the required output torque.

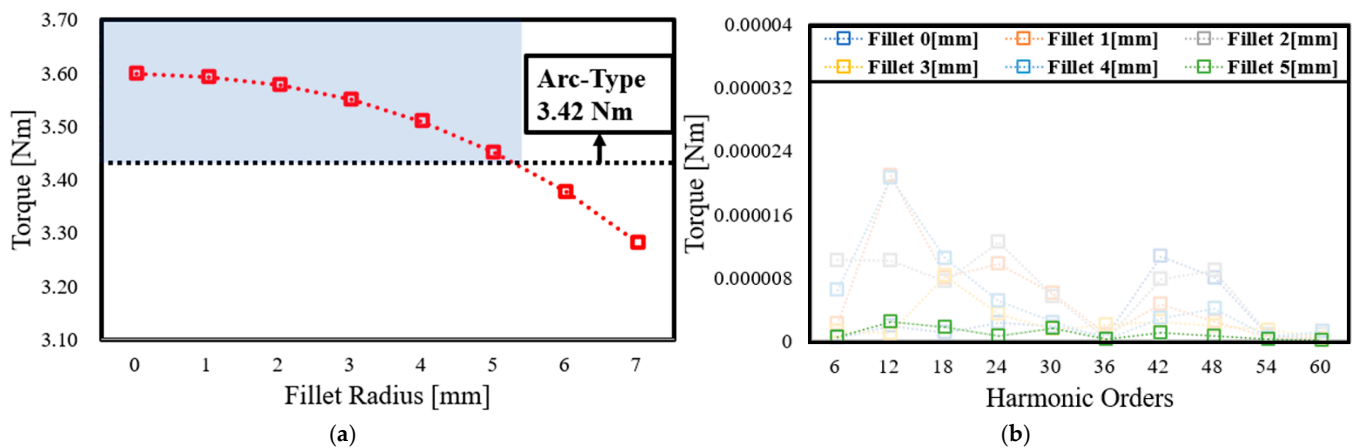


Figure 15. (a) Characteristics of average torque as a function of the magnet fillet radius; (b) harmonic orders as a function of the magnet fillet radius.

Based on these findings, the 5 mm fillet design was selected to maximize the reduction in noise and vibration without compromising electromagnetic performance. Consequently, a comparative FFT analysis of the conventional Arc-Type and the optimized Bar-Type with a 5 mm fillet is presented in Figure 16 for final performance validation. The FFT analysis reveals that for both models, the torque ripple is dominated by the 6th harmonic and its multiples, which is characteristic of the slot-pole combination of the designed motor.

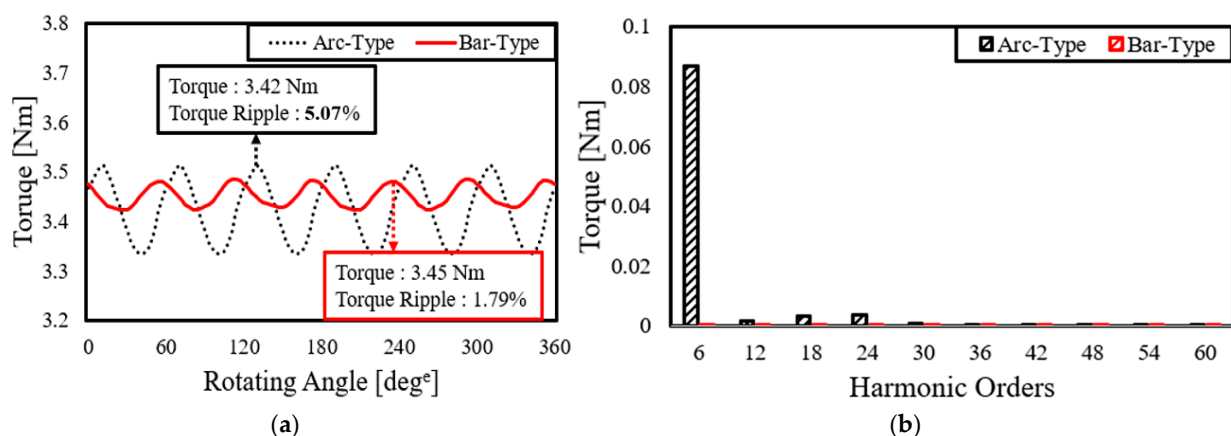
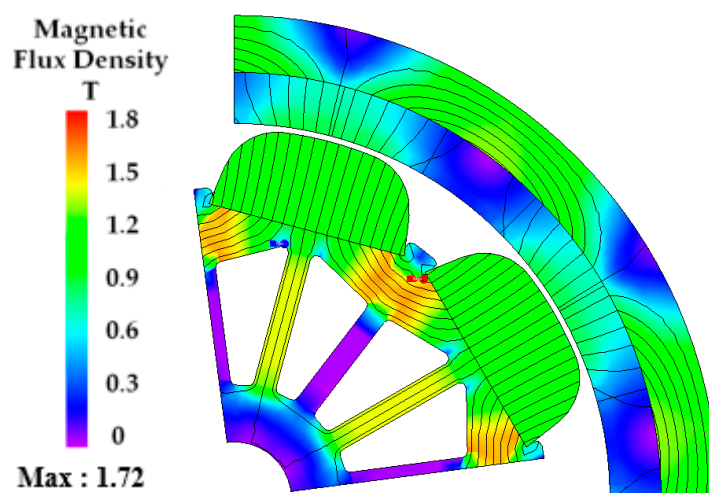


Figure 16. Torque and harmonic analysis: (a) comparison of torque waveforms; (b) comparison of harmonic orders.

According to the torque analysis illustrated in Figure 16a, the implementation of the fillet resulted in a decrease in the average torque of the Bar-Type rotor from 3.59 Nm to 3.45 Nm. Conversely, the torque ripple was reduced by approximately 50%, falling from 3.87% to 1.79%, primarily due to the effective suppression of dominant harmonic orders. Consequently, this configuration was selected as the final model. Table 4 and Figure 17 present the final results: Table 4 provides a comprehensive performance comparison of the electromagnetic performance between the conventional Arc-Type motor and the final optimized Bar-Type model with the 5 mm fillet, while Figure 17 shows the magnetic flux density distribution of the final optimized Bar-Type model.

Table 4. Performance comparison between the conventional Arc-Type and the optimized Bar-Type rotor models.

Performance		Arc-Type	Bar-Type	Unit
No-Load	Resistance	0.42		Ohm
	BEMF	17.52	17.66	V_{rms}
	L2L BEMF	25.11	25.17	V_{max}
Load	Torque	3.42	3.45	Nm
	Torque Ripple	5.07	1.79	%
	L2L Max	36.93	37.33	V_{max}
	Speed	1000		rpm
	Current	11.8		A_{rms}
	Current Density	17.78		A_{rms}/mm^2
	Copper Loss	175.44		W
	Core Loss	2.45	1.58	W
	Output Power	355.69	359.90	W
	Efficiency	66.66	67.03	%
Output	Weight	1.34	1.30	kg
	Power Density	258.64	276.85	W/kg

**Figure 17.** Magnetic flux density distribution of the final optimized Bar-Type model.

4. Conclusions

This paper presented a slotless SPMSM with a Bar-Type permanent magnet and a double-bridge rotor lightweight topology for 48 V rack-type EPS applications. The following conclusions are drawn: (1) Bar-Type magnet shape optimization: By introducing a non-uniform air-gap profile with a 28° side-cut angle, the Bar-Type magnet geometry achieves a no-load back-EMF THD of 0.38%, directly reducing cogging torque and torque ripple relative to the conventional Arc-Type design. (2) Magnet edge fillet optimization: A 5 mm fillet radius at the magnet extremities suppresses dominant torque harmonic orders while preserving an average torque of 3.45 Nm, which exceeds the conventional motor baseline of 3.42 Nm. Torque ripple was reduced from 3.87% to 1.79%, a 53.7% improvement. (3) Double-bridge rotor lightweight topology: The proposed rotor reduces the active part weight to 1.30 kg while maintaining rotor back-yoke flux density below the 1.8 T saturation limit. The structural safety factor was confirmed to be 1146 under maximum-speed centrifugal loading, far exceeding the general design requirement of 1.5–2.0. (4) FEA-based performance verification: The optimized design achieved an output power of 359.9 W at 1000 rpm with a torque of 3.45 Nm, yielding a gravimetric power density of 276.85 W/kg.

This work demonstrates a systematic design methodology for slotless R-EPS motors in 48 V systems and provides a viable engineering solution for next-generation automotive steering applications demanding both high power density and ultra-low NVH characteristics. Given the relatively high current density and the efficiency of approximately 67% reported in this study, future work will focus on thermal management and temperature-rise validation to assess motor reliability under continuous operating conditions [28], together with prototype fabrication, experimental validation, and closed-loop control validation under dynamic steering load profiles [29,30].

Author Contributions: Conceptualization, D.-Y.S. and W.-H.K.; methodology, D.-Y.S.; software, D.-Y.S.; validation, D.-Y.S., D.-H.C. and H.-S.H.; formal analysis, D.-Y.S. and D.-H.C.; investigation, D.-Y.S. and H.-S.H.; resources, D.D. and W.-H.K.; data curation, D.-Y.S.; writing—original draft preparation, D.-Y.S.; writing—review and editing, D.D. and W.-H.K.; visualization, D.-Y.S.; supervision, W.-H.K.; project administration, W.-H.K.; funding acquisition, W.-H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Korea Institute for Advancement of Technology (KIAT) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) (Project No. RS-2024-00436216, Human Resource Development Program for Industrial Innovation (Global)); and the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry and Energy (MOTIE) of the Republic of Korea, grant number RS-2023-00232767.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wrobel, J.; Pietrusiak, D.; Fiebig, W.; Czechowski, M. Automotive Electric Power Steering Systems NVH Performance Investigations. *Int. J. Automot. Technol.* **2022**, *23*, 1153–1161. [\[CrossRef\]](#)
2. Zhu, Z.Q.; Howe, D. Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles. *Proc. IEEE* **2007**, *95*, 746–765. [\[CrossRef\]](#)
3. Lee, C.-S.; Hwang, K.-Y.; Kim, W.-H. Design and Validation of SPMSM with Step-Skew Rotor for EPS System Using Cycloid Curve. *Machines* **2025**, *13*, 814. [\[CrossRef\]](#)
4. Pellegrino, G.; Vagati, A.; Guglielmi, P.; Boazzo, B. Performance Comparison Between Surface-Mounted and Interior PM Motor Drives for Electric Vehicle Application. *IEEE Trans. Ind. Electron.* **2012**, *59*, 803–811. [\[CrossRef\]](#)
5. Gieras, J.F.; Wing, M. *Permanent Magnet Motor Technology: Design and Applications*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2010.
6. Hanselman, D.C. *Brushless Permanent Magnet Motor Design*, 2nd ed.; Magna Physics Publishing: Lebanon, OH, USA, 2006.
7. Yongping, L.; Yong, L. Tooth-Slot Cogging Torque and Noise Analysis of Permanent Magnet Motors. In Proceedings of the Fifth International Conference on Electrical Machines and Systems (ICEMS 2001), Shenyang, China, 18–20 August 2001; pp. 860–862. [\[CrossRef\]](#)
8. Islam, R.; Husain, I.; Fardoun, A.; McLaughlin, K. Permanent-Magnet Synchronous Motor Magnet Designs with Skewing for Torque Ripple and Cogging Torque Reduction. *IEEE Trans. Ind. Appl.* **2009**, *45*, 152–160. [\[CrossRef\]](#)
9. Bianchi, N.; Bolognani, S. Design Techniques for Reducing the Cogging Torque in Surface-Mounted PM Motors. *IEEE Trans. Ind. Appl.* **2002**, *38*, 1259–1265. [\[CrossRef\]](#)
10. Zhu, Z.Q.; Ruangsinchaiwanich, S.; Howe, D. Synthesis of Cogging-Torque Waveform from Slot-Harmonic Spectra. *IEEE Trans. Ind. Appl.* **2006**, *42*, 650–657. [\[CrossRef\]](#)
11. Hwang, S.M.; Eom, J.B.; Jung, Y.H.; Lee, D.W.; Kang, B.S. Various Design Techniques to Reduce Cogging Torque by Controlling Energy Variation in Permanent Magnet Motors. *IEEE Trans. Magn.* **2001**, *37*, 2806–2809. [\[CrossRef\]](#)
12. Hao, W.; Zhang, G.; Liu, W.; Liu, H.; Wang, Y. Methods for Reducing Cogging Force in Permanent Magnet Machines: A Review. *Energies* **2023**, *16*, 422. [\[CrossRef\]](#)
13. Wang, D.; Wang, X.; Jung, S.-Y. Cogging Torque Minimization and Torque Ripple Suppression in Surface-Mounted Permanent Magnet Synchronous Machines Using Different Magnet Widths. *IEEE Trans. Magn.* **2013**, *49*, 2290–2296. [\[CrossRef\]](#)
14. Choi, D.-H.; Kim, D.-H.; Han, H.-S.; Jung, D.-H.; Kim, W.-H. Design of a Slotless Structure for Minimizing Cogging Torque and Torque Ripple in a Column Type EPS Motor for Vehicles. *IEEE Trans. Magn.* **2024**, *60*, 8700305. [\[CrossRef\]](#)

15. Praveen, R.P.; Ravichandran, M.H.; Sadasivan Achari, V.T.; Jagathy Raj, V.P.; Madhu, G.; Bindu, G.R. A Novel Slotless Halbach-Array Permanent-Magnet Brushless DC Motor for Spacecraft Applications. *IEEE Trans. Ind. Electron.* **2012**, *59*, 3553–3560. [\[CrossRef\]](#)
16. Park, J.-W.; Hwang, K.-Y.; Kim, W.-H. Performance Comparison Analysis and Process Suggestion Through Slotless SPMSM During High-Speed Operation. *AIP Adv.* **2023**, *13*, 025039. [\[CrossRef\]](#)
17. Xu, L.; Zhao, W.; Liu, G.; Song, C. Design Optimization of a Spoke-Type Permanent Magnet Vernier Machine for Torque Density and Power Factor Improvement. *IEEE Trans. Veh. Technol.* **2019**, *68*, 3446–3456. [\[CrossRef\]](#)
18. Zhao, W.; Lipo, T.A.; Kwon, B.-I. Material-Efficient Permanent-Magnet Shape for Torque Pulsation Minimization in SPM Motors for Automotive Applications. *IEEE Trans. Ind. Electron.* **2014**, *61*, 5779–5787. [\[CrossRef\]](#)
19. Hsieh, M.-F.; Hsu, Y.-C. A Generalized Magnetic Circuit Modeling Approach for Design of Surface Permanent-Magnet Machines. *IEEE Trans. Ind. Electron.* **2012**, *59*, 779–792. [\[CrossRef\]](#)
20. Choi, D.-H.; Jo, C.; Han, H.-S.; Kim, H.-G.; Kim, W.-H.; Kim, H. Design of a Six-Phase Surface Permanent-Magnet Synchronous Motor with Chamfer-Shaped Magnet to Reduce Cogging Torque and Torque Ripple for Large-Ship Propulsion. *Appl. Sci.* **2025**, *15*, 11400. [\[CrossRef\]](#)
21. Monissen, C.; Arslan, M.E.; Krings, A.; Andert, J. Mechanical Stress in Rotors of Permanent Magnet Machines—Comparison of Different Determination Methods. *Energies* **2022**, *15*, 9169. [\[CrossRef\]](#)
22. Roshen, W. Iron Loss Model for Permanent-Magnet Synchronous Motors. *IEEE Trans. Magn.* **2007**, *43*, 3428–3434. [\[CrossRef\]](#)
23. Sirimanna, S.; Balachandran, T.; Haran, K. A Review on Magnet Loss Analysis, Validation, Design Considerations, and Reduction Strategies in Permanent Magnet Synchronous Motors. *Energies* **2022**, *15*, 6116. [\[CrossRef\]](#)
24. Jo, C.; Kim, S.; Lee, J. Design of Rotor Pole Arrangement for Torque Ripple Reduction in Consequent Pole Permanent Magnet Synchronous Motors. *Machines* **2026**, *14*, 662. [\[CrossRef\]](#)
25. Zhu, Z.Q.; Liu, Y. Analysis of Air-Gap Field Modulation and Magnetic Gearing Effect in Fractional-Slot Concentrated-Winding Permanent-Magnet Synchronous Machines. *IEEE Trans. Ind. Electron.* **2018**, *65*, 3688–3698. [\[CrossRef\]](#)
26. Głąb, I.; Wszolek, T.; Drabek, T.; Czechowski, M.; Wróbel, J.; Pietrusiak, D. Identification of Magnetic-Borne Noise in Automotive Electric Power Steering Systems. *Energies* **2025**, *18*, 6181. [\[CrossRef\]](#)
27. Horváth, K.; Zelei, A. Simulating Noise, Vibration, and Harshness Advances in Electric Vehicle Powertrains: Strategies and Challenges. *World Electr. Veh. J.* **2024**, *15*, 367. [\[CrossRef\]](#)
28. Zhang, Y.; McLoone, S.; Cao, W.; Qiu, F.; Gerada, C. Power Loss and Thermal Analysis of a MW High Speed Permanent Magnet Synchronous Machine. *IEEE Trans. Energy Convers.* **2017**, *32*, 1468–1478. [\[CrossRef\]](#)
29. Kim, S.; Choi, M.; Sung, J. Experimental Verifications of Electric Power Steering Controller Based on Discrete-Time Sliding Mode Control with Disturbance Observer. *Int. J. Automot. Technol.* **2023**, *24*, 883–888. [\[CrossRef\]](#)
30. Na, S.; Li, Z.; Qiu, F.; Zhang, C. Torque Control of Electric Power Steering Systems Based on Improved Active Disturbance Rejection Control. *Math. Probl. Eng.* **2020**, *2020*, 6509607. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.