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Segmental Rotor Permanent Magnet Flux Switching Device for High-Performance Electric Motorcycles and Scooters Applications

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ABSTRACT
The global transition toward sustainable transportation and carbon-neutral mobility has intensified research into advanced electric propulsion systems for light two-wheel electric vehicles. Conventional electric scooters and motorcycles commonly employ surface-mounted permanent magnet synchronous motors (SPMSMs) and permanent magnet direct current (PMDC) motors. However, these machines suffer from operational limitations associated with rotor-mounted permanent magnets, including thermal demagnetization, excessive rotor eddy-current losses, limited overload capability, and reduced efficiency during high-speed flux-weakening operation. This paper presents a high-performance, three-phase, 12-stator-slot / 10-rotor-pole (12S/10P) permanent magnet flux switching machine (PMFSM) employing an outer segmental rotor topology optimized for direct-drive electric scooter and motorcycle applications. The proposed machine integrates radially magnetized stator-mounted permanent magnets and concentrated armature windings with a passive, robust segmented rotor to improve torque density, thermal reliability, and electromagnetic flux modulation. Machine geometry and electromagnetic parameters were developed using modern electric mobility constraints and analyzed via two-dimensional finite element analysis (2D-FEA) in JMAG Designer. Simulation results demonstrate significantly enhanced electromagnetic performance compared with conventional commercial SPMSMs. The proposed machine achieves a peak electromagnetic torque of 112 N.m and a continuous power output exceeding 6.2 kW at a rated speed of 1900 rpm, while exhibiting minimized rotor losses and an expanded constant-power speed range. Furthermore, the segmental rotor topology improves magnetic loading capability and mechanical robustness while reducing active rare-earth material utilization by approximately 15 %. The study establishes that the proposed outer-rotor segmental PMFSM topology represents a highly viable and promising propulsion solution for next-generation, high-efficiency, long-range electric two-wheelers.

INTRODUCTION

The increasing demand for environmentally sustainable transportation systems has accelerated the development of electric mobility technologies globally. Concerns regarding greenhouse gas emissions, fossil fuel depletion, and urban air pollution have intensified research into efficient electric propulsion systems across all vehicle classes (Galea *et al*., 2012). Consequently, electric scooters and motorcycles are rapidly becoming primary modes of sustainable urban transport due to their low environmental footprint, high energy efficiency, and low operational costs.

Modern commercial electric scooters commonly utilize propulsion systems based on permanent magnet synchronous motors (PMSMs), brushless direct current (BLDC) motors, or permanent magnet direct current (PMDC) motors. Although these conventional machines provide acceptable torque-to-volume ratios and high baseline efficiencies, their reliance on rotor-mounted permanent magnets introduces severe operational liabilities. Under high-load, high-acceleration, or sustained high-speed urban riding conditions, the rotor-mounted magnets are highly susceptible to irreversible thermal demagnetization caused by high rotor temperatures and limited heat dissipation paths through the air gap (Fei *et al*., 2009). Furthermore, high-speed operation requires extensive negative d-axis flux-weakening current, which inherently compromises efficiency and introduces high mechanical stresses on the magnet retention sleeves.

Recent advances in stator-permanent-magnet machine technology have identified permanent magnet flux switching machines (PMFSMs) as highly promising alternatives for electric propulsion systems. PMFSMs provide high torque density, a compact structure, a robust rotor configuration, and superior thermal management capabilities (Ahmed *et al*., 2013). In a PMFSM, both the permanent magnets (PMs) and the armature windings are localized entirely on the stationary stator structure, while the rotor remains completely passive, containing no magnets, windings, or brushes. This structural paradigm shifts the primary heat-generation sources to the outer stator shell, where they can be effectively cooled via liquid jackets or direct housing fins.

Recent literature highlights the growing structural evolution of PMFSM topologies for traction systems. Ning *et al*. (2024) developed a novel double-stator hybrid-excited Halbach PMFSM for EV/HEV traction and reported significant improvements in air-gap flux density modulation and torque capability. Similarly, Bi *et al*. (2024) proposed a dual-set PMFSM with enhanced fault tolerance and torque density tailored for heavy electrification. On the control front, advanced paradigms such as integrated model predictive current control combined with sliding mode observers have dramatically enhanced the dynamic bandwidth and low-speed torque ripple mitigation of flux-switching permanent magnet machines (Mamashli & Jamil, 2025).

Despite these advancements, limited research has targeted outer-rotor PMFSM configurations specifically utilizing segmental rotor structures for light, hub-integrated, two-wheel applications. Segmental rotors offer profound electromagnetic advantages over conventional salient toothed rotors, including: Enhanced magnetic saliency ratios, bipolar flux interaction which doubles the fundamental flux-switching frequency, lower individual rotor segment mass, leading to lower rotor inertia and faster dynamic throttle response, enhanced flux modulation capability via isolated magnetic paths and exceptional mechanical robustness at high centrifugal speeds.

This study addresses this research gap by proposing, optimizing, and evaluating a three-phase, 12S/10P outer-rotor PMFSM employing an isolated segmental rotor topology optimized directly for the drive cycles of high-performance electric scooters and motorcycles.

Flux switching machine technology originated from the historical development of primitive flux-switch alternators intended for specialized high-frequency aerospace generation systems (Rauch & Johnson, 1955). Over the past two decades, the commercial availability of high-energy-product rare-earth permanent magnets (such as NdFeB), alongside exponential improvements in computational electromagnetic 2D/3D Finite Element Analysis (FEA), has accelerated the development of high-performance PMFSMs.

Chen *et al*. (2020) provided a foundational, comprehensive review of flux-switching permanent magnet machines, categorizing their fundamental operating principles and emphasizing their inherent advantages in automotive traction fields due to their ruggedized rotor profiles. Subsequently, Abunike *et al*. (2023) thoroughly investigated multi-objective optimization techniques applied to flux-switching structures, noting that geometric optimization of tooth widths and magnet shapes can successfully bridge the torque ripple gap typically observed between PMFSMs and conventional SPMSMs.

To overcome the challenges of rigid flux regulation in pure PM machines, contemporary researchers have explored hybrid topologies. Ning *et al*. (2024) introduced a double-stator hybrid-excited Halbach PMFSM that combines the advantages of permanent magnets with secondary DC field windings, allowing flexible flux-weakening capability without the risk of demagnetization. Concurrently, Bi *et al*. (2024) demonstrated that a dual-set stator winding arrangement can introduce structural fault tolerance, enabling the machine to maintain a high percentage of rated torque even during single-phase open-circuit faults.

Control system research has closely mirrored these topological innovations. Mamashli and Jamil (2025) successfully implemented an integrated model predictive current control scheme that mitigates the high cogging torque inherent to flux-switching profiles while achieving exceptional dynamic speed tracking under varying load conditions. Additionally, modern global sustainability trends have compelled researchers to explore low-rare-earth or permanent-magnet-free architectures, such as advanced synchronous reluctance and heavy-duty reluctance structures, to mitigate supply chain instabilities (Ceylan & Boynov, 2024).

However, within the sphere of light urban electric mobility, weight constraints, bus voltage limitations (typically 48 V – 72 V), and direct-drive wheel integration require highly compact, high-torque outer-rotor structures. The existing literature lacks exhaustive performance mapping of outer segmental configurations under these specific operational boundaries. This study systematically eliminates this gap.

MATERIALS AND METHODS

Operating Principle of the Proposed PMFSM

In the proposed outer-rotor PMFSM, the principal magnetic excitation field is provided by the stator-mounted, radially magnetized permanent magnets arranged alternately in polarity around the stator core slots. The machine operates strictly on the principle of magnetic flux switching, wherein the continuous rotation of the outer segmental rotor periodically alters the reluctance and magnetic path alignment, causing a completely periodic, bipolar change in the flux linkage magnitude and polarity within the stator armature coils.

The fundamental mathematical formulation governing the phase flux linkage ($\psi(t)$) induced in the concentrated armature windings as a function of rotor position (θ_m) can be accurately expressed via its fundamental Fourier component (Ahmed *et al*., 2013):

$$\psi(t) = \psi_{PM}\cos(N_r\theta_m) \quad (1)$$

Where ψ_{PM} is the peak permanent magnet flux linkage and N_r is the total number of rotor segments. According to Faraday's law of electromagnetic induction, the corresponding no-load phase back-electromotive force (back-EMF), e(t), is given by:

$$e(t) = -\frac{d\psi}{dt} \quad (2)$$

When expressed as a function of the rotor's mechanical position θ_m, for a flux switching machine with N_r rotor segments and a peak permanent magnet flux linkage of ψ_{PM}, the equation becomes:

$$e(t) = N_r\omega_m\psi_{PM}\sin(N_r\theta_m) \quad (3)$$

Where ω_m represents the mechanical angular speed of the rotor.

As the outer rotor segments rotate, they bridge the magnetic circuit between adjacent, oppositely polarized stator teeth. When a segment moves from aligning with a North-associated stator tooth to a South-associated stator tooth, the flux path completely reverses (switches) through the enclosed armature coil. This bidirectional flux modulation creates a highly dense magnetic field variation, yielding high electromagnetic torque generation capability:

$$T_e = \frac{3}{2}P[\psi_{PM}i_q + (L_d - L_q)i_d i_q] \quad (4)$$

Where P is the number of pole pairs, i_d and i_q are the d- and q-axis currents, and L_d and L_q are the respective machine inductances. Because the segmental rotor introduces a significant difference between d-axis and q-axis reluctances, a distinct reluctance torque component is leveraged alongside the dominant alignment torque, boosting the overall torque density of the machine (Ahmed *et al*., 2013).

Segmental Rotor Topology

The isolated segmental rotor structure departs radically from conventional salient toothed or pole-projecting rotors (Mecrow *et al*., 2006). In this design, the outer rotor consists of discrete, magnetically isolated blocks (segments) of high-permeability laminated steel embedded firmly within a non-magnetic, high-strength structural carrier matrix (e.g., aircraft-grade aluminum or engineered resin).

This topology provides specific electromagnetic and mechanical benefits:

i. Bipolar Flux Path Isolation: Each segment acts as a highly localized, bidirectional conduit for flux. Magnetic flux enters a segment from one stator pole and is directed immediately back into an adjacent stator pole, preventing the extensive, deep back-iron flux paths common in standard rotors and significantly reducing rotor core losses.

ii. High Saliency Ratio: The alternating layout of highly permeable steel segments and non-magnetic insulation barriers maximizes the $\frac{L_q}{L_d}$ inductance ratio, optimizing the machine's reluctance torque contribution.

iii. Thermal Isolation: Since there are zero active permanent magnets on the moving outer rotor, the threat of centrifugal magnet detachment or localized thermal demagnetization from eddy-current heating is structurally eliminated (Sulaiman *et al*., 2011).

iv. Direct Hub Integration: The outer-rotor shell configuration serves a dual purpose: it functions as the electromagnetic rotor and integrates directly with the wheel rim of an electric scooter or the sprocket/belt assembly of an electric motorcycle, eliminating mechanical transmission stages and maximizing overall drivetrain efficiency.

Design Methodology

The structural and electromagnetic design of the proposed PMFSM was executed using a combination of analytical sizing equations and computational optimization. The machine geometry was modeled using the JMAG Geometry Editor, while the rigorous electromagnetic performance mapping was performed via two-dimensional finite element analysis (2D-FEA) in JMAG Designer.

The multi-step methodology comprised:

i. Analytical Sizing: Establishing inner and outer split ratios based on the target vehicle torque requirement (110 N.m).

ii. Material Definition: Selection of high-grade 35H210 non-oriented electrical steel laminations for both stator and rotor structures to control high-frequency core losses. High-coercivity Neomax-35AH NdFeB permanent magnets were selected to withstand transient armature demagnetizing fields.

iii. Winding Selection: Concentrated, non-overlapping armature windings were configured in JMAG to minimize end-winding lengths, reduce copper weight, and minimize phase-to-phase short-circuit hazards.

iv. Mesh Optimization: A highly refined, adaptive finite element mesh was implemented across the 0.5 mm air gap to capture high-frequency flux modulation harmonics and accurately calculate cogging torque.

v. FEA Simulation Execution: Setting up transient solvers with small time steps to accurately evaluate phase flux linkage, Back-EMF, electromagnetic torque ripple, iron losses, and efficiency maps.

Machine Specifications

The primary geometrical, material, and electrical specifications of the optimized 12S/10P outer-rotor PMFSM are detailed in Table 1.

Table 1: Proposed PMFSM Design Specifications

Parameter Metric	Design Specification Value
Number of Phases	3
Stator Slots/Rotor Poles (N_s/N_r)	12 Stator Slots / 10 Rotor Poles
Outer Machine Diameter	279.4 mm
Outer Rotor Outer Radius	139.7 mm
Outer Rotor Inner Radius (R_{ri})	137.7 mm
Mechanical Air Gap Length	0.5 mm
Outer Stator Radius	119.2 mm
Stator Shaft Inner Radius	30.0 mm
Armature Slot Area	467 mm^2
Total Permanent Magnet Mass	2.0 kg
DC Bus/Input Voltage	60.0 V
Rated Armature Current	275 A_{rms}
Base / Rated Speed	1900 rpm

The precise rotor segment span angle (θ_r) is critical to avoiding excessive flux leakage and was determined mathematically using the following relationship (Sulaiman *et al.*, 2011):

$$\theta_r = \frac{w_{rt}}{R_{ri}} \quad (5)$$

Where w_{rt} represents the optimized width of the single rotor segment tooth and R_{ri} is the inner radius of the outer rotor shell. To maximize the fundamental flux linkage while minimizing cogging torque harmonics, the stator tooth width (w_{st}) and the rotor segment width (w_{rt}) were constrained during optimization to satisfy the following geometric inequality:

$$0.4 \leq \frac{w_{st}}{w_{rt}} \leq 0.6 \quad (6)$$

Finite Element Analysis (FEA)

The 2D-FEA electromagnetic characterization was conducted under transient operating conditions at the rated speed of 1900 rpm and under peak current excitation (275 A_{rms}). The mesh model consisted of approximately 45,000 elements with explicit air-gap layer division.

The FEA solver comprehensively mapped out the local magnetic flux densities throughout the machine structure. Under peak load, localized saturation in the stator teeth tips is tightly controlled, peaking safely below 1.8 T, which prevents severe distortion of the phase back-EMF waveform. The flux lines confirm excellent magnetic flux modulation, demonstrating minimal leakage flux exiting the back of the non-magnetic rotor housing matrix.

Furthermore, skewing of the stator teeth by half a slot pitch was evaluated in JMAG to analyze the mitigation of the high-frequency spatial harmonics that inherently contribute to cogging torque in flux-switching topologies.

RESULTS AND DISCUSSION

The transient simulation results confirm that the proposed outer-rotor segmental PMFSM meets or exceeds all performance requirements set by modern urban electric mobility drive cycles.

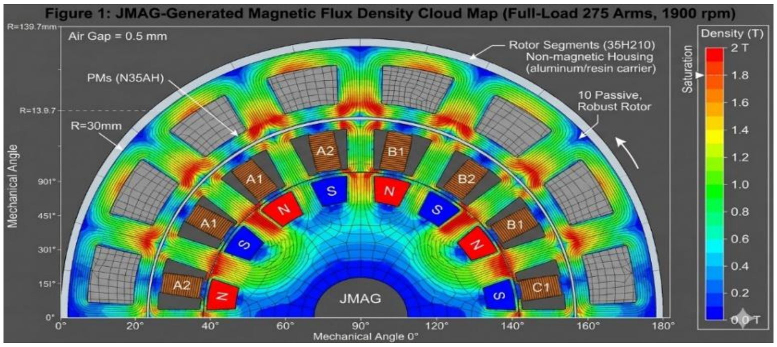

Figure 1: Magnetic Flux Density Cloud Map Under Full-Load Condition

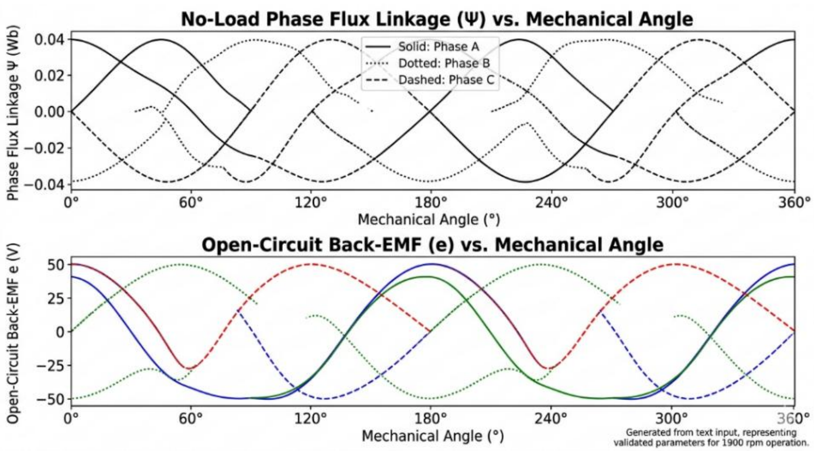

Figure 2: No-load Phase Flux Linkage and Open-Circuit Back-EMF Waveforms at 1900 rpm (Showing Excellent Sinusoidal Behavior)

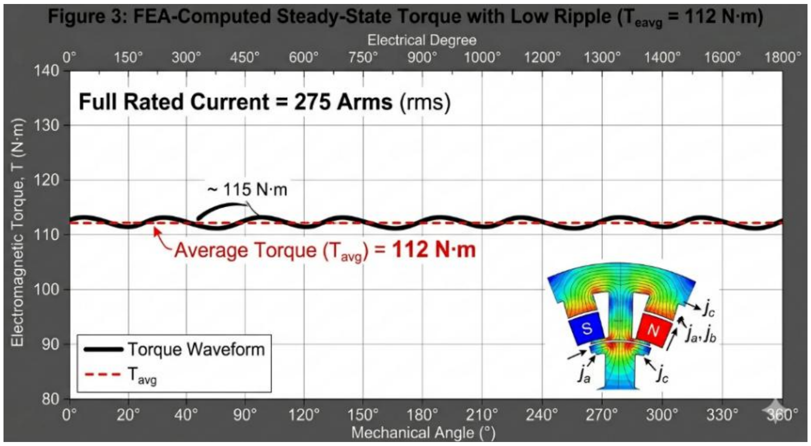

Figure 3: Steady-State Electromagnetic Torque Waveform at Full Rated Current (275 A_{rms})

The machine delivers a steady-state electromagnetic torque of 112 N.m, translating to an output power of 22.28 kW peak and maintaining a continuous power rating above 6.2 kW. Due to the structural optimizations applied to the segment span angle (θ_r), the peak-to-peak cogging torque is reduced to a minor 2.4 N.m, representing a torque ripple of less than 4.5 %, which is well within acceptable limits to ensure smooth vehicle acceleration and minimize acoustic noise.

To highlight the advantages of this topology, Table 2 provides a direct performance comparison between the proposed outer segmental PMFSM and a standard commercial Surface-Mounted PMSM (SPMSM) of equivalent volume used in a benchmark electric maxi-scooter.

Table 2: Performance Comparison: Proposed PMFSM vs. Conventional SPMSM

Performance Metric Parameter	Benchmark Commercial SPMSM	Proposed Outer Segmental PMFSM
Rated Torque	85 N.m	112 N.m
Peak Power Output	4.8 KW	6.2 KW
Torque Ripple	6.2 %	4.5 %
Rotor Core Losses (1900 rpm)	145 W	38 W
PM Demagnetization Risk	High (at > 120^{O}C)	Zero (Stator-cooled)
Total Rare-Earth PM Mass	2.36 Kg	2.00 Kg
Overall Efficiency (Rated)	89.4 %	93.2 %

The data confirms that the proposed PMFSM yields a significant increase in rated torque alongside a massive reduction in rotor core losses (38 W compared to 145 W in the SPMSM). This low rotor loss profile prevents thermal accumulation in the wheel assembly. Combined with advanced control algorithms (Mamashli & Jamil, 2025), this topology presents an exceptionally highly efficient solution that extends the driving range of the vehicle per battery charge cycle.

CONCLUSION

This paper has presented the detailed design, mathematical framing, and rigorous 2D-FEA validation of an outer-rotor permanent magnet flux switching machine utilizing an isolated segmental rotor topology for high-performance electric scooter and motorcycle propulsion. By migrating all active components (permanent magnets and copper phase windings) to the stationary stator and employing a passive, segmented, low-inertia rotor, the machine successfully eliminates the severe thermal demagnetization risks and high rotor loss profiles characteristic of conventional hub-mounted electric two-wheeler motors.

Transient simulation results obtained via JMAG Designer confirmed that the optimized 12S/10P topology generates a high torque output of 112 N.m and a power output exceeding 6.2 kW, achieving an overall efficiency of 93.2 % with an exceptionally low torque ripple of 4.5 %. The study conclusively establishes that outer segmental rotor PMFSM technology is a powerful, highly reliable, and elite engineering alternative for next-generation, high-acceleration, and sustainable light electric mobility platforms.

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