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PERFORMANCE EVALUATION OF A BLDC HUB MOTOR FOR TWO-WHEELER EV APPLICATIONS USING FINITE ELEMENT METHOD

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Abstract
This paper presents the design, finite element (FEM) analysis, and performance evaluation of a Brushless DC (BLDC) hub motor tailored for two-wheeler electric vehicle (EV) applications. The motor was modeled using ANSYS RMxprt for preliminary sizing and Maxwell 2D/3D for detailed electromagnetic analysis. Key parameters such as efficiency, torque, cogging torque, and air-gap flux density were evaluated under various operating conditions. A predefined six-step commutation logic based on rotor position signal was implemented in both simulation and experimental testing without the use of speed feedback or controllers. To investigate design optimization, the rotor pole embrace factor was varied from 0.5 to 0.9, and its impact on torque ripple and efficiency was analysed. Experimental validation was also carried out using a two-wheeler EV test bench, and results were compared with simulation outputs. The close agreement between the two confirms the reliability of the simulation model for practical applications.

Keywords: BLDC Hub Motor, FEM, Rotor Pole Embrace Factor, Two-Wheeler EV, Cogging Torque

I. INTRODUCTION

The BLDC hub motor has emerged as a preferred choice for two-wheeler EV propulsion due to its high efficiency [1]. It also offers compact construction and minimal maintenance, making it highly suitable for modern e-mobility [2]. Unlike conventional brushed DC motors, BLDC motors employ electronic commutation, which eliminates mechanical wear and enhances reliability [3]. The hub configuration further integrates the motor directly into the wheel assembly, thereby reducing transmission losses and simplifying the drivetrain [4].
Despite these advantages, optimizing BLDC motor performance requires detailed analysis of cogging torque, electromagnetic losses, and rotor geometry [5]. Among these, the rotor pole embrace factor—defined as the ratio of rotor pole arc to pole pitch plays a significant role in torque smoothness and efficiency [6]. Previous studies on e-bike and scooter hub motors have confirmed that geometry selection strongly influences electromagnetic performance [7]. Simulation tools such as ANSYS Maxwell have been widely applied for accurate prediction of flux distribution, cogging torque, and efficiency [8].
Power converter research has shown that advanced topologies can minimize torque ripple and improve energy conversion [9]. Sensored and sensorless BLDC models developed using MATLAB/Simulink provide effective validation platforms [10]. Furthermore, intelligent controllers including neural networks and adaptive PID schemes have demonstrated improvements in speed control performance [11]. E-bike controller implementations have validated the practical feasibility of these approaches in low-cost applications [12]. Additional MATLAB-based controller design studies have further reinforced the adaptability of BLDC systems in real-world EV platforms [13].
This study focuses on the modelling, simulation, and experimental validation of a BLDC hub motor designed for two-wheeler EV applications, with special emphasis on the impact of rotor pole embrace variation on performance metrics.

II. MODELING AND SIMULATION OF HUB BLDC MOTOR USING ANSYS

The motor design process began with **ANSYS RMxprt** to determine initial dimensions and winding configuration. The stator consists of 48 slots with slot heights Hs0 = 0.5 mm, Hs1 = 1.45 mm, and

Hs2 = 8.2 mm, and slot widths Bs0 = 2.5 mm, Bs1 = 3.0 mm, and Bs2 = 1.5 mm. The rotor has an outer diameter of 120 mm, inner diameter of 74.5 mm, and uses XG196/96 permanent magnets of 3.5 mm thickness with a pole embrace initially set at 0.8.

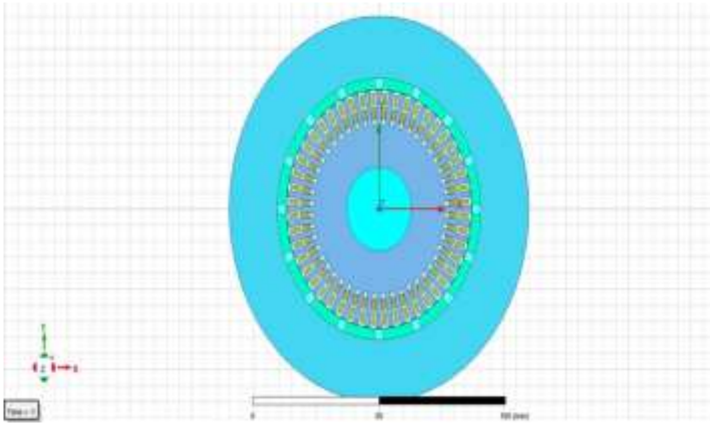

Fig.1 2D Maxwell model of Hub BLDC

The **Maxwell 2D** model depicted in Fig. 1 was used to compute cogging torque, back-EMF, and air-gap flux density, while **Maxwell 3D** model depicted in Fig. 2 captured end effects, eddy current losses, and thermal aspects. Mesh refinement and accurate material properties ensured simulation precision.

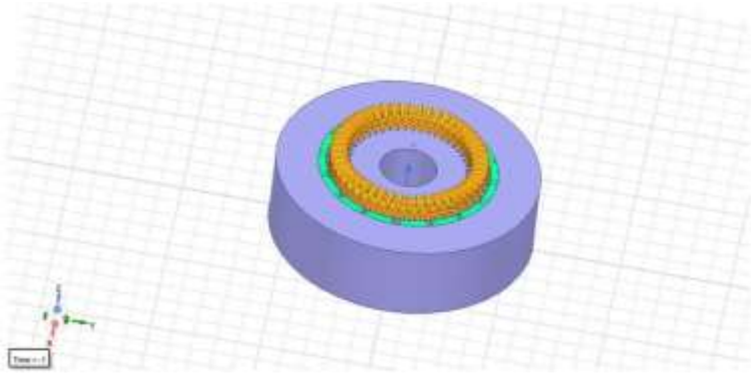

Fig.2 3D Maxwell model of Hub BLDC

Boundary conditions simulated rated voltage operation, and results were obtained for multiple rotor pole embrace values to study their influence on efficiency and torque ripple.

III. MODELING OF CONTROL SYSTEM

A control model was developed in ANSYS Simplorer to replicate the motor drive system. The inverter was modelled as a three-phase voltage source inverter (VSI) with six IGBT switches. Gate pulses were generated using a pre-defined six-step commutation logic based on rotor position signal as represented in Fig. 3.

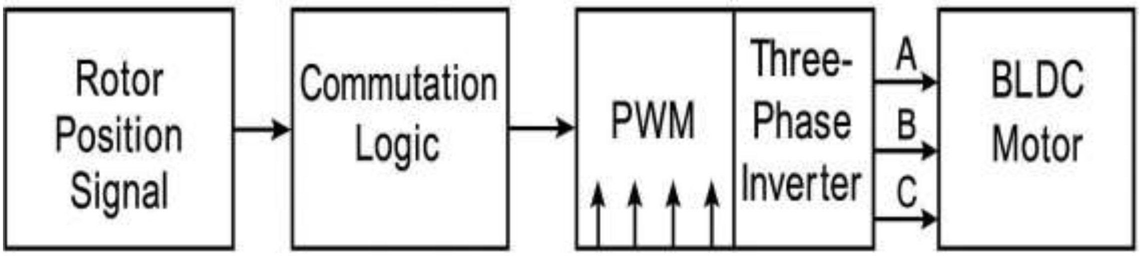

Fig.3 Block Diagram of Rotor Position Signal- Based Commutation Logic

This method ensured that two phases were energized at a time in a fixed sequence, avoiding the need for speed sensors or feedback controllers. The complete Simplorer simulation model of the BLDC hub motor drive system, including inverter, commutation logic, and measurement blocks, is shown in Fig. 4. The control block interfaced with the BLDC motor model to evaluate performance under variable loads.

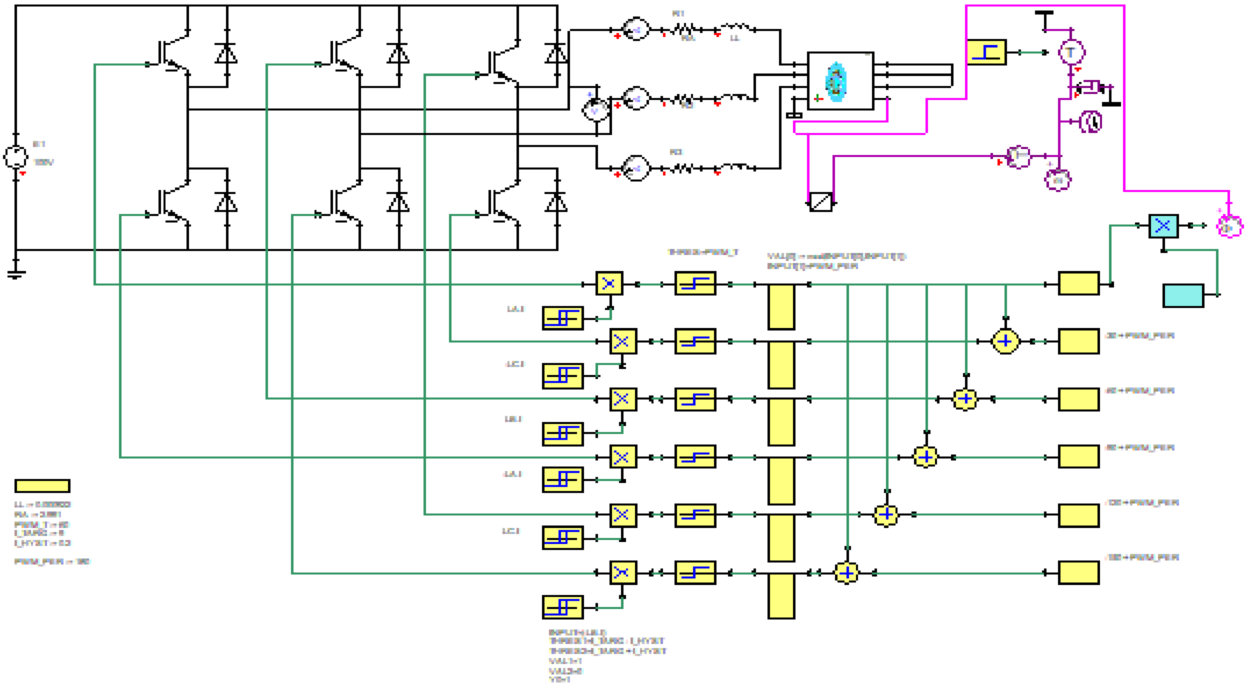

Fig.4 BLDC hub Motor drive and control

IV. ANALYSIS OF BLDC MOTOR PARAMETERS

Simulation runs were performed for pole embrace factors ranging from 0.5 to 0.9. Table-1, presents the variation and systematic analysis parameters such as efficiency, cogging torque, rated torque, current, and flux density.

- **Efficiency**
  The efficiency increased with pole embrace up to ~0.72, reaching a maximum value of ~74.3%. Beyond this point, efficiency plateaued and showed only marginal improvement. This behaviour can be explained by the fact that at lower embrace values (<0.6), the flux linkage between stator and rotor is weak, resulting in poor utilization of input current. As the embrace increases, more of the magnet arc contributes to the air-gap flux, reducing leakage and improving energy conversion. However, once the magnetic circuit approaches saturation, additional magnet arc length does not significantly improve flux linkage, which is why efficiency stabilizes after ~0.72.
- **Cogging Torque**
  The cogging torque reduced drastically from 1.65 Nm at 0.5 to about 0.15 Nm around 0.66–0.68. This is due to improved alignment between rotor poles and stator slots, which reduces the reluctance variation as the rotor moves. However, when the embrace becomes too high (>0.76), more flux interacts with slot openings simultaneously, leading to an increase in torque pulsations. Thus, an optimal range exists (0.66–0.72) where cogging torque is minimized.
- **Rated Torque**
  The rated torque increased steadily with pole embrace and reached ~2.7 Nm around 0.76. At higher embraces, although torque remains high, the waveform becomes more distorted due to ripple. This indicates that while high embrace favours torque, it compromises smoothness.

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Parameter	Min & Max. Values
Cogging Torque	Minimum (~0.15Nm) at embrace 0.66
Efficiency	Maximum (~74.35%) at 0.76–0.78, though flat from 0.7 onward
Rated Torque	Highest at higher embrace values (>0.76), around 2.70 Nm
Input Current	Lowest (~3.336A) around0.7–0.72
Total Losses	Decrease steadily till 0.7, minimum around 0.7–0.74
Air Gap Flux Density	Uniform around 0.440–0.442T for optimized regions

Table-1 Performance Comparison at Different Rotor Pole Embrace Values

These results indicate that the optimal design trade-off occurs between 0.66 and 0.72 pole embrace, balancing efficiency and smoothness. The effect of rotor pole embrace on motor performance is illustrated in Fig. 5, which shows that efficiency increases steadily from 70.9% at 0.5 pole embrace to approximately 74.3% at around 0.72–0.78.

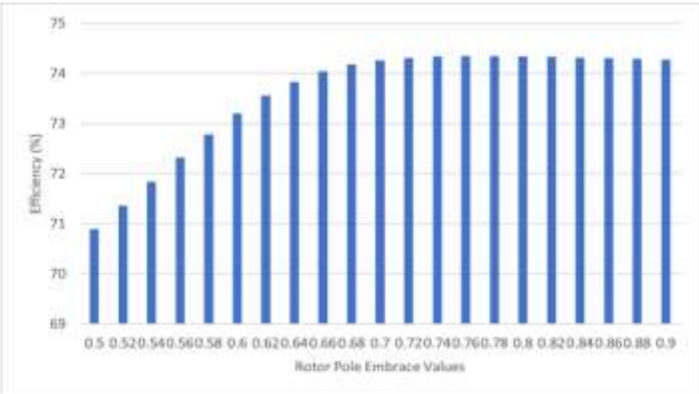


Fig. 5 Efficiency (%) vs Rotor Pole Embrace Factor

Beyond this range, efficiency plateaus, indicating minimal gains for higher embrace values. Fig. 6 compares cogging torque and rated torque over the same range. Cogging torque exhibits a sharp decline from 1.65 Nm at 0.5 to a minimum of approximately 0.15 Nm at 0.66–0.68, after which it rises gradually. Conversely, rated torque increases with pole embrace up to ~0.76, reaching about 2.7 Nm, but shows little improvement afterward.

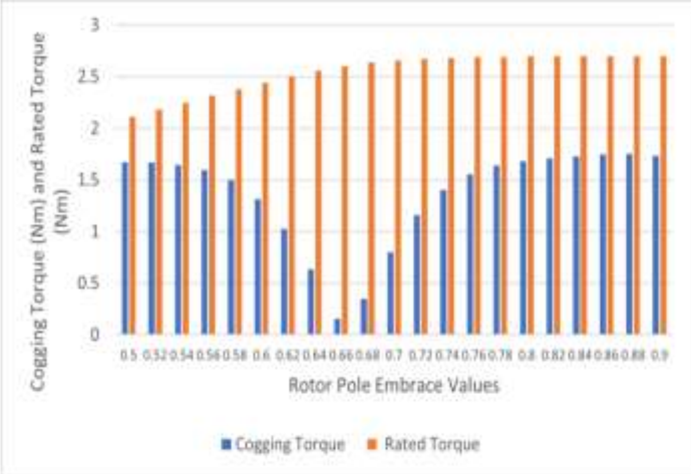


Fig. 6 Cogging Torque and Rated Torque vs Pole Embrace Factor

The cogging torque waveforms for multiple rotor pole embrace values, presented in Fig. 7, further confirm the trend that lower cogging torque amplitudes were observed near the optimal range of 0.66–0.72, while larger values occur for both low and high embraces. This waveform analysis also revealed that torque ripple amplitude increased outside the optimal region, impacting smoothness. These results substantiate the earlier conclusion that a rotor pole embrace between 0.66 and 0.72 offers the best trade-off between efficiency, torque output, and operational smoothness.

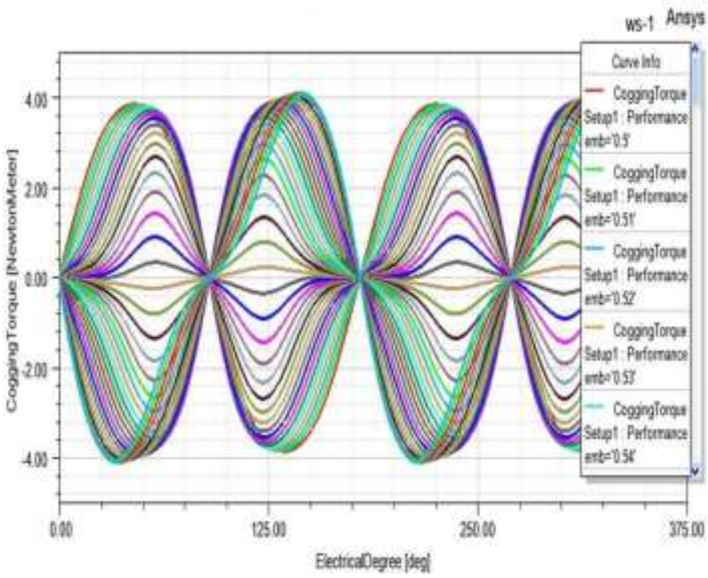


Fig. 7 Variation of Cogging Torque vs Rotor Electrical Angle for Various Pole Embrace Values

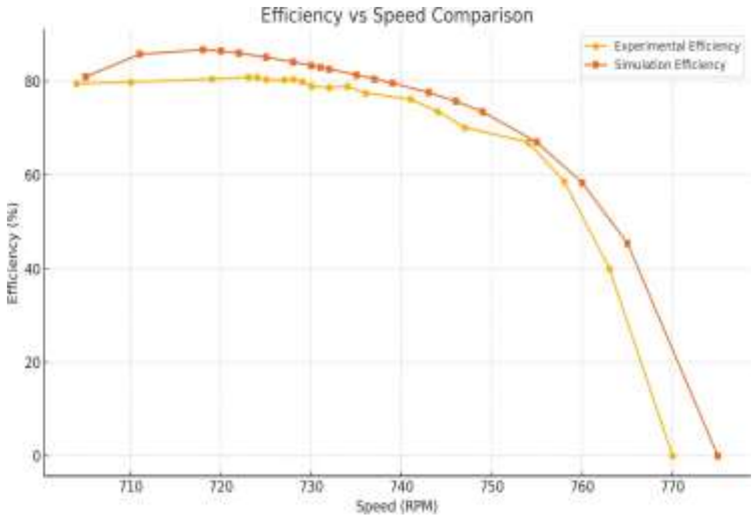
IV. OVERVIEW OF EXPERIMENTAL AND SIMULATION RESULTS

Performance tests were conducted on an EV two-wheeler BLDC hub motor test bench. Key comparisons are:

- **Efficiency vs Speed:**

Both experimental and simulated efficiency curves followed the same trend, peaking near 73–74% around 1300 rpm as depicted in Fig. 8 The close match validates the accuracy of the model. At higher speeds, the experimental efficiency showed a slightly sharper drop. This was due to thermal effects, additional mechanical losses (bearing friction, windage), and increased copper resistance with heating, which were not fully captured in the simulation.

Fig.8 Efficiency vs Speed Comparison



- **Torque vs Speed:**
  The torque output decreased with speed in both cases, as expected for BLDC motors under constant voltage supply as depicted in Fig. 9. However, the torque obtained experimentally was slightly lower at higher speeds. This difference arises from real-world factors such as battery voltage sag under load, inverter switching losses, and iron losses, which the simulation does not fully account for. Despite this, the overall decreasing trend confirms that the simulation successfully predicts the motor behavior.

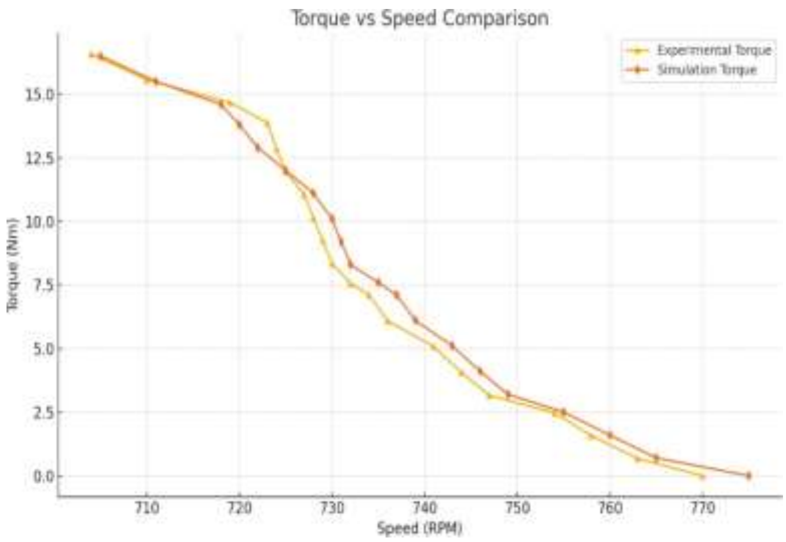


Fig. 9 BLDC Hub Motor Torque Comparison

- **Current vs Speed**

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The simulated and experimental current trends also matched closely, with only minor deviations as shown in Fig. 10. Under heavy load, the experimental current was slightly higher. This is explained by the drop in terminal voltage of the battery and non-ideal switching of power electronics, which forced the motor to draw more current to maintain torque.

The close correlation between the simulated results with the experimental hardware set-up confirms the simulation model's accuracy for real-world prediction.

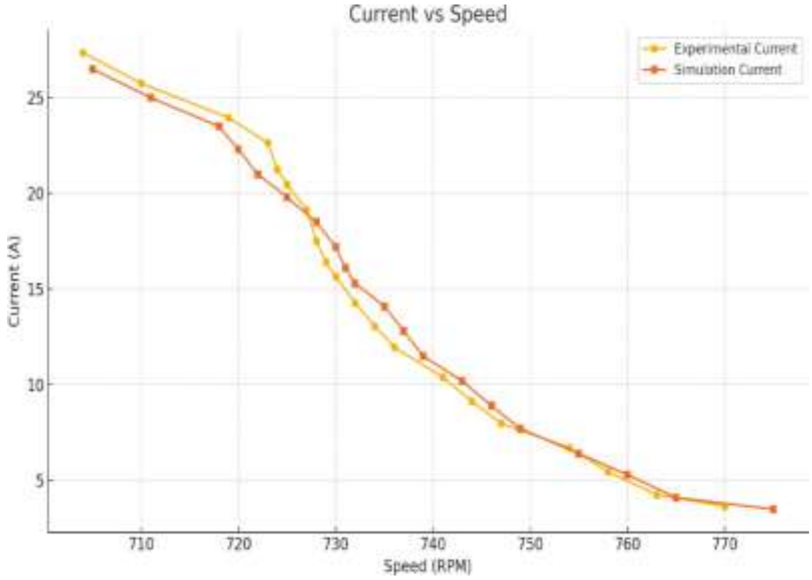

Fig. 10 BLDC Hub Motor Current Comparison

V. CONCLUSION

The presented BLDC hub motor design, modeled and optimized in ANSYS, demonstrates high efficiency and low cogging torque suitable for electric two-wheeler applications. Rotor pole embrace optimization between 0.66 and 0.72 yielded the best balance of efficiency and smoothness. Experimental validation confirmed simulation accuracy, underscoring the value of finite element modeling in reducing development time and cost. Future work could integrate thermal co-simulation and explore alternative magnet materials to further enhance performance.

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