Comparative Evaluation of Low-, Medium-, and High-Fidelity Permanent Magnet Synchronous Motor Models for Electric Vehicle Applications

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Abstract. The comparative evaluation of low-, medium-, and high-fidelity Permanent Magnet Synchronous Motor (PMSM) models is essential for selecting appropriate simulation strategies in electric vehicle (EV) design and analysis. This study investigates the dynamic performance of three PMSM models, each representing a different level of modelling fidelity, implemented in MATLAB/Simulink and subjected to identical operating conditions using a unified control structure. The low-fidelity model achieved the fastest dynamic response (reaching the 3500 RPM reference in 0.30 seconds) but lacked physical detail, making it suitable for rapid prototyping. The medium-fidelity model exhibited performance close to that of the high-fidelity model (reaching the 3500 RPM reference in 0.34 seconds), though with a less smooth start-up, offering a balance between accuracy and simulation efficiency. The high-fidelity model provided the most refined transient response and is better suited for applications involving detailed electromagnetic and thermal behaviour. The findings highlight the importance of aligning model fidelity with application requirements.

1 Introduction

The accelerating global shift toward sustainable mobility has intensified research and development in electric vehicles (EVs). Among the various subsystems in EVs, the powertrain plays a pivotal role in determining overall efficiency, performance, and drivability [1]. At the heart of the powertrain lies the electric motor, with the Permanent Magnet Synchronous Motor (PMSM) emerging as a preferred choice due to its high-power density, efficiency, and torque characteristics [2]. Accurate modelling of the PMSM is thus essential for virtual prototyping, control algorithm development, and performance optimization.

In the context of system-level EV simulations, engineers often face a critical trade-off between model fidelity and computational efficiency. High-fidelity models capture detailed electromagnetic and thermal behaviour but demand significant computational resources [3]. On the other hand, low-fidelity models are computationally inexpensive but may sacrifice critical dynamic behaviour or fail to represent motor performance under real-world load conditions [4]. Medium-fidelity models offer a compromise, incorporating more motor dynamics than basic models while avoiding the full complexity of detailed finite-element representations [5].

Selecting the appropriate fidelity level is not merely a modelling preference, it directly influences simulation turnaround time, accuracy of predicted performance, and suitability for applications such as early-stage design, real-time simulation, or hardware-in-the-loop (HIL) testing. Despite the abundance of PMSM modelling techniques, few studies have systematically evaluated how different fidelity levels perform under realistic EV operating conditions, especially in relation to vehicle type and application-specific needs.

This study presents a comparative evaluation of low, medium, and high fidelity PMSM models, all simulated within the MATLAB/Simulink environment. Using a consistent motor parameter set and test scenario, the study investigates how each model responds in terms of key performance metrics such as speed tracking, torque generation, current profile, and computational load. Simulations are conducted under real-world driving conditions to assess each model's suitability for different EV categories, including urban low-speed vehicles, commercial mid-range EVs, and high-performance electric cars.

By identifying the strengths and trade-offs associated with each fidelity level, this work aims to guide engineers, researchers, and designers in selecting the most appropriate motor model for their specific EV development phase and application domain.

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on PMSM modelling and fidelity trade-offs in EV applications. Section 3 describes the methodology used, including the modelling environment, system architecture, and performance metrics. Section 4 presents and discusses the simulation results across the three fidelity levels.

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Section 5 concludes the paper with insights on model suitability and future research directions.

2 Literature Review

The Permanent Magnet Synchronous Motor (PMSM) has long been recognized for its superior efficiency, torque density, and compact design, making it an optimal choice for electric vehicle (EV) propulsion systems. Foundational works such as those by Boldea and Nasar [6] established early modelling principles for PMSMs, addressing rotor dynamics, magnetic coupling, and control strategies. These models have since been extended to serve various simulation needs, ranging from conceptual design to hardware-in-the-loop (HIL) integration.

2.1 PMSM Modelling Techniques and Fidelity Levels

PMSM models are commonly categorized based on their level of fidelity, with trade-offs between computational cost and modelling accuracy. Low-fidelity models typically use idealized voltage and torque equations under steady-state or simplified dynamic assumptions. These are valuable for conceptual studies and control prototyping where speed is prioritized over precision [7].

Medium-fidelity models integrate essential nonlinearities such as flux linkage variations, saturation effects, and mechanical dynamics, providing more realistic behaviour without extensive computational burden [8]. These models are widely used for system-level simulation and preliminary controller testing.

In contrast, high-fidelity models often incorporate spatial harmonics, iron losses, and temperature-dependent parameters. Some even utilize field-oriented finite element methods (FEM) to capture magnetic saturation and detailed cogging effects [9]. These models are particularly suited for validation, fault analysis, and high-performance control design but demand significantly longer simulation times [9].

2.2 PMSM Modelling in EV Applications

In electric vehicle (EV) applications, Permanent Magnet Synchronous Motors (PMSMs) are commonly modelled using the d–q axis transformation (rotating reference frame), which effectively decouples the stator currents into direct (d-axis) and quadrature (q-axis) components. This approach simplifies the dynamic analysis and facilitates the implementation of advanced control strategies such as Field-Oriented Control (FOC). The mathematical formulation of the PMSM in the d–q reference frame is structured as follows: the electrical dynamics are described by equations (1) and (2), which define the d–q axis voltage equations; the flux linkages are expressed in equations (3) and (4); the electromagnetic torque equations are represented in (5) and (6); the mechanical dynamics of the rotor system are captured in equation (7); and the constraints on maximum stator current and back electromotive force (EMF) are defined in equations (8) and (9), respectively. This structured modelling approach provides a comprehensive foundation for simulating and controlling PMSMs in EV propulsion systems [7].

$$v_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (1)$$

$$v_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \quad (2)$$

$$\psi_d = L_d i_d + \psi_f \quad (3)$$

$$\psi_q = L_q i_q \quad (4)$$

$$T_e = \frac{3}{2} p\left(\psi_d i_q - \psi_q i_d\right) \quad (5)$$

If $i_d = 0$

$$T_e = \frac{3}{2} p\left(\psi_f i_q\right) \quad (6)$$

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \quad (7)$$

$$I_s = \sqrt{i_d^2 + i_q^2} \leq I_{s,max} \quad (8)$$

$$E = p\lambda_m \omega_{s,max} \leq \frac{Vdc}{\sqrt{3}} \quad (9)$$

Where:
v_d and v_q = d–q axis stator voltages
i_d and i_q = d–q axis stator currents
ψ_d and ψ_q = d–q axis flux linkages
R_s = stator resistance
L_d and L_q = d–q axis inductances
ψ_f = permanent magnet flux linkage
ω_e = electrical angular speed
T_e = electromagnetic torque
J = rotor inertia, B = friction coefficient
T_L = load torque, p = number of pole pairs

The d–q axis model of a Permanent Magnet Synchronous Motor (PMSM) directly corresponds to the control architecture used in electric vehicle (EV) motor drive systems, enabling efficient implementation of Field-Oriented Control (FOC) for high dynamic performance and precise torque regulation essential for traction. Additionally, flux-weakening techniques and associated control limits allow safe and efficient operation across a wide speed range, particularly above base speed. MATLAB/Simulink provides a robust simulation environment that supports detailed system-level modelling of the entire EV drivetrain, including the inverter, motor, and vehicle dynamics, making it a powerful tool for design, testing, and optimization of PMSM-based EV propulsion systems.

PMSM modelling for electric vehicle (EV) applications involves capturing the electromechanical dynamics of the motor with sufficient accuracy to enable effective control, efficiency evaluation, and system integration [10]. The d–q axis transformation is central to this process, as it simplifies the three-phase AC system into a two-axis DC equivalent that is easier to analyse and control. The d-axis controls the magnetic flux (aligned with the rotor), while the q-axis governs torque production. This decoupled structure allows for independent control of torque and flux via Field-Oriented Control (FOC), which is the standard technique used in EV inverters to optimize motor response and efficiency. The FOC uses a Park/Clarke transform to convert three-phase currents and voltages into d–q frame and then separate PI controllers to regulate the i_d and i_q, and then, speed PI controller for speed reference. The flux–weakening control is added for operation above base speed by adjusting i_d [11].

In the EV context, PMSMs are operated across a wide range of speeds and torques, often transitioning between constant torque (low speed) and constant power (high speed) regions10. The mathematical model accounts for back electromotive force (EMF), stator resistance, magnetic saturation, and rotor inertia, all of which influence energy efficiency and dynamic performance [10]. MATLAB/Simulink is used extensively to simulate these equations in block-based systems, where control algorithms (like Maximum Torque per Ampere, or MTPA, and flux weakening) can be tested under realistic drive cycles. This modelling approach supports system-level integration with battery packs, inverters, and vehicle dynamics, ensuring that PMSMs meet the high-performance and reliability standards required for modern electric mobility solutions.

2.3 Research Gap

The current body of literature on Permanent Magnet Synchronous Motor (PMSM) modelling in electric vehicle (EV) applications reveals a significant gap in the availability of a unified benchmarking framework [12]. Existing studies tend to focus either on high-fidelity dynamic models or simplified control-oriented representations, often without a standardized method for evaluating these models across a consistent set of performance and computational criteria. Furthermore, variations in testing environments, vehicle parameters, and drive cycles have led to inconsistent assessments, making it difficult for researchers and engineers to objectively determine which modelling approach best suits specific EV categories, such as passenger cars, commercial vehicles, or light-duty electric scooters [13, 14]. While literature exists on custom mathematical PMSM models, the selection of built-in models often lacks quantitative justification. This study aims to bridge that practical gap by presenting a direct, application-oriented benchmarking of three distinct, commercially available Simscape PMSM blocksets. By evaluating these specific models under a unified Field-Oriented Control (FOC) architecture and identical load scenarios, this work provides a highly accessible selection guide for practitioners working within the industry-standard Simulink environment. These models are evaluated under identical vehicle operating scenarios, including acceleration ramps, constant-speed cruising, and regenerative braking across standardized drive cycles such as the WLTP and UDDS. The benchmarking process examines both dynamic performance indicators such as torque response, speed tracking accuracy, and energy efficiency, and computational factors, including simulation speed and numerical stability. By correlating model fidelity with computational demand and EV application type, the study identifies the most appropriate PMSM modelling level for each category of EV. This contributes a structured decision-making tool for researchers and practitioners seeking optimized motor modelling approaches for control design, system simulation, and real-time implementation in electric mobility systems.

3 Methodology

This study compares the dynamic performance of low, medium, and high fidelity PMSM models in the MATLAB/Simulink environment, using consistent motor parameters and control strategies. Each model simulates an EV propulsion system under similar operating conditions and control objectives, enabling a fair evaluation of their responsiveness, accuracy, and computational suitability for different EV applications.

All simulations were performed using MATLAB R2025a and Simulink, with extensive use of Simscape Electrical blocks. A common Field-Oriented Control (FOC) framework was used across all models, incorporating both speed and current controllers to ensure uniform control dynamics

3.1 System Architecture

Each PMSM model was embedded within a complete EV drivetrain simulation architecture as shown in Figure 1. The drivetrain consists of DC Voltage Source (325 V), Average Value Voltage Source Converter (three-phase inverter), PWM Generator (two-level, 10 kHz switching frequency), Voltage-to-Duty Conversion and Gate Control, FOC Speed Controller Subsystem (used for all three models), Mechanical to Electrical Position Conversion, Ideal Rotational Motion Sensor and Torque Sensor, Mechanical Load (via Ideal Torque Source), Scopes for current, torque, rotor position, and speed. The entire system was grounded using Electrical Reference and Mechanical Rotational Reference blocks. Subsystems were grouped into controller logic, power electronics, and PMSM block (model-dependent).

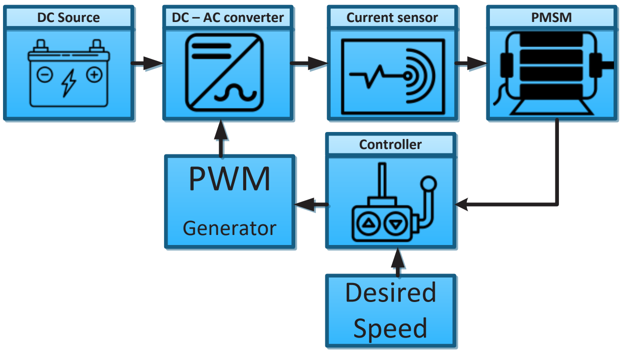


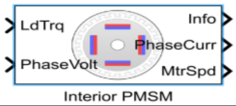
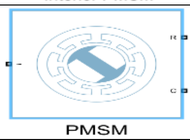
Fig. 1. System architecture

3.2 PMSM Fidelity Models

Each fidelity level used a different motor modelling approach, as shown in Table 1. This is because the low-fidelity block relies strictly on idealized lumped parameters and ignores magnetic saturation, spatial harmonics, and thermal effects, resulting in rapid computation. The medium-fidelity model introduces magnetic saturation and mechanical dynamics, providing a more realistic transient response. Finally, the high-fidelity model integrates FEM-parameterization and lookup tables to capture spatial harmonics, iron losses, and temperature sensitivities, justifying its high-fidelity label due to its advanced physical realism and correspondingly higher computational demand.

A consistent parameter set was used across all fidelity levels, including: Pole Pairs: 8, Stator Resistance Rs: 0.010087 Ω, Inductances: Ld = 243.68 µH, Lq = 297.58 µH, Rated Speed: 1000 RPM, Rated Current: 425 A, Flux Linkage: 0.0440 Wb, Inertia: 0.1243 kg·m², Max Torque: 200 Nm, DC Bus Capacitance: 1 mF, Control Sample Time Ts = 5 µs, Controller Cycle Time Tsc = 100 µs, Reference Speed: 3500 RPM (Note: Operation above the base rated speed of 1000 RPM is achieved via the integrated flux-weakening control scheme).

Table 1. PMSM fidelity description and application.

Model fidelity	Motor block set used	Description	Application
Low		L_d, L_q, R_s, FluxPM, and inertia values directly applied. It ignores iron losses, spatial harmonics, and thermal effects	Fast controller design, early-stage prototyping.
Medium		Accounts for saturation effects and mechanical dynamics. Realistic response to transient loading.	Mid-range EV simulation and control tuning.
High		Lookup tables: i_{dVec}, i_{qVec}, Loss and thermal models, Temperature sensitivity via alpha and alpha_flux, Iron and rotor/stator heat transfer with thermal mass models	High-performance simulation, thermal analysis, fault diagnostics.

3.3 Performance Metrics

The models were compared using the following performance metrics described in Table 2.

Table 2. Model performance metrics.

Metric	Description
Speed Tracking	Ability to reach and maintain desired speed (3500 RPM)
Electromagnetic Torque	Torque ripple and peak value comparison
Phase Current Response	Smoothness and distortion in three-phase waveforms
Rotor Position	Consistency of mechanical to electrical conversion
Computational Realism	Thermal and nonlinear behavior (especially in FEM model)

4 Results and Discussion

This section presents the outcomes from simulating the three PMSM models; low, medium, and high fidelity, under identical operational conditions. All models were evaluated using a common control structure and subjected to the same reference speed and loading scenario. The results, comprising motor speed, electromagnetic torque, three-phase current, and rotor position, are analysed to assess model behaviour, convergence speed, and application suitability.

4.1 Low-Fidelity Model Performance

The low-fidelity model, constructed using the Interior PMSM block, exhibited a prompt and efficient dynamic response. As shown in Figure 2, the low-fidelity model speed reached the reference of 3500 RPM in 0.30 seconds. This was faster than the medium and high-fidelity models (which reached the target at approximately 0.35 seconds), indicating superior computational agility and minimal inertia-induced delay. The current waveform appeared idealized with smooth transitions and symmetry, reflecting the simplified structure of the model which omits nonlinearities and losses. The electromagnetic torque plot demonstrated stable tracking with no visible ripple, while the rotor position progressed linearly over time. These results highlight the low-fidelity model's suitability for rapid prototyping, control development, and system-level design phases where speed is prioritized over physical realism. However, its inability to capture startup transients or account for magnetic saturation and loss components limits its relevance for scenarios involving thermal stress, fault analysis, or detailed efficiency studies.

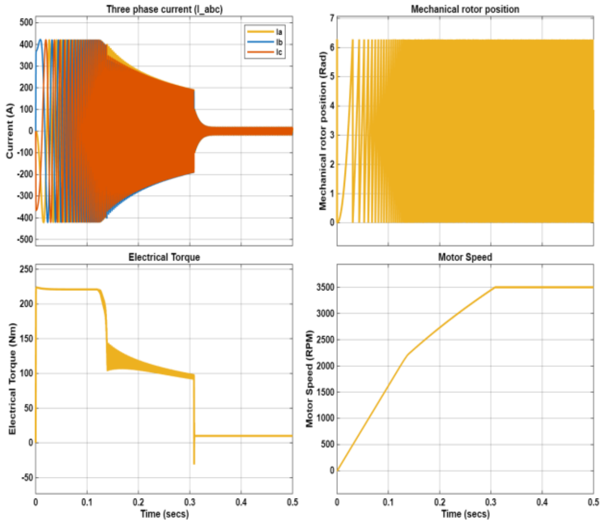


Fig. 2. Low-fidelity result

4.2 Medium-Fidelity Model Performance

The medium-fidelity PMSM model, built using the Simscape Electrical PMSM block, delivered results that closely matched those of the high-fidelity model, particularly in terms of final speed accuracy and current waveform profiles. Figure 3 shows that the motor achieved the 3500 RPM target shortly after the low-fidelity model but slightly before the high-fidelity one. However, the medium-fidelity model displayed a less smooth acceleration phase, with noticeable variations in the speed ramp-up. The torque waveform revealed minor fluctuations during the initial transient, while the current profiles retained their sinusoidal characteristics but with mild irregularities. Although iron loss and thermal ports were not activated in this simulation, the model retains the capacity to incorporate them, offering a flexible trade-off between complexity and accuracy. Its results suggest that the medium-fidelity PMSM model serves as a practical substitute for high-fidelity modelling in most control-oriented applications, especially when simulation speed and modular expansion (e.g., adding thermal effects later) are key considerations.

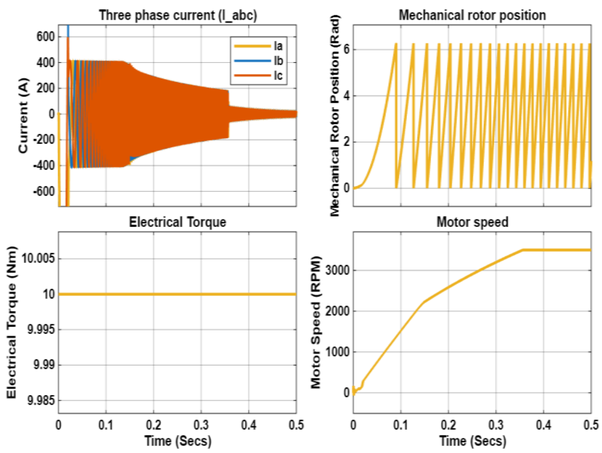


Fig. 3. Medium-fidelity result

4.3 High-Fidelity Model Performance

The high-fidelity model, configured using the FEM-parameterized PMSM block, provided a smoother and more refined dynamic response during the start-up phase compared to the medium-fidelity counterpart as seen in Figure 4. Although it attained the desired speed marginally later than the low-fidelity model, the speed transition was noticeably smoother and free of the jitter observed in the medium-fidelity response.

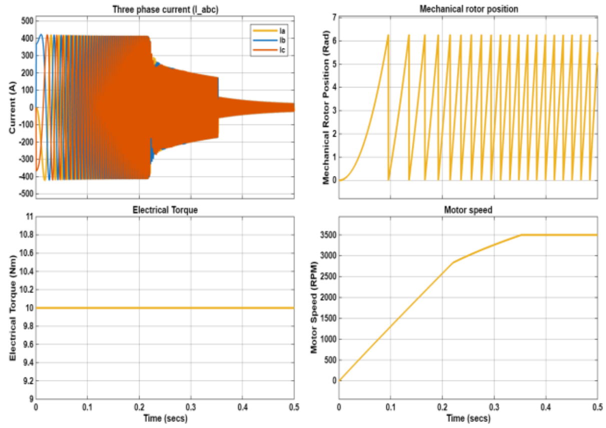


Fig. 4. High-fidelity result

The torque output was steady with low ripple, and the current signals were consistent with those of the medium-fidelity model. Because the scope of this study was restricted to evaluating baseline electromechanical transient behaviour, the ports for iron loss and thermal behaviour were not activated. Consequently, the high-fidelity model did not fully demonstrate its multiphysics potential in this specific simulation. Nonetheless, the structured accuracy of its initial electromechanical response underscores its foundational value for precision-critical studies, establishing a reliable baseline for future work that will activate these temperature-sensitive parameters and advanced diagnostic system. Its main limitation remains the higher computational burden relative to the other models.

4.4 Comparative Summary

All three simulated models reached the target speed of 3500 RPM under identical control and load conditions. However, transient behaviours and start-up smoothness varied. Low-Fidelity Model achieved the fastest response, consistent with typical outcomes in control-prototyping scenarios. As seen in Zhang et al. [9], empirical formula-based PMSM models produce fast simulation speeds while sacrificing transient accuracy. By contrast, Rajesh & Sebasthirani's low-fidelity FOPID-controlled models overshoot less than 5% but do not capture nonlinear effects [14]. Medium-Fidelity Model performed closely to the high-fidelity counterpart, particularly in steady-state accuracy. However, ripples during startup highlight physical effects not present in low fidelity. This aligns with findings from Simscape-based PMSM models that capture saturation but exclude iron losses unless enabled. The high-fidelity model delivered the smoothest and most stable transient response, closely mirroring results reported in the literature for FEM-parameterized PMSM models. For instance, a Simulink model validated against FEA showed torque errors as low as 2 - 4% compared to both finite-element simulations and experimental data, demonstrating high accuracy in transient and steady-state performance [15]. While such models demand higher computational resources, they are preferred when detailed electromagnetic behaviour, saturation effects, and fault dynamics must be accurately characterized. To provide a clearer perspective on the trade-offs between the three PMSM fidelity levels, Table 1 summarizes their key characteristics, simulation behaviours, and suitable application domains.

Table 3. Comparison of low-, medium-, and high-fidelity PMSM models based on simulation behaviour and application suitability.

Fidelity Level	Speed Tracking	Start-up Smoothness	Torque Ripple	Current Harmonics	Computation Time	Use Cases
Low	0.30s rise time	Very smooth	None	Minimal	Minimal	Control prototyping; concept-level studies
Medium	0.34s rise time	Mild ripple	Moderate	Mild distortion	Low–Medium	Commercial EV simulation; extendable with empirical losses, and thermal model.
High	0.34s rise time	Smoothest	minimal	Consistent with Medium-Fidelity	High	Fault diagnosis; thermal and saturation analysis

5 Conclusion

This study presented a comparative analysis of low, medium, and high fidelity PMSM models for electric vehicle applications using MATLAB/Simulink. While all three models produced similar steady-state results under identical conditions, their dynamic responses varied, particularly during startup. The low-fidelity model achieved the fastest speed response but lacked physical realism. The medium-fidelity model offered a good balance between accuracy and computational efficiency, though its startup behaviour was less stable than the high-fidelity counterpart. The high-fidelity model delivered the smoothest transient performance and remains best suited for applications requiring detailed electromagnetic and thermal modelling. Based on these insights, model selection should be guided by application needs, ranging from fast prototyping to advanced diagnostics. As future work, the high-fidelity model will be extended for fault injection studies and integrated with artificial intelligence algorithms to enable predictive fault detection and health monitoring in electric vehicle drivetrains.

This research was supported by the National Research Foundation, South Africa, with grant reference SRUG2205025715.

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