

MULTI-OBJECTIVE STATOR SLOT OPTIMIZATION FOR IPMSMs TO REDUCE COGGING TORQUE

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Abstract

The cogging torque caused by stator slotting is a primary electromagnetic excitation source inducing vibration and noise in interior permanent magnet synchronous motors (IPMSMs). This paper presents a multi-objective optimization strategy for stator slot opening dimensions ($Bs0$ and $Hs0$) of an 8-pole 48-slot V-shaped IPMSM using the response surface methodology (RSM). Based on a global finite element parametric sweep, 3D response surfaces are constructed to evaluate the trade-off between average torque and cogging torque. By introducing the relative torque ripple coefficient as the core optimization metric, the optimal configuration is identified at $Bs0 = 3.5$ mm and $Hs0 = 2.0$ mm. At this point, the coefficient reaches its global minimum of 3.77, successfully suppressing cogging torque while maintaining a high average torque of 2.85 N·m. Finally, the underlying physical mechanism is elucidated via local magnetic saturation analysis at the stator tooth tips, providing a robust design reference for low-ripple electrical machines.

1 Introduction

Permanent magnet synchronous motors (PMSMs) are widely utilized in electric vehicles and intelligent manufacturing due to their high power density and efficiency. However, with the increasing demands for operational comfort and reliability, suppressing electromagnetic vibration and acoustic noise has become a critical challenge. The cogging torque, induced by the uneven air-gap permeance from stator slotting, is identified as a primary excitation source that severely degrades the motor's vibro-acoustic performance^[1].

Traditional mitigation techniques predominantly focus on rotor-side modifications, such as skewed poles, permanent magnet segmented shifting, and pole arc optimization^[2]. Although effective in smoothing the air-gap magnetic field, these methods inevitably escalate manufacturing complexity, reduce mechanical strength, and compromise output performance. Conversely, optimizing stator-side structures, such as adjusting slot opening dimensions or introducing auxiliary slots, serves as a simpler and cost-effective alternative that effectively reconstructs the air-gap permeance without altering the rotor topology.

Accurate electromagnetic modeling is a fundamental prerequisite for structural optimization. Analytical calculations using complex relative air-gap permeance methods provide deep insights into the spatial distribution laws of the slotted magnetic field^[3], while parameterized nonlinear magnetic equivalent circuit (MEC) models offer efficient tools for rapid design and performance comparison. Nevertheless, a persistent challenge in stator slot dimension optimization is that the suppression of cogging torque often occurs at the expense of average output torque attenuation. This inherent "trade-off" conflict renders conventional single-objective optimization insufficient for achieving optimal comprehensive performance. To address this

limitation, the response surface methodology (RSM)^[4] has emerged as an advanced framework capable of efficiently constructing non-linear mappings between design variables and conflicting performance metrics to identify the optimal global compromise.

This paper presents a multi-objective optimization framework for the main stator slot opening width ($Bs0$) and depth ($Hs0$) of an 8-pole 48-slot V-shaped interior PMSM (IPMSM). Utilizing the Ansys Maxwell finite element analysis (FEA) platform, a global parametric sweep is conducted to construct 3D response surfaces. By introducing a relative torque ripple coefficient as the core evaluation index, global optimization is performed to achieve the minimization of cogging torque while sustaining a high average torque output. Furthermore, the underlying physical mechanisms of torque characteristics influenced by slot dimensions are elucidated through local magnetic saturation analysis at the stator tooth tips, establishing a robust theoretical and simulation foundation for high-performance, low-ripple motor design.

2. Theoretical Analysis of Torque Characteristics Influenced by Stator Slot Opening Parameters

In permanent magnet synchronous motors, electromagnetic performance mainly depends on the interaction between the air-gap magnetic field and the stator-rotor geometric structure. Stator slotting breaks the uniformity of the air-gap permeance, which is the root cause of torque ripple.

A. Cogging Torque Mechanism

Introducing stator slot opening dimensions $Bs0$ and $Hs0$ causes periodic fluctuations in equivalent air-gap permeance. To provide a clear geometric definition, the parameterized structure of the stator slot opening is illustrated in Fig. 1, where $Bs0$ and $Hs0$ explicitly denote the slot opening width

and slot opening depth, respectively. The cogging torque T_{cog} essentially minimizes the total magnetic reluctance, expressed as the partial derivative of the air-gap magnetic field energy W_{gap} with respect to the rotor position angle α :

$$T_{cog}(\alpha) = -\frac{\partial W_{gap}}{\partial \alpha} = -\frac{1}{2\mu_0} \frac{\partial}{\partial \alpha} \int_V B_r^2(\theta, \alpha) dV \quad (1)$$

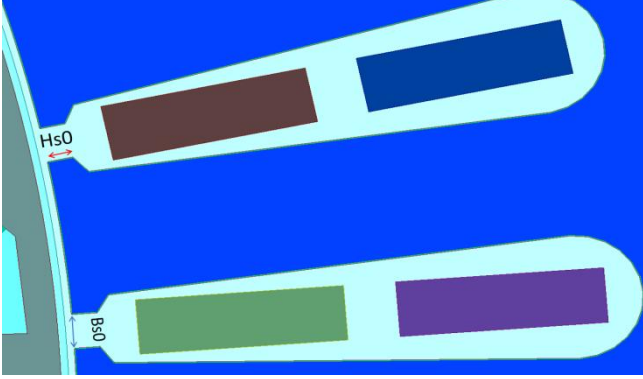


Fig. 1 Parameterized geometric variables of the stator slot opening.

where μ_0 is the vacuum permeability, B_r is the radial air-gap flux density, and V is the effective air-gap volume. From the above equation, altering the width and depth of the stator slot opening directly reshapes the distribution gradient of the air-gap flux density B_r , thereby causing dramatic changes in the cogging torque.

Specifically, the introduction of the stator slot opening width $Bs0$ alters the equivalent air-gap permeance by modifying the effective air-gap length δ_{eff} due to the magnetic flux fringing effect. This physical phenomenon can be mathematically quantified by Carter's coefficient^[5] k_c :

$$\delta_{eff} = k_c \delta = \frac{T_s}{T_s - \gamma \delta} \delta \quad (2)$$

$$\gamma = \frac{4}{\pi} \left[\frac{Bs0}{2\delta} \tan^{-1} \left(\frac{Bs0}{2\delta} \right) - \ln \sqrt{1 + \left(\frac{Bs0}{2\delta} \right)^2} \right] \quad (3)$$

where δ_{eff} is the effective air-gap length; k_c is the Carter's coefficient; δ is the physical air-gap length; T_s is the stator slot pitch; $Bs0$ is the stator slot opening width; and γ is the dimensionless auxiliary factor accounting for the magnetic field distortion caused by stator slotting. Consequently, the alteration of δ_{eff} directly modulates the radial air-gap flux density B_r in Eq. (1), establishing a rigorous analytical link between the geometric parameter $Bs0$ and the resulting torque characteristics.

Furthermore, the cogging torque fluctuates periodically with the rotor position, and its Fourier series expansion is given by:

$$T_{cog}(\alpha) = \sum_{n=1}^{\infty} T_n \sin(nN_c \alpha + \theta_n) \quad (4)$$

where T_n and θ_n are the amplitude and phase of the n order cogging torque harmonic, respectively; N_c is the least common multiple of the number of stator slots and rotor poles, which is $N_c = 48$ for the 8-pole 48-slot motor in this paper. Modifying the stator slot opening dimensions essentially modulates the Fourier coefficient T_n by altering the

harmonic distribution of the specific air-gap permeance, thereby achieving the suppression of the peak cogging torque.

B. Electromagnetic Torque Output

The average electromagnetic torque T_{avg} in the $d-q$ coordinate system is:

$$T_{avg} = \frac{3}{2} p [\psi_f i_q + (L_d - L_q) i_d i_q] \quad (5)$$

Where p is the pole pairs, ψ_f is the permanent magnet flux linkage, L_d and L_q are the d/q -axis inductances, and i_d and i_q are the d/q -axis currents. Modifying slot dimensions alters the main air-gap reluctance and $d-q$ inductances, thus affecting T_{avg} .

III. MOTOR MODELING AND MESH GENERATION

A 2D FEA model of the V-shaped IPMSM (Table I) is established using Ansys Maxwell as shown in Fig. 2^[6]. To ensure solution accuracy for cogging torque, adaptive mesh generation with local refinement is applied to the air-gap and stator slot openings as illustrated in Fig. 3. Low-loss DW310_35 silicon steel sheets are used for cores to minimize high-frequency eddy current losses, while N38UH NdFeB is selected for permanent magnets to ensure anti-demagnetization capability under heavy loads. Outer boundaries are set as Dirichlet boundaries with zero vector magnetic potential.

Table 1 Main parameters of the investigated ipmsm

Technical Parameters	Value
Number of stator poles/slots	8/48
Stator outer diameter(mm)	190
Stator inner diameter(mm)	125
Rotor outer diameter(mm)	123.8
Rotor inner diameter(mm)	70
Air- gap length(mm)	0.6
Stator material	DW310_35
Rotor material	DW310_35
Permanent magnet material	N38UH
Permanent magnet thickness(mm)	5
Rated speed(rpm)	3000

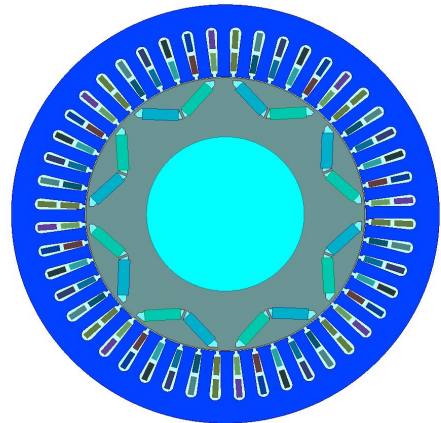


Fig. 2. 2D finite element model of the IPMSM

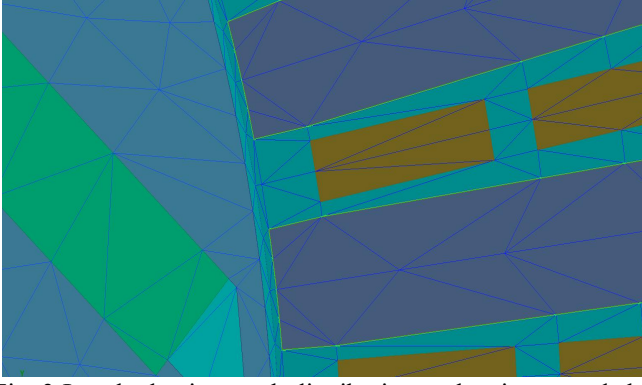


Fig. 3 Local adaptive mesh distribution at the air gap and slot openings

3. Multi-Objective Parametric Sweep and Response Surface Analysis of Stator Slot Opening

Using the Response Surface Methodology (RSM), the non-linear relationship between the objective functions (average torque T_{avg} and cogging torque T_{cog}) and the design variables ($Bs0$, $Hs0$) is established using a second-order polynomial model:

$$y(Bs0, Hs0) = \beta_0 + \beta_1 Bs0 + \beta_2 Hs0 + \beta_{11} Bs0^2 + \beta_{22} Hs0^2 + \beta_{12} Bs0 Hs0 \quad (6)$$

where $y(Bs0, Hs0)$ represents the predicted response value of the optimization objective function, denoting the average torque T_{avg} or the peak-to-peak cogging torque T_{cog} in this study; $Bs0$ and $Hs0$ are the stator slot opening width and depth, respectively; β_0 is the constant intercept; β_1 and β_2 are the linear regression coefficients; β_{11} and β_{22} are the quadratic regression coefficients; and β_{12} is the interaction regression coefficient^[7].

To systematically investigate the influence of stator slot opening dimensions on the comprehensive performance of the motor, the slot opening width $Bs0$ and depth $Hs0$ are selected as continuous optimization variables in this paper. Utilizing the parametric sweep technology in finite element analysis, the 3D response surfaces of the motor's torque characteristics are obtained, as shown in Fig. 4.

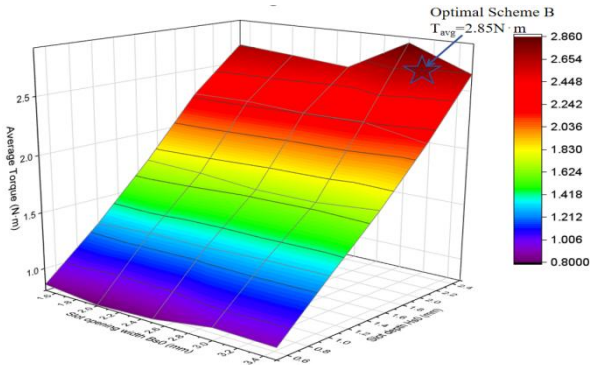


Fig. 4 3D response surface of average torque versus stator slot opening dimensions

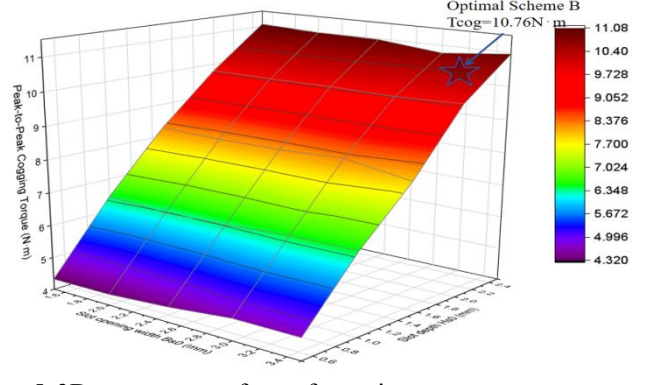


Fig. 5 3D response surface of cogging torque versus stator slot opening dimensions

As shown in Fig. 4, the average torque T_{avg} increases with larger slot dimensions owing to altered equivalent air gap and flux leakage. However, Fig. 5 reveals that excessive slot sizes severely disrupt air-gap permeance uniformity, causing a sharp surge in the peak-to-peak cogging torque. This indicates a typical trade-off conflict between output power and electromagnetic smoothness within the parameter space. To identify the optimal structural equilibrium, the relative torque ripple coefficient is introduced as the core multi-objective evaluation criterion. Global optimization is subsequently performed based on the dense 3D response data to effectively balance the motor's power density and operational stability^[8].

4. Magnetic Flux Density Distribution and Saturation Effect Analysis Under Different Optimization Schemes

To elucidate the electromagnetic mechanisms underlying the torque characteristics, a comparative analysis of the magnetic flux density distributions for two typical configurations is performed as shown in Fig. 6 and Fig. 7, with their core performance metrics summarized in Table II.

Table 2. Comparison of electromagnetic performance for different optimization schemes

Parameters	andInitial	Scheme A	Scheme B
Performance	Scheme		
Indicators			
Bs0(mm)	3.5	1.5	3.5
Hs0(mm)	2.5	0.5	2.0
Average torque(N·m)	2.64	0.85	2.85
Peak-to-peak cogging torque(N·m)	11.10	4.32	10.76
Relative torque ripple coefficient	4.20	5.08	3.77

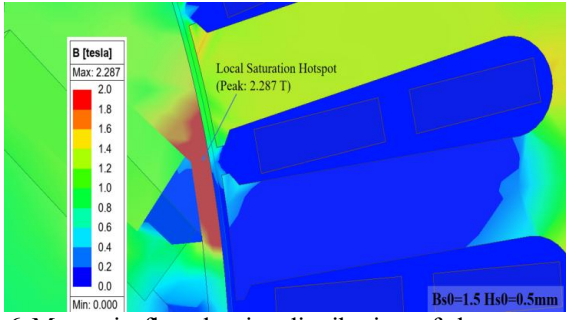


Fig. 6 Magnetic flux density distribution of the stator tooth tips under Scheme A

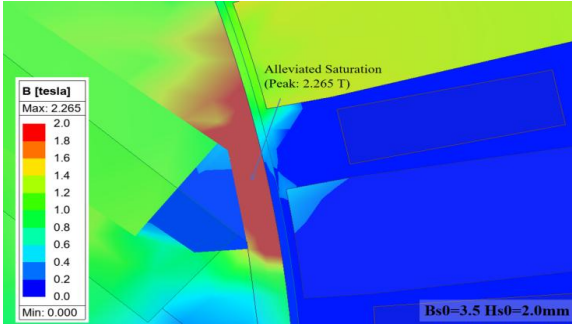


Fig. 7 Magnetic flux density distribution of the stator tooth tips under Scheme B (Optimal trade-off)

As shown in Fig. 6, Scheme A ($Bs0 = 1.5$ mm, $Hs0 = 0.5$ mm) exhibits a highly concentrated local magnetic saturation hotspot at the tooth tips, reaching a peak flux density of 2.287 T. This is primarily caused by a severe slot leakage effect, where the narrow slot opening significantly reduces the magnetic reluctance between adjacent tooth tips, leading to a localized magnetic short-circuit. Although this uniform leakage network smooths the air-gap permeance fluctuations—resulting in an exceptionally low cogging torque of 4.32 N·m—the leakage flux fails to contribute to the electromechanical energy conversion, causing the average torque to plummet to an insufficient 0.85 N·m, which fails to meet practical application requirements.

In sharp contrast, the optimal trade-off Scheme B ($Bs0 = 3.5$ mm, $Hs0 = 2.0$ mm) effectively eliminates these extreme local saturation hotspots, lowering the peak flux density to 2.265 T as illustrated in Fig. 7. Widening the slot opening cuts off the horizontal leakage paths, allowing the main flux to pass smoothly through the air gap and penetrate deeper into the stator teeth, which maximizes the utilization of the magnetic circuit. Consequently, despite a slight increase in air-gap permeance perturbation, Scheme B simultaneously elevates the average torque to its maximum of 2.85 N·m and suppresses the relative torque ripple coefficient (T_{cog}/T_{avg}) to a global minimum of 3.77. This correlation physically validates the efficacy and rationality of utilizing the comprehensive ratio method for multi-objective optimization.

5 Conclusion

This paper systematically optimizes the stator slot width ($Bs0$) and depth ($Hs0$) of a V-shaped IPMSM. Stator slot

dimensions significantly regulate torque characteristics; increasing $Bs0$ and $Hs0$ enhances average torque, whereas excessively large slots deteriorate air-gap permeance and exacerbate cogging torque. By employing a comprehensive ratio method via RSM, the optimal trade-off configuration ($Bs0 = 3.5$ mm, $Hs0 = 2.0$ mm) successfully balances high power density and operational smoothness, minimizing the relative torque ripple coefficient to 3.77. Magnetic field analysis confirms that eliminating local magnetic saturation at the stator tooth tips is the physical key to optimizing torque behavior, providing a robust simulation reference for low-ripple electrical machine design^[9].

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