Journal of Current Science and Technology, April-June 2026 Vol. 16 No. 2, Article 170
Copyright ©2018-2026, Rangsit University ISSN 2630-0656 (Online)

Cite this article: Prasetijo, H., Khairudin, M., Wirtayasa, K., Aliim, M. S., & Purnomo, W. H. (2026). Recent advances in cogging torque reduction for radial-flux PMSMs: A systematic and bibliometric review. *Journal of Current Science and Technology*, *16*(2), Article 170. https://doi.org/10.59796/jcst.V16N2.2026.170

Journal of Current Science and Technology
Journal homepage: https://jcst.rsu.ac.th

Recent Advances in Cogging Torque Reduction for Radial-Flux PMSMs: A Systematic and Bibliometric Review

Hari Prasetijo[1,2], Moh. Khairudin[3,*], Ketut Wirtayasa[4], Muhammad Syaiful Aliim[1],
and Widhiatmoko Herry Purnomo[1]

[1]Department of Electrical Engineering, Universitas Jenderal Soedirman, Purwokerto 53112, Indonesia
[2]Doctoral Program in Ilmu Teknik, Universitas Negeri Yogyakarta, Yogyakarta 55218, Indonesia
[3]Department of Electrical Engineering, Universitas Negeri Yogyakarta, Yogyakarta 55218, Indonesia
[4]Research Center for Energy Conversion and Conservation, National Research and Innovation Agency,
Bandung 10340, Indonesia

*Corresponding author; E-mail: moh_khairudin@uny.ac.id

Received 3 September 2025; Revised 26 September 2025; Accepted 6 October 2025; Published online 25 March 2026

Abstract

Cogging torque remains a critical barrier to achieving torque smoothness, energy efficiency, and structural reliability in radial-flux permanent magnet synchronous machines (RF-PMSMs), particularly in low-speed and variable-speed renewable energy systems. This study presents a systematic literature review (SLR) of 64 peer-reviewed journal articles, categorizing cogging torque mitigation strategies into five key domains: stator geometry, rotor geometry, magnet geometry, winding layout, and non-geometric techniques. To complement the synthesis, bibliometric mapping was performed using VOSviewer, and a Thematic Map was generated via Biblioshiny (Bibliometrix R) from article metadata. This integrated approach not only identifies widely adopted techniques but also uncovers underexplored yet high-potential research fronts. In particular, niche and emerging themes are highlighted as promising directions for innovation. The review also underscores the importance of multi-objective design optimization, advanced material strategies, and real-world validation under manufacturing and operational constraints. Overall, the study provides a structured and forward-looking contribution to advancing RF-PMSM design, with specific novelty in cogging torque reduction for high-performance and sustainable energy applications.

Keywords: *RF-PMSMs; stator geometry; rotor geometry; magnet geometry; winding layout; non-geometry techniques*

1. Introduction

The adoption of Permanent Magnet Synchronous Machines (PMSMs) has increased due to their clear advantages over excitation-based machines. Replacing rotor excitation with permanent magnets eliminates slip rings and external current sources, thereby enhancing system reliability (Hussien et al., 2022). This design also lowers rotor copper losses and improves thermal stability (Azom & Khan, 2025). Moreover, reduced conversion losses contribute to higher efficiency (Nguyen et al., 2025), while superior power density and power factor make PMSMs attractive for energy-efficient systems (Yu et al., 2024).

Permanent Magnet Synchronous Machines (PMSMs) are classified as rotary or linear and further divided by flux orientation into radial-flux and axial-flux types. Radial-flux PMSMs, producing flux perpendicular to the rotor shaft, are favored for their simple manufacturing and robust structure (Xiang et al., 2025), and their its practicality in generator applications has also been confirmed (Wei et al., 2021). As shown in Figure 1, a radial-flux permanent magnet machine is characterized by magnetic flux oriented perpendicular to the rotor shaft.

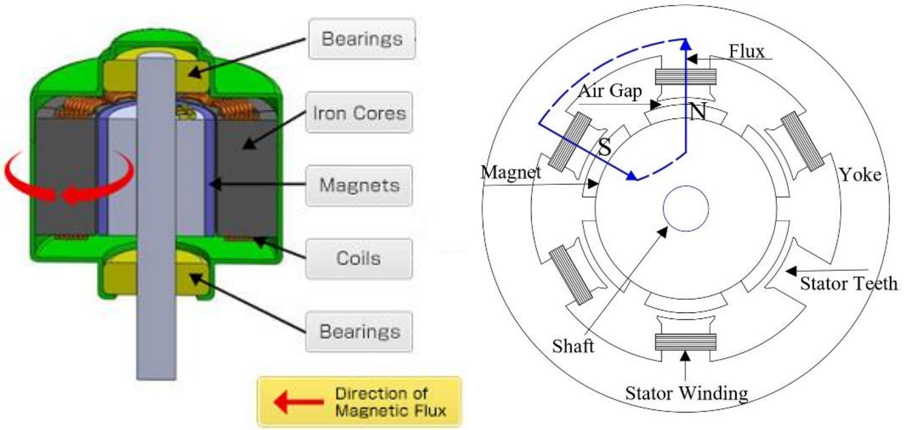

Figure 1 PMSMs radial-flux general topology. Adapted from Hassan et al. (2022), "Direct torque control of non-salient pole AFPMSMs with SVPWM inverter," *International Journal of Power Electronics and Drive Systems, 13*(4), 2014–2023.

Cogging torque remains a major limitation of PMSMs, arising from interactions between rotor magnets and stator teeth as flux seeks paths of minimum reluctance. This torque component adversely affects machine starting performance (Patel et al., 2023), induces torque ripple (Kanapara & Badgujar, 2020), mechanical vibration (Abduh et al., 2025), acoustic noise (Hu et al., 2022), efficiency degradation (Song et al., 2021), and back-EMF distortion (Youssef et al., 2025). These effects are particularly pronounced under low-speed operating conditions (Bu et al., 2021). Thus, reducing cogging torque is not only a design goal but also a prerequisite for smooth operation, efficiency, and durability in permanent magnet machines.

This study contributes a comprehensive and methodologically rigorous synthesis of cogging torque reduction strategies in radial-flux permanent magnet synchronous machines (RF-PMSMs). Unlike prior reviews that primarily focus on individual aspects—such as stator slotting or rotor shaping—this article systematically integrates 64 peer-reviewed studies spanning stator geometry, rotor geometry, magnet geometry, winding layouts, and non-geometric approaches, thereby offers a holistic perspective that is absent in earlier surveys. Furthermore, it addresses a critical research gap by coupling a systematic literature review (SLR) with bibliometric analysis, which enables not only the consolidation of state-of-the-art knowledge but also the identification of underrepresented yet high-potential research fronts within the Niche and Emerging quadrants of the thematic Map. This integrated approach represents the key novelty of the work, as it provides explicit insights into overlooked torque characteristics, design sensitivities, and underexplored methodological directions. Overall, the contribution of this study lies in establishing a structured and forward-looking framework that guides future innovations in RF-PM machine design and cogging torque mitigation, differentiating it from existing reviews.

2. Objectives

The objectives of this review are formulated to ensure methodological clarity and highlight the unique contributions of the study, as follows:

1. To systematically identify, classify, and analyze cogging torque reduction techniques in radial-flux permanent magnet synchronous machines (RF-PMSMs), based on 64 peer-reviewed articles published between 2020 and June 2025, covering stator geometry, rotor geometry, magnet geometry, winding layout, and non-geometric strategies.
2. To integrate systematic review findings with bibliometric analysis using VOSviewer and Biblioshiny (Bibliometrix R) to map research clusters, highlight underexplored yet high-potential themes, and formulate future directions for advancing cogging torque reduction in RF-PMSMs.

3. Materials and Methods

3.1 Materials

The literature search involved formulating precise terms, expanding them with relevant synonyms, and systematically screening retrieved articles using predefined inclusion and exclusion criteria. From this process, only high-impact and thematically relevant publications were selected for detailed analysis. The search was conducted in the Scopus database (http://scopus.com), which comprehensively indexes peer-reviewed literature across engineering and scientific fields. The exact query used was:

```
(TITLE-ABS-KEY (cogging torque) AND TITLE-ABS-KEY(radial)) AND PUBYEAR > 2019 AND PUBYEAR< 2026 AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English"))
```

The initial search identified 160 articles (2020–2025), with their bibliometric relationships visualized in Figure 2 using VOSviewer. The network highlights cogging torque as a central theme strongly linked to permanent magnets, finite element analysis, *and* permanent magnet motors, underscoring its importance in RF-PM machine research. Prominent associations with vibration analysis and structural optimization further reveal a shift toward simulation-driven, multiphysics approaches that integrate electromagnetic, structural, and vibro-acoustic considerations to enhance efficiency, durability, and operational performance.

The inclusion criteria required that studies explicitly analyzed, modeled, or experimentally validated cogging torque reduction strategies. From the 160 initially retrieved articles, 49 were excluded during the first screening because they addressed related issues such as torque ripple, vibration, or electromagnetic noise without quantifying cogging torque, or presented general motor design or control approaches not directly linked to cogging torque mechanisms. For example, a paper on acoustic noise in PM motors without reference to cogging torque was excluded, while a study evaluating slot/pole combinations to suppress cogging torque was included. This step yielded 111 relevant publications. A second screening stage further excluded 47 studies that focused on non-radial machine topologies (e.g., axial-flux, transverse-flux, flux-switching, or linear PM machines), resulting in a final dataset of 64 articles dedicated to cogging torque mitigation in radial-flux permanent magnet synchronous machines (RF-PMSMs). These two filtering stages ensured that only articles with direct and demonstrable contributions to cogging torque reduction in RF-PMSMs were retained for detailed analysis. Figure 3 shows the PRISMA flow diagram illustrating the systematic selection process that ensured transparency and reproducibility. The SLR process begins by accessing the selected database and identifying relevant journal articles. Retrieved publications are then extracted and systematically reviewed based on predefined inclusion criteria. The database's scope and accessibility are critical in ensuring the comprehensiveness and quality of the review.

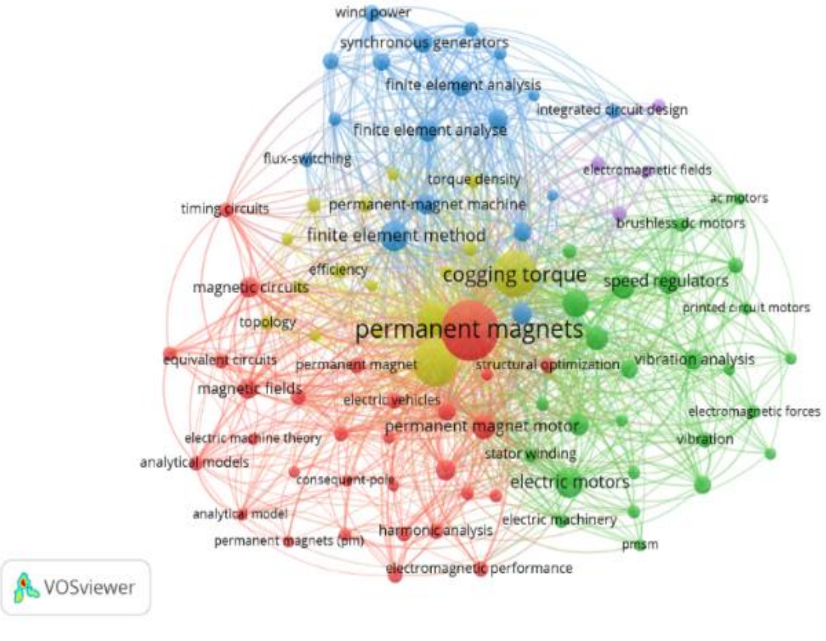

Figure 2 Bibliometrics network 160 references

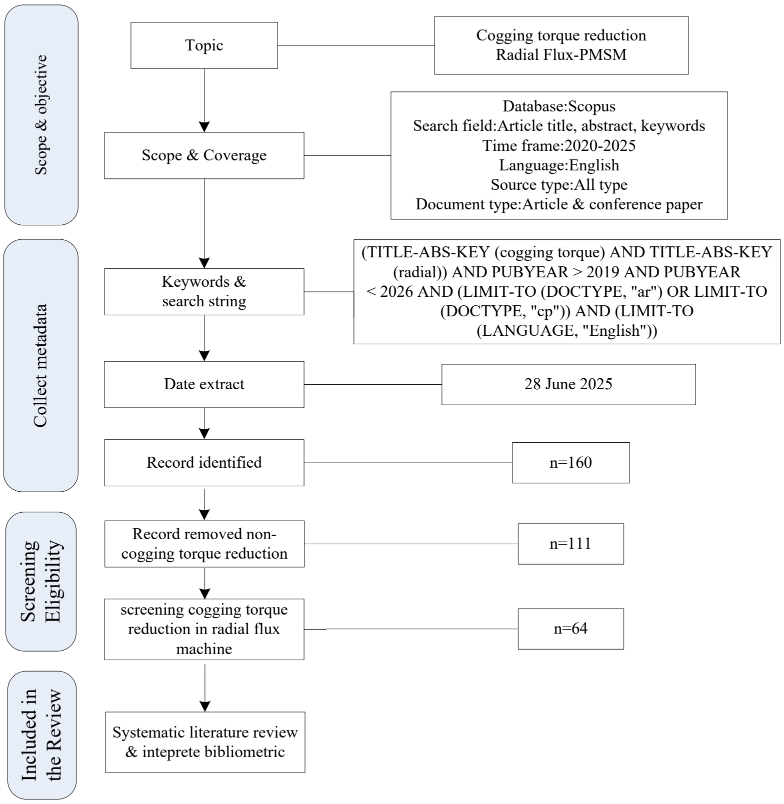

Figure 3 Article selection process using PRISMA method

Table 1 PICOC criteria

Criteria	Description
Population	Rotary permanent magnet synchronous machines (PMSMs) with radial-flux topology
Intervention	Application of geometric modifications (e.g., stator geometry, rotor geometry, permanent magnet configuration, and winding layout) and non-geometric techniques (e.g., control techniques, material selection, and magnetic field manipulation) aimed at mitigating cogging torque and torque ripple.
Comparison	Comparative evaluation of geometric versus non-geometric modifications in terms of their effectiveness in reducing cogging torque and torque ripple
Outcome	Development of PMSM designs with minimized cogging torque and torque ripple, leading to smoother operation and enhanced performance
Context	Applicable to both generator and motor systems across various domains, including renewable energy, electric vehicles, precision actuators, and industrial automation

Table 2 Research questions (RQ)

Research Question Number
RQ1: What stator geometric modification techniques have been proposed to reduce cogging torque in radial-flux permanent magnet synchronous machines (PMSMs)?
RQ2: What rotor geometric modification techniques have been proposed to reduce cogging torque in radial-flux permanent magnet synchronous machines (PMSMs)?
RQ3: What magnet geometric modification techniques have been proposed to reduce cogging torque in radial-flux permanent magnet synchronous machines (PMSMs)?
RQ4: What winding layout modification techniques have been proposed to reduce cogging torque in radial-flux permanent magnet synchronous machines (PMSMs)?
RQ5: What non-geometric techniques have been investigated for cogging torque mitigation in radial-flux permanent magnet synchronous machines (PMSMs)?
RQ6: What research gaps or future directions can be derived from current cogging torque reduction techniques in radial-flux PMSMs?

The PICOC framework establishes the scope of this SLR by structuring keywords that guide reference searches and research question formulation. This structured method ensures consistency and thematic alignment. The PICOC elements Population (P), Intervention (I), Comparison (C), Outcome (O), and Context (C) are outlined in Table 1. Based on these, Table 2 summarizes the main objective: to identify and categorize cogging torque reduction techniques in radial-flux PMSMs, covering both geometric and non-geometric strategies. This classification addresses RQ1–RQ5, while the synthesis informs gap identification and guides future directions under RQ6.

4. Result and Discussion

In the general expression of electromagnetic torque, as presented in equation (1), the cogging torque is represented by the second term of the equation:

$$T=\frac{1}{2}\,i^2\frac{dL}{d\theta}-\frac{1}{2}\phi^2\frac{dR}{d\theta}+Ni\frac{d\phi}{d\theta} \tag{1}$$

where ϕ is the magnetic flux, L is the inductance, R is the reluctance, N is the number of turns, i is the current, and θ is the rotor position. Since inductance is inversely proportional to reluctance, as expressed in equation (2), this relationship directly links variations in reluctance to the magnitude of cogging torque.

$$L=\frac{\lambda}{i}=\frac{N^2}{R}=N^2P \tag{2}$$

To address this parasitic effect, cogging torque reduction methods focus on minimizing air-gap flux variations and smoothing reluctance changes through both geometric and non-geometric strategies. In practice, these include stator slot and tooth modifications, rotor pole shaping, optimized magnet geometries, advanced winding layouts, and control-based approaches. Each method aims to weaken the reluctance variation ($\frac{dR}{d\theta}$) or redistribute flux density in the air gap, thereby suppressing cogging torque while preserving average torque and overall machine efficiency.

4.1 Stator Geometry Techniques

Cogging torque arises mainly from the interaction between rotor-mounted permanent magnets and the stator slot structure, making stator teeth and slot geometry modification an effective mitigation strategy. Key techniques include teeth shaping, teeth pairing, unequal teeth width, chamfering, slot opening variation, slot skewing, slotless design, and fractional-slot winding. These approaches are summarized in Table 3 under stator geometry modification techniques.

As an illustrative example, Figure 4 compares cogging-torque waveforms for 9S8P, 9S10P, 12S10P, 12S14P, 12S8P, and 12S4P. The traces show that slot–pole selection shifts dominant cogging orders and peak-to-peak amplitudes: co-prime or near co-prime pairs (e.g., 9S10P) tend to distribute harmonics and yield smoother torque, whereas pairs with common factors (e.g., 12S8P, 12S4P) strengthen slot–pole alignment and elevate ripple. This highlights the need to tune S/P combinations to weaken air-gap permeance modulation and reduce cogging torque in RF-PM machines (Xiang et al., 2024).

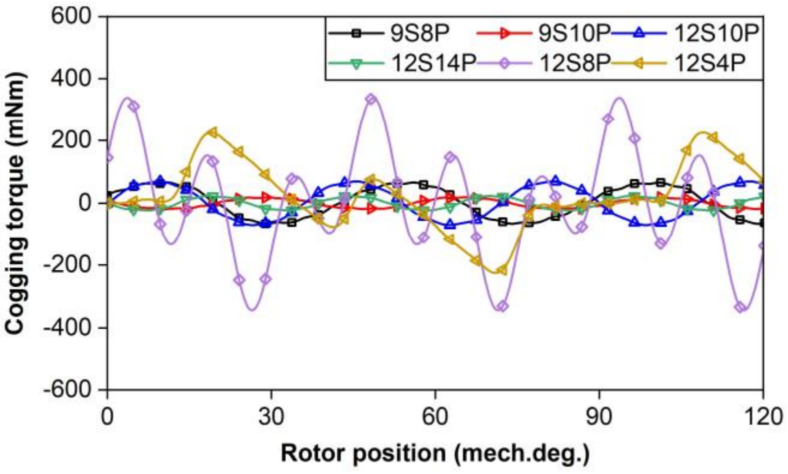

Figure 4 Influence of Slot and Pole Number Combinations on cogging torque

Table 3 Stator geometry techniques

No	Techniques	References
1	Teeth:	
	teeth shaping	Kim & Jung, 2020; Xiang & Zhu, 2022; Jhankal & Patel, 2024; Won et al., 2024; Jang et al., 2024
	unequal teeth width	Tong et al., 2020; Yang et al., 2022
2	Slot:	Krishnan et al., 2024; Sayed & Erturk, 2021
	slot opening variation	Choi et al., 2024; Vukotić et al., 2020
	slot skewing	Dajaku, 2021; Liu et al., 2023
	slotless design	Tong et al., 2020; Yang et al., 2022
	Fractional-Slot	Krishnan et al., 2024; Sayed & Erturk, 2021

Teeth shaping has proven effective in reducing cogging torque while enhancing auxiliary performance. A tooth pairing method achieved approximately 50% cogging torque reduction without lowering the average torque (Kim & Jung, 2020). Optimization of tooth edge inset width (TEIW) reduced cogging torque by 48.24% (9.66 Nm to 5.00 Nm) with negligible impact on torque (Jhankal & Patel, 2024). Circular chamfers were the most effective for cogging torque reduction (~30%) (Won et al., 2024), while linear and eccentric chamfers better suppressed torque ripple and vibration further applied surrogate-based tooth-tip chamfering, achieving 82% lower cogging torque, 80% less torque ripple, a 12% torque density increase, and 42% material savings (Jang et al., 2024).

Unequal teeth width strongly affects cogging torque and vibration across slot–pole combinations. For a 12-slot/10-pole machine, a 0.7 tooth-width ratio reduced torque ripple and vibration by 8.2%, whereas in a 12-slot/8-pole design, vibration increased despite cogging torque suppression (Wu et al., 2023). In dual-stator machines, a squirrel-type unequal distribution cut torque ripple by 56.57% and cogging torque by over 50% without notable torque loss, underscoring its suitability for high-quality torque applications (Yao et al., 2024).

Slot opening variation alters air-gap flux distribution and slot permeance harmonics to suppress cogging torque. An analytical model combining subdomain, conformal mapping, and equivalent circuit methods was proposed, which accurately predicted cogging torque under eccentricity and magnet defects while also reducing computational cost (Tong et al., 2020). Combining two machine units with different pole/slot ratios but equal slot openings maximized the least common multiple of poles and slots, yielding substantial cogging torque reduction with standardized slot widths (Yang et al., 2022).

Slot skewing remains a proven method for reducing cogging torque and vibration. In six-phase BLDC motors for EVs, a 10° skew lowered cogging torque from 0.557 Nm to 0.08 Nm while maintaining torque output (Krishnan et al., 2024). Similarly, in RF-PMSGs for small wind turbines, progressive skewing cut cogging torque by up to 56%, improving smoothness without affecting average torque (Sayed & Erturk, 2021).

Slotless stator designs eliminate cogging torque by removing slot–magnet interactions. In a column-type EPS motor, a slotless stator design reduced cogging torque by 90.5% and torque ripple by 48.1% while enhancing gravimetric power density (Choi et al., 2024). Across different rotor topologies, slotless machines consistently exhibited negligible cogging torque, underscoring their suitability for precision and noise-sensitive applications (Vukotić et al., 2020).

Fractional-slot concentrated winding (FSCW) reduces cogging torque by decoupling harmonics and improving torque quality. A 24-slot/20-pole configuration was shown to lower THD, reduce torque ripple, and achieve a high winding factor, resulting in a compact and efficient design (Dajaku, 2021). The effectiveness of fractional-slot concentrated winding in suppressing cogging torque and enhancing torque density was further confirmed, providing a strong theoretical foundation for high-performance RF-PM machines (Liu et al., 2023).

4.2 Rotor Geometry Techniques

Key rotor geometry techniques for cogging torque reduction include rotor skewing, pole shaping, pole arc variation, flux barriers, and spoke-type structures, each strongly influencing air-gap flux and torque characteristics. Validated through analytical, numerical, and experimental studies, these methods suppress cogging torque while maintaining or enhancing electromagnetic performance. Table 4 summarizes the main findings from recent investigations into rotor geometry approaches.

As an illustrative example, Figure 5 illustrates the cogging torque waveform comparison between a conventional arc-shaped rotor and the proposed straight-shaped rotor in a small wind generator. The straight-shaped design reduces the abrupt permeance variation at slot openings, resulting in a more sinusoidal flux distribution. This modification led to a dramatic decrease in cogging torque, from 280.7 mNm in the baseline model to 16.2 mNm in the proposed configuration, corresponding to a 96% reduction, while maintaining nearly identical efficiency and EMF characteristics. Such results confirm that rotor shaping offers a highly effective strategy for minimizing cogging torque without incurring significant penalties in electromagnetic performance (Kang et al., 2024).

Rotor skewing is a well-established technique for reducing cogging torque, torque ripple, and vibration. A segmented skew rotor in a U-shaped PM motor was shown to reduce cogging torque from 55 Nm to 3 Nm, torque ripple from 42 Nm to 7 Nm, and noise by 22.4 dB without efficiency loss (Liu et al., 2022). A step-skewed PMSM optimized via transfer learning achieved over a tenfold reduction in 24th-order cogging torque while also cutting FEA computation time (Won et al., 2023). A coaxial magnetic gear with skewed modulators and unequal air gaps lowered cogging torque from 49.45% to 5.76%, with additional reductions in core and eddy current losses (Khaledi & Kashani, 2025b). Adjusting magnet angles in segmented rotors further reduced cogging torque by 82.53%, confirming the simplicity and effectiveness of the method (Hua et al., 2024).

Rotor pole shaping is widely applied for harmonic suppression and cogging torque reduction. Eccentric pole profiles were shown to reduce total harmonic distortion from 36% to 7.8% and cogging torque from 40.57 Nm to 0.03 Nm (Zhou et al., 2022). Surface shaping in SPMSMs and IPMSMs lowered cogging torque to 1.7% and 0.6% of baseline values, with negligible penalties (Yamazaki & Seki, 2023). A hybrid star-type rotor topology achieved 56.02% cogging torque reduction and 17.67% iron loss reduction, verified through optimization and FEA (Khaledi et al., 2024). Permeance-based rotor shaping further achieved a 99% reduction in cogging torque, albeit with an 18% drop in back-EMF (Fang et al., 2025), while additional improvements were reported when this method was combined with rotor skewing (Bahrami-Fard et al., 2025).

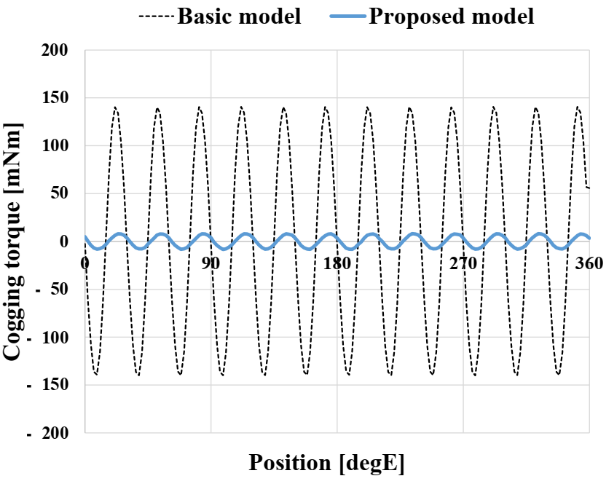

Figure 5 Influence rotor shaping on cogging torque

Table 4 Rotor geometry techniques

No	Techniques	Reference
1	Rotor skewing	Liu et al., 2022; Won et al., 2023; Khaledi & Kashani, 2025b; Hua et al., 2024
2	Rotor pole shaping	Zhou et al., 2022; Yamazaki & Seki, 2023; Khaledi et al., 2024; Kang et al., 2024; Fang et al., 2025; Bahrami-Fard et al., 2025
3	Spoke-type structure	Peng et al., 2022; Deepak et al., 2024
4	Flux barriers	Yamamoto & Hidaka, 2024; Mushenya & Khan, 2023

Spoke-type rotors strengthen flux paths and structural integrity while reducing cogging torque. A segmented spoke-type rotor with staggered pole widths was shown to reduce cogging torque, torque ripple, and vibration, delivering slot-skew–like performance with lower axial force and simpler manufacturability (Peng et al., 2022). Among four inner-rotor topologies, the spoke-embedded design achieved the lowest cogging torque of 0.028 Nm and the highest efficiency of 96%, confirming its suitability for low-power EVs and compact generators (Deepak et al., 2024).

Flux barrier modifications redirect magnetic flux to weaken cogging-inducing harmonics while preserving torque. An asymmetric flux-barrier structure in concentrated winding IPMSMs reduced torque ripple to 0.17 Nm under high load and 0.274 Nm under low load without compromising efficiency (Yamamoto & Hidaka, 2024). Alternating flux-barrier integration in a vernier machine also suppressed cogging harmonics and improved flux modulation, although detailed numerical results were not reported (Mushenya & Khan, 2023). These findings highlight flux barriers as effective solutions for high-precision, low-vibration PM machines.

4.3 Magnet Geometric Modification Techniques

Magnet geometric modification techniques are pivotal for cogging torque reduction in radial-flux permanent magnet machines, as they directly affect flux distribution, harmonic suppression, and electromagnetic symmetry. Recent advances include radial offset positioning, pitch skewing, magnet topology optimization, surface shape variation, fractional pole concentration, thickness adjustment, dual-layer configurations, and pole arc variation. These methods, validated through analytical models, finite element simulations, and experiments, demonstrate their impact on cogging torque suppression, efficiency improvement, and material utilization. Table 5 summarizes the key techniques and representative findings from high-impact studies.

As an illustrative example, Figure 6 illustrates the effect of magnet geometric modification through a straight-shaped rotor design, which redistributes the air-gap flux density to suppress cogging torque. This approach demonstrated that altering magnet surface geometry can achieve a substantial reduction in cogging torque up to 96% compared with the baseline—while maintaining efficiency loss below 0.2%. Such results highlight the effectiveness of magnet shaping as a practical and low-cost technique for improving torque quality in small wind power generators, offering a compelling direction for compact renewable energy applications (Jhankal & Patel, 2023).

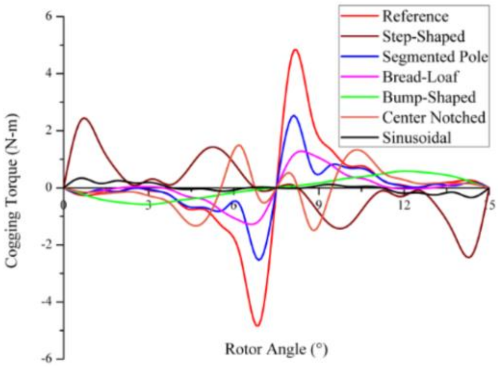

Figure 6 Influence surface magnet shape on cogging torque

Table 5 Magnet configuration techniques

No	Techniques	No. References
1	Radial Offset Magnet Positioning	Zamani Faradonbeh et al., 2020; Panchal et al., 2022
2	Pitch Skewing of Magnet	Constantin et al., 2022; Anuja et al., 2022; Chi et al., 2024
3	Topology Optimization of Magnet Area	Ruzbehi & Hahn, 2022; Mostaman, 2023; Tian et al., 2024
4	Surface Magnet Shape Variation	Kurt & Dalcalı, 2023; Jhankal & Patel, 2023; Sarac, 2023; Xiang et al., 2023
5	Fractional Pole Concentration	Qi et al., 2023; Said et al., 2024
6	Varying Magnet Thickness	Du et al., 2024; Xiang et al., 2024; Ganesh et al., 2022
7	Dual-Layer Magnet Configuration	Khaledi & Kashani, 2025a; Pan & Jing, 2021
8	Pole Arc Variation	Liang et al., 2020; Mostaman et al., 2023; Abduh et al., 2024

Radial offset positioning suppresses cogging torque by inducing harmonic phase cancellation. A 4° permanent magnet shift reduced cogging torque from 0.022 Nm to 0.003 Nm while maintaining acceptable THD (Zamani Faradonbeh et al., 2020). Similarly, angular displacement in surface-mounted PM BLDC motors achieved a 45.5% reduction (1.1 Nm to 0.6 Nm) and lowered back-EMF THD from 8.03% to 6.54%, confirming its effectiveness without sacrificing torque output (Panchal et al., 2022).

Pitch skewing reduces cogging torque by redistributing magnetic flux and suppressing harmonics. Adjusting magnet angles cut cogging torque from 3.826 Nm to 0.0041 Nm and torque ripple from 167.5% to 25.7%, with only a 4.2% torque penalty (Constantin et al., 2022). Combining a 3° phase shift with asymmetric pole arc adjustment further reduced cogging torque by 66.6% and raised efficiency to 94.13% (Anuja et al., 2022). A skewed segmented magnet design also lowered cogging torque from 7.247 Nm to 2.047 Nm and slightly improved efficiency in a 5.5 kW outer-rotor SPMSM (Chi et al., 2024).

Magnet topology optimization reduces cogging torque while minimizing magnet usage. A binary genetic algorithm cut magnet volume by 22.2% while improving torque and back-EMF smoothness (Ruzbehi & Hahn, 2022). Local optimization in an RFPMG lowered cogging torque by 63%, saved 0.9 kg of magnet, and boosted voltage by 13.64% (Mostaman, 2023). A two-stage ISSA–NSGA-II model achieved a 16.7% reduction in cogging torque and an over 100% efficiency gain, demonstrating the effectiveness of system-level optimization (Tian et al., 2024).

Surface magnet shaping adjusts flux distribution to suppress cogging torque and harmonics. Inclined and skewed double-rectangular magnets reduced cogging torque by 80% and lowered THD to 1.85% (Kurt & Dalcalı, 2023). A quasi-cylindrical pole pattern further provided an 82.3% torque reduction and 9% torque gain, experimentally validated in prototypes (Xiang et al., 2023).

Fractional pole concentration suppresses cogging torque by exploiting magnetic asymmetry. Unequal north–south pole arrangements shifted the cogging order, validated through prototype testing (Qi et al., 2023). Optimized pole-arc shaping within fractional poles reduced cogging torque by 99.04% while preserving torque output (Said et al., 2024).

Magnet thickness variation strongly influences cogging torque. Deviations in thickness and remanence altered cogging harmonics, while tolerance control improved reliability (Du et al., 2024). A ± 0.1 mm variation induced a 7% torque deviation under eccentricity (Xiang et al., 2024), whereas interior magnet thickness optimization reduced cogging torque without affecting torque output in IPM motors (Ganesh et al., 2022).

Dual-layer magnet configurations enhance flux concentration and effectively mitigate cogging torque. A hybrid L-type design integrating rare-earth and ferrite magnets achieved an 85.5% reduction with reduced magnet volume, lower core losses, and only minor torque penalties (Khaledi & Kashani, 2025a). Similarly, an irregular dual-layer Halbach array cut cogging torque by 56.9% in the inner rotor and 76.5% in the outer rotor while improving flux concentration and torque smoothness in double-rotor PM machines (Pan & Jing, 2021).

Pole arc optimization effectively balances air-gap flux density while suppressing cogging torque. Adjusting pole arcs reduced cogging torque while also lowering vibration and noise, emphasizing its multiphysics relevance (Liang et al., 2020). An optimal pole arc ratio of 0.49 reduced cogging torque to 0.6986 Nm and improved voltage output, representing a 69.88% reduction compared with baseline (Mostaman et al., 2023). Combining pole arc adjustment with magnet reshaping achieved a 99.04% cogging torque reduction, underscoring its strategic value for renewable-energy generator design and sustainable power systems (Abduh et al., 2024).

4.4 Winding Layout Modification Techniques

Winding layout modification is a key strategy for cogging torque reduction in radial-flux permanent magnet machines, as it shapes magnetomotive force distribution and harmonic alignment. Current studies highlight fractional-slot winding and optimized coil arrangements, which effectively reduce cogging torque, torque ripple, and unbalanced magnetic pull while improving efficiency and reducing copper usage. Table 6 summarizes these techniques, supported by analytical, numerical, and experimental validations demonstrating their impact on torque quality and overall performance.

As an illustrative example of winding layout modification, Figure 7 compares the cogging torque waveforms of RF-PMSGs wound with integral slot distributed winding (ISDW), Fractional-Slot distributed winding (FSDW), and Fractional-Slot concentrated winding (FSCW). The results, validated through 2D and 3D finite element simulations, show that FSDW achieved the lowest cogging torque and ripple torque, while FSCW offered reduced copper mass and manufacturing simplicity at the expense of slightly higher distortion. ISDW exhibited the highest harmonic content and torque pulsation, underscoring the importance of winding selection in balancing electromagnetic performance, efficiency, and practicality for wind turbine generators (Iracheta-Cortez et al., 2024).

Fractional-slot winding disrupts slot/pole harmonic alignment, thereby reducing cogging torque and improving electromagnetic balance. Shifting from a 9-slot to a 12-slot design significantly lowered cogging torque and improved back-EMF symmetry under static eccentricity (Park et al., 2021). An optimized fractional-slot configuration achieved a 98.68% reduction in cogging torque and a 28.57% decrease in unbalanced magnetic pull while maintaining mechanical and electromagnetic robustness (Nur et al., 2024). Similarly, non-standard arrangements such as 8p13s further reduced torque ripple from 14% to below 1% with minimal radial force penalties, underscoring the potential of fractional-slot winding for enhancing torque quality in RF-PM machines (Königs et al., 2025).

Optimizing coil arrangements shapes flux distribution and harmonic behavior, offering a complementary route for cogging torque mitigation. A comparative study of ISDW, FSDW, and FSCW showed that FSDW minimized cogging torque and harmonic distortion, while FSCW provided balanced performance with reduced copper usage (Ortiz-García et al., 2023).

4.5 Non-Geometric Techniques

Non-geometric techniques offer alternative pathways for cogging torque reduction by improving electromagnetic behavior beyond structural modifications. These include Halbach magnetization, control-based strategies, and material engineering, which suppress cogging torque through flux modulation, active regulation, or enhanced magnetic properties. Supported by analytical models, simulations, and experiments, these methods have proven effective in lowering cogging torque while improving torque smoothness, efficiency, and reliability. Table 7 outlines recent developments and outcomes that complement traditional geometry-based approaches.

Non-geometric techniques such as control-based methods effectively suppress cogging torque without altering machine geometry. As illustrated in Figure 8, torque ripple waveforms under three scenarios—cogging map off, cogging map on, and cogging map with CHC demonstrate progressive improvement in torque smoothness. The addition of a cogging torque map already reduces oscillations; however, integrating a Current Harmonics Controller (CHC) achieves the most significant ripple attenuation, ensuring precise current tracking and smoother torque production. This highlights how advanced control schemes can complement design-based methods by actively compensating cogging harmonics in real time (Sumega et al., 2020).

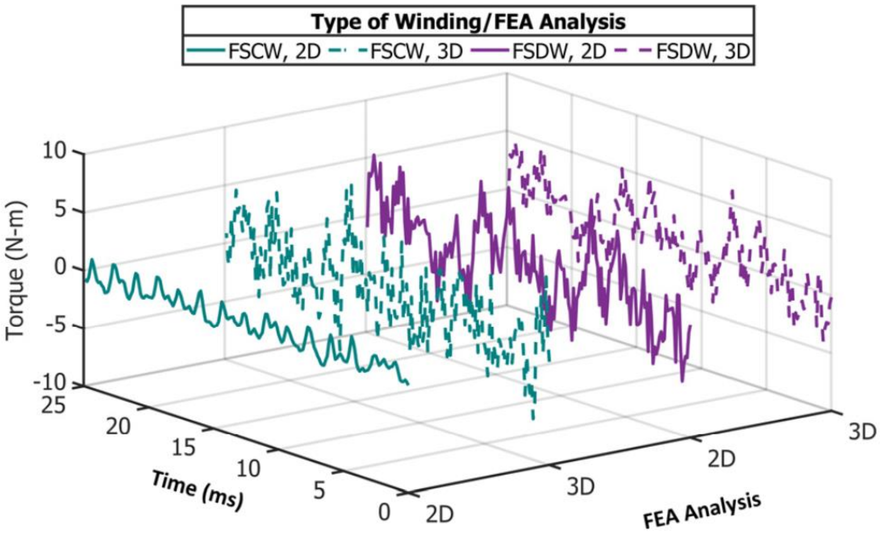

Figure 7 Influence winding layout modification on cogging torque

Table 6 Winding layout techniques

No	Techniques	References
1	Fractional-Slot Winding	Park et al., 2021; Nur et al., 2024; Königs et al., 2025
2	Coil/Winding arrangement pattern	Ortiz-García et al., 2023; Iracheta-Cortez et al., 2024

Tabel 7 Non-geometric techniques

No	Techniques	References
1	Halbach magnetization	Liu et al., 2021; Nobahari & Vahedi, 2022
2	Control-based	Sumega et al., 2020; Dini & Saponara, 2020; Nos et al., 2020
3	Material engineering	Nos et al., 2020; Thenmozhi et al., 2022b; Abbass & Ali, 2023

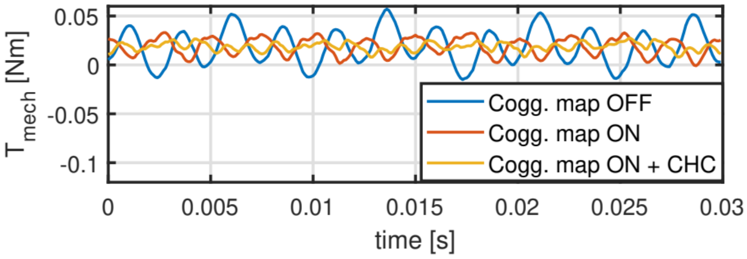

Figure 8 Influence control base method on cogging torque

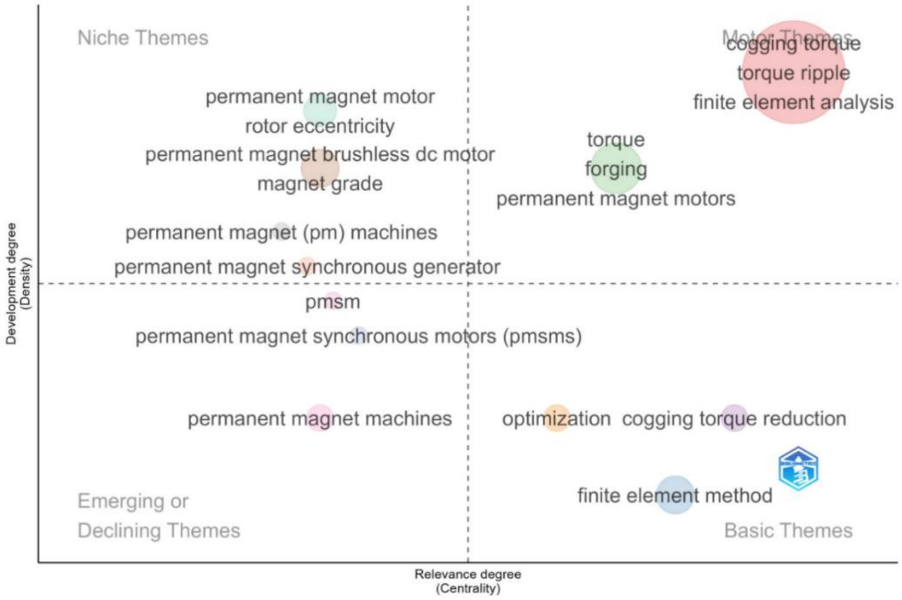

Figure 9 Thematic map

Halbach magnetization improves flux uniformity, suppressing cogging torque and enhancing efficiency. An optimized design based on magnetic field energy equivalence reduced cogging torque compared with conventional surface-mounted types while preserving torque smoothness (Liu et al., 2021). Similarly, a modified Halbach array improved air-gap flux distribution, yielding stable torque and significant cogging torque reduction without requiring structural modifications (Nobahari & Vahedi, 2022).

A nonlinear scheme combining feedback linearization with an extended Kalman filter further minimized cogging torque in sensorless motors by embedding a deterministic torque model to ensure precise rotor estimation and robust suppression (Dini & Saponara, 2020). Likewise, a proportional-integral-resonant (PIR) controller compensated speed harmonics, reducing cogging torque and cutting speed pulsations 14-fold without requiring structural changes or additional sensors (Nos et al., 2020).

Material engineering exploits magnetic material properties to reduce cogging torque while sustaining overall performance. Comparative analyses demonstrated that Alnico-9NB minimized cogging torque while maintaining 95.4% efficiency and stable torque up to 3200 rpm (Thenmozhi et al., 2022a), whereas Ceramic 10 yielded the lowest cogging torque and smoothest torque profile, and NdFeB and Samarium Cobalt provided higher torque output for EVs despite slightly increased cogging (Thenmozhi et al., 2022b). Further studies confirmed that NdFeB magnets significantly reduced cogging torque and ripple compared with Alnico while delivering superior torque across operating ranges, underscoring material selection as a critical design factor (Abbass & Ali, 2023).

5. Future Works

Building on the systematic review of 64 peer-reviewed articles spanning stator geometry, rotor geometry, magnet geometry, winding layout, and non-geometric techniques this study integrates a bibliometric analysis through a thematic map generated from BibTeX metadata using Biblioshiny (Bibliometrix R), as shown in Figure 9.

The results reveal underrepresented, high-potential research areas, particularly those situated in the Niche and Emerging or Declining quadrants, thereby highlighting opportunities for innovation in cogging torque mitigation (Kaiser & Kuckertz, 2024; Catone, 2023).

Future research on cogging torque reduction in RF-PM machines should focus on areas that bridge technical maturity with conceptual novelty. A key direction is the systematic re-evaluation of conventional topologies such as stator slot shapes and rotor pole geometries through advanced finite element modeling and surrogate optimization. These approaches, aligned with niche and emerging themes, create opportunities to revisit overlooked torque traits and uncover design sensitivities that were previously underappreciated.

Material innovation also emerges as a critical vector for advancement. Exploration of alternative magnet grades, such as ferrite or Alnico, presents a path toward reducing cogging torque while addressing cost and thermal management in low-speed applications. This area, though isolated in current literature, is technically well-formed and thus primed for deeper integration.

6. Conclusion

This systematic literature review synthesizes cogging torque mitigation strategies for radial-flux permanent magnet synchronous machines (RF-PMSMs) by examining 64 peer-reviewed articles, categorized into five key domains: stator geometry, rotor geometry, magnet geometry, winding layout, and non-geometric techniques. Each category presents specific design approaches that contribute to cogging torque reduction with varying levels of implementation complexity and performance trade-offs. To deepen the analysis, bibliometric tools, including VOSviewer and Biblioshiny were used to generate a co-occurrence network and thematic map, which helped identify research clusters and underdeveloped areas. Notably, niche and emerging themes were revealed as promising directions for future research.

Despite considerable progress, challenges remain in integrating cost, manufacturability, and real-world validation into advanced designs. The field stands to benefit from multi-objective optimization frameworks, exploration of alternative magnetic materials, and stronger linkages between numerical simulations and experimental verification. This review provides a structured understanding of current strategies and offers guidance for future research to enhance torque smoothness, efficiency, and robustness in RF-PMSMs—particularly in renewable energy and industrial applications where precision and reliability are critical.

7. Acknowledgment

This research was supported by LPPM UNSOED through contract No. 10.33/UN23.34/PT.01/VI/2025.

8. Abbreviations

Abbreviation	Full Term
RF-PMSMs	Radial-flux permanent magnet synchronous machines
AFPMSMs	Axial-flux permanent magnet synchronous machines
IPMSMs	Internal permanent magnet synchronous machines
FSCW	Fractional-slot concentrated winding
SPMSMs	Surface permanent magnet synchronous machines
ISDW	Integral slot distributed winding
FSDW	Fractional-Slot distributed winding

Abbreviation	Full Term
EMF	Electromotive force
THD	Total harmonic distortion
9S8P	9 slot 8 pole
CHC	Current Harmonics Controller
PIR	proportional-integral-resonant

9. CRediT Statement:

Hari Prasetijo: Conceptualization, Methodology, Validation
Mohammad Khairudin: Conceptualization, Supervision
Ketut Wirtayasa: Conceptualization, Supervision
Muhammad Syaiful Aliim: Writing – Original Draft, Visualization
Widhiatmoko Herry Purnomo: Data Curation, Review & Editing

10. References

Abbass, E. A., & Ali, A. M. (2023). Effect of changing magnet material on cogging torque and torque ripple of brushless DC motor. *Al-Iraqia Journal for Scientific Engineering Research*, *2*(1), 57-67. https://doi.org/10.58564/IJSER.2.1.2023.61

Abduh, S., Karunanithi, S., & Nur, T. (2025). Analysis of the cogging torque reduction in permanent magnet generators for a very low wind speed. *Energies*, *18*(11), Article 2802. https://doi.org/10.3390/en18112802

Abduh, S., Nur, T., & Muljadi, E. (2024). Achieving magnetic force and cogging torque reduction in a permanent magnet generator with concentrated slot technique and pole arc optimization at magnet edge [Conference presentation]. *2024 27th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Fukuoka, Japan. https://doi.org/10.23919/ICEMS60997.2024.10921128

Anuja, T. A., Arun Noyal Doss, M., Senthilkumar, R., Rajesh, K. S., & Brindha, R. (2022). Modification of pole pitch and pole arc in rotor magnets for cogging torque reduction in BLDC motor. *IEEE Access*, *10*, 116709–116722. https://doi.org/10.1109/ACCESS.2022.3217233

Azom, M. A., & Khan, M. Y. A. (2025). Recent developments in control and simulation of permanent magnet synchronous motor systems. *Control Systems and Optimization Letters*, *3*(1), 84-91. https://doi.org/10.59247/csol.v3i1.173

Bahrami-Fard, M., Liang, J., Chen, P., Hair, C., Moallem, M., Pekarek, S., & Fahimi, B. (2025). Cogging torque minimization strategies in interior permanent magnet synchronous motors. *IEEE Access*, *13*, 49597-49610. https://doi.org/10.1109/ACCESS.2025.3550797

Bu, F., Yang, Z., Gao, Y., Pan, Z., Pu, T., Degano, M., & Gerada, C. (2021). Speed Ripple Reduction of Direct-Drive PMSM Servo System at Low-Speed Operation Using Virtual Cogging Torque Control Method. *IEEE Transactions on Industrial Electronics, 68*, 160-174. https://doi.org/10.1109/TIE.2019.2962400

Catone, M. C. (2023). The role of open data in digital society: The analysis of scientific trending topics through a bibliometric approach. *Frontiers in Sociology*, *8*, Article 1134518. https://doi.org/10.3389/fsoc.2023.1134518

Chi, D. D., Huu, H. B., Thanh, B. D., & Quoc, V. D. (2024). A novel skewed permanent magnet technique for improving performances of SPMSMs with outer rotor type [Conference presentation]. *2024 Tenth International Conference on Communications and Electronics (ICCE)*. IEEE, Danang, Vietnam. https://doi.org/10.1109/ICCE62051.2024.10634690

Choi, D. H., Kim, D. H., Han, H. S., Jung, D. H., & Kim, W. H. (2024). Design of a slotless structure for minimizing cogging torque and torque ripple in a column type EPS motor for vehicles. *IEEE Transactions on Magnetics*, *60*(9), 1-5. https://doi.org/10.1109/TMAG.2024.3428343

Constantin, A. I., Tudor, E., Marin, D., Dumitru, C., & Mihaiescu, M. G. (2022). Case studies related to the optimization of a surface mounted permanent magnets synchronous generator applied for a small hydrokinetic turbine [Conference presentation]. *2022 International Conference and Exposition on Electrical and Power Engineering (EPE).* IEEE, Iasi, Romania. https://doi.org/10.1109/EPE56121.2022.9959837

Dajaku, G. (2021). Advanced multi-phase fractional slot concentrated windings: Characteristics and potentials. *Electrical Engineering*, *103*(1), 397-406. https://doi.org/10.1007/s00202-020-01088-2

Deepak, M., Kumar, C. S., Karthick, M., & Manokaran, J. (2024). Investigation of Different Inner Rotor Structures on BLDC Motors Performance for Traction Applications [Conference presentation]. *2024 IEEE International Conference on Smart Power Control and Renewable Energy (ICSPCRE)*. IEEE, Rourkela, India. https://doi.org/10.1109/ICSPCRE62303.2024.10675063

Dini, P., & Saponara, S. (2020). Design of an observer-based architecture and non-linear control algorithm for cogging torque reduction in synchronous motors. *Energies*, *13*(8), Article 2077. https://doi.org/10.3390/en13082077

Du, J., Zhong, R., Wu, Z., & Hua, W. (2024). Influence of manufacturing tolerance in ring magnet on cogging torque of surface permanent magnet synchronous machine. *IEEE Transactions on Energy Conversion*, *39*(2), 1301-1313. https://doi.org/10.1109/TEC.2023.3349329

Fang, L., Zhang, Y., Li, D., & Qu, R. (2025). High-torque density and low-torque ripple-oriented design method for multi-harmonics surface-mounted PM vernier machine. *IEEE Transactions on Industry Applications*, *61*(3), 3687–3700. https://doi.org/10.1109/TIA.2025.3540726

Ganesh, C. J., Vijay, G. S., & Siddappa, I. B. (2022). Modelling of interior permanent magnet motor and optimization of its torque ripple and cogging torque based on design of experiments and artificial neural networks. *Engineered Science*, *18*, 193-203. http://doi.org/10.30919/es8d677

Hassan, A. Y., Rohieem, A. G., & Salem, S. M. S. (2022). Direct torque control of non-salient pole AFPMSMs with SVPWM inverter. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *13*(4), 2014-2023. https://doi.org/10.11591/ijpeds.v13.i4.pp2014-2023

Hu, K., Zhang, G., & Zhang, W. (2022). Analysis and design of electromagnetic vibration and noise reduction method of permanent magnet motor. *Journal of Low Frequency Noise, Vibration and Active Control*, *41*(1), 359-373. https://doi.org/10.1177/14613484211038405

Hua, S., Zhang, X., Zhang, J., Yu, C., Meng, F., Wang, W., ... & Hu, W. (2024). Improved skew method in permanent magnet motor with segmented rotors for reducing cogging torque. *Progress In Electromagnetics Research C*, *141*, 185-193. https://doi.org/10.2528/PIERC23101906

Hussien, S. A., Deab, M. A., & Alrowais, F. (2022). Maximization of the power delivered from permanent magnet synchronous generator wind energy conversion system to the grid based on using moth flame optimization. *Indonesian Journal of Electrical Engineering and Computer Science*, *27*(3), 1347-1357. https://doi.org/10.11591/ijeecs.v27.i3.pp1347-1357

Iracheta-Cortez, R., Vázquez, E., & Durante-Gómez, W. (2024). Analyzing the performance of radial-flux permanent magnet synchronous generators with different winding designs for applications in wind turbine*s* [Conference presentation]. *2024 International Conference on Electrical Machines (ICEM)*. IEEE, Torino, Italy. https://doi.org/10.1109/ICEM60801.2024.10700092

Jang, G. H., Kim, S., & Choi, G. (2024, November). Design and optimization of an outer-rotor PMSM for torque ripple minimization [Conference presentation]. *2024 27th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Fukuoka, Japan. https://doi.org/10.23919/ICEMS60997.2024.10921025

Jhankal, T., & Patel, A. N. (2023). Design and cogging torque reduction of radial flux brushless DC motors with varied permanent magnet pole shapes for electric vehicle application. *Transactions on Energy Systems and Engineering Applications*, *4*(2), 1-13. https://doi.org/10.32397/tesea.vol4.n2.535

Jhankal, T., & Patel, A. N. (2024). Optimization of cogging torque in radial flux brushless DC motor using a novel stator side approach [Conference presentation]. *2024 IEEE 3rd International Conference on Electrical Power and Energy Systems (ICEPES)*. IEEE, Bhopal, India. https://doi.org/10.1109/ICEPES60647.2024.10653502

Kaiser, M., & Kuckertz, A. (2024). Bibliometrically mapping the research field of entrepreneurial communication: Where we stand and where we need to go. *Management Review Quarterly*, *74*, 2087–2120. https://doi.org/10.1007/s11301-023-00355-3

Kanapara, A. J., & Badgujar, K. P. (2020). Performance improvement of permanent magnet brushless DC motor through cogging torque reduction techniques [Conference presentation]. *2020 21st National Power Systems Conference (NPSC)*. IEEE, Gandhinagar, India. https://doi.org/10.1109/NPSC49263.2020.9331855

Kang, J., Lee, J., Ham, S., Chun, Y., & Kim, H. (2024). A study on new straight shape design to reduce cogging torque of small wind power generator. *Machines*, *12*(6), Article 412. https://doi.org/10.3390/machines12060412

Khaledi, M. M., & Kashani, S. A. A. (2025a). Design of an L-Shaped Hybrid PM Array in Coaxial Magnetic Gear [Conference presentation]. *2025 16th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*. IEEE, Tabriz, Iran. https://doi.org/10.1109/PEDSTC65486.2025.10911918

Khaledi, M. M., & Kashani, S. A. A. (2025b). Mitigation of cogging torque in coaxial magnetic gear by rotors skew-shaping [Conference presentation]. *2025 12th Iranian Conference on Renewable Energies and Distributed Generation (ICREDG)*. IEEE, Tabriz, Iran. https://doi.org/10.1109/ICREDG66184.2025.10966079

Khaledi, M. M., Kashani, S. A. A., & Zaj, M. M. (2024). A new star-type rotor topology in radial flux magnetic gear [Conference presentation]. *2024 4th International Conference on Electrical Machines and Drives (ICEMD)*. IEEE, Tehran, Iran. https://doi.org/10.1109/ICEMD64575.2024.10963496

Kim, G. H., & Jung, T. U. (2020). Stator teeth pairing design for reduction of cogging torque of dual RFPM generator [Conference presentation]. *2020 IEEE 19th Biennial Conference on Electromagnetic Field Computation (CEFC)*. IEEE, Tehran, Iran. https://doi.org/10.1109/ICEMD64575.2024.10963496

Königs, M., Kremp, C., Holtorf, J. H., Harmel, M., & Löhlein, B. (2025). Improvement of the performance of electric drives with concentrated windings: Reduction of torque ripple through non-standard stator slot numbers. *e+ i Elektrotechnik und Informationstechnik*, *142*(5), 268-277. https://doi.org/10.1007/s00502-025-01326-0

Krishnan, G. H., Prabhu, S., Reddy, L. S., Chandrasekar, P., Chennakesava, M., & Kalyan, P. P. (2024). Cogging torque reduction strategies in six-phase BLDC motors: Skewing and back EMF tuning for EV applications [Conference presentation]. *2024 10th International Conference on Electrical Energy Systems (ICEES)*. IEEE, Chennai, India. https://doi.org/10.1109/ICEES61253.2024.10776880

Kurt, E., & Dalcalı, A. (2023). Effects of magnet shapes on total harmonic distortion and cogging torque in a permanent magnet synchronous generator for wind turbines. *Clean Energy*, *7*(5), 1058-1068. https://doi.org/10.1093/ce/zkad046

Liang, X., Zhao, W., Liu, Y., Wang, X., & Kwon, B. I. (2020). *Multi-physics analysis of surface inset permanent magnet motors with different slot-pole combinations* [Conference presentation]. *2020 IEEE 3rd Student Conference on Electrical Machines and Systems (SCEMS)*. IEEE, Jinan, China. https://doi.org/10.1109/SCEMS48876.2020.9352268

Liu, D., Geng, W., Li, Q., Guo, J., Wu, C., & Ge, S. (2022). Electromagnetic analysis and vibration reducing of segmented skew rotor for built-in u-shaped permanent magnet motor [Conference presentation]. *2022 Joint MMM-Intermag Conference (INTERMAG)*. IEEE, New Orleans, LA, USA. https://doi.org/10.1109/INTERMAG39746.2022.9827842

Liu, M., Zhu, X., Xiang, Z., Quan, L., Wang, T., & Zhu, T. (2021). Cogging torque reduction of Halbach array permanent magnet motor based on magnetic field energy equivalence [Conference presentation]. *2021 IEEE 4th International Electrical and Energy Conference (CIEEC)*. IEEE, Wuhan, China.

https://doi.org/10.1109/CIEEC50170.2021.9510795

Liu, Z., Yang, Z., Wang, X., Yu, P., & Li, Z. (2023). Design of multi-phase permanent magnet synchronous motor with fractional-slot windings for electromagnetic vibration reduction considering stator teeth modulation. *IET Electric Power Applications*, *17*(9), 1123-1135. https://doi.org/10.1049/elp2.12327

Mostaman, A. (2023). Design optimization and analysis of radial flux permanent magnet generator using local optimization method. *El-Cezeri*, *11*(1), 58-64. https://doi.org/10.31202/ecjse.1319963

Mostaman, N. A., Sulaiman, E., & Jenal, M. (2023). Cogging torque reduction for permanent magnet structure of radial flux permanent magnet generator. *IOP Conference Series: Earth and Environmental Science*, *1281*(1), 012054. https://doi.org/10.1088/1755-1315/1281/1/012054

Mushenya, J., & Khan, A. (2023). Torque analysis in an alternating flux-barrier permanent magnet vernier machine [Conference presentation]. *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, Nashville, TN, USA. https://doi.org/10.1109/ECCE53617.2023.10362331

Nguyen, K. A., Hieu, L. D., Pham, V. T., & Ngo, V. Q. B. (2025). Enhanced model predictive current framework for a PMSM powered by three-level NPC inverters with DC-link voltage self-balancing mechanisms. *Results in Engineering*, *27*, Article 105918. https://doi.org/10.1016/j.rineng.2025.105918

Nobahari, A., & Vahedi, A. (2022). Modified Halbach design for torque profile improvement in a permanent magnet synchronous motor dedicated to an electric city bus. *IET Electric Power Applications*, *16*(12), 1410-1425. https://doi.org/10.1049/elp2.12143

Nos, O. V., Shtein, D. A., Leus, G. S., Nos, N. I., Abramushkina, E. E., & Ignatev, E. A. (2020). The simplified control technique for PMSM torque ripple reduction [Conference presentation]. *2020 21st International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)*. IEEE, Chemal, Russia. https://doi.org/10.1109/EDM49804.2020.9153527

Nur, T., Abduh, S., & Muljadi, E. (2024). Optimal design of fractional slot number using response surface method on the cogging torque and unbalanced magnetic pull reduction in permanent magnet machine [Conference presentation]. *2024 27th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Fukuoka, Japan. https://doi.org/10.23919/ICEMS60997.2024.10921044

Ortiz-García, E., Iracheta-Cortez, R., & Vázquez, E. (2023). Analyzing the performance of radial-flux PMSGs through different types of windings [Conference presentation]. *2023 IEEE 41st Central America and Panama Convention (CONCAPAN XLI)*. IEEE, Tegucigalpa, Honduras. https://doi.org/10.1109/CONCAPANXLI59599.2023.10517552

Pan, Y., & Jing, L. (2021). Characteristic research on double rotor permanent magnet motor with irregular Halbach array. *Progress in Electromagnetics Research M*, *104*(6), 133-144. http://doi.org/10.2528/PIERM21071903

Panchal, T. H., Patel, A. N., & Patel, R. M. (2022). Reduction of cogging torque of radial flux permanent magnet brushless DC motor by magnet shifting technique. *Electrical Engineering & Electromechanics*, *3*, 15-20. https://doi.org/10.20998/2074-272X.2022.3.03

Park, J. C., Park, S. H., Kim, J. H., Lee, S. G., Lee, G. H., & Lim, M. S. (2021). Diagnosis and robust design optimization of SPMSM considering back EMF and cogging torque due to static eccentricity. *Energies*, *14*(10), Article 2900. https://doi.org/10.3390/en14102900

Patel, A. N., Doshi, P. J., Mahagoakar, S. C., & Panchal, T. H. (2023). Optimization of cogging torque in interior permanent magnet synchronous motor using optimum magnet v-angle. *Electrical Engineering & Electromechanics*, *6*, 16-20. https://doi.org/10.20998/2074-272X.2023.6.03

Peng, C., Wang, D., Feng, Z., & Wang, B. (2022). A new segmented rotor to mitigate torque ripple and electromagnetic vibration of interior permanent magnet machine. *IEEE Transactions on Industrial Electronics*, *69*(2), 1367-1377. https://doi.org/10.1109/TIE.2021.3063869

Qi, J., Zhu, Z. Q., Yan, L., Jewell, G. W., Gan, C., Ren, Y., ... & Hilton, C. (2023). Analytical analysis of cogging torque in permanent magnet machines with unequal north and south poles, with particular reference to consequent pole machines. *IEEE Transactions on Energy Conversion*, *38*(2), 1361-1375. https://doi.org/10.1109/TEC.2022.3221917

Ruzbehi, S., & Hahn, I. (2022). Topology optimization of a PM synchronous machine based on novel metaheuristic algorithm for lower cogging torque and magnet volume [Conference presentation]. *2022 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, Shanghai, China, https://doi.org/10.1109/ICIT48603.2022.10002791

Said, S. M., Nur, T., & Herlina, H. (2024). The application of magnet structures to reduce the cogging torque associated with fractional slot number in permanent magnet generators. *Energies*, *17*(11), Article 2505. https://doi.org/10.3390/en17112505

Sarac, V. (2023). Performance analysis of various rotor topologies of surface PM synchronous motor. *Journal of Electrical Engineering*, *74*(2), 85–94. https://doi.org/10.2478/jee-2023-0011

Sayed, A. E., & Erturk, E. R. C. A. N. (2021). Minimizing cogging torque in permanent magnet synchronous generators for small wind turbine applications. *International Journal of Renewable Energy Research*, *11*(2), 691-700.

Song, Y., Zhang, Z., Yu, S., Zhang, F., & Zhang, Y. (2021). Analysis and reduction of cogging torque in direct-drive external-rotor permanent magnet synchronous motor for belt conveyor application. *IET Electric Power Applications*, *15*(6), 668-680. https://doi.org/10.1049/elp2.12048

Sumega, M., Rafajdus, P., & Stulrajter, M. (2020). Current harmonics controller for reduction of acoustic noise, vibrations and torque ripple caused by cogging torque in PM motors under FOC operation. *Energies*, *13*(10), Article 2534. https://doi.org/10.3390/en13102534

Thenmozhi, G., Radhika, A., Mithun, B., Dhineesh, M., & Abissek, B. (2022a). A simulation-based investigation on the Performance of BLDC motor used in Electric Vehicles for varied magnetic materials [Conference presentation]. *2022 8th International Conference on Advanced Computing and Communication Systems (ICACCS)*. IEEE, Coimbatore, India. https://doi.org/10.1109/ICACCS54159.2022.9785117

Thenmozhi, G., Sivakumar, S., Arun, B., Sivakumar, S., Nirmala, M., & Radhika, A. (2022b). An investigation on the performance of permanent magnet brushless DC motor based on different materials [Conference presentation]. *AIP Conference Proceedings*, Coimbatore, India. https://doi.org/10.1063/5.0108137

Tian, D., Wu, X., Meng, H., & Su, Y. (2024). A two-stage multi-objective design optimization model for a 6 MW direct-drive permanent magnet synchronous generator. *Energies*, *17*(16), Article 4147. https://doi.org/10.3390/en17164147

Tong, W., Li, S., Pan, X., Wu, S., & Tang, R. (2020). Analytical model for cogging torque calculation in surface-mounted permanent magnet motors with rotor eccentricity and magnet defects. *IEEE Transactions on Energy Conversion*, *35*(4), 2191-2200. https://doi.org/10.1109/TEC.2020.2995902

Vukotić, M., Rodić, D., Benedičič, B., & Miljavec, D. (2020). Cogging torque in slotless permanent magnet machines. *Journal of Electrical Engineering*, *71*(3), 195-202. https://doi.org/10.2478/jee-2020-0026

Wei, Y., Cheng, Z., Si, J., Jin, F., Gao, C., & Gan, C. (2021). Analysis of a direct-drive permanent magnet synchronous generator with novel toroidal winding. *IET Renewable Power Generation*, *15*(10), 2237-2245. https://doi.org/10.1049/rpg2.12158

Won, Y. J., Kim, J. H., An, S. M., & Lim, M. S. (2024). Comparative study of cogging torque, torque ripple, and vibration on stator tooth chamfer types in permanent magnet synchronous motors. *IEEE Transactions on Magnetics*, *60*(9), 1-5. https://doi.org/10.1109/TMAG.2024.3412965

Won, Y. J., Kim, J. H., Park, S. H., Lee, J. H., An, S. M., Kim, D. Y., & Lim, M. S. (2023). Transfer learning-based design method for cogging torque reduction in PMSM with step-skew considering 3-D leakage flux. *IEEE*

Transactions on Magnetics, *59*(11), 1-5. https://doi.org/10.1109/TMAG.2023.3294601

Wu, Z., Fan, Y., & Wang, X. (2023). Effects of Unequal-tooth stator on electromagnetic vibration of fractional-slot concentrated winding permanent magnet motors [Conference presentation]. *2023 26th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Zhuhai, China. https://doi.org/10.1109/ICEMS59686.2023.10344500

Xiang, D., & Zhu, Z. Q. (2022). Influence of slot and pole number combinations on cogging torque in PM machines with tooth bulge and rotor eccentricity [Conference presentation]. *2022 International Conference on Electrical Machines and Systems(ICEMS)*. IEEE, Chiang Mai, Thailand https://doi.org/10.1109/ICEMS56177.2022.9983075

Xiang, D., Zhu, Z. Q., Liang, D., Wu, Y., Xu, F., & Cheng, Y. (2024). Interaction effects of PM tolerances and rotor eccentricities on cogging torque of 12-slot/10-pole PM machines. *IEEE Transactions on Industry Applications*, *60*(5), 6648-6659. https://doi.org/10.1109/TIA.2024.3400945

Xiang, P., Yan, L., Liu, X., He, X., Du, N., & Wang, H. (2025). Structural topology design for electromagnetic performance enhancement of permanent-magnet machines. *Chinese Journal of Mechanical Engineering*, *38*(1), Article 26. https://doi.org/10.1186/s10033-025-01184-z

Xiang, P., Yan, L., Xiao, H., He, X., & Du, N. (2023). Development of a novel radial-flux machine with enhanced torque profile employing quasi-cylindrical PM pattern. *IEEE Transactions on Energy Conversion*, *38*(4), 2772-2783. https://doi.org/10.1109/TEC.2023.3279339

Yamamoto, S., & Hidaka, Y. (2024). Study on torque ripple reduction of asymmetric flux barrier using topology optimization and frozen permeability method [Conference presentation]. *2024 27th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, Fukuoka, Japan. https://doi.org/10.23919/ICEMS60997.2024.10921446

Yamazaki, K., & Seki, Y. (2023). Zeroization of cogging torque of permanent magnet machines by optimizing rotor surface shape: comparison between surface and interior types. *IEEE Transactions on Magnetics*, *59*(5), 1-4. https://doi.org/10.1109/TMAG.2023.3255928

Yang, J., Chen, J., Yang, G., & Zhang, C. (2022). Research on cogging torque characteristics of permanent magnet synchronous machines with the same number of poles and slots. *Journal of Magnetism and Magnetic Materials*, *561*, Article 169730. https://doi.org/10.1016/j.jmmm.2022.169730

Yao, R., Wang, H., Xu, Y., Sha, Y., & Feng, C. (2024). Torque ripple reduction of new dual-stator machines using squirrel stator teeth in uneven distribution [Conference presentation]. *2024 IEEE International Magnetic Conference-Short papers (INTERMAG Short papers)*. IEEE, Rio de Janeiro, Brazil. https://doi.org/10.1109/INTERMAGShortPapers61879.2024.10576814

Youssef, M. Z., Elahi, A., & Ihsan, A. (2025). An optimized permanent magnet motor for pumps in electric/hybrid vehicles: Design and experimentation. *IEEE Access*, *13*, 54028–54039. https://doi.org/10.1109/ACCESS.2025.3551606

Yu, Y., Chai, F., Pei, Y., Doppelbauer, M., & Lee, C. H. (2024). Investigation of power factor characteristic in permanent magnet motors for in-wheel direct drive application. *IEEE Transactions on Energy Conversion*, *39*(3), 1699-1710. https://doi.org/10.1109/TEC.2024.3360048

Zamani Faradonbeh, V., Taghipour Boroujeni, S., & Takorabet, N. (2020). Optimum arrangement of PMs in surface-mounted PM machines: cogging torque and flux density harmonics. *Electrical Engineering*, *102*(3), 1117-1127. https://doi.org/10.1007/s00202-020-00925-8

Zhou, Y., Liu, K., Yang, X., Miao, H., & Zeng, C. (2022). Open-circuit magnetic field and cogging torque of spoke-type permanent-magnet machine with different pole shape [Conference presentation]. *2022 IEEE 5th International Electrical and Energy Conference (CIEEC)*. IEEE, Nangjing, China. https://doi.org/10.1109/CIEEC54735.2022.9845831