

Article

Manufacturing and Experimental Validation of an Outer-Rotor Permanent Magnet-Assisted Synchronous Reluctance Motor for In-Wheel Electric Vehicle Drive

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Abstract

This study presents the prototype manufacturing and experimental validation of a 1 kW, 750 rpm three-phase outer-rotor permanent magnet-assisted synchronous reluctance motor (PMASynRM) designed for in-wheel electric vehicle applications. The work is based on a previously reported electromagnetic design and finite element method (FEM)-based optimization framework and focuses on the physical implementation and experimental evaluation of the proposed motor. The prototype was manufactured using M470-50A grade electrical steel laminations and arc-shaped N35H NdFeB permanent magnets embedded within a three-barrier transversally laminated anisotropic rotor structure. A custom-built experimental test bench consisting of the PMASynRM prototype, a PMSM generator with a controllable resistive load bank, a torque transducer, and a precision power analyzer was developed to evaluate motor performance under controlled operating conditions. Experimental investigations were carried out under four steady-state load conditions—no-load, 13 Nm, 20 Nm, and 26 Nm—as well as during dynamic stepwise load transitions representative of in-wheel drive operation. The measured results show good agreement with FEM predictions, with a maximum efficiency of 90.55% at nominal load and efficiency values remaining above 87% under overload conditions up to 26 Nm. Minor differences between simulation and experimental results are mainly associated with mechanical friction, bearing losses, and manufacturing tolerances that are not fully captured in the numerical model. The study provides experimental validation of an outer-rotor PMASynRM prototype under multi-load steady-state and dynamic operating conditions for in-wheel electric vehicle applications.

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1. Introduction

The rapid depletion of fossil fuel resources and the growing global emphasis on environmental sustainability have significantly accelerated the transition toward electric and hybrid electric vehicles (EVs and HEVs), as reported by Cai et al. [1]. In parallel with

this transition, the development of efficient, compact, and reliable electric propulsion systems has become an important research focus in modern transportation technologies. Recent studies by Nardo et al. and Gallicchio et al. [2,3] highlight the growing demand for traction motors capable of providing high torque density at low speeds, wide constant-power operating range, low torque ripple, and high efficiency over a broad operating region. Since electric motors directly influence vehicle efficiency, driving capability, and overall system reliability, their design plays a central role in the development of modern EV propulsion systems.

Conventional permanent magnet synchronous motors (PMSMs) are widely adopted in electric vehicle applications due to their high torque density and efficiency, as demonstrated by Cai et al. and Morimoto et al. [1,4]. However, the strong dependence on rare-earth permanent magnets introduces significant economic and supply-chain concerns, as discussed by Katona and Orosz [5]. For this reason, permanent magnet-assisted synchronous reluctance motors (PMASynRMs) have attracted considerable attention as an alternative traction motor topology. By combining reluctance torque with reduced permanent magnet excitation embedded within the rotor flux barriers, PMASynRMs provide a favorable balance between performance, cost, and material efficiency while maintaining a relatively simple and mechanically robust rotor structure, as highlighted by Nardo et al. and Gallicchio et al. [2,3].

In recent years, many studies have focused on improving the electromagnetic performance of PMASynRMs through optimized rotor geometries, refined flux-barrier configurations, and advanced permanent magnet placement strategies. Contributions by Wang et al. [6], Mohanarajah et al. [7], Kim and You [8], Reyes et al. [9], Ghorbani et al. [10], Shao et al. [11], and Adăscăliței et al. [12] demonstrate that parametric design approaches and multi-objective optimization techniques can significantly improve torque density, reduce torque ripple, and enhance efficiency under practical design constraints such as magnetic saturation, manufacturability, and material cost. Despite these developments, most reported PMASynRM studies still rely primarily on simulation-based performance evaluation, while experimentally validated prototype studies remain relatively limited in the literature.

Parallel to these developments, outer-rotor motor topologies have attracted growing attention for direct-drive in-wheel electric vehicle applications. Studies by Islam et al. [13], Aghazadeh et al. [14], Inte et al. [15], Bozkurt et al. [16,17], Li et al. [18], and Sivasamy et al. [19] have shown that the outer-rotor configuration provides a larger effective torque arm than conventional inner-rotor designs, enabling high torque production at low rotational speeds without requiring mechanical transmission elements. This feature makes outer-rotor topologies particularly attractive for in-wheel drive systems, where compact packaging, high low-speed torque capability, and drivetrain simplicity are among the primary design considerations. Several recent studies have specifically investigated outer-rotor PMASynRM topologies for light electric vehicle and e-bike applications, including the works reported by Li et al. [18], Sivasamy et al. [19], Nasiri-Zarandi et al. [20], Nobahari et al. [21], and Yenipinar et al. [22]. Although these studies demonstrate the potential of outer-rotor PMASynRM configurations for traction applications, comprehensive experimental validation of manufactured prototypes under both steady-state and dynamic loading conditions remains relatively scarce in the literature.

In this context, the present study extends the authors' previously reported electromagnetic design and FEM-based optimization work [16,17] toward the physical realization and experimental evaluation of the proposed motor topology. Unlike earlier studies primarily focused on electromagnetic design and numerical analysis, this work places particular emphasis on prototype manufacturing, experimental implementation, and validation under both steady-state and dynamic operating conditions. The main

contributions of this study can be summarized as follows: (i) manufacturing of a three-phase outer-rotor PMASynRM incorporating a three-barrier rotor topology with arc-shaped embedded permanent magnets; (ii) development of a custom test bench enabling torque, power, and efficiency measurements under controlled load conditions; (iii) systematic steady-state performance evaluation at four different load levels; and (iv) dynamic load transition testing to investigate transient operating behavior. The experimental results are quantitatively compared with FEM predictions, providing practical insights into the feasibility and performance of outer-rotor PMASynRM-based in-wheel drive systems.

2. Operating Principle and Design Background of the PMASynRM

Synchronous reluctance motors (SynRMs) are characterized by an anisotropic rotor structure consisting of flux barriers and flux-carrying bridges. This anisotropy gives rise to a distinct difference between the direct-axis (d-axis) and quadrature-axis (q-axis) inductances, which plays a fundamental role in determining the electromagnetic torque production and efficiency of the machine. In conventional SynRM designs, the rotor geometry is optimized to maximize magnetic flux linkage along the d-axis while minimizing it along the q-axis, thereby increasing the saliency ratio and improving torque capability [2,3].

During the rotor design process, increasing the width of the flux-carrying bridges along the d-axis enhances the corresponding inductance L_d . However, this modification may simultaneously increase the q-axis inductance L_q , which can adversely affect the saliency ratio. Consequently, achieving a high L_d/L_q ratio requires a careful balance between electromagnetic performance and mechanical robustness, particularly in applications involving high centrifugal forces and limited geometric freedom, such as in-wheel electric vehicle drives [11,12].

To overcome the inherent limitations of pure reluctance torque production, permanent magnets can be embedded within the rotor flux barriers, leading to the PMASynRM topology. In a PMASynRM, the magnetic field generated by the permanent magnets interacts with the stator current, introducing an additional torque component that complements the classical reluctance torque. This hybrid torque production mechanism enables improved torque density and power factor while maintaining a relatively simple and robust rotor structure with reduced permanent magnet volume compared to conventional permanent magnet synchronous motors [10].

Electromagnetic Torque Components of the PMASynRM

A PMASynRM produces electromagnetic torque through the combined effects of reluctance torque and permanent magnet torque. This hybrid torque production mechanism enables improved torque density and power factor compared to conventional synchronous reluctance motors, while maintaining a relatively simple and mechanically robust rotor structure.

The reluctance torque component originates from the inductance difference between the direct-axis and quadrature-axis magnetic paths and can be expressed as given in Equation (1):

$$T_{rel} = \frac{3}{2}p(L_d - L_q)I_d I_q \quad (1)$$

where p denotes the number of pole pairs, and I_d and I_q represent the stator current components along the d- and q-axes, respectively.

In addition to the reluctance torque, the interaction between the magnetic flux generated by the embedded permanent magnets and the stator current produces the permanent magnet torque component. This contribution can be written as shown in Equation (2):

$$T_{pm} = \frac{3}{2} p \phi I_q \quad (2)$$

where ϕ denotes the amplitude of the magnetic flux produced by the permanent magnets.

Accordingly, the total electromagnetic torque of the PMASynRM is expressed as the superposition of these two components, as given in Equation (3):

$$T = \frac{3}{2} p [(L_d - L_q) I_d I_q + \phi I_q] \quad (3)$$

As indicated by Equations (1)–(3), the electromagnetic performance of the PMASynRM is primarily governed by two key factors: the inductance difference ($L_d - L_q$) and the magnitude of the permanent magnet flux (ϕ). Both parameters are strongly influenced by the rotor topology, including the geometry of the flux barriers, the thickness of the flux-carrying bridges, and the placement and type of permanent magnets. Therefore, careful design and optimization of the rotor structure are essential to achieve high torque density, low torque ripple, and stable operation suitable for electric vehicle applications, as demonstrated by Reyes et al. [9], Bozkurt et al. [16], and Bozkurt et al. [17].

In the context of electric vehicle applications, these design considerations become even more critical for outer-rotor and in-wheel motor configurations. The outer-rotor topology introduces additional mechanical constraints due to increased rotor inertia and centrifugal stresses, which must be accounted for during the electromagnetic design stage. The complete electromagnetic design and parametric optimization of the rotor geometry based on these principles were reported in the authors' previous work [16], which serves as the direct basis for the prototype manufacturing and experimental characterization presented in this study.

3. Electromagnetic Design and FEM Analysis

The electromagnetic design presented in this section is based on the optimization framework originally reported in [16] and is summarized here to provide context for the prototype manufacturing and experimental validation presented in subsequent sections. Designing an in-wheel electric motor requires careful consideration of both performance objectives and practical implementation constraints. In particular, achieving high torque density at low rotational speeds while maintaining low torque ripple and high efficiency represents a primary challenge for outer-rotor traction motors. In this study, the proposed outer-rotor PMASynRM is analyzed using a finite element method (FEM)-based approach, enabling accurate evaluation of magnetic field behavior and torque characteristics prior to prototype fabrication. The proposed topology incorporates a three-barrier transversally laminated anisotropic rotor structure combined with arc-shaped embedded permanent magnets. This configuration was selected in the previous design study to effectively utilize both reluctance torque and permanent magnet torque, thereby improving torque density, efficiency, and torque smoothness while maintaining mechanical robustness and manufacturability for in-wheel electric vehicle applications.

3.1. Design Specifications and Constraints

The proposed motor is designed as a direct-drive traction unit for electric vehicle applications. The main design targets include a rated output power of 1 kW, a nominal rotational speed of 750 rpm, and a rated torque of 12.73 Nm. These specifications are selected to represent typical operating conditions of in-wheel drive systems used in light electric vehicles, where compactness and torque capability are prioritized over high-speed operation. The key technical specifications targeted during the electromagnetic design process are summarized in Table 1 [16].

Table 1. Initial specifications of the designed motor.

Parameter	Value
Number of phases	3
Rated power (W)	1000
Rated torque (Nm)	12.73
Rated speed (rpm)	750
Rated current (rms) (A)	<13
Frequency (Hz)	50
Phase voltage (V)	36
Rotor outer diameter (mm)	265
Stator outer diameter (mm)	193
Steel material	M470-50A
Magnet material	N35H NdFeB
Efficiency	>90%

The rated current value (<13 A rms) was determined during the electromagnetic design stage based on the specified performance requirements of the proposed motor, including 1 kW rated power, 12.73 Nm rated torque, 750 rpm rated speed, and 36 V phase voltage. The selected current level enables the motor to satisfy the required power and torque specifications while maintaining an efficiency target exceeding 90%.

In addition to electromagnetic performance targets, several geometric and mechanical constraints are imposed by the in-wheel integration requirement. The outer diameter and axial length of the motor are limited by the available wheel hub volume, while the outer-rotor structure necessitates sufficient mechanical strength to withstand centrifugal stresses during operation.

3.2. FEM Model and Simulation Setup

A two-dimensional time-stepped FEM model of the proposed outer-rotor PMASynRM is developed to analyze the electromagnetic behavior of the motor. The model incorporates nonlinear magnetic material properties to accurately capture saturation effects in the stator teeth, rotor bridges, and flux barriers. The permanent magnets embedded within the rotor are modeled using appropriate magnetization characteristics based on their material properties.

The FEM simulations are performed under steady-state operating conditions at the nominal speed of 750 rpm. Stator currents are applied according to the rated operating point, and the electromagnetic torque is computed using the Maxwell stress tensor method. Mesh refinement is applied in critical regions such as the air gap, flux barriers, and magnet edges to ensure numerical accuracy without excessive computational cost.

During the electromagnetic design process, key rotor geometry parameters were iteratively adjusted to improve torque performance while maintaining mechanical integrity. These parameters include the shape and angular span of the flux barriers, the thickness of the flux-carrying bridges, and the placement of permanent magnets within the rotor. The optimization was performed through successive FEM simulations by evaluating the resulting torque characteristics and magnetic field distribution at the rated operating point. This iterative approach enabled the identification of a rotor topology that provides a favorable balance between torque density, torque ripple, and manufacturability without relying on complex numerical optimization algorithms. Among the evaluated configurations, the three-barrier rotor topology was selected as the optimal design, yielding an output torque of 12.87 Nm and a torque ripple of 6.96%—the lowest among all evaluated alternatives, as reported in [16]. The adopted FEM model is based on a two-

dimensional electromagnetic formulation, which enables efficient evaluation of the magnetic field distribution and torque characteristics with reasonable computational cost. In the simulations, end-winding effects, axial flux leakage, and certain three-dimensional mechanical assembly details are neglected. Therefore, minor discrepancies between FEM predictions and experimental measurements may arise due to three-dimensional electromagnetic effects and practical manufacturing tolerances that cannot be fully captured within the 2D modeling framework. Nevertheless, the close agreement between simulation and experimental results confirms that the adopted FEM approach provides sufficiently accurate performance estimation for the proposed motor topology.

3.3. Magnetic Field Distribution and Performance Indicators

The magnetic field distribution obtained from FEM simulations provides insight into the effectiveness of the proposed rotor topology. The flux lines generated by the interaction of the stator windings and permanent magnets are observed to be symmetrically distributed, indicating balanced magnetic loading across the machine. The flux density levels within the stator teeth and rotor bridges remain below saturation limits, confirming that the selected geometry effectively utilizes the magnetic materials as illustrated in Figure 1.

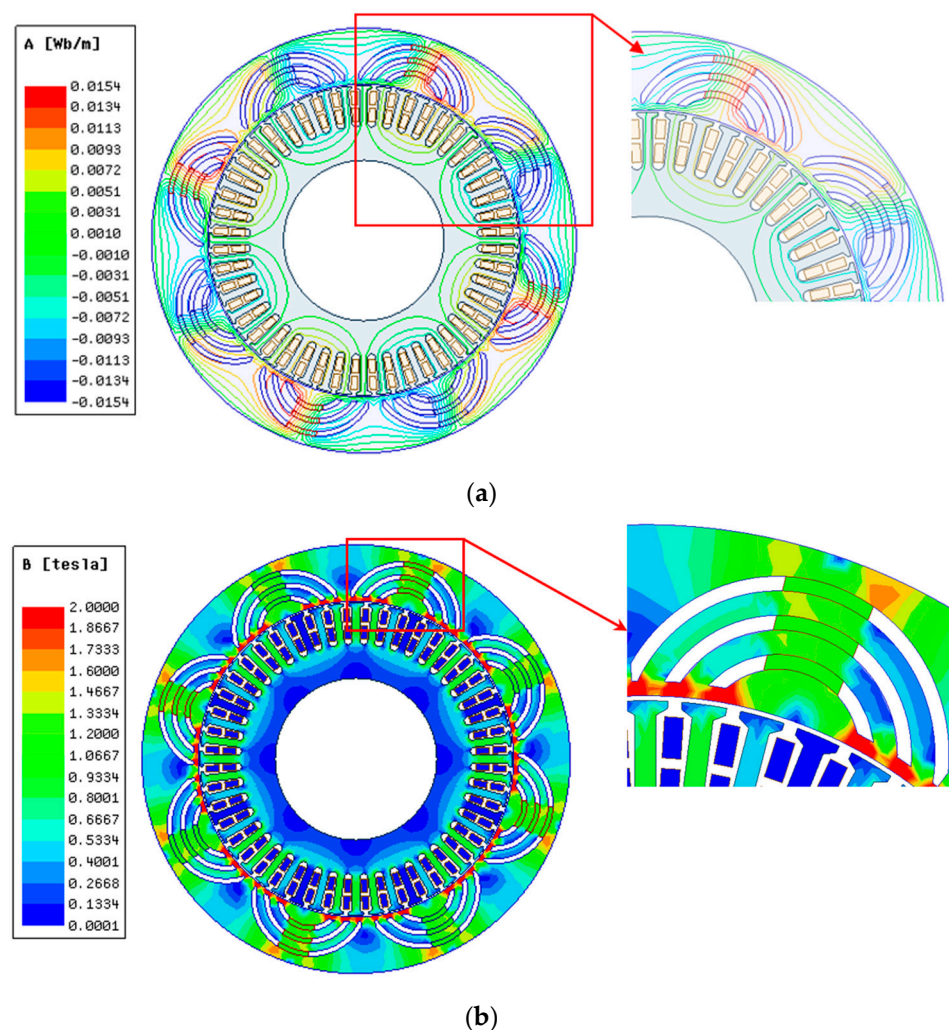


Figure 1. PMASynRM (a) magnetic flux line distribution, (b) magnetic flux density. The red boxes in (a) and (b) indicate the enlarged regions shown to the right.

The electromagnetic design and optimization process leading to the selection of the three-barrier rotor topology was reported in detail in [16]. Key electromagnetic

performance indicators, including torque production, torque ripple, and efficiency-related quantities, are extracted from the FEM results. The combination of reluctance torque and permanent magnet torque contributes to smooth torque characteristics across the operating point, with the torque ripple maintained within acceptable limits for in-wheel electric vehicle operation, while the selected slot–pole configuration and winding arrangement help suppress harmonic components in the air-gap flux density. These simulation outcomes form the basis for subsequent prototype manufacturing and experimental validation, which are presented in the following sections.

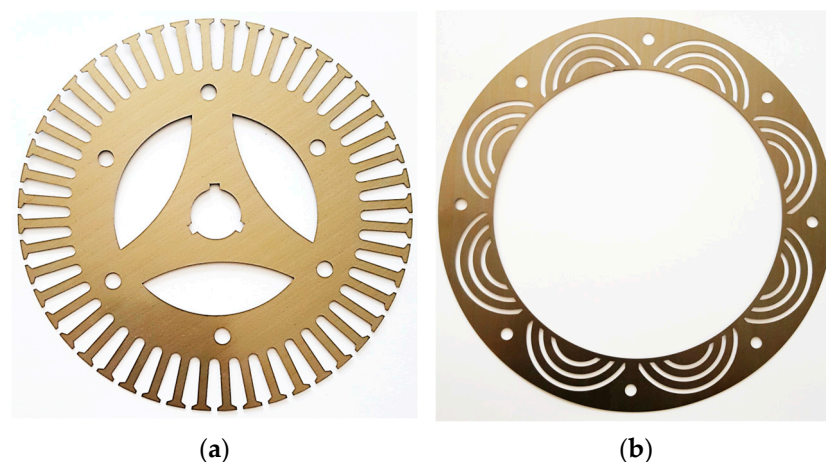
4. Prototype Manufacturing and Assembly

Following the completion of the electromagnetic design and FEM-based analysis reported in [16], a prototype of the proposed outer-rotor PMASynRM was manufactured to experimentally validate the simulation results and to assess the practical feasibility of the design. Particular attention was given to ensuring that the manufactured components accurately reflected the dimensions and material properties used in the numerical model.

4.1. Lamination and Magnet Fabrication

The stator and rotor laminations were fabricated from M470-50A grade electrical steel sheets using precision laser cutting techniques to achieve the designed flux barrier and slot geometries with minimal edge burring. This material was selected for its favorable balance between core loss characteristics and mechanical strength, consistent with the material properties assumed in the FEM model. The stator core was assembled by stacking the laminations and subsequently wound according to the specified three-phase distributed double-layer winding configuration.

Arc-shaped N35H NdFeB permanent magnets were embedded within the predefined rotor flux barriers to realize the intended permanent magnet-assisted reluctance structure. The stator and rotor laminations and the arc-shaped permanent magnets used in the prototype are shown in Figure 2. The magnet dimensions and magnetization direction were verified against the design specifications prior to assembly to ensure consistency with the FEM model assumptions. During the assembly process, the permanent magnets were secured within the rotor flux barriers using a fast-curing structural metal adhesive. In addition to the adhesive bonding, the rotor barrier geometry and the associated iron bridges provide mechanical containment of the magnets. Owing to the relatively low operating speed of the proposed motor (750 rpm), no evidence of magnet displacement or movement was observed during assembly or experimental testing.



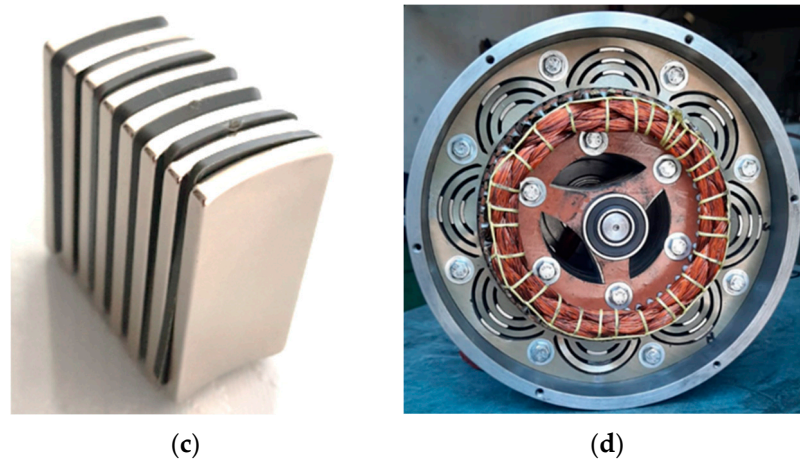


Figure 2. (a) Stator lamination, (b) Rotor lamination, (c) Arc-shaped magnets, (d) Magnet placement within rotor barriers.

4.2. Assembly and Mechanical Integration

After the lamination and magnet placement processes, the rotor and stator assemblies were integrated into the outer housing. The mechanical components, including the motor shaft and end covers, were designed and manufactured to ensure proper alignment and mechanical stability during operation, as presented in Figure 3. Special care was taken to maintain uniform air-gap length and concentricity between the rotor and stator, as deviations in these parameters directly influence torque production, iron loss distribution, and vibration characteristics.

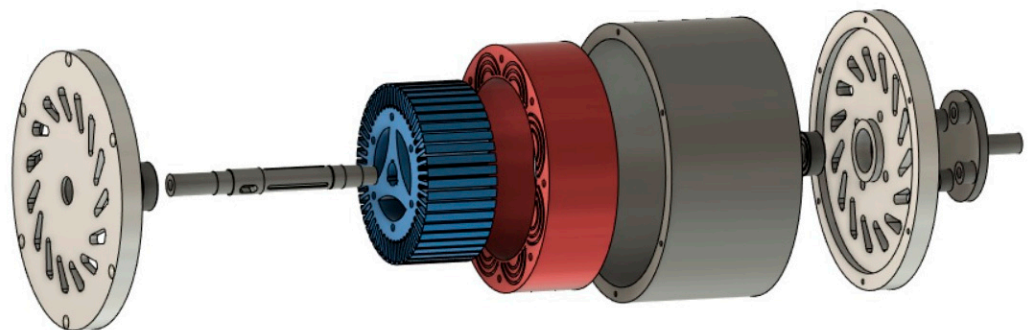


Figure 3. Assembly of motor components.

The complete assembly procedure was carried out in multiple stages to facilitate accurate positioning of the rotor and stator components, as illustrated in Figure 4. Initially, the rotor was mounted inside the outer housing, followed by precise insertion and fixation of the stator assembly. Finally, the front and rear covers were secured to form the fully assembled motor prototype.

During the assembly process, particular attention was paid to maintaining the designed air-gap length of 1 mm, as even minor eccentricities introduced at this stage can contribute to discrepancies between simulated and experimentally measured performance—a point further discussed in Section 6. The staged assembly approach enabled effective control of mechanical tolerances and ensured consistency with the design specifications defined in [16].

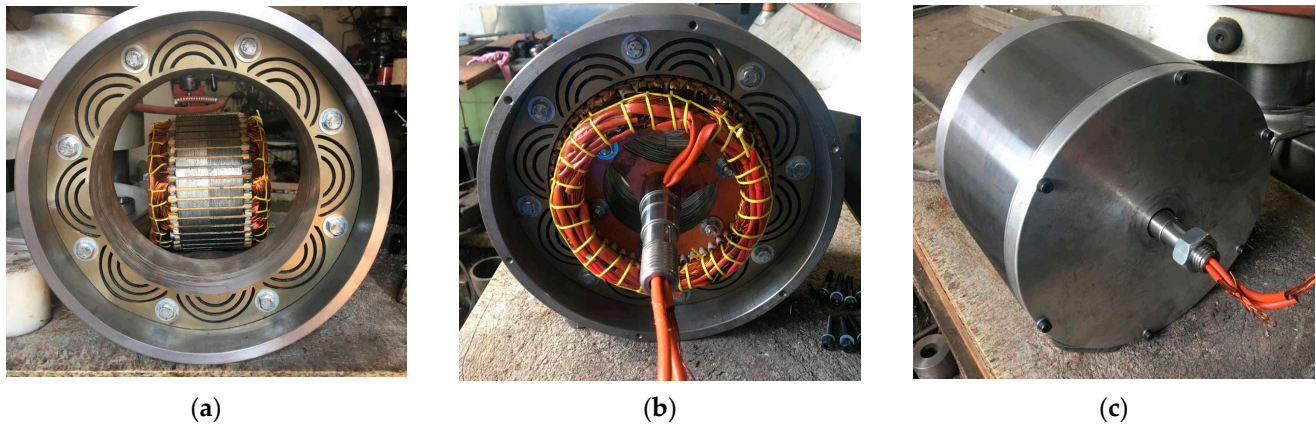


Figure 4. Assembly stages: (a) Rotor–housing integration, (b) Rotor–stator assembly, (c) Fully assembled motor prototype.

The manufactured components and the sequential assembly stages presented in Figures 2–4 highlight the physical realization of the proposed motor. The fabricated prototype serves as the basis for the experimental performance evaluation presented in the following section.

5. Experimental Setup and Performance Evaluation

The experimental evaluation of the proposed outer-rotor PMASynRM was conducted to validate the FEM-based electromagnetic design and to assess the motor’s performance under realistic operating conditions. All experimental tests were performed using a custom-built test bench specifically configured for low-speed, high-torque electric motor characterization.

5.1. Experimental Test Setup

The experimental performance evaluation of the proposed outer-rotor PMASynRM prototype was conducted using a custom-built test bench designed for low-speed, high-torque electric motor characterization. A photograph of the assembled test bench is provided in Figure 5.

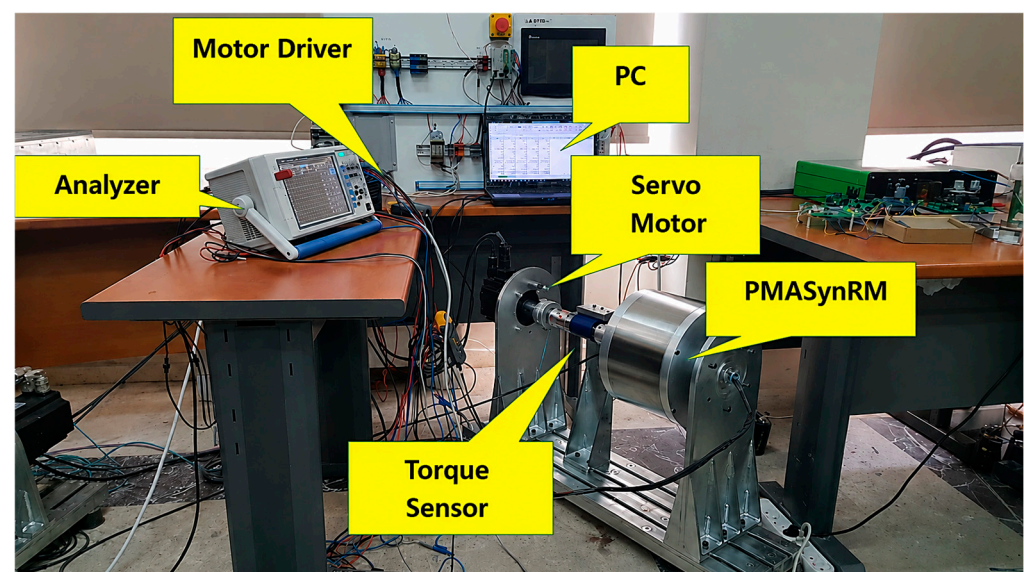


Figure 5. Experimental test setup used for performance validation.

The test bench configuration consists of the PMASynRM prototype mechanically coupled to a permanent magnet synchronous motor (PMSM) operating in generator mode. The generator-side PMSM was connected to a controllable resistive load bank, enabling precise adjustment of the load torque applied to the test motor. An Invertek Drives E3 variable-frequency drive was used to control the PMASynRM prototype throughout the experimental tests. Mechanical torque and rotational speed were measured using a Kistler torque/speed sensor with a rated capacity of 50 Nm mounted along the common shaft. Electrical quantities, including phase voltages, phase currents, input power, output power, and power factor, were recorded using a Hioki PW3390 precision power analyzer. All tests were conducted at the target operating speed of 750 rpm.

The measurement chain was verified prior to testing by running the system under no-load conditions and confirming that the recorded quantities were consistent with the expected no-load behavior of the motor. All steady-state measurements were averaged over a sufficient number of electrical cycles to minimize the effect of measurement noise, and dynamic test data were recorded at a sufficiently high sampling rate to capture transient load transitions with adequate temporal resolution.

5.2. Steady-State Performance Tests

Steady-state experiments were conducted at a constant rotational speed of 750 rpm under four load conditions: no-load, 13 Nm, 20 Nm, and 26 Nm. These levels were selected to evaluate motor behavior at nominal operation as well as under progressive overload conditions.

The measured phase voltage and current waveforms at each load level are presented in Figure 6. Each sub-figure shows the instantaneous voltage and current signals along with their corresponding RMS and peak values. The waveforms confirm that the motor operates with stable, sinusoidal excitation across all tested load levels, with no observable distortion in the voltage supply. As the load torque increases, the phase current amplitude rises accordingly, while the voltage waveform remains largely unaffected, indicating consistent inverter-side behavior throughout the tests.

A quantitative comparison between FEM simulation results and experimental measurements is provided in Table 2. To facilitate direct assessment of model accuracy, the relative deviation between simulated and measured values is also included.

Table 2. Comparison of simulation and experimental results at various load levels.

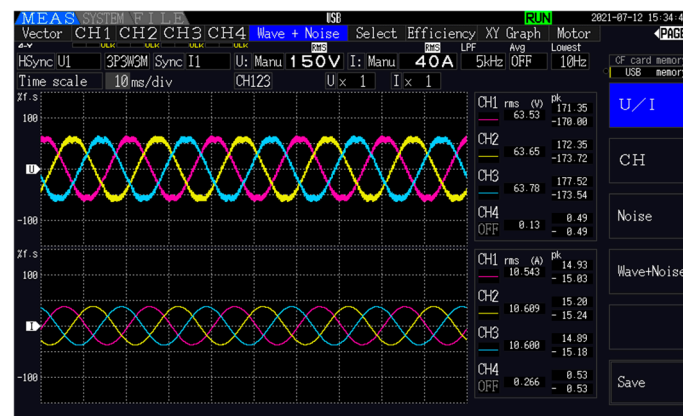
Load (Nm)	Simulation Input Power (W)	Experimental Input Power (W)	Deviation (%)	Simulation Output Power (W)	Experimental Output Power (W)	Deviation (%)	Simulation Efficiency (%)	Experimental Efficiency (%)
13	1107.18	1210.40	9.3	1010.87	1095.97	8.4	91.30	90.55
20	1796.02	1815.05	1.1	1548.42	1613.47	4.2	86.21	88.89
26	2100.80	2275.01	8.3	1709.80	1994.67	16.6	81.38	87.68

Note: Bold values represent the experimental measurements.

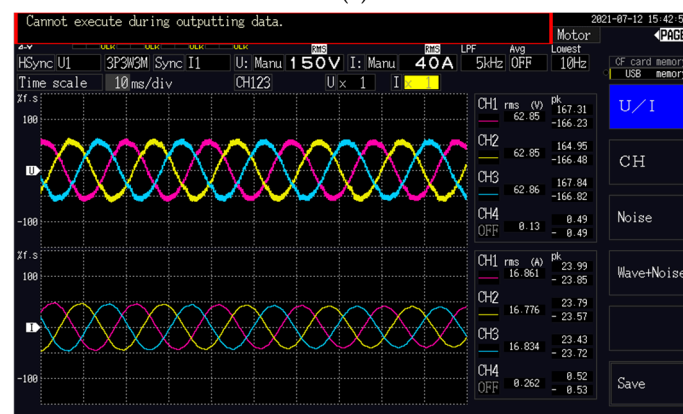
At the nominal load of 13 Nm, the measured phase current was approximately 10.6 A, in close agreement with the FEM-predicted value. The experimental efficiency at this operating point reached 90.55%, confirming that the motor meets the design target of greater than 90%. Under overload conditions of 20 Nm and 26 Nm, efficiency remained above 87%, demonstrating robust performance beyond the rated operating point.

The observed deviations in input and output power—particularly at 13 Nm and 26 Nm—are primarily attributed to losses not fully captured in the FEM model. These include mechanical losses arising from bearing friction and shaft windage, additional iron losses due to manufacturing tolerances in the lamination stack, and minor air-gap eccentricity effects introduced during assembly. Notably, the efficiency deviation between

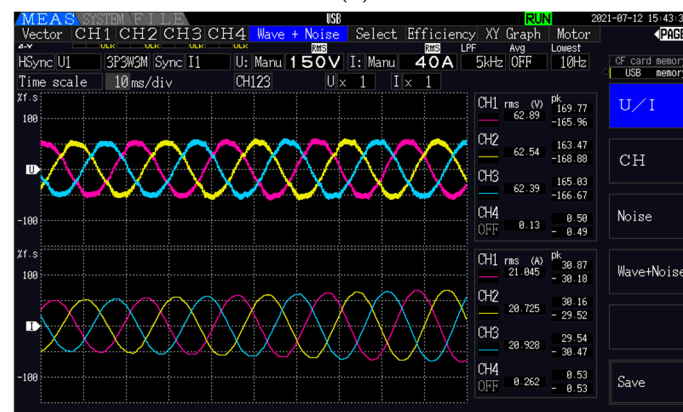
simulation and experiment remains within 2 percentage points across all load levels, confirming that the FEM model provides a reliable basis for performance prediction despite these simplifications.



(a)



(b)



(c)

Figure 6. Experimental results under different load conditions: (a) operation at 13 Nm, (b) operation at 20 Nm, (c) operation at 26 Nm.

5.3. Dynamic Load Tests

To assess the transient performance of the proposed motor, dynamic load tests were conducted by applying stepwise increases in load torque while maintaining the nominal speed of 750 rpm. The motor operated under no-load conditions for 6 s, followed by 13 Nm for 7 s, 20 Nm for 8 s, and 26 Nm for 3 s, representing a dynamic step load sequence intended to emulate varying operating conditions of in-wheel electric vehicle drives.

The time-domain variations in electromagnetic torque, mechanical output power, and rotational speed during these load transitions are presented in Figure 7, where all three quantities are plotted on a common time axis. The torque and power responses show clear stepwise increases consistent with the applied load profile, while the speed trace confirms that the motor maintains stable operation close to the nominal value of 750 rpm throughout the entire test sequence.

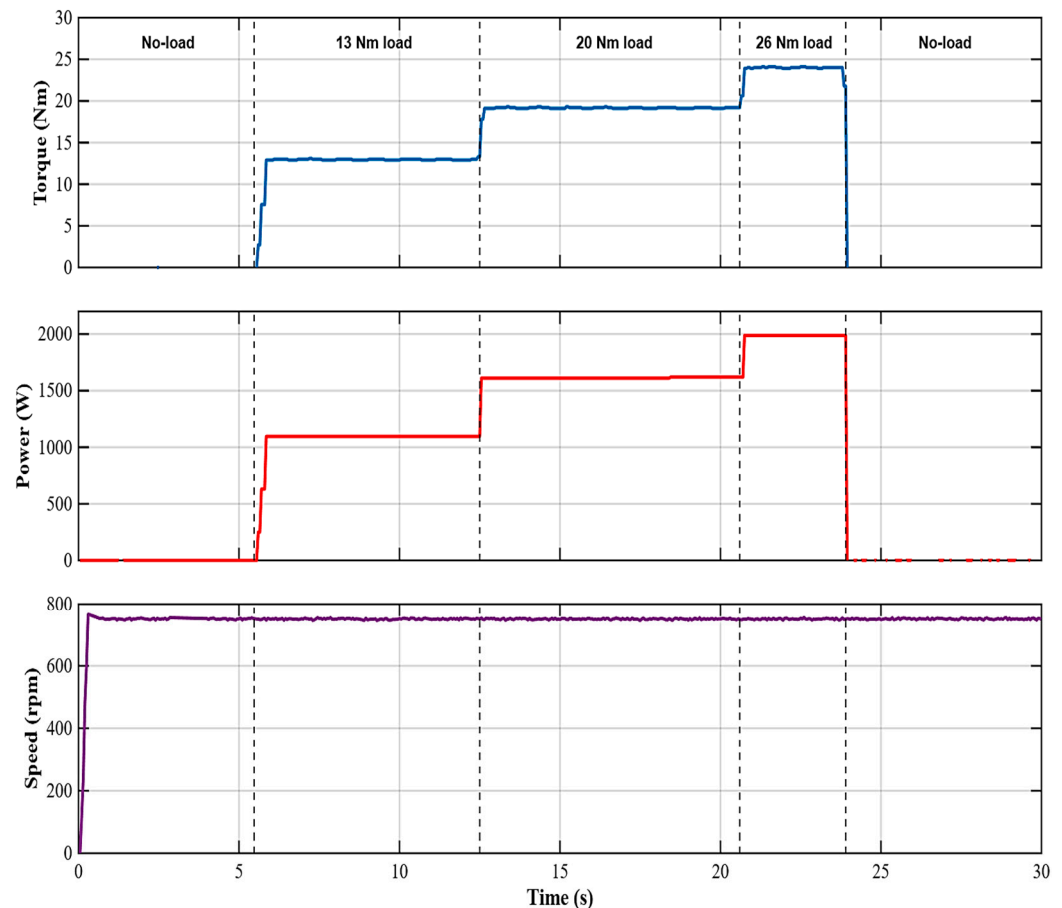


Figure 7. Dynamic variations in torque, power, and speed under different load transitions. The dashed vertical lines indicate the load transition instants, and the shaded regions represent the corresponding operating conditions: no-load, 13 Nm, 20 Nm, 26 Nm, and the final no-load condition. No low-pass filtering is applied to the measured data.

Minor oscillations are observable in the torque and power signals immediately following each load transition. These transient fluctuations are primarily associated with the dynamic response of the resistive load bank and mechanical coupling effects between the PMASynRM prototype and the PMSM generator, rather than intrinsic motor instability. The absence of low-pass filtering in the data acquisition system also contributes to the apparent noise level in the recorded signals. Importantly, the motor recovers to steady-state operation promptly after each load step, with no signs of speed instability or sustained torque oscillation, confirming the robust dynamic behavior of the proposed design. The transient responses further indicate that the proposed motor-drive system possesses adequate dynamic stiffness under rapid load variations. Following each load transition, the motor speed rapidly converges back to the nominal operating point without sustained oscillation or instability. These response characteristics indicate stable electromechanical operation of the proposed outer-rotor PMASynRM under dynamically varying load conditions relevant to practical in-wheel electric vehicle applications. Although the proposed motor topology is designed to achieve reduced torque ripple characteristics through the

combined reluctance and permanent magnet torque production mechanism, direct quantitative experimental torque ripple analysis was not performed in the present study. This limitation is mainly associated with the experimental setup, including the limited resolution of the torque transducer, mechanical coupling effects between the PMASynRM prototype and the PMSM generator, measurement noise in the recorded data, and the absence of low-pass filtering applied to the measured data. Nevertheless, the stable torque and speed responses observed during steady-state and dynamic operation indirectly indicate acceptable torque smoothness characteristics for the intended in-wheel electric vehicle application.

Overall, the dynamic test results complement the steady-state findings presented in Section 5.2 and provide further evidence that the proposed outer-rotor PMASynRM is capable of stable operation under varying load conditions representative of electric vehicle drive cycles.

6. Discussion

The experimental results presented in Section 5 demonstrate that the proposed outer-rotor PMASynRM successfully meets the targeted performance objectives for in-wheel electric vehicle applications. In particular, the close agreement observed between FEM-based predictions and experimental measurements confirms the validity of the adopted electromagnetic design methodology and the suitability of the proposed three-barrier rotor topology. These findings further validate the electromagnetic design framework originally reported in [16], confirming that simulation-based predictions provide a reliable foundation for prototype realization and that the adopted FEM model can serve as an effective tool for design-stage performance estimation. Although experimental back-EMF measurements were not included within the scope of the present study, the close agreement between FEM predictions and experimentally measured torque, power, and efficiency characteristics provides additional confidence in the accuracy of the adopted electromagnetic model. Compared to previous studies primarily focused on electromagnetic design and numerical analysis, the present work additionally demonstrates the practical feasibility of the proposed topology through prototype manufacturing and comprehensive experimental validation under both steady-state and dynamic operating conditions.

A comparison between the simulation and experimental results reveals that the measured input power values are slightly higher than those predicted by FEM analysis across all tested load conditions, with deviations reaching up to 9.3% at nominal load and 8.3% under the 26 Nm overload condition, as summarized in Table 2. This discrepancy can be systematically attributed to three principal sources. First, mechanical losses arising from bearing friction, shaft windage, and coupling misalignment between the PMASynRM prototype and the PMSM generator are not captured in the two-dimensional FEM framework. Second, additional iron losses resulting from manufacturing tolerances in the lamination stack—including burring at cut edges and residual stresses introduced during laser cutting—contribute to elevated core losses compared to the idealized material properties assumed in the simulation. Third, minor air-gap eccentricity effects introduced during assembly may alter the local flux distribution and increase harmonic losses beyond the levels predicted by the model. Furthermore, axial flux leakage and certain three-dimensional electromagnetic effects neglected in the adopted 2D FEM formulation may also contribute to the observed deviations, particularly under higher loading conditions where local magnetic saturation becomes more pronounced. Temperature-dependent variations in winding resistance and magnetic material characteristics during operation may additionally influence the experimental efficiency values. Despite these sources of discrepancy, the overall agreement between simulation and experimental results remains satisfactory across the investigated operating range, confirming that the FEM

model provides a reliable and practical basis for design-stage performance prediction. A further examination of the FEM loss components indicates that the reduction in efficiency observed between nominal-load and overload operating conditions is primarily associated with increased winding copper losses. While the core loss increases only slightly from approximately 7.8 W to 9.1 W, the winding copper loss rises from approximately 76 W to 357 W as a consequence of the higher stator current required to generate the increased torque. Therefore, the observed reduction in efficiency from 90.55% at nominal load to 87.68% at the 26 Nm overload condition is predominantly attributed to copper losses (I²R losses), whereas the contribution of iron losses remains comparatively limited.

Regarding steady-state performance, the test results confirm that the prototype achieves a maximum efficiency of 90.55% at nominal load, satisfying the design target of greater than 90%. Efficiency remains above 87% under overload conditions up to 26 Nm, indicating consistent and robust performance across a wide torque range. This behavior highlights the effectiveness of combining reluctance torque and permanent magnet torque in the PMASynRM topology. The embedded permanent magnets enhance torque production and power factor without significantly increasing magnet volume, thereby addressing both performance and material usage concerns relevant to electric vehicle applications.

With regard to transient behavior, the dynamic load test results further confirm the robustness of the proposed motor design under varying operating conditions. Although minor oscillations are observed in the speed and power responses during rapid load transitions, these fluctuations are primarily associated with the dynamic response of the resistive load bank and the mechanical coupling between the PMASynRM prototype and the PMSM generator, rather than intrinsic motor instability. The absence of low-pass filtering in the data acquisition system also contributes to the apparent noise level in the recorded signals. Importantly, the motor recovers to steady-state operation promptly after each load step, with no signs of speed instability or sustained torque oscillation, confirming the robust dynamic behavior of the proposed design under operating conditions representative of electric vehicle drive cycles.

To contextualize the achieved performance within the existing literature, Table 3 summarizes key performance metrics of recently reported PMASynRM and outer-rotor motor designs.

Table 3. Comparison of performance metrics and structural characteristics of related PMASynRM studies.

Reference	Topology	Structural Characteristics	Power (W)	Speed (rpm)	Torque (Nm)	Efficiency (%)	Experimental
Proposed	Outer-rotor PMASynRM (EV)	Three-barrier TLA rotor with arc-shaped embedded magnets	1000	750	13	90.55	Yes
Nobahari et al. [21]	Modified PMASynRM (EV)	Axially segmented IPM-SynRM rotor topology	1500	1500	~11.44	90.1	Yes
Yenipinar et al. [22]	Outer-rotor PM-SynRM (EV)	Outer-rotor PM-assisted synchronous reluctance structure	2000	2000	>35 (max)/10 (rated)	90	No
Bozkurt et al. [16]	Outer-rotor PMASynRM (EV)	Three-barrier TLA rotor with arc-shaped embedded magnets	1000	750	12.87	91.30	No

As indicated in the table, the proposed motor is among the very few studies providing multi-load steady-state and dynamic experimental results on a manufactured outer-rotor PMASynRM prototype for in-wheel electric vehicle applications. Nobahari et al. [21]

present experimental validation of a modified axially segmented IPM-SyRM configuration for a small electric vehicle, reporting a mean torque of 11.44 Nm and an efficiency of 90.1%—results that are broadly consistent with the performance achieved in the present work despite the different rotor topology and power rating. Yenipinar et al. [22] report an outer-rotor PM-assisted synchronous reluctance motor design with promising simulation results; however, their study remains limited to FEM-based analysis without prototype testing. This further highlights the limited availability of experimentally validated outer-rotor PMASynRM studies reported in the literature. Additional thermal and experimental investigations of outer-rotor PMASynRM topologies have also been reported by Nasiri-Zarandi et al. [23], further supporting the practical feasibility of this machine configuration for light electric vehicle applications. In addition to the reported performance metrics, the compared studies exhibit notable differences in rotor topology and structural configuration. The proposed motor employs a three-barrier transversally laminated anisotropic rotor structure with arc-shaped embedded permanent magnets, whereas Nobahari et al. [21] utilize an axially segmented rotor configuration. Such structural differences influence electromagnetic performance, torque production mechanisms, manufacturability, and mechanical integration requirements. Therefore, direct comparison based solely on power, torque, and efficiency values may not fully reflect the design trade-offs associated with each topology. To provide a more comprehensive evaluation, the principal structural characteristics of the compared motor designs have been summarized in Table 3.

Beyond the direct performance comparisons, recent studies have further advanced the design of PMASynRMs by incorporating multi-objective optimization, manufacturing uncertainty analysis, and multi-physics considerations such as thermal effects. In particular, Gözüa ık and Akar [24] report an axial flux PMASynRM design integrating coupled electromagnetic–thermal optimization for electric vehicle applications, demonstrating the growing interest in multi-physics design frameworks. Related hub motor-oriented PM-assisted synchronous reluctance motor designs have also been reported in recent studies, focusing primarily on electromagnetic design and feasibility analysis, as presented by Akpunar Bozkurt [25]. While these works demonstrate the potential of PMASynRM topologies for electric vehicle propulsion, many of them primarily emphasize numerical optimization or simulation-based performance evaluation. In contrast, the present work focuses on a balanced and experimentally validated design approach in which electromagnetic performance, manufacturability, and practical implementation constraints are jointly addressed. In addition to the electromagnetic design and experimental validation presented in this study, advanced control and parameter estimation techniques—such as those proposed by Akpunar and Iplikci [26]—can further enhance the overall performance of PM-assisted electric drive systems, particularly under varying operating conditions and transient loading scenarios.

From a structural perspective, the outer-rotor configuration proves advantageous for in-wheel applications by enabling high torque production at low rotational speeds through an increased effective air-gap radius. The larger air-gap radius inherent to the outer-rotor topology enhances torque capability while simplifying the drivetrain architecture through direct-drive operation, eliminating the need for mechanical transmission elements. The manufactured prototype has an outer rotor diameter of 265 mm, a stator outer diameter of 193 mm, and a stack length of 80 mm. Including the active electromagnetic components, housing, end covers, and shaft, the total assembled motor weight is approximately 44.85 kg. Compared to several previously reported outer-rotor PMASynRM studies primarily limited to simulation-based analysis, the present study additionally provides comprehensive experimental validation under both steady-state and dynamic loading conditions, thereby offering practical verification of the proposed topology for real operating scenarios. Nevertheless, the outer-rotor structure also introduces certain practical

challenges, including increased rotor inertia, sensitivity to air-gap uniformity during assembly, and additional mechanical considerations associated with rotor balancing and structural integrity. The experimental validation confirms that the proposed design effectively balances electromagnetic performance, mechanical integrity, and manufacturability—all of which are critical requirements for practical in-wheel motor implementations.

7. Conclusions

This study presented the prototype manufacturing and experimental validation of a three-phase outer-rotor permanent magnet-assisted synchronous reluctance motor (PMASynRM) intended for in-wheel electric vehicle applications. This work extends the electromagnetic design and FEM-based optimization framework previously reported in [16] to the physical realization and experimental evaluation of the proposed motor.

The analytical formulation of torque production, combining reluctance torque and permanent magnet torque components, provided a clear theoretical foundation for the electromagnetic design process. Based on this framework, the rotor geometry and magnet placement were iteratively optimized to achieve a favorable balance between electromagnetic performance, mechanical robustness, and manufacturability. The resulting design successfully met the targeted specifications, including a rated power of 1 kW and a nominal speed of 750 rpm. The prototype was fabricated using precision-cut M470-50A grade electrical steel laminations with arc-shaped N35H NdFeB permanent magnets embedded within a three-barrier rotor structure, ensuring consistency with the material properties and geometric parameters defined in the FEM model.

A prototype of the proposed motor was manufactured and experimentally evaluated using a custom-built test bench. The main findings of this study can be summarized as follows. First, the experimental results demonstrate strong agreement with FEM predictions, with efficiency deviations remaining within 2 percentage points across all tested load levels, confirming the reliability of the adopted simulation methodology. Second, the prototype achieved a maximum efficiency of 90.55% at nominal load and sustained efficiency above 87% under overload conditions up to 26 Nm, meeting the design targets established in [16]. Third, the dynamic load tests confirmed stable transient behavior under stepwise load transitions, with no signs of speed instability or sustained torque oscillation. Fourth, to the best of the authors' knowledge, this work represents the first experimental validation of an outer-rotor PMASynRM prototype under multi-load steady-state and dynamic operating conditions for in-wheel electric vehicle applications. A comparison with recently reported PMASynRM and outer-rotor motor designs, summarized in Table 3, further confirms that experimental validation on manufactured prototypes under multiple loading conditions remains scarce in the existing literature, underscoring the contribution of the present study.

The experimental observations further confirmed that the outer-rotor configuration is well suited for in-wheel applications, as it enables high torque production through an increased effective air-gap radius while allowing direct-drive operation without mechanical transmission elements. Minor discrepancies between simulation and experimental results were systematically attributed to mechanical losses, lamination manufacturing tolerances, and minor assembly-induced air-gap eccentricity, none of which detract from the overall effectiveness of the proposed design.

In conclusion, the proposed outer-rotor PMASynRM represents a competitive and practical solution for electric vehicle propulsion systems where compactness, torque density, and efficiency are critical. Future work will focus on the implementation of advanced control strategies, such as field-oriented control, model predictive control, and regenerative braking algorithms, in order to further improve the dynamic performance and efficiency of the proposed motor drive system. In particular, the high saliency characteristics

of the outer-rotor PMASynRM topology provide promising opportunities for advanced torque control and parameter estimation techniques. In addition, detailed thermal modeling and coupled electro-thermal analysis will be investigated to ensure reliable operation under prolonged operating conditions and varying environmental conditions.

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