

Torque Ripple Minimization Techniques In Three Phase Synchronous Reluctance Motor And Permanent Magnet Assisted Synchronous Reluctance Motor: A Review

V Rajini¹, V. S. Nagarajan^{2*}, Bharatiraja .C³, Krtin Narayanan¹, and N Christina Lydia Grace¹

¹Department of Electrical and Electronics Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Kalavakkam, Tamil Nadu, 603110, India

²Department of Electrical and Electronics Engineering, SSN School of Engineering, Shiv Nadar University Chennai, Kalavakkam, Tamil Nadu, 603110, India

³Centre for Electric Mobility, SRM Institute of Science and Technology, SRM Nagar, Kattankulathur, 603203, Chengalpattu, Chennai, TN, India

*Corresponding author. E-mail: nagarajanvs@snuchennai.edu.in

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Synchronous Reluctance Motor (SynRM), Permanent-Magnet-assisted Synchronous Reluctance Motor (PMA-SynRM), and Ferrite-Assisted Synchronous Reluctance (FASR) motor topologies have emerged as promising alternatives for high efficiency electric drive applications due to their reduced rotor losses, robust construction, and potential for reduced dependence on rare earth materials. However, torque ripple remains a major performance limitation in these machines, leading to vibration, acoustic noise, speed pulsation and reduced drive quality. This paper presents a comprehensive review of torque ripple mitigation techniques reported in the literature for three major reluctance based synchronous machine variants: pure SynRM, PMA-SynRM, and FASR machines. The reviewed techniques include rotor flux barrier number and geometry optimization, barrier shape refinement, rib and bridge design, permanent magnet placement and shaping, ferrite magnet arrangement, rotor skewing and step skewing, stator slot/pole and winding configuration optimization and control based harmonic current injection. The review highlights the relative effectiveness, practical constraints and performance trade offs of these methods with respect to average torque, efficiency, power factor, demagnetization risk, manufacturability and mechanical integrity. By consolidating the available literature, this paper aims to provide a structured understanding of torque ripple reduction strategies and to identify suitable design and control approaches for achieving smoother torque production in SynRM, PMA-SynRM, and FASR motor drives.

Keywords: Ferrite Assisted Synchronous Reluctance (FASR), Finite Element Analysis (FEA), Permanent Magnet assisted Synchronous Reluctance (PMA-SynRM), Rotor step skew, Slot/pole selection, Synchronous Reluctance Motor (SynRM), Torque ripple.

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1. Introduction

Synchronous motors (SM) are widely used in electric drives because their rotor runs at the same speed as the rotating magnetic field produced by the stator. Among SMs, the

Permanent Magnet Synchronous Motor (PMSM) has become one of the most preferred choices because the rotor magnets provide excitation without rotor copper loss. As a result, PMSMs offer high torque density, high efficiency and good performance over a wide speed range. However,

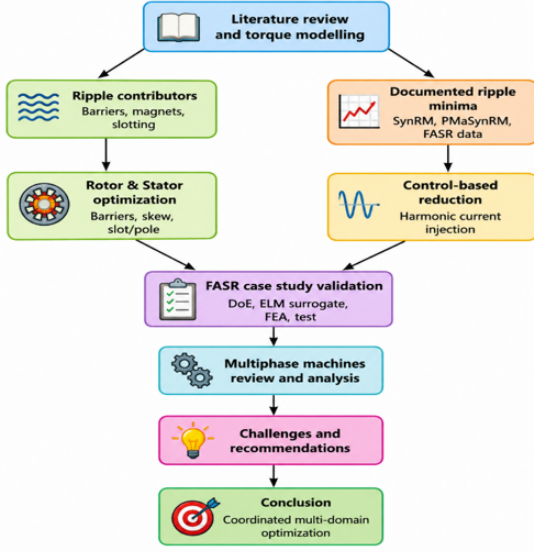


Fig. 1. Graphical Abstract

these advantages are strongly dependent on rare earth permanent magnets such as NdFeB. The use of these magnets increases cost and creates concerns related to supply chain uncertainty, price variation, sustainability and thermal demagnetization.

These limitations have driven the development of magnet-free synchronous machines, particularly the Synchronous Reluctance Motor [1] (SynRM). SynRM produces torque through reluctance, using rotor flux barriers to create a difference between direct- and quadrature-axis inductances. This eliminates magnets and rare-earth materials, offering a simple, robust, lowcost, and magnet-free solution. However, SynRMs generally have lower power factor and torque density than PMSMs and are sensitive to flux-barrier design, saturation, slotting, and mechanical ribs, which can increase torque ripple, vibration, and acoustic noise. To bridge the performance gap between PMSMs and pure SynRMs, PM-assisted SynRMs (PMa-SynRMs) use a small amount of permanent magnet material within the rotor flux barriers, improving torque density and power factor while retaining reluctance torque. Ferrite-Assisted SynRMs (FASRs) use low-cost ferrite magnets, reducing rare-earth dependence while enhancing airgap flux and torque. However, ferrite magnets require careful design of their placement, thickness, and demagnetization limits [2]. Despite their advantages, SynRM, PMa-SynRM, and FASR machines can exhibit significant torque ripple, leading to vibration, acoustic noise, and reduced drive quality. Therefore, this paper reviews torque-ripple reduction techniques, including flux-barrier optimization, magnet placement, rotor skewing, slot/pole selection, winding de-

sign, and harmonic-current compensation, while considering torque, efficiency, power factor, manufacturability, and mechanical reliability [3–7]. Section 2 presents the materials and methods used for the review while section 3 presents Torque Ripple reduction mechanisms in SynRM and PMa-SynRM along with section 4 presenting the summary. Section 5 discusses a case study on torque ripple reduction in an FASR prototype and Section 6 describes the challenges and recommendations and section 7 concludes the paper.

2. Materials and methods

2.1. Review scope and classification

This review examines torque-ripple minimization in three-phase SynRM, PMa-SynRM, and FASR machines, with FASR considered a ferrite-magnet subclass of PMa-SynRM. The studies are grouped by torque mechanism: field excitation, reluctance torque, and hybrid magnet-reluctance torque. Comparisons consider machine topology, slot/pole combination, flux-barrier design, magnet material and placement, rotor skewing, current-control methods, torque-ripple definition, and validation through FEA or experiments.

2.2. Electromagnetic Torque Expression

The electromagnetic torque of a synchronous reluctance motor can be expressed in the rotating dq reference frame as:

$$T_e = \frac{3}{2}(p * (L_d - L_q) * i_d * i_q) \quad (1)$$

where p is the number of pole pairs, L_d and L_q are the direct-axis and quadrature-axis inductances respectively. Since a pure SynRM has no permanent magnet flux linkage, torque is produced by the rotor saliency only.

For PMSM, IPMSM, PMa-SynRM and FASR machines, the corresponding torque expression is

$$T_e = \frac{3}{2}[p * (L_d - L_q)i_d * i_q + \lambda_{pm} * i_q] \quad (2)$$

where λ_{pm} denotes the flux linkage produced by the permanent magnets. The second term, $\lambda_{pm}i_q$, is the magnet torque. The first term, $(L_d - L_q)i_d i_q$, is the reluctance torque. For surface mounted PMSM, $L_d \approx L_q$ and the reluctance component is small, for IPMSM, PMa-SynRM and FASR, the rotor barriers and embedded magnets create saliency, so both components can contribute to torque. Saliency produces reluctance torque because the rotor has two different magnetic reluctances. The stator field therefore stores more magnetic energy when it is aligned with the high inductance d-axis than when it is aligned with the

low inductance q-axis. When both i_d and i_q are present, the machine develops a torque that tends to pull the rotor toward the minimum reluctance, maximum inductance position.

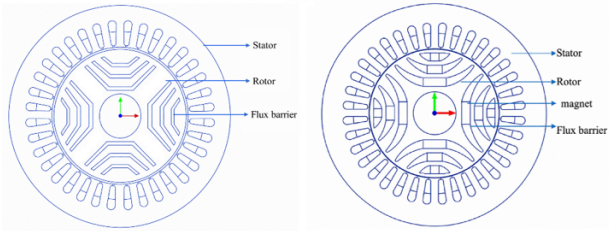


Fig. 2. Schematic of Syn RM and PmaSynRM

3. Torque ripple reduction mechanisms in SynRM and PMA-SynRM

Although SynRMs have low rotor losses and simple rotor construction, torque ripple remains a major challenge due to slotting, inverter harmonics, magnetic saturation, and MMF distortion. In multiphase SynRMs, the higher phase number improves stator MMF distribution and suppresses lower-order harmonics, resulting in smoother torque and reduced pulsations. Multiphase topologies [8] also provide additional harmonic subspaces for selective harmonic compensation, improving performance under normal and fault conditions. Torque ripple mainly arises from slotting effects, saturation, winding distribution, and inverter-induced current harmonics [9]. Flux barrier geometry and ribs: The shape, number, position of rotor flux barriers and the thickness and layout of mechanical ribs, affect the harmonic content of the air-gap flux density [3], [4].

1. Magnet Placement (PMA-SynRM/FASR): Magnet location and arrangement influence harmonic content and combined reluctance-magnet torque ripple [5].
2. Slotting and Permeance Harmonics: Stator slotting and rotor anisotropy generate airgap harmonics, causing torque pulsations [6].
3. Current Waveform Distortion: Inverter and control-induced current harmonics can interact with rotor anisotropy and slotting, increasing torque ripple [7].
4. Multiphase Current Utilization: Multiphase windings distribute torque production and provide greater harmonic cancellation, resulting in smoother torque [8].

FASR motors use ferrite magnets with lower remanence and higher coercivity than NdFeB, leading to lower air gap flux and different demagnetization margins, but the

underlying torque ripple mechanisms are analogous to those of PMA-SynRM. In all cases, torque ripple must be evaluated in conjunction with average torque, efficiency, thermal limits, and mechanical stress constraints [2].

3.1. Rotor Flux-Barrier Number and Geometry

One of the most influential design parameters in SynRM type machines is the number and shape of rotor flux barriers per pole. Increasing the number of barriers can improve the saliency ratio and average torque, but also complicates mechanical integrity and may introduce additional harmonics if not carefully designed. Fig. 3 shows the rotor flux barrier shapes that is commonly found in Syn RM and permanent magnet assisted SynRM motors.

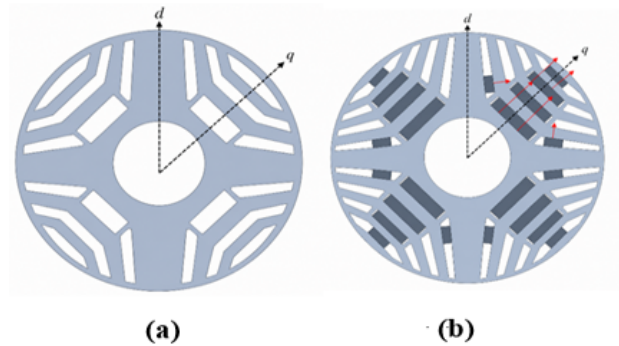


Fig. 3. Rotor Flux Barrier Layout: (a) Pure SynRM [10-figure 2(a)], (b) PMA-SynRM [10-figure 2(b)]

3.1.1. Number of Flux Barriers

Parametric studies suggest that 3-4 flux barriers per pole provide a good balance between torque, efficiency, saliency, and torque ripple in industrial-scale SynRMs. Fewer barriers reduce saliency and worsen flux guidance, increasing ripple, while excessive barriers can weaken ribs, increase saturation, and generate higher air-gap harmonics. Studies show that increasing the number from 1-2 to 3-4 barriers significantly reduces torque ripple and improves average torque, whereas further increases offer limited benefits due to leakage flux and rib saturation [3].

3.1.2. Barrier Shape: Rectangular, Circular, and Topology-Optimized

Comparative studies show that curved, circular, and topology-optimized flux barriers can significantly reduce torque ripple by suppressing harmonic interactions and improving flux distribution compared with conventional rectangular barriers. Optimized barrier curvature and end angles further enhance electromagnetic and vibro-acoustic performance. Their optimized rotor structures showed

massive torque ripple reductions compared with conventional rectangular barrier designs. Fig. 4 demonstrates how the increase in curvature of the rotor barriers from V_1 to V_3 leads to lower torque ripple while improving the average torque produced [4].

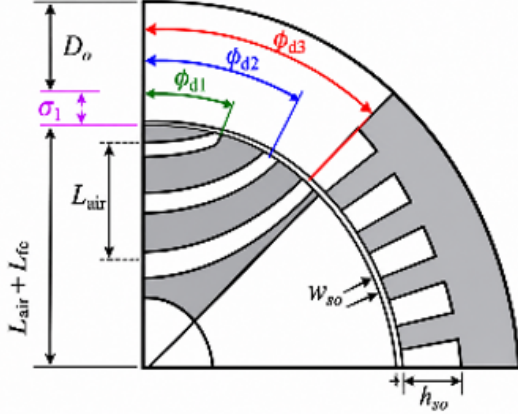


Fig. 4. Rotor Barrier Shape parameters for Optimization [4 - figure 3]

3.1.3. Mechanical Ribs and Structural Constraints

Tangential and radial ribs that ensure rotor mechanical integrity introduce leakage paths that affect L_d and L_q and thus torque ripple. Co-design approaches treat rib thickness as optimization variables under stress constraints, targeting safe operation at the rated and maximum speeds while minimizing their impact on torque pulsations [4]. For highspeed SynRM and PMA-SynRM, this mechanical-electromagnetic trade-off is critical for realizing low ripple at rated torque without exceeding material stress limits.

3.2. Permanent Magnet Placement and Shaping (PMA-SynRM, FASR)

In PMA-SynRM and FASR machines, magnet placement within the flux barriers adds design degrees of freedom for shaping the air-gap flux density, which can either aggravate or mitigate torque ripple [5].

3.2.1. Layer Specific Placement and Hybrid Magnet Use

Several studies demonstrate that placing magnets selectively in specific barrier layers can reduce torque ripple while preserving average torque. For example, using higher performance magnets in outer layers and ferrite in inner layers improves demagnetization margin and air-gap flux shaping, enabling hybrid designs with small rare-earth content but competitive torque ripple. Multi-objective optimizations often identify solutions with rare-earth magnet volume reduced to a few percent of total magnet volume,

yet with ripple levels comparable to all rare earth PMA-SynRM. Fig. 5 represents the various combinations of magnet placement in the rotor barriers so that the air gap flux distribution can be optimized for lower torque ripple production.

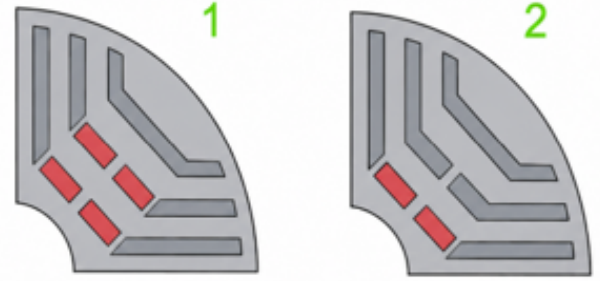


Fig. 5. Permanent Magnet Placing In Rotor Flux Barriers [11 - figure 5]

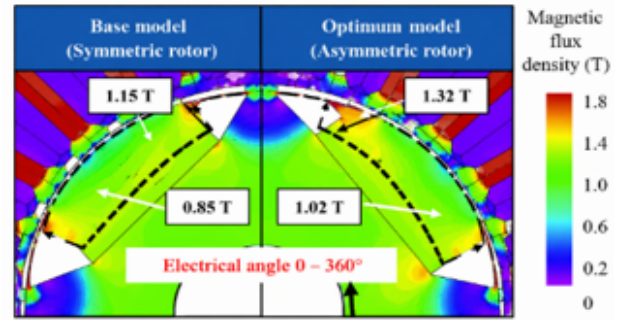


Fig. 6. Asymmetric Magnet Placement In Rotor Flux Barriers [12 - figure 5(a)]

3.2.2. Asymmetric Placement and Magnetic Field Shifting

Asymmetric magnet placement [10] and barrier shaping can shift the magnet and reluctance torque axes, improving torque alignment while increasing average torque and reducing torque ripple. However, careful optimization is required to avoid introducing low-order harmonics. FEA-based sensitivity analysis has shown that asymmetric magnet placement can increase magnet flux density from 1 T to 1.7 T while reducing torque ripple.

3.2.3. Magnet Shape and Thickness

Rectangular magnet blocks are often replaced with arc-shaped, V-shaped, or spoke-like segments which are better aligned with the barrier curvature of the rotor. These shapes support a more uniform flux distribution and reduce local flux saturation thus lowering torque pulsations caused by. Magnet thickness strongly impacts demagnetization robustness, especially for ferrite magnets in FASR,

and thus constrains geometric optimization aimed at ripple reduction [2].

3.2.4. Rotor Skewing and Step Skew Designs

Rotor skewing reduces cogging torque and torque ripple by averaging spatial harmonics along the rotor axis. Step skewing is a practical alternative to continuous skew, with three or more segments often providing effective harmonic cancellation while limiting torque loss. Optimized skew angle and flux-barrier positioning can further suppress dominant torque harmonics while maintaining acceptable average torque [2], [11].

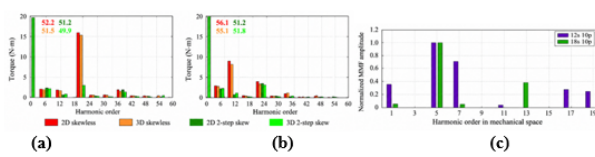


Fig. 7. (a) Torque harmonic comparison for different pole and barrier combinations under skew optimization 13-figure 6(b) MMF spectrum comparison between conventional 12-slot/10-pole and proposed 18-slot/10-pole windings 3.3 Stator Slotting and Winding Configuration

The stator slot/pole combination and winding layout strongly influence MMF harmonics and torque ripple. Proper slot/pole selection can reduce low-order harmonics and torque pulsations without significantly affecting efficiency. Distributed windings generally provide smoother MMF and lower torque ripple, while concentrated windings offer simpler construction and shorter end windings but produce higher space harmonics. Therefore, concentrated-winding SynRM and PMa-SynRM designs require optimized rotor geometry or advanced control to achieve low torque ripple [6].

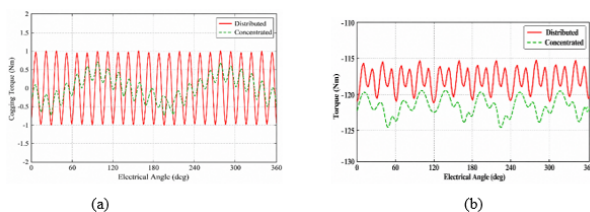


Fig. 8. (a) Cogging torque comparison between distributed and concentrated windings[14-figure 5] (b) Torque waveform comparison between distributed and concentrated windings [14-figure 6]

3.3. Control Based Torque Ripple Reduction

Rotor and stator design measures can be simultaneously implemented alongside current control strategies which are aimed at shaping the stator current waveform so that the inherent torque harmonics of the rotor can be counteracted smoothly [7].

3.3.1. Harmonic Current Injection

Harmonic current injection only superimposes the selected sinusoidal components (usually the 3rd, 5th and 7th harmonics) on the fundamental current reference in order to cancel specific torque orders. Recent data driven harmonic current optimization simultaneously minimizes torque ripple and injection losses by determining optimal injected harmonic currents through multi-objective optimization rather than empirical tuning. This approach requires very careful tuning to prevent excessive copper losses while maintaining thermal limits as a result of current from the stator windings. Fig. 9a in this paper illustrates a representative setup of harmonic current injection and Fig. 9b showcases the corresponding torque-waveform improvement [9].

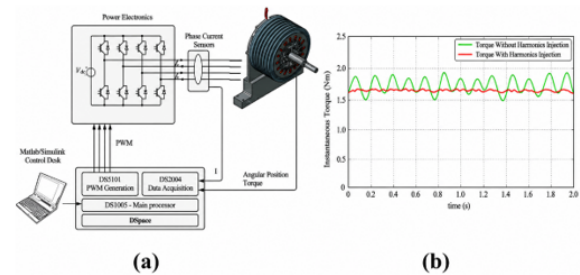


Fig. 9. (a) Harmonic current injection setup using PWM based power electronic control 9 -figure 11 Instantaneous torque comparison with and without harmonic current injection[30-figure 15]

3.4. Multiphase SynRM and PMa-SynRM

Extending from three to five and six phases enables inherent cancellation of certain torque-producing harmonics. Five-phase and six-phase SynRMs reduce dominant torque harmonics through harmonic cancellation and optimized flux-barrier-end design, with experimental validation demonstrating improved torque smoothness compared with conventional three-phase machines. Five-phase SynRM and PMa-SynRM prototypes generally exhibit lower ripple than their three phase counterparts, though published minimum values are slightly higher than those of the best optimized three phase designs [8].

4. Summary and discussion

The discussion shows that torque-ripple reduction in SynRM, PMa-SynRM, and FASR machines requires a combined electromagnetic design approach. Rotor flux barriers and magnet placement influence saliency and air-gap flux, while slot/pole selection, winding design, and current shaping control MMF and torque harmonics. Multiphase windings further support harmonic cancellation. Thus, practical low-ripple designs generally combine multiple techniques while balancing torque density, efficiency, power factor, mechanical integrity, cost, and control complexity.

5. Case study examination

5.1. Case Study of Torque Ripple Reduction Using FASR Motor

This case study [2] presents a 3-phase, 4-pole, 36-slot FASR motor for an electric trike, targeting 1.2 kW and 8 Nm. The motor uses a 159 mm stator diameter, 0.52 mm air gap, 40% slot fill, Y30 ferrite magnets, and M1000-65A steel. 3D FEA comparisons showed that the FASR achieved 8 Nm with a 64 mm stack and a torque ripple of 8.75%, lower than SynRM (9.31%) and the spoke ferrite motor (28.48%), making it a suitable traction option.

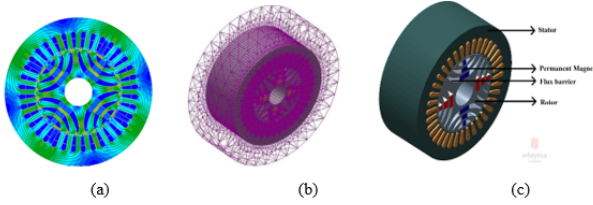


Fig. 10. (a) Flux Density Map of FASR Prototype Under Rated Load Conditions (b) 3D meshed Finite Element Model of FASR Motor (c) 3D Model of FASR Motor

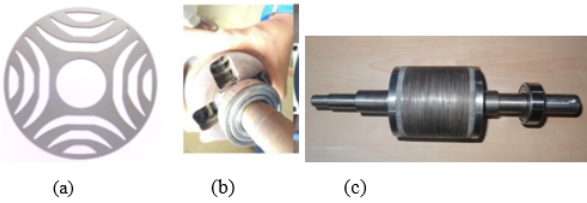


Fig. 11. (a) Rotor Flux Barrier Lamination (b) Rotor Flux Barrier Prototype with Ferrite Magnets (c) Top View of Rotor of FASR Motor

A 27-run Definitive Screening Design (DSD) identified θ_1 , θ_3 , δ_1 , δ_2 , and δ_3 as the most sensitive parameters. An ELM surrogate model reduced evaluation time from 15

minutes to about 500 ms, enabling efficient rotor optimization and prototype fabrication. At 1.2 kW, 8Nm, and 2.9 A RMS, the optimized FASR achieved 8.46% simulated and 9.79% experimental torque-ripple reduction, with average torque of 8.1 Nm in FEA and 7.85 Nm experimentally.

6. Challenges and recommendations

The main challenge in SynRM and PM-assisted SynRM is reducing torque ripple without sacrificing torque, efficiency, power factor, or mechanical strength. Techniques such as fluxbarrier optimization, rotor skewing, and magnet shaping can reduce ripple but may affect overall performance and rotor reliability. FASR motors reduce rare-earth dependence but require careful magnet placement and thickness due to lower ferrite flux density. Since torque ripple results from geometric harmonics, saturation, inverter effects, and current distortion, a single optimization method is insufficient.

A coordinated electromagnetic-mechanical-control co-design is therefore recommended, combining optimized 3-4 flux barriers per pole, magnet placement, skewing, slot/pole selection, and harmonic current injection. The final design should be validated through both FEA simulation and experimental testing to achieve low torque ripple with high performance and mechanical reliability.

7. Conclusion

This paper reviewed torque-ripple reduction techniques for three-phase SynRM, PMa-SynRM, and FASR machines. The results show that torque ripple depends on rotor geometry, magnet placement, stator slotting, winding design, and control strategy, requiring a coordinated optimization approach. Effective techniques include flux-barrier and shape optimization, selective magnet placement, rotor skewing, slot/pole optimization, and harmonic current injection. In particular, 3-4 flux barriers per pole, topology-optimized barriers, and multi-step skewing provide a good balance between torque ripple, torque density, and efficiency. The FASR case study also demonstrates the effectiveness of combining DoE, surrogate-based optimization, and FEA, supported by experimental validation. Future research should focus on multi-objective optimization, AI-assisted design, advanced harmonic compensation, and realcondition experimental validation for EVs and high-performance electric drives.

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tankulathur, Tamilnadu India.

References

- [1] N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, and E. Fornasiero, (2016) "Electric Vehicle Traction Based on Synchronous Reluctance Motors" **IEEE Transactions on Industry Applications** 52(6): 4762–4769. DOI: [10.1109/TIA.2016.2599850](https://doi.org/10.1109/TIA.2016.2599850).
- [2] V. S. Nagarajan. "Design Optimization and Analysis of Ferrite Assisted Synchronous Reluctance Motor". Meta-data retained from the manuscript; exact repository record/title could not be independently retrieved during verification. (PhD dissertation). Anna University, 2018.
- [3] N. Bianchi, S. Bolognani, D. Bon, and M. Dai Pré, (2009) "Rotor Flux-Barrier Design for Torque Ripple Reduction in Synchronous Reluctance and PM-Assisted Synchronous Reluctance Motors" **IEEE Transactions on Industry Applications** 45(3): 921–928. DOI: [10.1109/TIA.2009.2018960](https://doi.org/10.1109/TIA.2009.2018960).
- [4] N. Bianchi, M. Degano, and E. Fornasiero, (2015) "Sensitivity Analysis of Torque Ripple Reduction of Synchronous Reluctance and Interior PM Motors" **IEEE Transactions on Industry Applications** 51(1): 187–195. DOI: [10.1109/TIA.2014.2327143](https://doi.org/10.1109/TIA.2014.2327143).
- [5] H. Cai, B. Guan, and L. Xu, (2014) "Low-Cost Ferrite PM-Assisted Synchronous Reluctance Machine for Electric Vehicles" **IEEE Transactions on Industrial Electronics** 61(10): 5741–5748. DOI: [10.1109/TIE.2014.2304702](https://doi.org/10.1109/TIE.2014.2304702).
- [6] S. M. Taghavi Araghi, A. Kiyoumars, and B. Mirzaeian Dehkordi, (2023) "Synchronous Reluctance Machines with New Type of Fractional-Slot Concentrated-Windings Based on the Concept of Stator Slot Shifting" **IET Electric Power Applications** 17(1): 92–108. DOI: [10.1049/elp2.12248](https://doi.org/10.1049/elp2.12248).
- [7] L. Yan, Y. Liao, H. Lin, and J. Sun, (2019) "Torque Ripple Suppression of Permanent Magnet Synchronous Machines by Minimal Harmonic Current Injection" **IET Power Electronics** 12(6): 1368–1375. DOI: [10.1049/iet-pel.2018.5647](https://doi.org/10.1049/iet-pel.2018.5647).
- [8] C. Jedryczka, M. Mysinski, and W. Szelag, (2024) "Development and Analysis of Six-Phase Synchronous Reluctance Motor for Increased Fault Tolerance Capabilities" **Energies** 17(10): 2351. DOI: [10.3390/en17102351](https://doi.org/10.3390/en17102351).
- [9] S. Yammine, C. Hénaux, M. Fadel, and F. Messine, (2018) "Torque Ripple Reduction in a SynRM at a Constant Average Torque by Means of Current Harmonics Injection" **Progress In Electromagnetics Research C** 80: 167–180. DOI: [10.2528/PIERC17101801](https://doi.org/10.2528/PIERC17101801).
- [10] J.-C. Park, J.-H. Kim, S.-H. Park, K.-O. Kim, M.-H. Sung, and M.-S. Lim, (2023) "Design Optimization Using Asymmetric Rotor in IPMSM for Torque Ripple Reduction Considering Forward and Reverse Directions" **IEEE Transactions on Magnetics** 59(11): 8205805. DOI: [10.1109/TMAG.2023.3292295](https://doi.org/10.1109/TMAG.2023.3292295).
- [11] C. Gallardo, C. Madariaga, J. A. Tapia, and M. Degano, (2023) "A Method to Determine the Torque Ripple Harmonic Reduction in Skewed Synchronous Reluctance Machines" **Applied Sciences** 13(5): 2949. DOI: [10.3390/app13052949](https://doi.org/10.3390/app13052949).