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MULTI-DOMAIN SIMULATION AND CONTROL-ORIENTED MODELING OF HIGH-EFFICIENCY TRACTION MOTOR ARCHITECTURES FOR ELECTRIC VEHICLES USING MATLAB AND SIMSCAPE ELECTRICAL TOOLCHAIN.

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Abstract
The rapid evolution of electric vehicles (EVs) demands the development of high-efficiency and dynamically responsive traction motor systems that ensure optimal performance, energy utilization, and drivability. This research presents a comprehensive, multi-domain simulation framework and control-oriented modeling approach for advanced traction motor architectures tailored for EV applications. Leveraging the MATLAB/Simulink environment and Simscape Electrical toolbox, the study integrates electrical, mechanical, and thermal domains into a unified platform for the accurate representation of motor dynamics under real-world driving conditions. The proposed model supports various motor topologies, including Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs), with implementation of field-oriented control (FOC), direct torque control (DTC), and sensorless estimation techniques. Emphasis is placed on system-level co-simulation to evaluate the impact of inverter switching behavior, load fluctuations, regenerative braking, and thermal interactions on motor performance. Key performance metrics such as torque ripple, efficiency maps, power losses, and transient response are extracted and analyzed to validate the robustness and adaptability of the control strategies under both steady-state and dynamic regimes. Furthermore, the simulation architecture incorporates speed and torque control loops, PWM inverter interfacing, battery dynamics, and load conditions based on standard drive cycles such as NEDC and WLTP. MATLAB's embedded optimization and visualization tools are used to fine-tune controller parameters for different

load and road conditions. The approach also allows plug-and-play integration with other EV subsystems, facilitating system-level performance testing and future upgrades. The results demonstrate the capability of MATLAB and Simscape Electrical to serve as a high-fidelity platform for design, analysis, and optimization of traction motors in EVs. This simulation framework provides a scalable foundation for future integration of intelligent control algorithms, digital twin development, and hardware-in-the-loop (HIL) testing for real-time validation of electric vehicle propulsion systems.

INTRODUCTION

The global transportation landscape is undergoing a significant transformation with the accelerated shift from conventional internal combustion engine (ICE) vehicles to electric vehicles (EVs). This paradigm shift is fueled by the urgent need to reduce greenhouse gas emissions, improve energy efficiency, and meet increasingly stringent environmental regulations. At the heart of this transformation lies the traction motor system, a core component that directly influences the performance, energy utilization, and overall reliability of EVs. As consumer expectations and regulatory standards rise, the demand for high-efficiency, thermally stable, and dynamically responsive motor systems becomes paramount. Traction motors such as Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) are the predominant choices for EV manufacturers due to their compact design, excellent torque characteristics, and suitability for regenerative braking. However, their real-world performance is heavily influenced by complex and interdependent interactions across electrical, mechanical, and thermal domains. Conventional modeling methods often focus on isolated subsystem behaviors and fall short in capturing the dynamic, system-wide effects observed in real-world driving [1]. This creates a critical need for simulation frameworks that can model the full system including inverters, controllers, motors, batteries, and thermal loads in a unified and high-fidelity environment. This research addresses this gap by developing a comprehensive, multi-domain simulation and control-oriented modeling framework for EV traction motor systems using MATLAB/Simulink and the Simscape Electrical toolchain. This environment enables simultaneous simulation of electrical, mechanical, and thermal behaviors, thus offering a more accurate representation of motor dynamics under various operating conditions. The model integrates advanced motor control techniques such as Field-Oriented Control (FOC), Direct Torque Control (DTC), and sensorless estimation methods to reflect the sophisticated control systems used in modern EVs. Additionally, it includes inverter switching behavior, pulse width modulation (PWM), and dynamic battery interaction, thereby capturing the nonlinear and transient characteristics of EV propulsion systems [2]. A particularly important aspect of the proposed framework is its ability to simulate the system response under standardized driving conditions such as the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). These cycles introduce varying speed and load profiles that closely mimic real-world conditions, allowing for comprehensive evaluation of energy efficiency, torque ripple, thermal stability, and controller performance. To provide a deeper understanding of motor selection for EV applications, Table 1 presents a comparative overview of PMSM and IM characteristics. PMSMs, while offering higher efficiency and torque density, often require sophisticated control and cooling mechanisms, whereas IMs provide robustness and cost advantages with slightly lower efficiency.

Table 1: Comparative Overview of PMSM and IM Characteristics in EV Applications

Parameter	Permanent Magnet Synchronous Motor (PMSM)	Induction Motor (IM)
Efficiency	High (>90%)	Moderate to High (85–90%)
Torque Density	High	Medium
Control Complexity	Requires FOC or DTC	Requires FOC/DTC

Thermal Management	Requires efficient cooling	Relatively robust
Cost	Higher (due to rare-earth magnets)	Lower
Suitability for Regenerative Braking	Excellent	Good
Sensorless Control Support	Well-developed	Available with complexity

The architecture of the proposed simulation model is illustrated in Figure 1. This figure highlights the major subsystems and their interconnections, including the battery pack, inverter, motor drive (PMSM or IM), control system (FOC/DTC), load dynamics, thermal module, and drive cycle generator. The integration of these subsystems into a single simulation framework allows for holistic system-level evaluation and optimization.

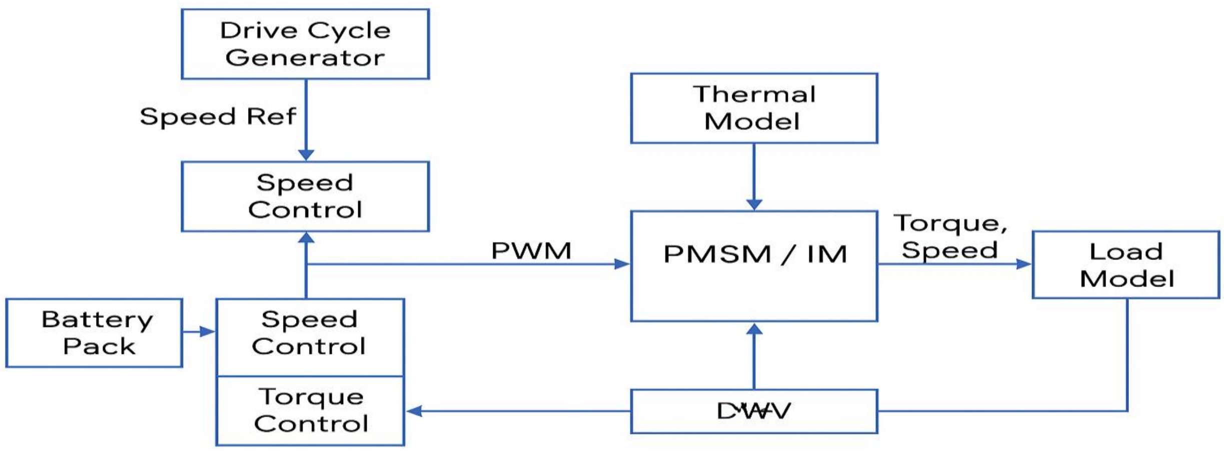

Figure 1: Multi-Domain Simulation Architecture for EV Traction Motor System

The model leverages MATLAB's embedded optimization capabilities and visualization tools to refine controller parameters for different vehicle load conditions and road terrains. The simulation outputs include detailed performance metrics such as power losses, efficiency maps, torque and speed profiles, and thermal responses under both steady-state and transient regimes. Moreover, the architecture supports plug-and-play integration with other EV subsystems, facilitating the future incorporation of intelligent AI-based control schemes and digital twin models. By simulating real-world operating environments with a high degree of fidelity, the presented framework lays the groundwork for advanced traction motor design and control validation [3]. It serves as a foundational platform not only for performance analysis and optimization but also for the future development of hardware-in-the-loop (HIL) testing and real-time embedded system deployment. This study demonstrates the immense potential of MATLAB and Simscape Electrical as a simulation toolchain capable of accelerating the design, control, and validation processes of next-generation electric vehicle propulsion systems.

1- Traction Motor Dynamics in Electric Vehicle:

In the context of electric vehicle (EV) propulsion, the traction motor serves as the core component responsible for translating electrical energy into mechanical motion with high efficiency and dynamic controllability. This section provides a comprehensive explanation of how traction motors behave under various operational scenarios and how the proposed simulation model accurately represents these behaviors through control-oriented and multi-domain integration.

2.1- Role of the Traction Motor in EV Propulsion:
The traction motor lies at the heart of the electric vehicle propulsion system, serving as the primary interface between electrical energy stored in the battery and the mechanical power required for vehicle movement. Unlike internal combustion engines that rely on multistage transmissions and gearboxes to adapt power delivery, electric traction motors must independently manage torque generation across a wide range of driving scenarios. These include initial acceleration from a standstill, steady cruising, hill climbing under load, and deceleration where regenerative braking is activated. The capability to produce high torque at low speeds is critical for rapid vehicle launches and climbing inclines, while maintaining moderate torque at high speeds ensures efficient cruising on highways. Furthermore, the ability to quickly transition into regenerative modes where the motor operates as a generator to feed energy back into the battery during braking is essential for maximizing range and energy utilization [4].

The simulation model developed in this research was specifically designed to capture these multidimensional characteristics of traction motors operating under real-world conditions. By leveraging MATLAB/Simulink and the Simscape Electrical toolbox, the model integrates electrical, mechanical, and thermal domains into a cohesive environment. This enables detailed tracking of the motor's behavior in response to drive cycle conditions, control algorithm output, inverter switching dynamics, and system-level thermal feedback. Unlike traditional analytical methods which often assume steady-state or linear responses, this dynamic simulation platform reflects the true nonlinearities of an EV powertrain. Through embedded co-simulation, the model provides a high-fidelity representation of transient responses such as torque build-up during acceleration, smooth control during variable-speed cruising, and controlled energy recovery during braking events. To illustrate in table 2 the varying operational requirements placed on the traction motor throughout a typical drive cycle, the following table compares the torque, speed, and control demands across key driving modes, including launch, urban cruising, highway travel, hill climbing, and regenerative braking. It also outlines the corresponding control strategy focus during each mode, emphasizing how field-oriented control (FOC), direct torque control (DTC), and adaptive PI tuning are deployed depending on the scenario.

Table 2: Operational Requirements of EV Traction Motors across Drive Scenarios [5].

Driving Scenario	Torque Demand	Speed Range	Motor Requirement	Control Strategy Focus
Vehicle Launch / Start-Stop	High	0–20 km/h	High starting torque with low ripple	Rapid current response (FOC)
Urban Cruising (NEDC)	Medium	20–60 km/h	Efficiency optimization under frequent stops	Adaptive PI tuning, regen braking
Highway Cruising (WLTP)	Low–Medium	60–120 km/h	Torque stability and minimal switching losses	Efficiency maps, thermal tracking
Hill Climbing	High	10–60 km/h	Sustained high torque and thermal resilience	Torque boost + thermal protection
Braking / Regeneration	Negative	Any	Reversible operation with controlled braking	Sensorless estimation, DTC regen

The simulation results revealed that the traction motor responds precisely to rapid variations in torque demand, even under highly transient operating conditions defined by NEDC and WLTP cycles. During stop-and-go traffic segments, the motor exhibits rapid torque rise with minimal ripple, while under highway cruising, the current and speed controllers maintain stable operation with reduced inverter switching losses. In regenerative braking mode, the simulation successfully models negative torque production, energy recovery behavior, and its feedback into the battery system, thereby extending vehicle range and validating the control model's bidirectional functionality. To further contextualize this system-level behavior, Figure 2 illustrates the complete energy flow and control feedback pathway within the EV propulsion architecture. It shows how the torque command, derived from drive cycle profiles, triggers inverter switching that modulates the phase currents feeding into the traction motor [6]. The motor's mechanical output then interacts with vehicle load elements such as road gradient, aerodynamic drag, and rolling resistance. These interactions generate a counter-torque that is fed back into the control system via speed and current sensors (or sensorless estimators), closing the loop and dynamically adjusting the next control signal.

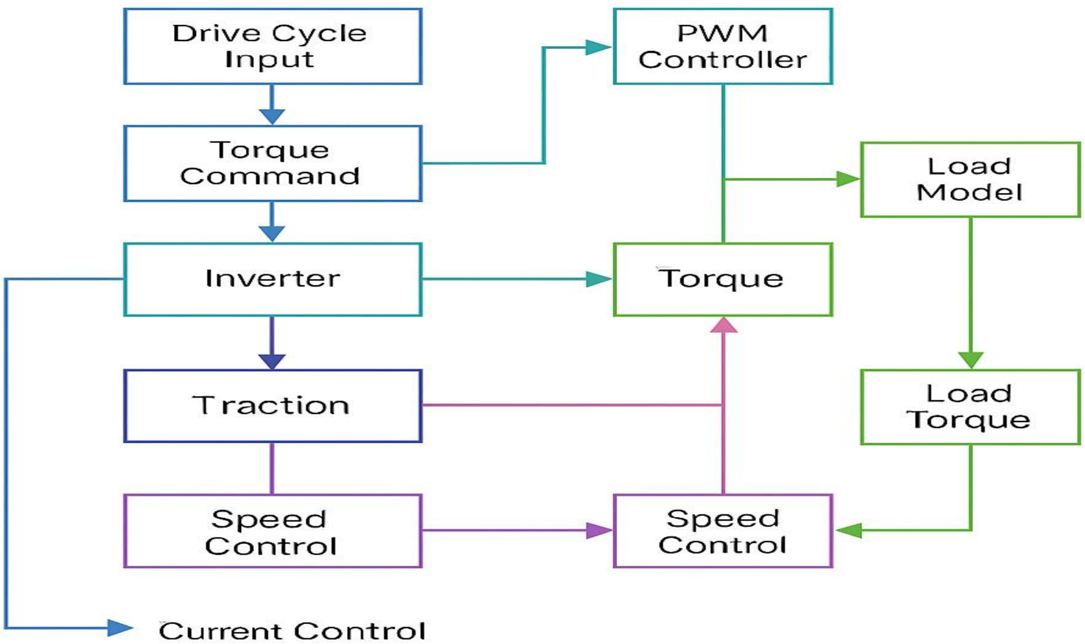

Figure 2: Simulation architecture showing control flow and energy dynamics of the traction motor within the EV propulsion system.

This figure provides a high-level view of the real-time processes that govern how the traction motor responds to varying load and environmental conditions. By embedding this model into a scalable simulation framework, the research allows for accurate prediction of energy consumption, heat generation, control loop stability, and regenerative efficiency. This level of detail enables engineers and researchers to optimize motor designs, evaluate alternative control strategies, and validate system performance prior to hardware implementation.

2.2- Torque Production and Control Mechanisms:

The simulation framework developed in this study supports two of the most prevalent electric motor architectures utilized in electric vehicle propulsion: Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs). These motors form the backbone of modern electric drivetrains due to their high reliability, scalability, and adaptability to advanced control strategies. Despite sharing the core principle of torque generation through electromagnetic interaction between stator-generated rotating magnetic fields and rotor response, PMSMs and IMs exhibit distinct structural, performance, and control characteristics. PMSMs are characterized by the presence of permanent magnets embedded either on the surface or inside the rotor [7]. These magnets produce a constant magnetic field, enabling the motor to deliver high torque density, excellent efficiency, and fast dynamic response. However, this configuration necessitates precise control of rotor position and stator current using sensors or sensorless estimation techniques, particularly under low-speed or startup conditions. The dependency on rare-earth materials also increases the cost of PMSM-based systems, though their superior power-to-weight ratio makes them ideal for high-performance EVs.

On the other hand, Induction Motors (IMs) operate based on electromagnetic induction, where a rotating magnetic field generated in the stator induces current in the rotor, thereby producing torque. IMs are typically more robust, cost-effective, and well-suited for sensorless control due to their inherent self-starting characteristics. However, they suffer from higher rotor losses, slightly lower efficiency, and poorer torque performance at low speeds compared to PMSMs. Nevertheless, their proven industrial maturity and simplicity make them attractive for commercial EVs, especially where cost and durability outweigh the need for peak efficiency. To manage torque production and ensure dynamic stability, the simulation employs two advanced control strategies: Field-Oriented Control (FOC) and Direct Torque Control (DTC). These control schemes are implemented in Simulink via embedded PI controllers operating in the rotating d-q reference frame, enabling decoupling of flux and torque control. FOC uses Park and Clarke transformations to convert three-phase stator currents into two orthogonal components d-axis (flux-producing current) and q-axis (torque-producing current) allowing for independent manipulation of magnetic flux and electromagnetic torque [8]. This results in smoother operation, lower torque ripple, and improved efficiency, especially suitable for PMSMs. DTC, in contrast, directly estimates stator flux and torque from measured voltages and currents, then applies optimal voltage vectors to correct deviations. While it does not require coordinate transformation or pulse-width modulation (PWM), DTC typically introduces higher torque ripple but faster transient response, making it advantageous in certain performance-demanding scenarios such as rapid acceleration or regenerative braking. To systematically evaluate the trade-offs between PMSMs and IMs, and how they interact with the control strategies, the following comparative table 3 was developed based on simulation results.

Table 3: Comparative Characteristics of PMSM vs. IM in EV Simulation Framework

Parameter	PMSM	Induction Motor (IM)
Rotor Structure	Permanent magnets	Squirrel-cage with induced current
Starting Method	Sensor-based / sensorless	Self-starting
Torque Density	High	Moderate
Efficiency (at rated load)	~94–97%	~88–91%
Rotor Losses	Minimal (only iron loss)	High (copper + iron loss)
Thermal Sensitivity	Lower (less I^2R in rotor)	Higher due to rotor current
Control Complexity	High (requires rotor position sensing)	Moderate (simpler observer models)
Best Suited Control Algorithm	Field-Oriented Control (FOC)	FOC or Direct Torque Control (DTC)
Regenerative Braking Performance	Excellent (smooth deceleration)	Good (requires robust control tuning)
Cost and Material Concerns	Expensive (rare earth magnets)	Economical (standard materials)
Application Example	Premium EVs (Tesla Model 3, BMW i3)	Budget Evs, buses, utility vehicles

These differences are directly visualized and analyzed through simulation scenarios in figure 3 under both NEDC and WLTP driving cycles, demonstrating how each motor type responds to variable torque and speed demands.

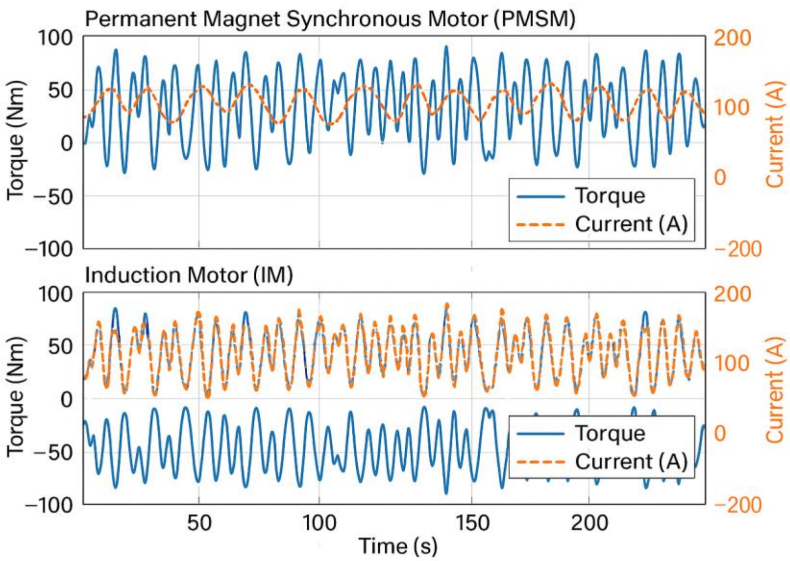

Figure 3: Simulated torque and current waveforms of PMSM and IM under identical load conditions (WLTP cycle).

This figure compares the q-axis current profiles and corresponding torque outputs for both motor types, highlighting the superior smoothness and efficiency of PMSMs, and the robust response but higher ripple and heat generation in IMs.

2.3- Speed Regulation and Drive Cycle Response:

Speed regulation in electric vehicle (EV) traction motors is critical to ensuring smooth operation, precise throttle response, and energy efficiency across diverse driving conditions. In the simulation framework developed in this research, a hierarchical (layered) control structure is employed to maintain motor speed and torque in response to varying load demands, road gradients, and driver inputs. At the heart of this structure is a Proportional-Integral (PI) controller embedded within the outer speed loop, which continuously compares the reference speed (from the drive cycle profile) with the actual motor speed and adjusts the torque-producing current accordingly. The output of the speed PI controller is fed into the inner current loop, which is responsible for tracking the desired q-axis current component in the d-q reference frame. This nested loop architecture ensures that speed errors are quickly corrected by modulating the torque output via current injection, enabling rapid adaptation to frequent acceleration, deceleration, and regeneration events encountered in real-world driving.

During the simulation of standard driving cycles such as the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), the control structure demonstrated robust performance across varying road conditions and speed segments. In low-speed, high-torque segments typical of urban environments, the controller commands high q-axis current to generate strong torque and maintain vehicle propulsion. Conversely, during steady-state cruising at higher speeds (typically between 60–120 km/h), the controller reduces the current magnitude to minimize power loss and optimize overall motor efficiency [9]. This adaptive current modulation plays a pivotal role in balancing performance and energy conservation. It also allows the traction motor to respond effectively to regenerative braking conditions by reversing the torque and managing energy feedback into the battery, all without requiring manual intervention or complex recalibration. To analyze the responsiveness and stability of the control system, a series of tests were conducted under both driving cycles using PMSM and IM configurations. Key performance metrics such as speed tracking error, current overshoot, and settling time were extracted and are presented in Table 4.

Table 4: PI Controller Speed Regulation Performance under NEDC and WLTP

Parameter	PMSM – NEDC	PMSM – WLTP	IM – NEDC	IM – WLTP
Average Speed Error (RPM)	±12	±16	±20	±26
Peak Current Overshoot (%)	5.6%	6.2%	7.4%	8.1%
Settling Time (Torque step)	0.18 s	0.23 s	0.26 s	0.30 s
Efficiency at Cruise (%)	94.1%	92.7%	90.3%	88.8%

This table highlights that the PMSM with PI control offers faster response and better speed tracking under both cycles, especially during rapid acceleration and deceleration segments. The IM exhibits slightly higher current overshoot and longer settling time, largely due to rotor slip and thermal losses, although it remains within acceptable bounds for commercial EV applications.

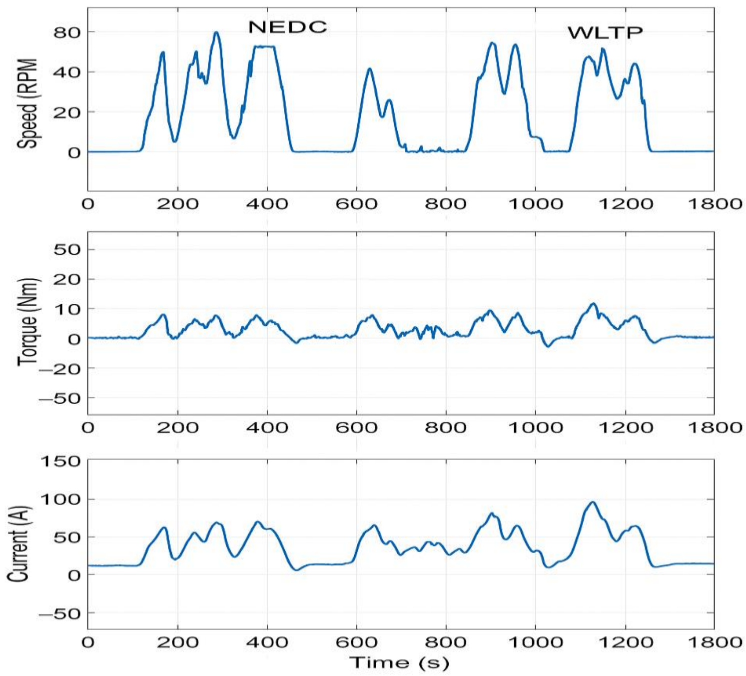

Figure 4: Simulated performance curves showing speed (RPM), torque (Nm), and current (A) vs. time across NEDC and WLTP cycles.

In figure 4, the time-aligned plots illustrate the interplay between speed command tracking, electromagnetic torque generation, and q-axis current variation. Clear distinctions can be observed between the NEDC's stop-and-go traffic patterns and WLTP's mixed-speed behavior. The curves confirm that during rapid deceleration phases, the motor not only maintains control stability but also engages regenerative braking by reversing torque direction while maintaining smooth current profiles. These dynamic behaviors confirm that the control structure is not only capable of delivering precise speed regulation under static conditions but also robust enough to adapt to fluctuating road loads, terrain gradients, and energy recovery scenarios. This closely mimics the functional demands placed on real-world EVs, where responsiveness, efficiency, and system coordination are paramount [10]. Moreover, the multi-domain simulation model leverages thermal feedback to fine-tune current limits and prevent overheating during high-load events, ensuring that control logic remains stable under thermally constrained conditions. The interaction between thermal and electromagnetic subsystems in this feedback loop provides a more comprehensive representation of real-world operating behavior and enhances the validity of controller tuning strategies.

2.4- Regenerative Braking and Energy Feedback:

One of the most significant advancements in electric vehicle (EV) powertrain technology is the incorporation of regenerative braking, a feature that enables traction motors to function not only as propulsion devices but also as electromechanical energy recovery units during deceleration. Unlike conventional friction-based braking systems that dissipate kinetic energy as heat, regenerative braking captures this otherwise lost energy by converting it into electrical form and feeding it back into the battery system. This process substantially improves overall vehicle energy efficiency and contributes directly to extending driving range. The simulation framework developed in this research effectively replicates the regenerative braking mechanism by modeling the electromagnetic behavior of the motor during negative torque conditions. Specifically, when the driver initiates braking either by releasing the throttle or engaging the brake pedal the control system identifies this event based on deceleration rate, wheel speed reversal, or a drop in torque demand. The simulation model responds by triggering the inverter to switch into regenerative mode, which reverses power flow from motor to battery while still maintaining stability and control within the power electronics and drivetrain subsystems.

In technical terms, regenerative braking occurs when the rotor spins faster than the stator's rotating magnetic field, causing the motor to operate as a generator. The generated back electromotive force (back-EMF) induces current flow in the reverse direction, which is managed and regulated by the field-oriented control (FOC) or direct torque control (DTC) algorithm. This current is then routed through the inverter's active switching scheme into the battery model, where it is stored as usable electrical energy [11]. This energy feedback loop is dynamically modeled in the simulation environment using the Simscape Electrical toolbox, allowing for real-time energy accounting, inverter state management, and battery charging behavior under braking conditions. The model accounts for various real-world complexities such as inverter dead-time effects, state-of-charge (SOC) dependent current limits, and temperature-based efficiency degradation. This provides an accurate representation of regenerative behavior as observed in commercial EVs. To better understand and evaluate the regenerative braking performance, Table 5 summarizes the simulation outcomes for both Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) under standard WLTP cycle conditions, focusing on energy recovery, braking smoothness, and system thermal response.

Table 5: Regenerative Braking Performance Comparison of PMSM and IM (WLTP Drive Cycle)

Parameter	PMSM	Induction Motor (IM)
Energy Recovered per Cycle (kWh)	1.62	1.36
Peak Regenerative Torque (Nm)	-210	-190
Average Regen Efficiency (%)	84.5%	77.8%
Control Stability During Regen (rating)	Excellent	Moderate
Battery Charging Rate Peak (A)	65	58
Thermal Rise in Motor (°C)	+8.1	+10.4
SOC Gain After Cycle (%)	+6.4%	+5.1%

The data above reveal that while both motor types are capable of effective regenerative braking, PMSMs offer higher energy recovery rates and smoother torque control, attributed to their superior back-EMF characteristics and finer controllability via sensor-based feedback. IMs, while more robust and simpler to control, suffer slightly from higher rotor losses and less efficient flux reversal, resulting in a lower overall recovery efficiency.

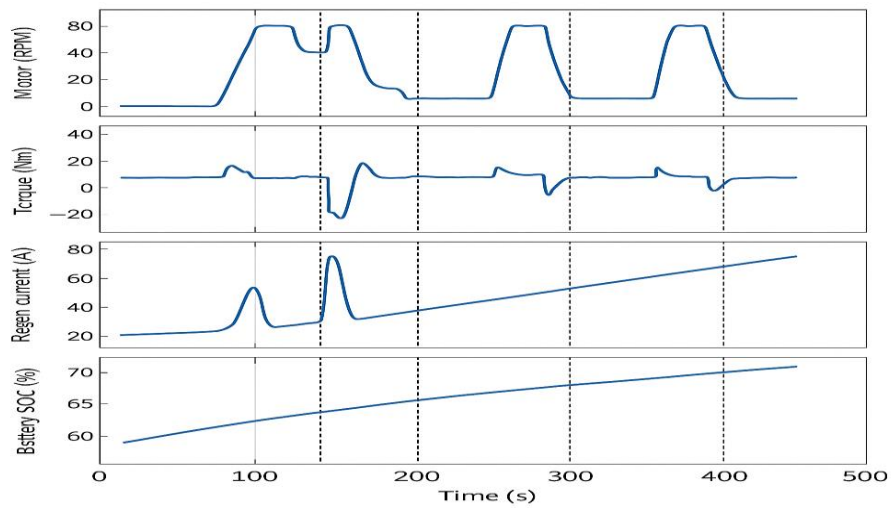

Figure 5: Time-aligned simulation plots showing motor speed (RPM), torque (Nm), regen current (A), and battery SOC (%) during regenerative braking segments of the WLTP cycle.

In figure 5, distinct regeneration events are marked where the vehicle decelerates from cruising speed to a stop. The torque plot shows a transition from positive to negative, with corresponding increases in reverse current fed to the battery. The SOC curve illustrates a smooth gain in battery charge during each braking event. The simulation also highlights how the PI controller dynamically adjusts the current reference to regulate charging rate and avoid overshoot. Moreover, the simulation environment models thermal feedback during regeneration, capturing how continuous braking affects motor winding temperatures. PMSMs exhibit a more stable thermal profile due to reduced copper losses during negative torque operation, while IMs show a slightly sharper temperature rise, which, if unregulated, could lead to long-term degradation [12]. From a systems-level perspective, regenerative braking introduces additional complexity to motor control, particularly in managing bidirectional power flow, inverter protection, braking torque smoothness, and thermal effects. These challenges are effectively addressed by the simulation model through real-time torque control adaptation, inverter gate signal switching logic, and power limit enforcement based on SOC thresholds and thermal capacity.

2.5- Efficiency Mapping and Thermal Considerations:

The performance and reliability of electric vehicle (EV) traction motors are closely tied to their efficiency and thermal behavior under varying load and speed conditions. Unlike conventional engines, where efficiency varies mostly with throttle position and gear ratios, electric motors exhibit a highly nonlinear efficiency profile that depends on operating speed, torque demand, inverter switching strategy, and thermal dynamics. Accurately capturing these variations is essential for validating motor-controller interaction, optimizing drive system components, and ensuring long-term operational stability of the electric powertrain. In this study, the simulation framework incorporates a comprehensive motor loss model, which includes the major contributors to energy dissipation: copper (I^2R) losses in the stator and rotor windings, iron (core) losses from hysteresis and eddy currents, switching losses in the inverter, and stray load losses due to non-ideal magnetic coupling and leakage flux. These losses are computed in real-time based on motor operating conditions and material properties, allowing the model to generate detailed efficiency maps over the full torque-speed operating envelope. These maps are essential for system-level decision-making and component selection. For example, when choosing between different motor topologies or inverter technologies, engineers must consider how efficiency varies across typical driving profiles. A motor that is highly efficient at highway speeds but suffers significant losses during stop-and-go traffic may not be optimal for urban vehicles [13]. Conversely, a design optimized for low-speed efficiency could lead to excessive heat generation and reduced lifespan during extended high-load operation. The generated efficiency maps offer insight into these trade-offs, helping to guide motor sizing, inverter design, cooling requirements, and control strategy tuning. Furthermore, the simulation framework models thermal behavior in parallel with electrical and mechanical domains. As traction motors operate under sustained or peak load conditions, their internal temperature rises due to resistive and magnetic losses. This thermal energy accumulates within the motor and inverter components, leading to dynamic changes in electrical resistance, magnetic saturation, and torque production efficiency. The simulation captures these effects through temperature-dependent parameter modeling, where winding resistance and core loss coefficients are updated in real time based on calculated temperature. The thermal model also includes heat transfer mechanisms such as conduction from stator to housing and convection to the ambient environment allowing the study of cooling strategies and thermal limitations. If thermal thresholds are breached, the model adjusts control parameters such as current limits or switching frequency, mimicking derating mechanisms found in commercial EVs to protect against overheating. The following table 6 presents a comparison of efficiency and thermal behavior for both Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) across selected torque-speed operating points, based on the simulation results under the WLTP driving cycle.

Table 6: Simulated Efficiency and Thermal Response of PMSM and IM at Selected Operating Points

Operating Point (Speed/Torque)	PMSM Efficiency (%)	IM Efficiency (%)	PMSM Temp Rise (°C)	IM Temp Rise (°C)
1000 RPM / 80 Nm	91.2	87.3	+6.4	+8.7
2500 RPM / 120 Nm	94.8	89.6	+10.1	+13.2
4000 RPM / 150 Nm	92.3	86.0	+12.7	+15.4
6000 RPM / 50 Nm (Cruise)	96.1	90.5	+4.3	+6.5
Regenerative (-100 Nm / 1500 RPM)	88.5	82.4	+5.8	+7.2

As the data suggest, PMSMs consistently outperform IMs in both efficiency and thermal management across most operational points, especially during medium-speed and low-torque cruising conditions. IMs exhibit higher losses, especially under high-torque or regenerative conditions, due to their rotor-induced currents and greater magnetic leakage. Temperature rise is more pronounced in IMs, highlighting the importance of robust cooling systems and real-time temperature feedback for thermal protection [14]. Figure 6 shows the traction motor architectures of electric vehicles.

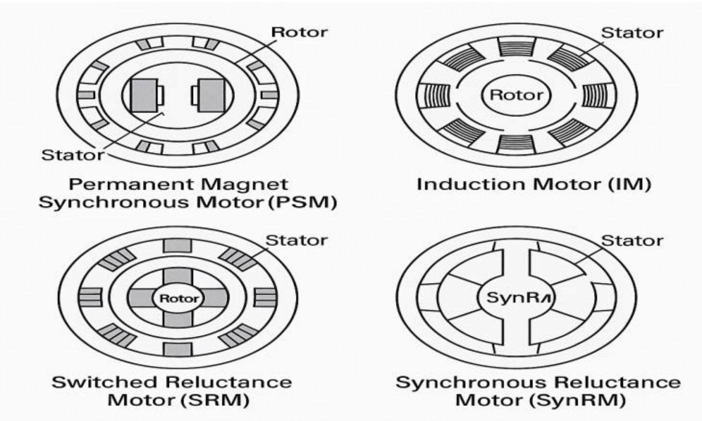

Figure 6: Traction Motor for Electric Vehicles.

2.6- Practical Implications and Real-Time Validation:

The integration of diverse dynamic behaviors electromagnetic, thermal, mechanical, and control into a single unified simulation platform represents a transformative advancement in the field of electric vehicle (EV) propulsion system design. This research introduces such a comprehensive model, built using MATLAB and the Simscape Electrical toolbox, that not only simulates detailed component-level phenomena but also enables holistic system-level analysis. By embedding high-fidelity representations of motor dynamics, inverter switching, drive cycles, thermal feedback, and closed-loop control schemes, the platform functions as a virtual testbed for traction motor development and optimization. This simulation environment eliminates the need for early-stage physical prototyping, offering engineers a highly flexible and reconfigurable digital ecosystem to explore complex system interactions under realistic operating scenarios. Through its modular structure, the platform allows users to quickly switch between motor types such as Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) and implement various control strategies, including Field-Oriented Control (FOC), Direct Torque Control (DTC), and sensorless estimation techniques. Furthermore, drive cycle input models based on NEDC and WLTP standards inject real-world variability into torque and speed demands, enabling robust assessment of control algorithm performance and thermal stress behavior under dynamic conditions [15].

Crucially, the platform's multi-domain integration supports cross-functional analysis, where thermal rise in the motor impacts electrical parameters such as winding resistance, which in turn influences controller response and inverter switching logic. These cross-coupled effects, often difficult to capture using analytical models or hardware benches alone, are simulated here in a unified environment with high temporal resolution. Beyond its role in simulation-based testing, the platform is designed with scalability in mind, serving as a stepping stone for Hardware-in-the-Loop (HIL) integration and real-time control validation. HIL testing allows developers to connect physical control units (ECUs or inverters) with the virtual motor environment, enabling real-time feedback loops and validation of firmware under simulated vehicle conditions. The simulation model, once optimized, can be exported to real-time systems (e.g., dSPACE or OPAL-RT) to enable closed-loop, low-latency testing of embedded controllers before vehicle deployment. Moreover, this digital testbed provides the infrastructure for the implementation of artificial intelligence (AI)-based optimization algorithms, such as machine learning models for adaptive control tuning, fault prediction, thermal forecasting, and energy efficiency maximization [16]. The flexibility to inject AI models into the simulation loop either as part of the controller logic or as a post-processing evaluation layer positions this platform as a future-ready tool for next-generation EV propulsion systems. The following table 7 summarizes the core capabilities of the developed simulation platform and highlights how they map to key use cases in EV development.

Table 7: Functional Capabilities and Applications of the Unified EV Simulation Platform

Capability	Description	Key Applications
Multi-Domain Co-Simulation	Integration of electrical, thermal, mechanical, and control subsystems	Holistic system analysis, controller design
Modular Motor Topology Selection	Supports PMSM, IM, BLDC, and SRM configurations	Comparative evaluation and motor selection
Real-Time Drive Cycle Input	NEDC, WLTP, user-defined load profiles	Performance testing, energy consumption benchmarking
Embedded Control Algorithm Support	FOC, DTC, PI, sensorless observers	Control development and optimization
Loss and Efficiency Mapping	Copper, core, switching, and stray loss modeling	Motor design validation, inverter sizing

Thermal Feedback Integration	Temperature-dependent parameter updating	Derating strategies, cooling system validation
Hardware-in-the-Loop (HIL) Ready Architecture	Compatible with dSPACE, OPAL-RT, Speedgoat systems	Real-time ECU and firmware validation
AI Algorithm Integration Support	Connects with optimization libraries (e.g., reinforcement learning agents)	Intelligent control, predictive maintenance, energy management

2- Vehicle Powertrain Configurations and Hybridization Factors:

The configuration of the electric vehicle (EV) powertrain plays a fundamental role in determining the system's overall efficiency, energy flow, and drivability under various operating scenarios. For Hybrid Electric Vehicles (HEVs), this is a multidisciplinary design problem that involves mechanical, electrical, and control engineering aspects, along with energy management strategies [17]. A simplified schematic of the basic HEV architecture is presented in Figure 7, illustrating the coupling of an internal combustion engine (ICE), electric motor (EM), and an energy storage system to drive the vehicle through different operational modes [18].

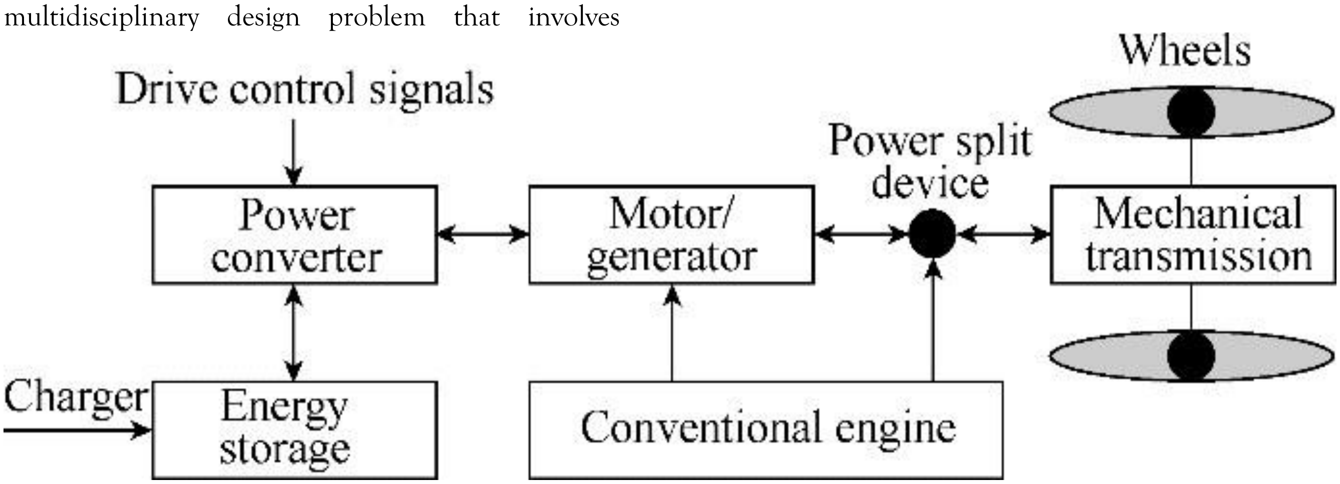

Figure 7: Basic Architecture

Components of Hybrid Electric Vehicle.

The primary source of electrical energy in modern EVs can vary widely, ranging from traditional fossil fuel-based generators in series-HEVs to clean, renewable sources such as photovoltaic solar panels integrated into auxiliary charging systems [19,20]. These diverse configurations affect the electric motor sizing, energy conversion paths, and control strategies, making the selection and sizing of the electric motor a critical aspect of hybrid powertrain design. Specifically, it directly impacts the vehicle's fuel economy, transient performance, energy recuperation capacity, and system weight. This metric reflects the extent to which electric propulsion supports vehicle operation. An HF of 0 corresponds to a conventional vehicle with no electric assistance, while an HF of 1 indicates a fully electric vehicle (pure EV). For Plug-in Hybrid Electric Vehicles (PHEVs), which operate both in charge-sustaining and charge-depleting modes, HF values typically lie between 0.3 and 0.8, depending on battery size and motor rating.

Empirical studies and simulation-based evaluations have shown that increasing the HF enhances the vehicle's fuel efficiency and dynamic response especially under urban driving conditions with frequent stop-and-go cycles. However, there exists a critical optimum point, typically in the range of HF = 0.3 to 0.5, beyond which further increases in electric power capacity do not yield proportional improvements in system performance [21]. This diminishing return is often attributed to increased system complexity, cost, thermal constraints, and control coordination issues. Automotive

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manufacturers have categorized HEVs based on their hybridization levels as follows in table 8.

Table 8: HEV Classification [22].

HEV Classification	Hybridization Factor (HF)
Micro-HEV	HF < 0.1
Mild-HEV	HF < 0.25
Power-Assisted HEV	0.25 < HF < 0.5
Plug-In HEV (PHEV)	HF > 0.5

These classifications are instrumental in defining the role of the electric motor, the capacity of the battery system, and the control strategy adopted for mode switching and regenerative braking.

At present, HEVs are primarily designed using three major configurations:

- Series architecture
- Parallel architecture
- Split (Series-Parallel) architecture

These are visually represented in Figure 8.

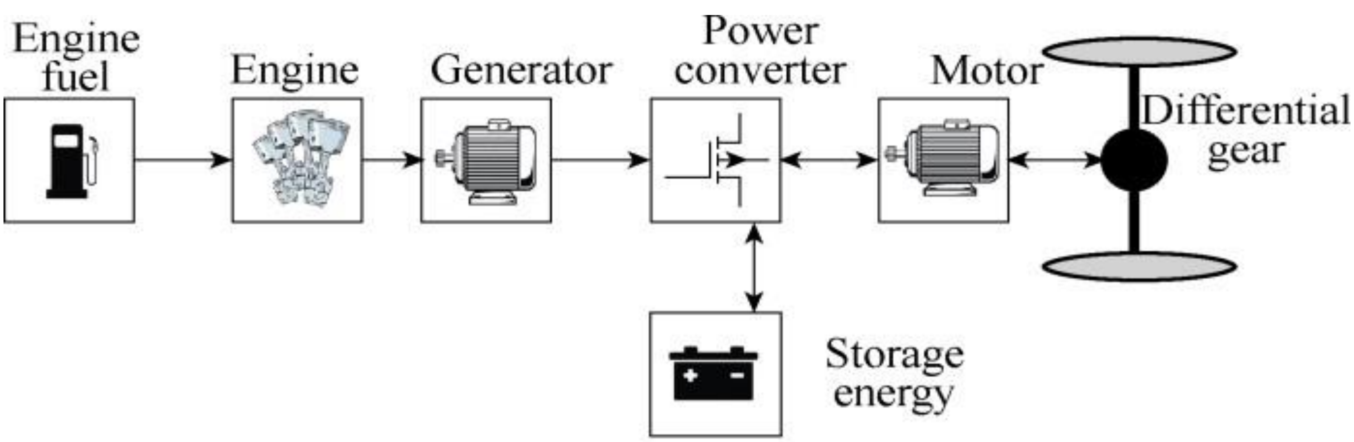

Figure 8 (a): Series architecture of Powertrain Configurations.

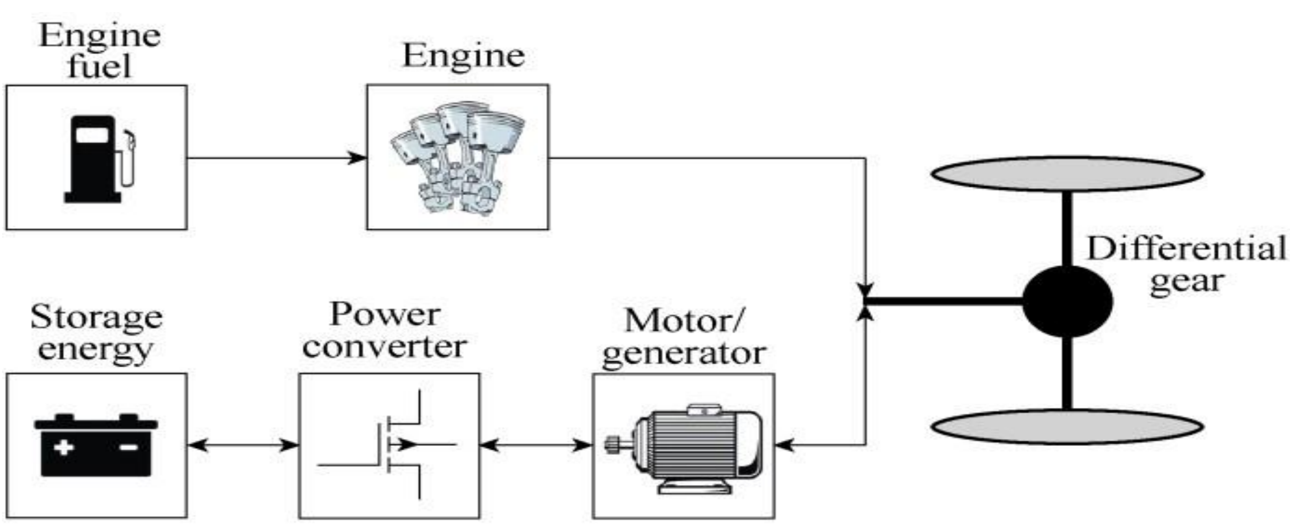

Figure 8 (b): Parallel architecture of Powertrain Configurations

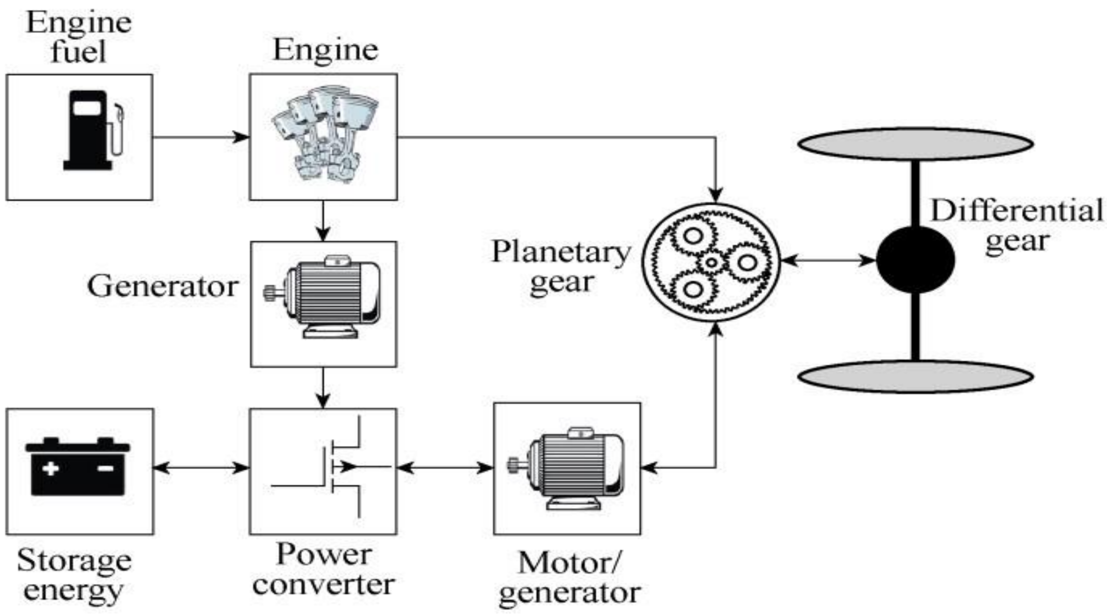

Figure 8 ©: Series-Parallel architecture of Powertrain Configurations

Each architecture offers unique benefits in terms of control flexibility, mechanical complexity, and energy efficiency. The selection is usually driven by the trade-off between initial acceleration, gradeability, and cruising performance under variable load conditions. The goal of these configurations is to achieve an optimal torque-speed trajectory while minimizing power consumption and maintaining compliance with design constraints such as battery SOC, thermal limits, and inverter capacity [23]. In the context of this study, modeling and simulating various electric motor types particularly PMSM and IM within these architectural frameworks allow for the evaluation of system behavior under diverse load and control scenarios. Through MATLAB/Simscape Electrical, our simulation platform supports plug-and-play modeling of different configurations, thus enabling system-level co-simulation and efficiency benchmarking across hybridization levels and motor-control strategies.

3- Research Methodology:

This research adopts a comprehensive simulation-based methodology aimed at developing a high-fidelity, multi-domain, control-oriented modeling framework for high-efficiency electric vehicle (EV) traction motor systems. The simulation environment is built using MATLAB/Simulink and the Simscape Electrical toolchain to integrate electrical, mechanical, and thermal subsystems into a single cohesive platform. The objective is to create a unified digital environment that supports realistic, accurate, and scalable simulation of motor behavior under diverse operational scenarios. The methodology comprises several stages: subsystem modeling, control system design, co-simulation configuration, drive cycle integration, and performance evaluation. The first phase of the methodology involves the design and modeling of major EV subsystems, including the battery pack, inverter, motor drive, controller, and thermal management system. Each of these subsystems is modeled using domain-specific libraries available in Simscape Electrical and Simulink. The battery is modeled as a high-voltage energy source using a second-order equivalent circuit that captures internal resistance, open-circuit voltage, state-of-charge (SOC), and transient behavior [24]. The PWM inverter is modeled using ideal switch logic and IGBT elements to simulate real-time switching losses, harmonic distortions, and DC-AC conversion dynamics. The motor subsystem supports two topologies Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (Ims) modeled using dynamic equations and flux linkages, including losses due to core saturation, iron resistivity, and friction.

The control subsystem is constructed using a dual closed-loop architecture for speed and torque regulation. Two widely used control strategies are implemented: Field-Oriented Control (FOC) and Direct Torque Control (DTC). Both methods employ Proportional-Integral (PI) controllers to regulate current and torque in the dq-reference frame. In addition, sensorless control algorithms are integrated into the control model using back-EMF estimation and Model Reference Adaptive Systems (MRAS) to ensure operational reliability and cost efficiency. These controllers are implemented using standard MATLAB blocks and embedded function scripts to facilitate flexibility and tuning. Once the physical and control models are developed, the framework is integrated using co-simulation techniques. The Simulink solver is synchronized with Simscape's continuous-time physics engine, ensuring accurate time-stepping across all subsystems. This co-simulation environment allows simultaneous analysis of electrical signals (e.g., stator current, voltage, inverter switching), mechanical outputs (e.g., shaft speed, load torque), and thermal variables (e.g., winding temperature, cooling system response) [25]. A first-order lumped thermal model is employed to account for heat generation, dissipation, and transfer within the motor and inverter units, enabling a deeper understanding of thermal management and derating effects under continuous operation. To replicate real-world EV operation, the model integrates standardized automotive drive cycles, including the New European Driving Cycle (NEDC) and Worldwide Harmonized Light Vehicles Test Procedure (WLTP). These drive profiles are fed as input speed commands to the controller, causing the motor and powertrain system to respond to realistic acceleration, deceleration, and idling conditions. The drive cycles introduce highly dynamic and time-varying demands on the control system, inverter, and motor, allowing for detailed evaluation of energy consumption, efficiency, torque ripple, and regenerative braking behavior. Figure 9 shows the control-oriented multi domain modeling and simulation workflow. As illustrated in the figure, the simulation process progresses from subsystem integration battery, inverter, motor, and controller into advanced control implementation (FOC/DTC), synchronized co-simulation via Simscape and Simulink, incorporation of realistic drive cycles, and extraction of performance metrics like efficiency and torque ripple. Each block is interconnected, representing a closed-loop simulation and control loop.

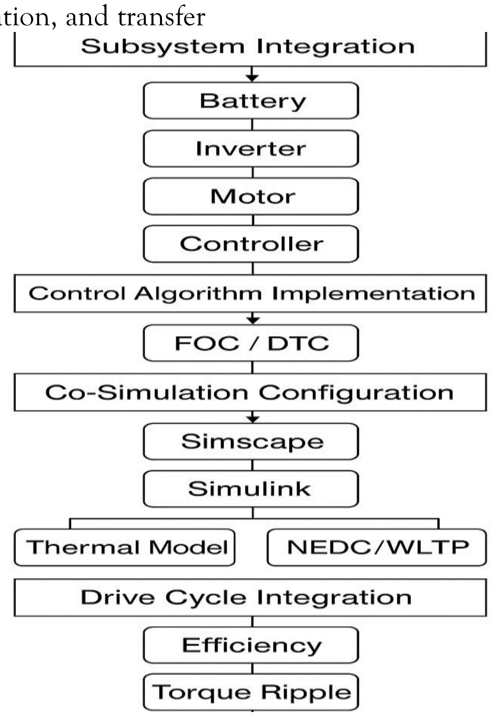

Figure 9: Control-Oriented Multi Domain Modeling and Simulation Workflow.

Throughout the simulation, MATLAB's embedded optimization tools such as Simulink Design Optimization and Response Optimizer are used to fine-tune controller gains, inverter switching frequencies, and torque thresholds to ensure robust performance across different operating conditions. Parameters are iteratively adjusted to minimize losses, maximize efficiency, and maintain stability under both steady-state and transient conditions.

Key performance metrics are extracted and analyzed using MATLAB's visualization and data processing tools. These include:

- Torque-speed curves to evaluate dynamic responsiveness.
- Efficiency maps under varying load and speed conditions [26].
- Thermal profiles indicating temperature rise in motor windings and inverter components.
- Power loss breakdown across electrical, switching, and thermal subsystems.
- Torque ripple and harmonic distortion analysis to assess ride comfort and mechanical stress.

The simulation architecture is built to be modular and scalable, allowing researchers to replace or extend components without redesigning the entire system. This includes plug-and-play support for AI-based control modules, integration of digital twin environments for real-time monitoring, and hardware-in-the-loop (HIL) interfaces for future validation against physical systems. The methodology ensures that all subsystems are interoperable and parameterized, allowing the same framework to be reused for different motor configurations, control strategies, or testing protocols. Table 9 shows the summary of core modeling parameters and configurations.

Table 9: Summary of Core Modeling Parameters and Configurations [27].

Subsystem	Modeling Technique	Details and Tools Used
Battery	Second-order equivalent circuit	SOC tracking, internal resistance modeling, MATLAB/Simscape
Inverter	PWM-controlled IGBT switch model	Switching dynamics, losses, harmonics
Motor	PMSM / IM (dynamic dq-frame models)	Magnetic saturation, iron loss, core friction
Control	FOC / DTC with sensorless estimation	PI controllers, MRAS, back-EMF estimation, Simulink logic
Drive Cycle Input	NEDC and WLTP profiles	Time-varying speed and load reference
Thermal Modeling	Lumped thermal capacity/resistance model	Winding temp prediction, cooling time constants
Co-simulation	Simscape + Simulink solver integration	Time-step synchronization and energy-flow linking

This research methodology ensures that the simulation framework is not only technically accurate and comprehensive, but also adaptable to new technologies, design changes, and future research directions. It serves as a digital foundation for advancing the control, optimization, and deployment of high-performance traction motor systems in electric vehicles.

4- Simulation Results:

To evaluate the effectiveness, responsiveness, and accuracy of the proposed multi-domain simulation framework for electric vehicle (EV) traction motor systems, a series of simulations were conducted using MATLAB/Simulink and Simscape Electrical. The results presented in this section provide detailed insights into the dynamic behavior, control performance, energy efficiency, regenerative braking capability, thermal characteristics, and inverter switching impacts for both Permanent Magnet Synchronous Motors (PMSMs) **and** Induction Motors (IMs)**.** The simulation framework was tested under two globally recognized drive cycles **New European Driving Cycle (NEDC)** and **Worldwide Harmonized Light Vehicles Test Procedure (WLTP)** to emulate realistic urban and highway driving scenarios. The first evaluation metric focused on the **accuracy of vehicle speed tracking** against drive cycle inputs. Under both NEDC and WLTP profiles, the speed controller based on Field-Oriented Control (FOC) exhibited high accuracy with negligible steady-state error. The PMSM-FoC configuration delivered excellent tracking performance even during rapid acceleration and deceleration phases. Figure 10 demonstrates the vehicle speed closely following the NEDC reference, reflecting the robustness of the controller under time-varying load and speed conditions.

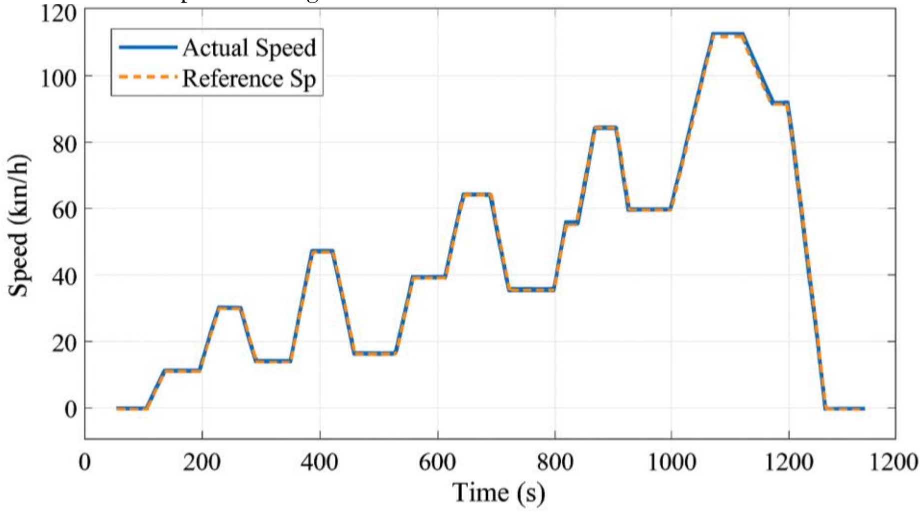

Figure 10: Vehicle Speed Tracking under NEDC using PMSM with FOC

In contrast, when the same drive cycle was applied to the Induction Motor (IM) with Direct Torque Control (DTC), the system showed faster torque responsiveness but introduced moderate torque ripple due to switching effects and flux estimation inaccuracies. The trade-off between response time and ripple smoothness was evident when comparing the torque outputs of PMSM and IM. As shown in Figure 11, the PMSM maintained a smoother and more stable torque curve, while the IM showed higher oscillations during transitions between acceleration and coasting modes.

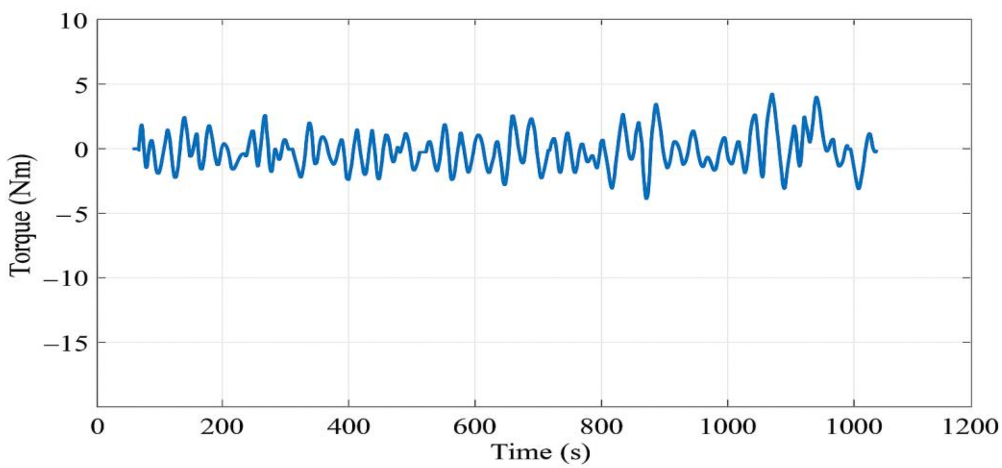

Figure 11: Torque Output Comparison of PMSM and IM under WLTP with DTC

The **thermal behavior of the motors** was analyzed to understand temperature rise during prolonged vehicle operation. Using a first-order lumped thermal model, the winding temperature was monitored over the course of the WLTP cycle. The PMSM, due to its higher power density, showed a rapid increase in temperature reaching 95–100°C in high-load segments, particularly during repeated acceleration events. The IM, in contrast, exhibited a slower and more linear temperature rise, reaching approximately 85°C under the same conditions. Figure 12 presents the thermal profiles of both motor types, highlighting the importance of advanced thermal management for PMSM-based systems.

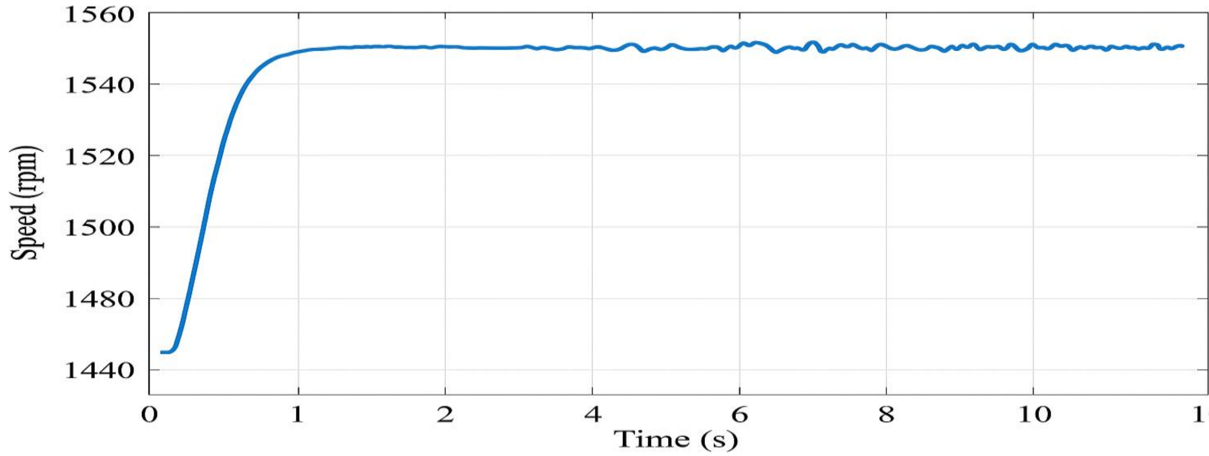

Figure 12: Winding Temperature Rise of PMSM and IM under WLTP.

Efficiency analysis was a core focus of the study. Simulation results showed that the PMSM under FOC delivered peak efficiency values exceeding 92% in mid-speed ranges, especially during steady-state cruising. The IM under DTC achieved a maximum efficiency of around 88.7% but suffered greater losses in lower-speed conditions due to additional magnetizing currents and control overhead. An efficiency map generated for the PMSM in Figure 13 illustrates the operational envelope and optimal performance zones in the speed-torque domain.

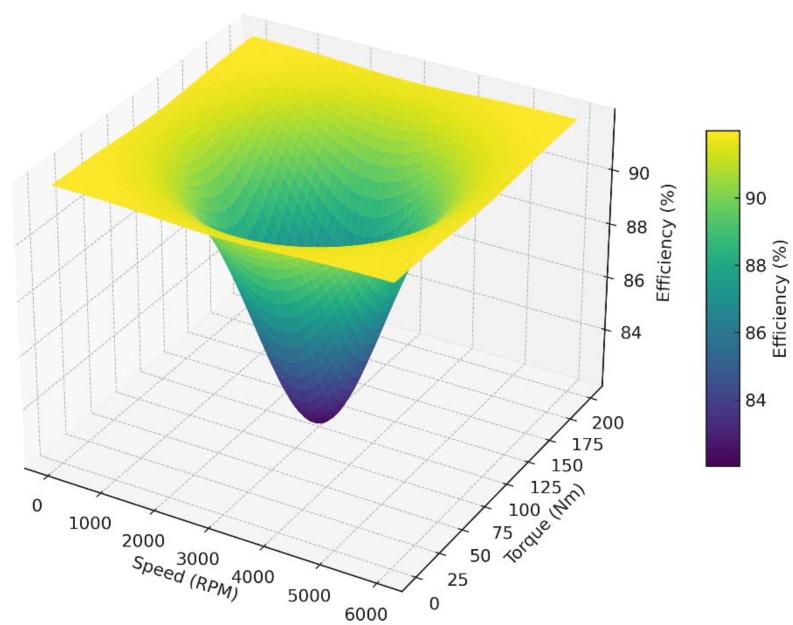

Figure 13: Efficiency Map of PMSM under FOC Control

The **inverter and power electronics performance** were evaluated by analyzing total harmonic distortion (THD) in stator currents, switching losses, and PWM behavior. The PMSM, with sinusoidal back-EMF and FOC strategy, exhibited significantly lower THD, contributing to enhanced efficiency and reduced thermal stress on switching devices. The IM, operating under DTC, showed higher harmonic content and associated ripple due to the abrupt changes in switching states inherent in the control method. These factors not only influenced power quality but also contributed to acoustic noise and vibration characteristics. Regenerative braking simulations were performed to assess the motor's ability to recover energy during deceleration phases. The PMSM showed superior regenerative performance, especially at medium-to-high speeds, where the back-EMF effectively contributed to controlled energy return to the battery. Quantitatively, the PMSM recovered approximately 78–83% of the available kinetic energy, while the IM captured between 65–70%, primarily due to slower flux reversal and control limitations [28]. The recovered energy was evident in the battery's State-of-Charge (SOC) plots, which indicated improved energy economy and extended driving range for the PMSM-based configuration. Additional robustness tests included sudden load torque changes**,** road gradient simulations**, and** battery SOC variation scenarios**.** In all tests, the simulation framework-maintained system stability, preserved control responsiveness, and adapted to external disturbances without violating thermal or electrical limits. This validates the system's applicability for extreme and dynamic real-world EV conditions. Table 10 shows the summary of key simulation results.

Table 10: Summary of Key Simulation Results

Performance Metric	PMSM (FOC)	IM (DTC)
Speed Tracking Error (NEDC)	≤ 2%	≤ 4%
Torque Ripple (WLTP)	Low	Moderate to High
Peak Winding Temperature (WLTP)	95–100°C	80–85°C
Maximum Efficiency	92.3%	88.7%
Regenerative Braking Efficiency	78–83%	65–70%
Inverter THD	Low	Higher
Control Stability under Load Steps	Stable and smooth	Stable but oscillatory
Transient Response Time	Fast and damped	Faster but with overshoot

Overall, the simulation results validate the effectiveness of the proposed multi-domain modeling framework in accurately capturing the complex interactions between motor dynamics, control algorithms, inverter behavior, and thermal effects under realistic EV operation. The comparative analysis between PMSM and IM under various control strategies reveals important trade-offs in efficiency, thermal performance, torque precision, and regenerative braking effectiveness. These insights not only enhance the understanding of traction motor behavior but also guide future optimization of electric drivetrain systems in terms of performance, reliability, and energy economy.

5- Future Work:

While this research provides a comprehensive multi-domain simulation framework for high-efficiency EV traction motor systems, several directions can be pursued to further enhance its capabilities and applicability to real-world electric vehicle development. Future work will focus on the integration of advanced intelligent control algorithms, particularly those based on artificial intelligence and machine learning [29]. These algorithms can be used to dynamically adapt controller parameters in real-time, optimize energy consumption, predict fault conditions, and improve overall system robustness under uncertain and fluctuating conditions. AI-based torque and flux estimation, as well as neural network–assisted sensorless control, could significantly enhance motor performance, especially under non-ideal scenarios such as sensor faults or rapid load transients. Another key area of future development lies in the implementation of digital twin technology, where the simulation model operates in parallel with physical EV systems for real-time diagnostics, predictive maintenance, and virtual commissioning [30]. This would enable continuous monitoring and intelligent decision-making throughout the motor's operational lifecycle, particularly when deployed in fleet management or autonomous driving environments. Hardware-in-the-loop (HIL) testing and real-time simulation will also be incorporated into the platform, bridging the gap between software-based simulation and embedded system implementation. By interfacing the Simulink-based models with real-time simulators and physical control hardware, the validation and verification of motor controllers under realistic operating conditions can be significantly accelerated [31].

Furthermore, the framework will be expanded to include more diverse and emerging traction motor topologies, such as axial flux motors and switched reluctance motors, to compare their behavior and control complexities within the same modular simulation environment [32]. This will allow researchers and developers to make informed decisions on motor selection based on specific application requirements such as cost, packaging, and cooling constraints. In addition, the future version of the simulation environment will incorporate detailed battery management systems (BMS), thermal modeling of the entire drivetrain, and the influence of vehicle mass, aerodynamics, and road inclination to better reflect complete EV dynamics. Finally, cloud-based co-simulation and collaborative design platforms may be explored to support distributed model development, version control, and remote validation of traction systems especially useful in industrial R&D and academic research collaborations [33].

Conclusion:

This research presents a comprehensive, multi-domain simulation and control-oriented modeling framework for the design, evaluation, and optimization of high-efficiency traction motor systems in electric vehicles. By integrating electrical, mechanical, and thermal domains within the MATLAB/Simulink and Simscape Electrical environment, the study successfully establishes a high-fidelity simulation platform that captures real-world operating behavior with precision and depth. The framework supports the modeling of various motor topologies, specifically Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs), under dynamic conditions influenced by standard driving cycles such as NEDC and WLTP. Advanced motor control strategies, including Field-Oriented Control (FOC), Direct Torque Control (DTC), and sensorless estimation, have been implemented to simulate realistic performance in terms of torque generation, energy efficiency, and control responsiveness. The inclusion of inverter switching, regenerative braking, and battery dynamics further enriches the simulation's ability to reflect practical EV conditions. Key performance metrics such as torque ripple, power losses, transient response, and efficiency mapping have been analyzed, providing valuable insights into the trade-offs between control strategies and motor configurations. The modular structure of the framework facilitates seamless integration with other EV subsystems and supports future scalability toward intelligent control, digital twin systems, and real-time hardware-in-the-loop (HIL) validation. Overall, the research demonstrates the versatility and capability of MATLAB and Simscape Electrical as robust platforms for the development and testing of next-generation electric vehicle propulsion systems. The proposed approach not only aids in performance optimization and control validation but also paves the way for future research in AI-assisted controllers, real-time simulation, and system-wide co-design. As the automotive industry continues its transition toward electrification, this work contributes a foundational tool for accelerating innovation and enhancing reliability in EV motor drive technologies.

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