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Performance Evaluation of Outer Rotor Permanent Magnet Direct Drive In-Wheel Motor Based on Air-Gap Field Modulation Effect

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Abstract: The different pole–slot combinations of outer rotor surface-mounted permanent magnet (ORSPM) motors are designed and analyzed to satisfy EV driving requirements. Firstly, the analytical model for various slot–pole combinations of ORSPM motors is proposed based on the air-gap field modulation effect. Then, some of the in-wheel motor parameters and requirements are obtained for the vehicle system. In addition, some special pole–slot combination ORSPM motors are built to achieve higher flux density, and the electromagnetic performance is compared based on the finite element (FE) model, revealing that the 56-slot/48-pole (54s48p) in-wheel motor has a higher torque density and superior flux weakening capability than other cases. Finally, a 13 kW prototype with 54s48p is manufactured and tested to confirm the effectiveness of the FE analysis.

Keywords: air-gap field modulation effect; ORSPM; slot–pole combinations; FEM



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1. Introduction

With advancements in electric vehicle (EV) technologies, in-wheel motors have emerged as an optimal solution due to their shortened mechanical transmission chain, enhanced energy conversion efficiency, and excellent dynamic performance [1,2]. In addition, in-wheel drive also provides more space for passengers and batteries while enhancing the vehicle's control flexibility through distributed in-wheel drive [3]. However, to satisfy the performance requirements of modern EVs, in-wheel motors need to have superior torque density, high energy efficiency, broad operational speed ranges, and low torque ripple [4,5].

To resolve these conflicts, the permanent magnet (PM) motor provides a good solution for the application of EVs because of its advantages of superior torque and high-efficiency capabilities [6,7]. Compared with distributed winding PM machines, the fractional-slot concentrated windings PM machines have greater efficiency region, shorter axial length, and higher torque density owing to high slot fill factor and magnetic field distribution [8,9].

Recently, two typical types of in-wheel motors have emerged: one is a low-speed direct drive motor, which is characterized by high torque density [10,11]. The other is the high-speed motor with a mechanical reduction mechanism, which is characterized by high power density [12,13]. The absence of mechanical transmission components in direct-drive in-wheel motors makes them particularly suitable for club cars, as this configuration completely avoids the energy losses typically occurring in conventional drivetrains [14,15]. To improve torque density, researchers have investigated various direct drive motor topologies. To enhance reluctance torque and extend speed range, a 24-slot/20-pole in-wheel motor is designed and the 18 kW prototype is manufactured in [16]. To enhance operational reliability, a novel fault-tolerant in-wheel motor is proposed and analyzed in [17]. To achieve

higher energy conversion efficiency, a spoke-type PM motor topology is designed in [18–21]. This motor features a salient structure, which demonstrates enhanced torque performance, higher efficiency region, and a significantly improved flux-weakening capability compared with the conventional PM motor. In [22], an E-core outer-rotor in-wheel direct drive motor is proposed, which investigates and optimizes the design parameters to improve the output torque. A comprehensive comparative analysis of different outer-rotor PM motor topologies specifically designed for in-wheel EV in [23]. The results demonstrate that multi-phase machine configurations exhibit superior electromagnetic properties. In [24], the innovative inclined U-shaped PM design is designed to optimize flux concentration capability, ultimately demonstrating superior output torque. In addition, axial flux PM (AFPM) motors have been extensively investigated due to their superior torque density characteristics compared with radial flux motors [25,26]. The design optimization of single rotor-double stator AFPM motor is detailed in [27,28]. Due to the manufacturing complexities and expensive production costs associated with YASA motors, the outer rotor SPM (ORSPM) motor topologies are considered the preferred alternative for direct drive in-wheel propulsion systems.

Within the context outlined, ORSPM motors have attracted much attention due to their advantages such as compact structure and low mechanical loss. However, the relationship between different slot–pole combinations and the electromagnetic performance of the ORSPM motors has still not been revealed. Most of the existing studies focus on topological innovation and lack a systematic analysis of the influence of different slot–pole configurations on the air-gap magnetic field modulation effect, especially the collaborative optimization problem of high torque density and field-weakening capability. Therefore, this paper mainly concentrates on investigating comprehensive electromagnetism characteristics with different slot–pole combinations for ORSPM motors through analytical models and finite element (FE) analysis and provides a theoretical basis for engineering practice. This paper makes the following significant contributions:

- (1) The analytical model (AM) is established for ORSPM in-wheel motors based on the magnetic field modulation effect.
- (2) The relationship between pole pairs and resultant air-gap flux density is investigated and the feasible slot–pole combinations are summarized to improve the flux density.
- (3) The ORSPM motors with some special pole–slot combinations are built and compared, which demonstrate that the 54s48p in-wheel motor has superior electromagnetic performance.

This paper is organized as follows: In Section 2, research methodology and ORSPM motors topologies are introduced. In Section 3, the AM is derived and the feasible slot–pole combinations for ORSPM motors are investigated. In Section 4, the electromagnetic properties such as back electromotive force(back-EMF), torque performances, cogging torque, output torque, and flux weakening capabilities across various slot–pole combinations are studied, respectively. In Section 5, a comprehensive analysis of the FE results is discussed. In Section 6, an 18 kW prototype is manufactured and tested, confirming the FE predictions. Finally, some conclusions are summarized in Section 7.

2. Methodology and Topologies of the ORSPM Motors

This paper studies a general and comprehensive characteristic of slot–pole combinations, focusing on the impact of magnetization modes on critical electromagnetic performances. The flowchart of the research methodology is shown in Figure 1.

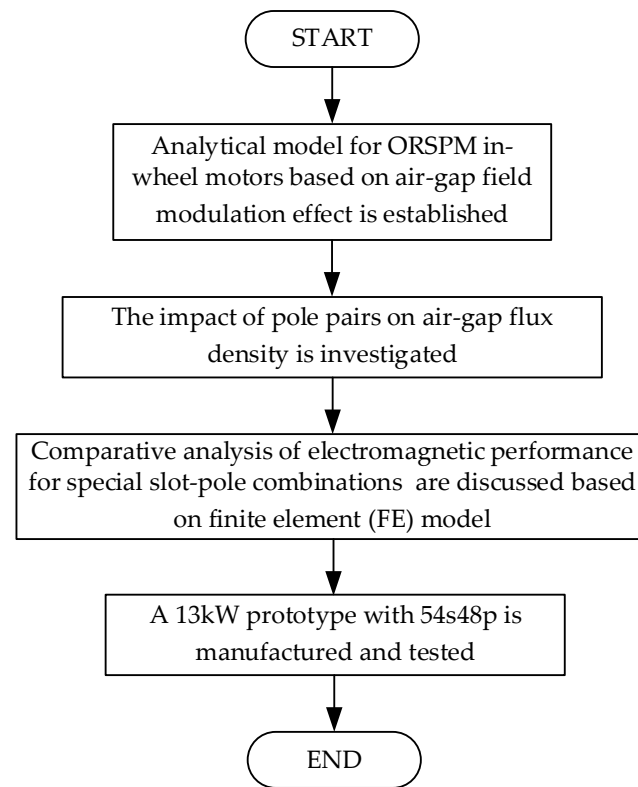


Figure 1. Flowchart of research methodology.

Considering the relatively higher winding factor, 36-slot/32-pole (36s32p), 48s40p, 54s48p, and 60s56p are selected, with their topological structures shown in Figure 2. A higher winding factor can effectively reduce magnetic field harmonics, thereby reducing harmonic losses and maintaining a stable output torque. In addition, to perform a fair comparison, four ORSPM motors with rotor radius, current density, air-gap length, and active stack length are kept consistent to eliminate the influence of geometric size differences on performance and ensure the fairness of the comparison, as shown in Table 1.

Table 1. Main design parameters of the four ORSPM motors.

Items		ORSPM Motors			
Stator slots	36	48	54	60	
Rotor poles	32	40	48	56	
Rotor outer radius, mm		157.5			
Stator outer radius, mm		147.0			
Rotor inner radius, mm		148.0			
Stator inner radius, mm		120			
Air-gap length, mm		1.0			
PM thickness, mm		4.0			
Active stack length, mm		48			
Peak current, A		83			
PM grade		30UH			
Steel grade		BAT1500			

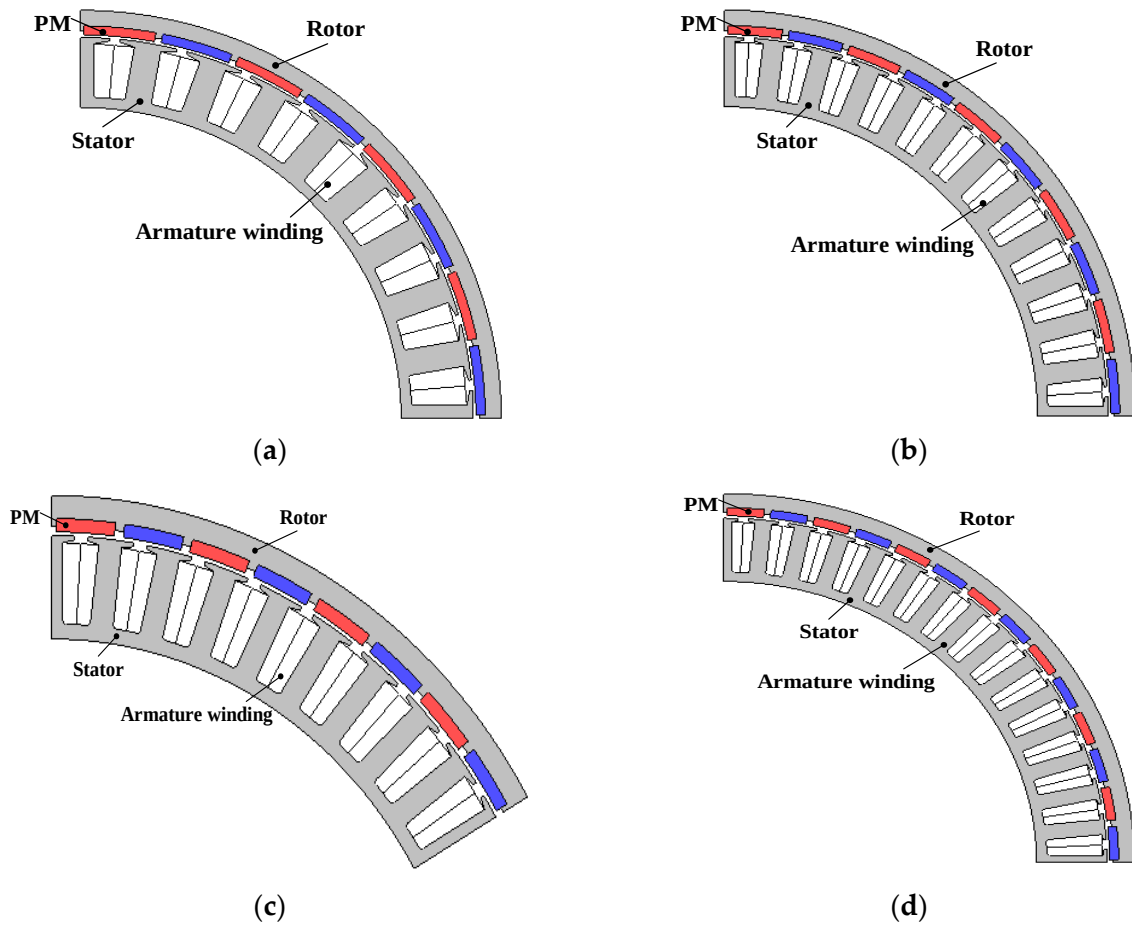


Figure 2. The ORSPM motors topologies: (a) 36s32p; (b) 48s40p; (c) 54s48p; (d) 60s56p.

3. Analytical Model and Slot–Pole Combinations of the ORSPM In-Wheel Motor

3.1. PM MMF-Permeance Model

The analytical expression for PM magnetomotive force (MMF) can be given by the following:

$$F_{PM} = \sum_{i=1}^{\infty} F_{PMi} \cos[iZ_r(\theta - \theta_0 - \Omega_r t)] \quad (1)$$

where Z_r is PM pole pairs, Ω_r is the rotor speed, θ is the rotor position angle.

The i th PM MMF coefficient F_{PMi} can be calculated as follows:

$$F_{PMi} = \frac{2}{i\pi} \frac{B_r h_{PM}}{\mu_0 \mu_r} [(-1)^i - 1] \quad (2)$$

where B_r is the remanent PM flux density, h_{PM} is the PM thickness, μ_r is the relative permeability.

The equivalent permeance of air-gap region can be mathematically formulated as

$$\Lambda_g = \Lambda_{g0} + \sum_{j=1}^{\infty} \Lambda_{gj} \cos(jZ_s \theta) \quad (3)$$

Λ_{g0} and Λ_{gj} can be, respectively, expressed as

$$\Lambda_{g0} = \frac{\mu_0}{g'} (1 - 1.6\lambda \frac{b_s}{t_s}) \quad (4)$$

$$\Lambda_{gj} = \frac{\mu_0}{jg'} \frac{4}{\pi} \lambda \left[0.5 + \frac{(jb_s/t_s)^2}{0.78125 - 2(jb_s/t_s)^2} \right] \sin(1.6\pi \frac{jb_s}{t_s}) \quad (5)$$

$$\lambda = 0.5 - \frac{1}{2\sqrt{1 + \left(\frac{b_s}{2t_s} \frac{t_s}{g}\right)^2}} \quad (6)$$

$$g' = g + \frac{h_{PM}}{\mu_0} \quad (7)$$

where b_s is the slot opening width, g corresponds to the air-gap length, t_s represents the slot pitch.

According to (1)–(7), the no-load flux density in the air-gap region can be given by

$$B_g = \Lambda_g F_{PM} = \frac{g}{2\mu_0} \Lambda_{g0} \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} F_{PMi} \Lambda_{sm} \sin[(jZ_s \pm iZ_r)\theta \mp iZ_r(\theta_0 + \Omega_r t)] \quad (8)$$

The phase A flux linkage can be expressed as

$$\psi_A = r_g L_{stk} \int_0^{2\pi} B_g N_a(\theta) d\theta \quad (9)$$

where r_g represents the air-gap radius and L_{stk} denotes the stack length.

$N_a(\theta)$ signifies the winding distribution function, mathematically expressed as follows:

$$N_a(\theta) = \sum_{h=1}^{\infty} \frac{2}{h\pi} N_s k_{wh} \cos(h\theta) \quad (10)$$

where N_s is the per phase series-turns and k_{wh} is the wh harmonic winding factor.

$$e_A = -\frac{d\psi_A}{dt} = \frac{g N_c L_{stk} r_g}{\mu_0} \Lambda_{g0} \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \frac{F_{PMi} \Lambda_{sj} k_{w|jZ_s \pm iZ_r|}}{jZ_s \pm iZ_r} \sin\left[(jZ_s \pm iZ_r) \frac{\pi}{N_s}\right] \cos[iZ_r(\theta_0 + \Omega_r t)] \quad (11)$$

The electromagnetic torque can be expressed as

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega_r} \quad (12)$$

Thus, the average torque can be calculated as

$$T_{avg} = \frac{3g}{2\mu_0} r_g L_{stk} N_s I_A \Lambda_{g0} F_{PM1} \sum_{j=1}^{\infty} \frac{\Lambda_{sj}}{jZ_s \pm Z_r} k_{w|jZ_s \pm Z_r|} \quad (13)$$

Considering the flux density main order harmonic, average torque can be represented as follows:

$$T_{avg} = 3r_g L_{stk} N_s I_A \left\{ \frac{Z_r}{Z_r} B_{Z_r} k_{w|Z_r|} + \frac{Z_r}{2Z_s - Z_r} B_{|2Z_s - Z_r|} k_{w|2Z_s - Z_r|} + \frac{Z_r}{3Z_r} B_{3Z_r} k_{w|3Z_r|} + \frac{Z_r}{2Z_s + Z_r} B_{|2Z_s + Z_r|} k_{w|2Z_s + Z_r|} \right\} \quad (14)$$

The air-gap flux density of the 54-slot/48-pole ORSPM machine is shown in Figure 3, and various air-gap field harmonics also can be obtained.

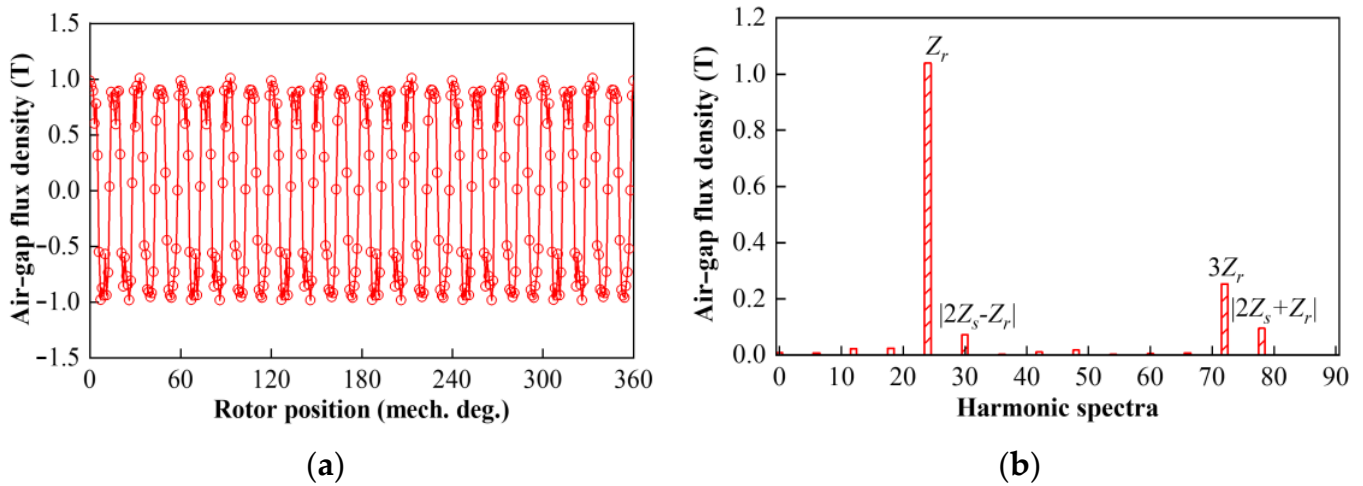


Figure 3. The air-gap flux density under no-load conditions: (a) waveforms; (b) harmonic spectra.

3.2. Feasible Slot–Pole Combinations

Taking into account that the maximum speed is 1200 r/min and switching loss effects, the rotor pole pairs are restricted to 30. Figure 4 illustrates the air-gap flux density fundamental amplitudes across various pole-pair configurations, revealing that pole pairs 16, 20, 24, and 28 have comparatively higher fundamental amplitudes of air-gap flux density while maintaining the same PM volume.

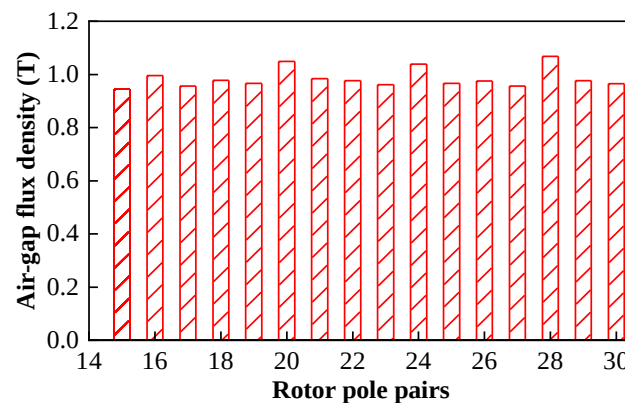


Figure 4. The fundamental amplitudes of air-gap flux density with different pole pairs.

4. Performance Evaluation

4.1. No-Load Characteristics

Figure 5 illustrates the no-load magnetic flux density distributions of the four ORSPM configurations, revealing higher flux concentration in the stator teeth of 48s40p and 54s48p designs compared to their 36s32p and 60s54p counterparts due to their relatively lower flux leakage. In addition, the comparative analysis shown in Figure 6a illustrates that the 48s40p and 54s48p configurations have higher back-EMFs than the other cases. It is worth noting that the proportion of the third harmonic in 54s48p is only 5%, significantly lower than 12% in 36s32p, indicating that the harmonic distortion rate of the air-gap magnetic field is lower. In addition, the 54s48p configuration increases the fundamental amplitude by 20% compared with the 36s32p configuration, thereby increasing the average torque.

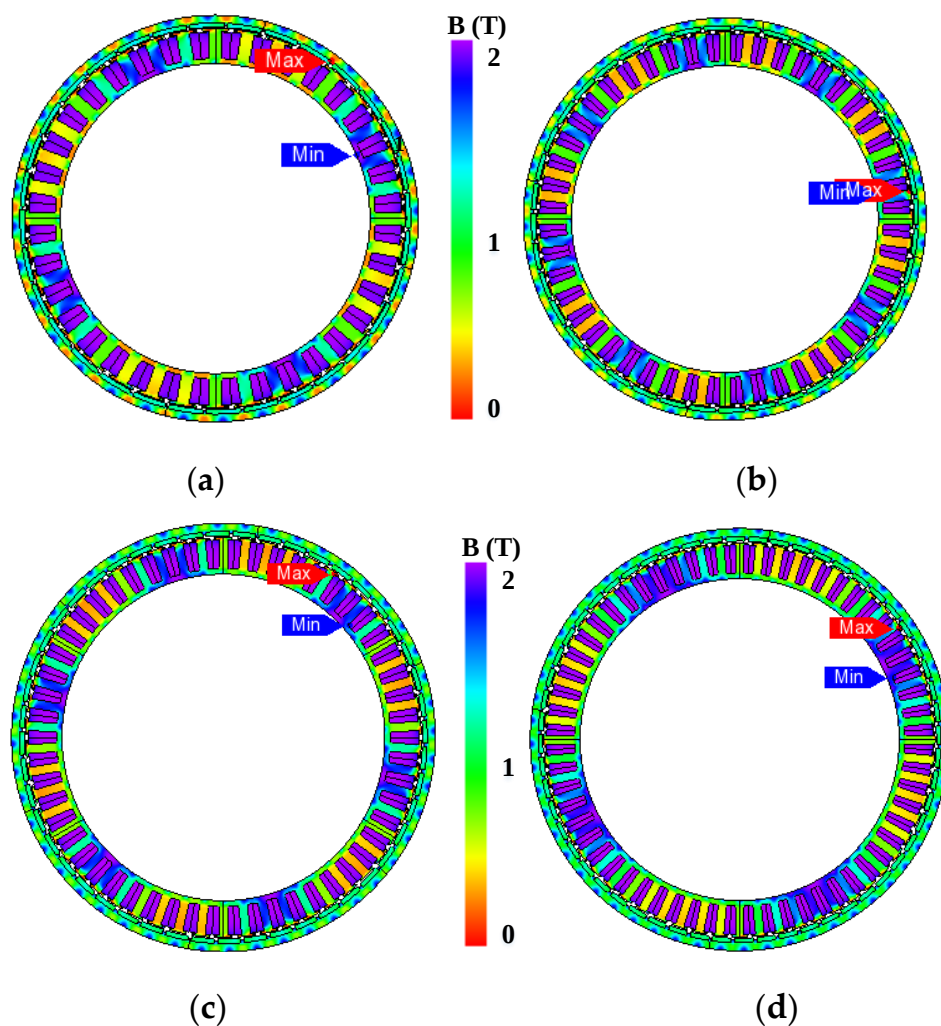


Figure 5. No-load magnetic flux density distribution: (a) 36s32p; (b) 48s40p; (c) 54s48p; (d) 60s56p.

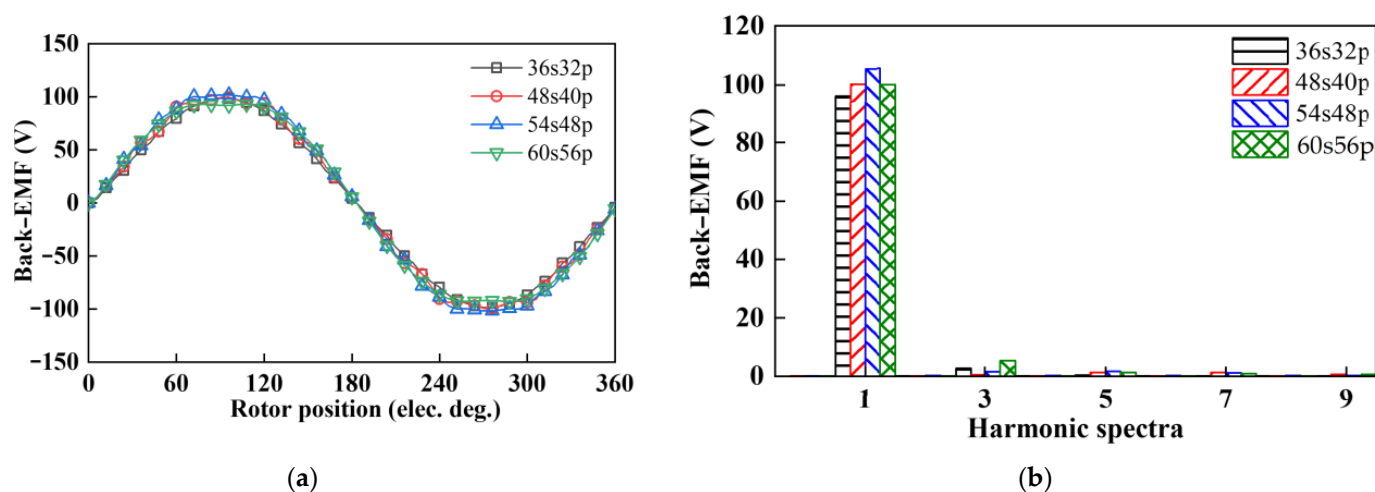


Figure 6. BackEMFs of the four ORSPM motors: (a) waveforms; (b) harmonic spectra.

Cogging torque arises from the magnetic interaction between stator slot openings and PMs, which needs to be minimized to limit noise and vibration. As shown in Figure 7, there are significant differences in cogging torque with different pole–slot combinations. Among the investigated configurations, the 48s40p motor demonstrates the maximum cogging

torque amplitude of 3.6 N·m, while the 60s56p topology exhibits the minimum value at 0.35 N·m. The peak cogging torque of the 54s48p motor is about 1.1 N·m.

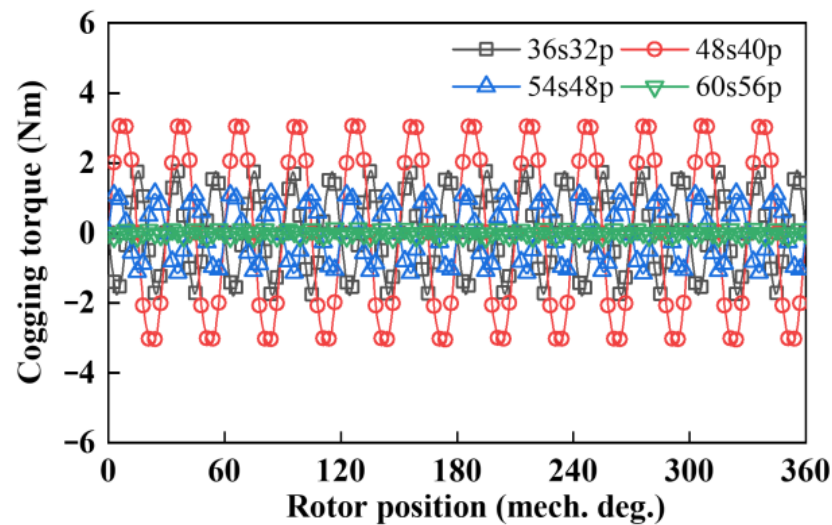


Figure 7. The waveform of cogging torque.

4.2. On-Load Torque

The on-load voltage for in-wheel motor can be obtained by

$$U = \sqrt{(-\omega_e L_q i_q + R_a i_d)^2 + (-\omega_e L_d i_d + \omega_e \psi_f + R_a i_q)^2} \quad (15)$$

where i_d and i_q are the d - and q -axis currents, ω_e is the electrical rotational speed, L_d and L_q are the d - and q -axis inductance, R_a is phase resistance, and ψ_f represents the PM flux linkage.

For an in-wheel motor system, the constraints between i_d and i_q are

$$i_d^2 + i_q^2 \leq 3I_p^2 \quad (16)$$

where I_p is the maximum permissible phase current constrained by the controller.

In addition, due to the limited dc voltage U_{dc} , the motor's operational voltage needs satisfy the following condition:

$$U \leq \frac{U_{dc}}{\sqrt{2}} \quad (17)$$

Meanwhile, the electromagnetic torque can be calculated as

$$T_e = p[\psi_f i_q + (L_d - L_q)i_d i_q] \quad (18)$$

For the ORSPM motors, the $i_d = 0$ control is employed to reduce control complexity. The average torque characteristics versus current density under no-load conditions are illustrated in Figure 8, demonstrating that the 54s48p motor has the highest average torque at the same current density. To investigate the ORSPM motor reluctance torque capability, the peak torque characteristics versus current density are shown in Figure 9.

Table 2 presents the corresponding inductances of the proposed ORSPM motors. The motors can generate reluctance torque due to the differences between the d -axis inductance and the q -axis inductance of different slot-pole combinations. The torque characteristics versus the current angle can be observed in Figure 9a. The four ORSPM motors achieve peak average torques at an electrical current angle of 15 degrees, demonstrating that the generation of reluctance torque can be effectively achieved by controlling the current angle.

In addition, compared with the other cases, the 54s48p structure exhibits a relatively higher average torque, as shown in Figure 9b.

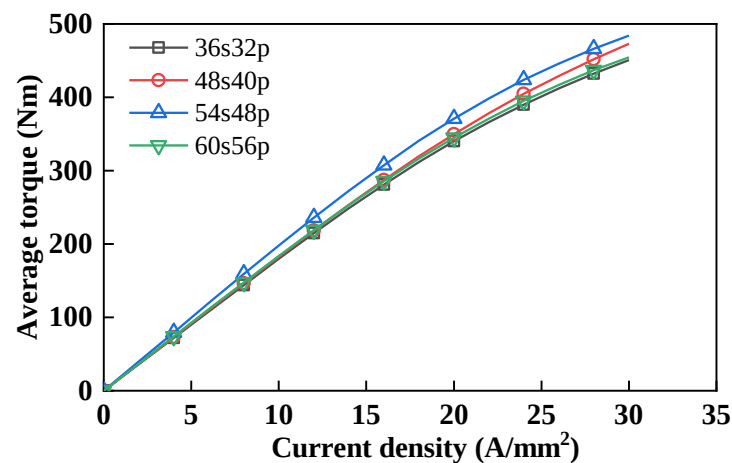


Figure 8. On-load torque versus current density characteristics.

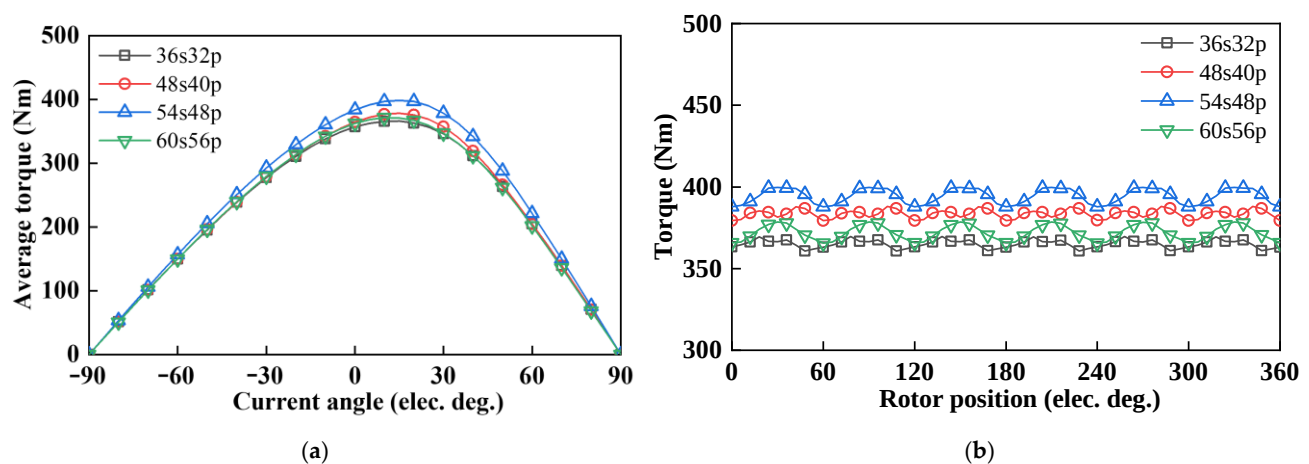


Figure 9. On-load torque characteristics: (a) torque versus current angle; (b) output torque waveform.

Table 2. The d- and q-axis inductance of the four ORSPM motors.

Stator-Pole Combinations	36s32p	48s40p	54s48p	60s56p
L_d , (mH)	0.64	0.40	0.43	0.41
L_q , (mH)	0.89	0.67	0.65	0.58

4.3. Field-Weakening Capability and Efficiency

Due to the DC voltage limitation, it is challenging for PM motors to operate over a wide speed range. Figure 10 illustrates the torque and power characteristics of the proposed motor design. The higher d-axis inductance offsets the PM field through the field-weakening current, expanding the constant power region. Due to the relatively smaller d-axis inductance, the 48s40p structure exhibits a relatively lower field-weakening capability compared with other cases, as shown in Figure 10a. In addition, 36s32p, 54s48p, and 60s54p exhibit a better constant power ability at high speed. Figure 11 presents the efficiency distribution of four ORSPM machine configurations, whose maximum efficiencies are 96.13%, 95.94%, 95.95%, and 95.85%, respectively.

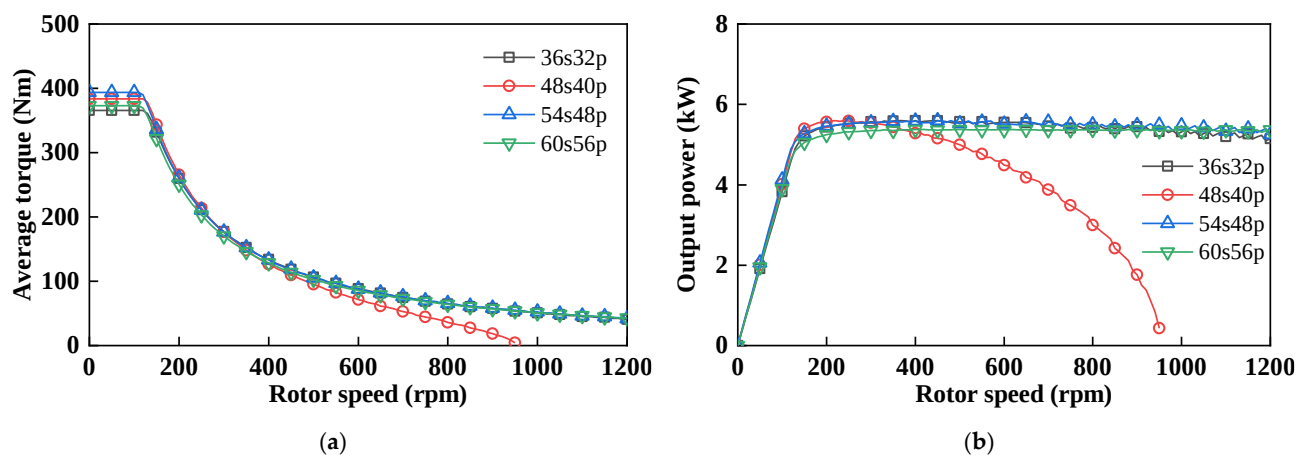


Figure 10. Torque and power characteristics: (a) average torque; (b) output power.

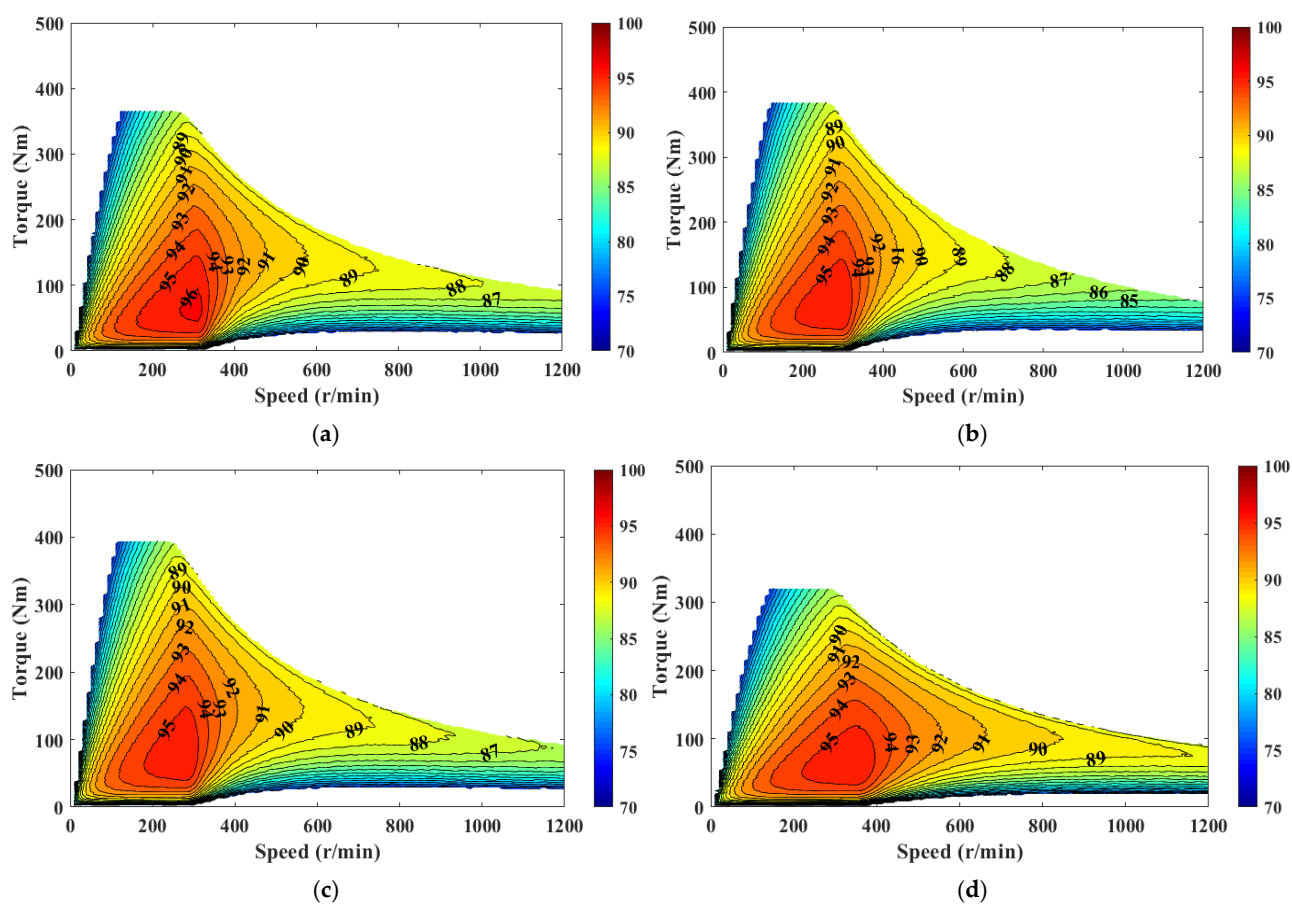


Figure 11. Efficiency maps: (a) 36s32p; (b) 48s40p; (c) 54s48p; (d) 60s56p.

5. Discussion

This paper explores the performance of ORSPM motors applied to in-wheel EVs with different slot–pole combinations. In previous studies, different types of motor topologies have been proposed and their contributions are compared [29–31], as shown in Table 3.

Table 3. Contribution comparison.

Topology	Contribution Comparison
ORSPM in-wheel motor	Investigating the relationship between pole pairs and resultant air-gap flux density and the ORSPM motors with some special pole–slot combinations are built and compared, which demonstrate the 54s48p in-wheel motor has superior electromagnetic performance.
Internal rotor interior PM motor	The electromagnetic performance is compared and analyzed with other three different types of traditional rotor topologies.
Spoke-type PM motor	The respond surface (RS) method and black-hole (BH) algorithm are used to enhance the efficiencies of multi-objective optimization processes.
Outer-rotor PM motor	The comparative analysis of different outer-rotor PM motors designed for in-wheel EV which demonstrates that multi-phase motors exhibit superior electromagnetic properties.
Axial flux PM (AFPM) motor	The AFPM motor is investigated due to its superior torque density characteristics compared with radial flux PM motors.

The comparison of electromagnetic characteristics for various slot–pole combinations is shown in Table 4. The 54s48p configuration exhibits a higher back-EMF amplitude due to reduced tooth saturation and lower flux leakage. The goodness factor for cogging torque is described in [32]

$$C_T = \frac{2p \cdot Q_s}{N_c} \quad (19)$$

where $2p$ is the pole number and Q_s is the slot number, and N_c is the smallest common multiple between $2p$ and Q_s .

Table 4. Comparison of electromagnetic characteristics.

Parameter	36s32p	48s40p	54s48p	60s56p
Back-EMF amplitude(V)	95.5	102.5	105.6	99.8
Cogging peak Torque(Nm)	1.6	3.6	1.1	0.35
Average torque(Nm)	362.5	385.6	396.5	370.3
Maximum efficiency	96.13%	95.94%	95.95%	95.85

The greater the goodness factor, the greater the cogging torque. The 60s56p configuration exhibits lower peak cogging torque due to the smaller goodness factor. As shown in Table 2, the larger salient pole ratio of 54s48p results in additional reluctance torque, leading to a higher average torque. In addition, the maximum efficiency of motors with four different pole–slot combination ORSPM motors can all reach above 95%. Therefore, the overall comparison shows that 54s48p has better electromagnetic properties.

6. Experimental Verification

A 13 kW ORSPM motor with 54s48p was manufactured and tested to verify the above analyses and FEA results. The prototype and test rig are presented in Figure 12. The prototype was dragged by 150 kW PMSM, and the armature winding resistance and inductance were tested by an LCR detector (HIOKI 3522-50 LCR Hitester, HIOKI, Japan).

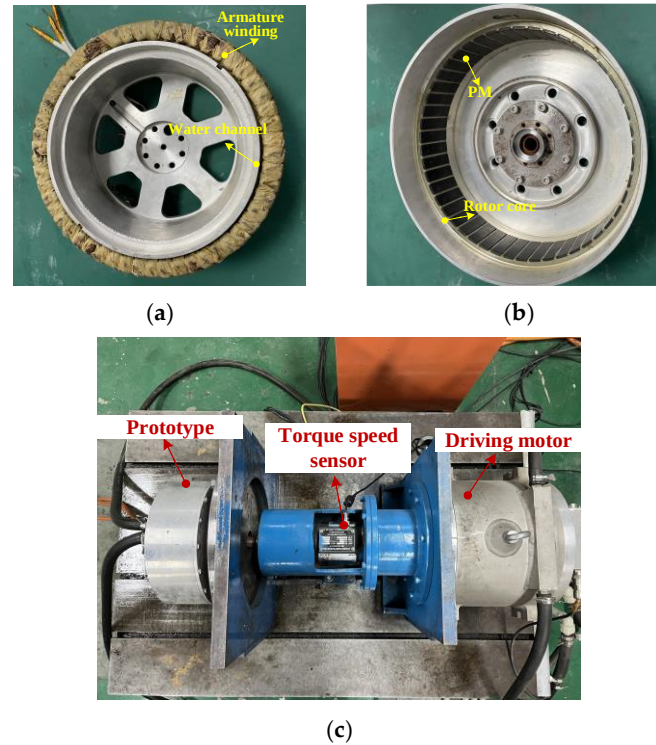


Figure 12. Prototype and test rig: (a) stator and armature windings; (b) PMs and rotor; (c) testing platform.

6.1. No-Load Test

Figure 13 presents the measured back-EMF waveforms at a condition of 400 r/min. The line voltage at 400 r/min under no-load is approximately 129 Vrms, while the corresponding FE prediction value yields 131 Vrms, which shows a good agreement between the FE prediction and the measurement. Figure 14 illustrates the back-EMFs obtained from FE simulations and experimental measurements at different rotor speeds. A minor discrepancy exists between experimental measurements and FE predictions due to the axial flux leakage and manufacturing tolerances inherent in 2D FE simulation.

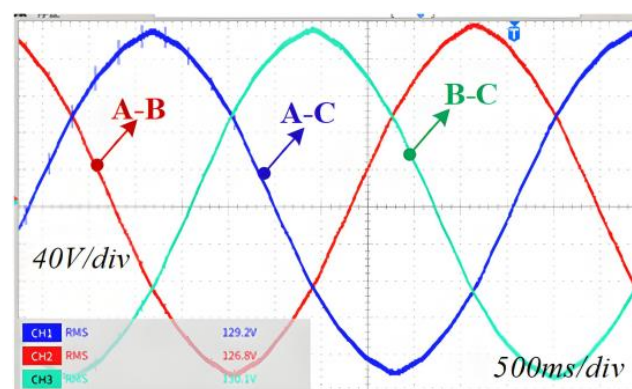


Figure 13. Back-EMF under 600 r/min.

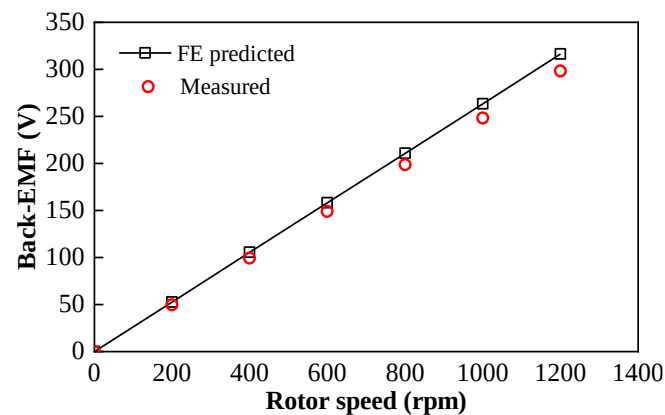


Figure 14. Back-EMFs with different rotor speeds.

The static electromagnetic parameters of the prototype are shown in Table 5. The FE-predicted exhibits a strong correlation with experimental measurements, with an error below 5% for both phase resistance and d- and q-axis inductances at 20 °C.

Table 5. Static electromagnetic parameters of the prototype.

Parameter	FE-Predicted	Tested
Back-EMF coefficient	0.3275	0.3225
Phase resistance (at 20 °C)	0.046 Ω	0.044 Ω
d-axis inductance	0.434 mH	0.431 mH
q-axis inductance	0.655 mH	0.653 mH

6.2. On-Load Test

To confirm the predicted on-load performance, comprehensive testing was carried out to evaluate output torque and operating efficiency. When the phase current is small, the measured average torque is close to the FE-predicted, as shown in Figure 15. However, significant axial flux leakage occurs under overload conditions. The error between the measured torque and the FE-predicted increases significantly as the phase current increases. The torque-speed curve of the experiment is shown in Figure 16. Friction loss and mechanical loss exist in the experiment, which causes a slight deviation between the measurement and FE results. The error increases with the increase in the speed, and the maximum error is less than 5%. The efficiency map is illustrated in Figure 17, revealing that the prototype's maximum efficiency is about 94.6% removing the efficiency of the controller, which is lower compared with the FE-predicted. This efficiency error is less than 3% due to the friction losses and mechanical losses, which confirm the effectiveness of both the theoretical and FE analyses.

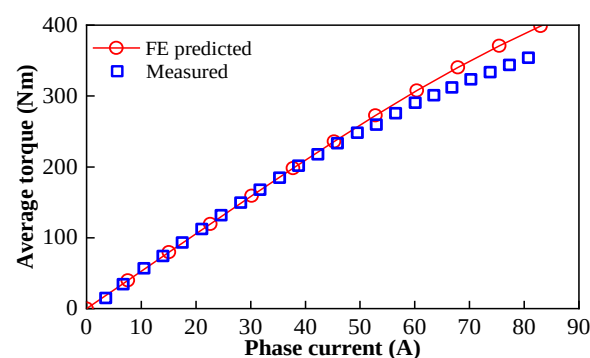


Figure 15. The average torque versus phase current.

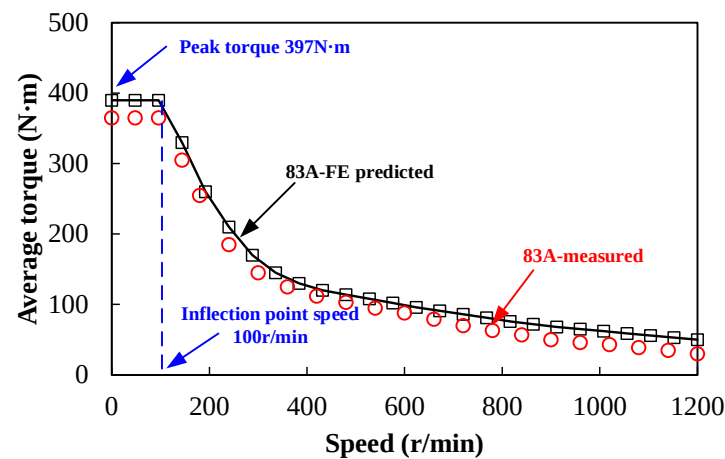


Figure 16. FE-predicted and measured average torque with speed.

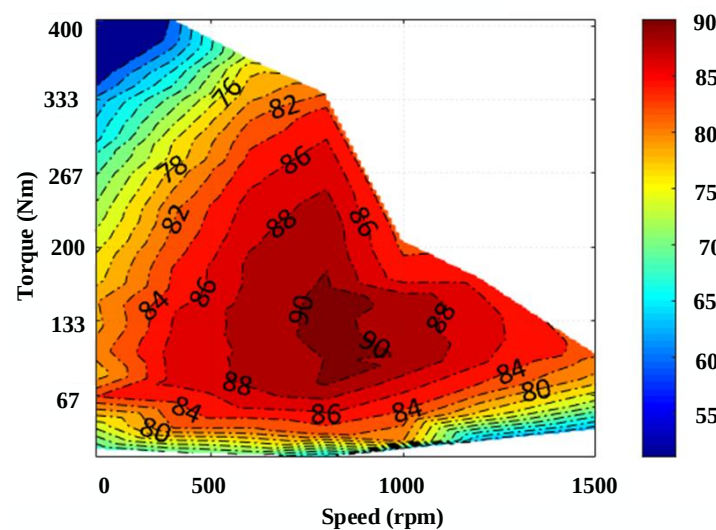


Figure 17. Tested efficiency map of the prototype.

7. Conclusions

This paper presents a comprehensive electromagnetic characteristics analysis of the ORSPM motors with various slot-pole configurations for direct drive system applications. The basic electromagnetic performances, including flux density, average torque, field-weakening capability, and efficiency, are calculated by the FE method, which reveals that the 54s48p configuration achieves optimal characteristics, with the back-EMF amplitude of 105.6 V, the average torque of 396 Nm, and a maximum efficiency of 95.95%. Finally, a 13 kW prototype with 54s48p is manufactured and tested. The strong correlation between experimental measurements and FE predictions validates the effectiveness of the theoretical and FE analyses.

In the future, based on the existing research, we will adopt 3-D FEA to more accurately calculate the electromagnetic performance. Additionally, we will employ multi-objective optimization algorithms to optimize other design parameters of the motor.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

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