

Article

Simulation-Based Design of Ultra-Fast Dynamic Torque Control for Electric Vehicle Permanent Magnet Motor Drives

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Abstract

Electric Vehicle drive systems must provide fast torque response, low or minimal torque ripple, robustness to both parameter variations and external disturbances. Permanent Magnet Synchronous Motors (PMSMs) are commonly found in electric vehicle propulsion applications due to their high power density, high efficiency, and excellent dynamic performance. However, performance degradation in torque control of PMSMs under time-varying conditions arises from the nonlinear characteristics of motors and their high sensitivity to changes in system parameters. This paper presents a torque-control method with high dynamic bandwidth that combines three techniques: (1) Nonlinear Sliding Mode Torque Control; (2) Predictive Current Control; and (3) Disturbance Estimation. The sliding mode controller provides improved robustness against uncertainties about the system. In addition, the predictive current control provides improved accuracy in current tracking and significantly reduces the time required to achieve a steady state. A disturbance observer is used to compensate for load disturbances and model errors in the motor model. The integrated control architecture is simulated and modeled in MATLAB/Simulink for a typical EV driving environment. The simulation framework produced faster and more accurate torque tracking than conventional PI-type vector controllers, as well as reduced torque ripple and improved disturbance rejection under similar operating conditions. The results demonstrate that the proposed method is a viable candidate for high-performance EV propulsion systems while acknowledging practical limitations such as chattering, tuning complexity, sampling time sensitivity, and the need for further experimental validation.

Keywords: electric vehicle (EV); permanent magnet synchronous motors (PMSMs); proportional-integral (PI) controller; electric vehicle propulsion



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1. Introduction

The rapid expansion of electric vehicles (EVs) has created a need for high-performance motor drive systems that deliver rapid dynamics, are highly efficient, and operate reliably across diverse driving conditions. Among all options, Permanent Magnet Synchronous Motors (PMSMs) are ideal for EV propulsion due to their high power density, high efficiency, and excellent torque characteristics [1,2]. Achieving precise and ultra-fast torque control in PMSM drives remains a significant challenge due to parameter uncertainties, inherent nonlinear dynamics, and external disturbances.

While PI-based vector control is widely used for PMSM drives due to its simplicity and ease of implementation, it exhibits inferior dynamic performance, slower transient responses, increased torque ripple under parameter variations, and reduced system efficiency [3,4]. Since EV applications demand rapid torque responses during acceleration,

regenerative braking, and stability control, more advanced control methodologies must be adopted to overcome these limitations.

To address the growing challenges posed by EV systems, researchers have focused extensively on advanced nonlinear control techniques. Because sliding mode control (SMC) techniques are inherently robust to uncertainties about the controlled element, they have been extensively studied for EV applications. SMC provides strong, stable operation and rapid dynamic performance, making it ideal for high-performance motor drive systems. However, we must address several issues: chattering and implementation complexity.

Along with the SMC, model predictive current control (MPCC) has gained considerable attention in the EV community for its rapid current-tracking capabilities and improved steady-state performance. For example, current tracking with the deadbeat MPCC method can provide rapid convergence and reduced tracking error; therefore, it is highly effective for permanent magnet synchronous motor (PMSM) drive systems. In addition, the introduction of Disturbance Observer (DO) shows promise in estimating unknown disturbances and compensating for modeling errors, further enhancing system robustness and performance.

Current EV drive system developments now focus on integrated control architectures that integrate the aforementioned control methods to take full advantage of each method's strengths. Significant research on motor design optimization, improved drive system performance, and fault-tolerant operation demonstrates the need for robust and adaptive control techniques for next-generation EV applications [5–7]. In addition, continued progress in power electronics, converters, and intelligent control techniques will enhance overall efficiency and reliability [8–11].

In response to these advancements, this paper presents a simulation-based ultra-fast dynamic torque control method for PMSM drive systems that combines nonlinear sliding mode control (SMC), model predictive current control (MPCC), and a disturbance observer (DO). The proposed method aims to improve torque tracking performance, reduce ripple, and enhance robustness under variable operating conditions, offering a viable solution for next-generation EV propulsion. The term “ultra-fast” refers quantitatively to the achieved torque rise time of 7.2 ms and settling time of 12.6 ms, which represent improvements of greater than 60% over conventional PI-based control under the same simulation conditions (see Table 1). The main contributions of this paper are as follows: (1) A novel hybrid control architecture integrating SMC, MPCC, and DO for PMSM-based EV drives is proposed and validated through simulation. (2) A comprehensive comparative study against conventional PI-based vector control is conducted, demonstrating superior dynamic torque response, reduced torque ripple, and improved disturbance rejection. (3) The combined effect of the three control strategies in mitigating chattering, improving current tracking accuracy, and compensating for unknown load disturbances is systematically analyzed. The remainder of this paper is organized as follows: Section 2 presents a review of relevant literature. Section 3 describes the proposed control method and mathematical modeling. Section 4 details the MATLAB/Simulink simulation framework. Section 5 presents and discusses the simulation results. Section 6 concludes the paper with key findings and future directions.

Although hybrid PMSM control schemes have been reported previously, the specific combination proposed here is differentiated as follows. In contrast to cascaded SMC–PI structures, the present architecture removes the inner PI current loop entirely and replaces it with a finite-control-set MPCC that selects the optimal inverter voltage vector directly, eliminating modulator and current-loop gain tuning. In contrast to conventional SMC–DO designs that compensate only the mechanical load torque, the disturbance observer here is embedded within the torque loop and supplies a feed-forward term ($T_{\text{comp}} = T_{\text{ref}} + \hat{T}_L$) ahead of the current loop. Relative to deadbeat-MPCC schemes, the sliding-mode outer loop

adds a Lyapunov-guaranteed robustness margin against the $\pm 20\%$ parameter mismatch examined in Section 5. Quantitatively, the proposed scheme attains a 7.2 ms torque rise time, 3.1% torque ripple and a 9.4 ms disturbance-recovery time, improving on the PI baseline by 61.1%, 68.4% and 67.1%, respectively; these are the metrics against which the present contribution should be judged relative to prior hybrid schemes.

Table 1. Performance comparison between conventional PI control and proposed hybrid control.

Proposed Hybrid Control (SMC + MPCC + DO)	Conventional PI Control	Performance Parameter
7.2	18.5	Torque Rise Time (ms)
12.6	35.4	Torque Settling Time (ms)
3.1	9.8	Torque Ripple (%)
1.9	6.5	Speed Overshoot (%)
16.3	42.7	Speed Settling Time (ms)
2.4	5.9	Current THD (%)
0.9	2.8	Steady-State Torque Error (%)
9.4	28.6	Disturbance Recovery Time (ms)
0.62	1.85	Current Tracking Error (A)
95.6	91.2	Overall System Efficiency (%)

2. Literature Review

Researchers have conducted extensive studies over the past several years to enhance the electrical performance of electric vehicles (EVs) that use PMSM drive systems and advanced control techniques.

Through investigations into PMSM design for optimal performance, it has been established that the selection and matching of PMSM properties are essential for the efficient operation of EVs. Different interior PMSM configurations significantly improve performance characteristics such as torque density and efficiency [1,5]. In addition to understanding PMSM designs in EVs, many researchers have recommended approaches to optimize the performance of PMSM drive systems for real-world EV applications by developing driving cycles prior to motor optimization for those cycles [6].

A large body of literature has reported the feasibility of using predictive current control as an alternative method for controlling PMSM drives, owing to its ability to provide very fast dynamic responses and accurate current tracking [3]. In addition to predictable current control methods, many strategies have been developed to optimize the performance of feed-forward torque control in nonlinear machinery [12].

The most important areas of research on motor drive systems have primarily focused on their robustness and reliability. For example, fault-tolerant control methods for multi-phase PMSMs have been developed to increase system reliability during critical operations [7], and survivability-based protection strategies have been created to enable stable performance during fault events [13].

Within the area of electric vehicle (EV) propulsion, recent innovations include a variety of new motor configurations, with numerous in-wheel (or hub) motor systems being developed, which exhibit superior efficiency and compactness relative to prior vehicle-related technologies [14,15]. The control of regenerative braking systems will also significantly improve energy recovery from vehicle operations and overall performance [4].

Beyond motor control, there have been several important advances in both power electronic converters for EVs and energy management systems. For example, new converter topologies have enabled the production of multilevel inverters and DC–DC converters,

thereby improving power quality, operating efficiency, and the overall stability of EV systems [16–19]. In addition, the use of intelligent control techniques (e.g., neuro-fuzzy and artificial neural network (ANN) controllers) has increased the adaptability and operational performance of renewable energy and EV-integrated systems by enabling new control algorithms [10,20,21].

Before implementing control schemes in actual operations, simulations have proven valuable for evaluating each scheme. State-of-the-art simulation techniques using MATLAB/Simulink have enabled engineers to comprehensively analyze the dynamic response of all systems under varied operating conditions, providing reasonable confidence in evaluating each proposed control scheme [11].

Even though there have been many improvements in motor control with respect to torque ripple reduction, quick dynamic response time, and reliability under variable input parameters, this remains an area of active research. The current state of the art typically uses one or more methods but does not meet all requirements simultaneously (rapid response time, accuracy, and disturbance rejection).

Thus, this research introduces an integrated control architecture that combines sliding-mode torque control, model predictive current control, and disturbance-observer-based estimation for permanent magnet synchronous-type electric vehicle driveline applications.

3. Proposed Method

Figure 1 illustrates the power circuit configuration of the PMSM-based electric vehicle drive system. The system uses a manufacturer's high-voltage battery to supply DC power to drive the vehicle. To reduce voltage ripple and to provide stable DC power under dynamic load conditions, a DC link capacitor is connected across the DC bus, providing the necessary DC power for propulsion. A voltage source inverter (VSI) converts DC power into three-phase AC power using controlled switching signals generated by a control algorithm. The VSI outputs a three-phase voltage to drive the PMSM. As a result, the PMSM converts electrical energy into mechanical torque to propel the vehicle. Current sensors measure phase currents required for current regulation and torque estimation, while speed and position sensors measure rotor speed and angle for coordinate transformation, torque calculation, and closed-loop control. Overall, power flows from the battery through the DC link and the inverter to the PMSM, enabling electromechanical energy conversion.

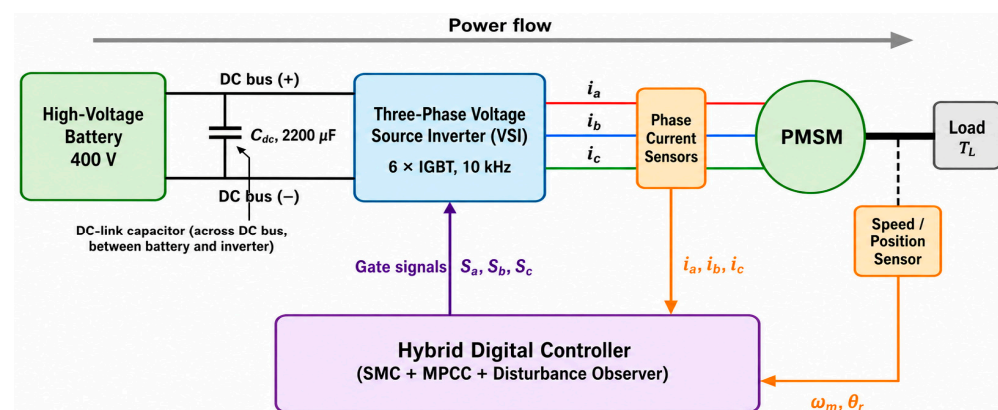


Figure 1. Proposed power Circuit for PMSM-Based EV Drive.

Figure 2 illustrates a two-layered hybrid architecture for controlling the torque response/robustness of drive systems using permanent magnet synchronous motors (PMSMs). The top layer of the architecture is the reference generation, where reference speed and torque are generated based on the vehicle's requirements to operate properly. The bottom layer contains a sliding-mode torque controller that compares the reference

torque to the actual electromagnetic torque in order to generate control signals for the torque. This controller provides robustness in the presence of uncertainties in parameters and disturbances from outside the system. Within the control loop is the disturbance observer, which estimates unknown load torque disturbances and compensates for them in real time, improving the stability and dynamic performance of the system. The predictive current controller takes in a reference current component and predicts how the current will behave next using system model(s). The predictive controller will determine which inverter switch settings are optimal for rapid tracking and reduced steady-state error by minimizing a cost function. All feedback signals, such as motor speed, rotor position, and phase currents, are continuously monitored to enable closed-loop control. The complete control framework can provide accurate torque regulation, reduced torque ripple, and a higher disturbance rejection capability, making it suitable for electric vehicle propulsion applications with high-performance requirements.

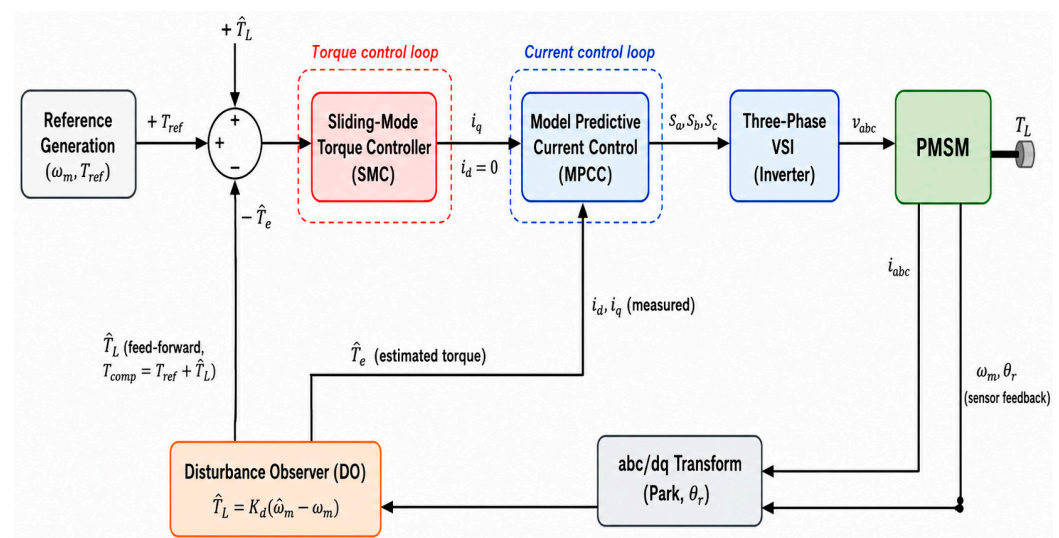


Figure 2. Proposed Hybrid Control Block Diagram for PMSM-Based EV Drive System.

3.1. Control Objective

In this project, there is an emphasis on developing a high-bandwidth torque control scheme that provides low torque ripple and remains robust under parameter uncertainty and load variation. The hybrid nonlinear controller will integrate the following control strategies:

- Sliding Mode Torque Control;
- Model Predictive Current Control;
- Disturbance Observer.

This controller will offer two independent loops (i.e., torque and current regulation), which will allow for a rapid response time, accurate regulation, and optimized inverter switching frequencies.

3.2. PMSM Mathematical Model

The PMSM is modeled in the synchronous rotating dq reference frame.

Electrical Dynamics

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (1)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_f \quad (2)$$

where v_d and v_q are stator voltages;

i_d and i_q are stator currents;
 R_s is stator resistance;
 L_d and L_q are inductances;
 ω_e is electrical angular speed;
 λ_f is permanent magnet flux.

In Equations (1) and (2), the terms $L_a(di_a/dt)$ and $L_q(di_q/dt)$ represent the inductive voltage drops along the d- and q-axes, respectively, the cross-coupling terms $\omega_e L_q i_q$ and $\omega_e L_a i_a$ account for speed-dependent coupling between the axes, and $\omega_e \lambda_e$ is the back-EMF contribution from the permanent magnet flux linkage $\lambda_e = 0.175$ Wb. The stator flux linkages along the d- and q-axes are defined as $\psi_a = L_a i_a + \lambda_e$ and $\psi_q = L_q i_q$, respectively, completing the electromagnetic model of the surface PMSM.

Electromagnetic Torque Equation

$$T_e = \frac{3}{2} \frac{P}{2} [\lambda_f i_q + (L_d - L_q) i_d i_q] \quad (3)$$

For surface PMSM (where $L_d \approx L_q$):

$$T_e = \frac{3}{2} \frac{P}{2} \lambda_f i_q \quad (4)$$

Mechanical Dynamic Equation

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \quad (5)$$

where J = Moment of inertia;
 B = Friction coefficient;
 T_L = Load torque.

3.3. Sliding Mode Torque Control Design

Define torque tracking error:

$$e_T = T_{ref} - T_e \quad (6)$$

Sliding surface is defined as:

$$S = e_T + \lambda e_T dt \quad (7)$$

where λ = Positive control gain.

Sliding Mode Control Law

$$u = u_{eq} + u_{sw} \quad (8)$$

Equivalent control:

$$u_{eq} = k_e e_T \quad (9)$$

Switching control:

$$u_{sw} = k_s \text{sign}(s) \quad (10)$$

To reduce chattering, the saturation function is used:

$$u_{sw} = k_s \text{sat}(s/\phi) \quad (11)$$

where K_s = Switching gain;
 ϕ = Boundary layer thickness.

3.4. Model Predictive Current Control

The discrete current model is derived as:

$$i(K+1) = i(k) + \frac{T_s}{L}(V(k) - Ri(k) - e(k)) \quad (12)$$

where T_s = Sampling time;

$e(k)$ = Back EMF.

Cost Function for Predictive Control

$$J = (i_d^* - i_d)^2 + (i_q^* - i_q)^2 \quad (13)$$

The optimal switching state is selected by minimizing the cost function.

To improve the optimality of the predictive controller and account for switching effort, the cost function is extended to include a voltage constraint penalty term as follows: $J = (i_a^* - i_a(k+1))^2 + (i_q^* - i_q(k+1))^2 + \lambda v \|V(k) - V(k-1)\|^2$, where λv is a weighting factor that penalizes switching frequency and balances current tracking error against switching effort. A two-step prediction horizon is employed to improve the accuracy of the current predictions before cost function evaluation.

$$V_{opt} = \operatorname{argmin}(J) \quad (14)$$

3.5. Disturbance Observer Design

Disturbance torque estimation:

$$\hat{T}_L = K_d(\omega_m - \hat{\omega}_m) \quad (15)$$

Observer dynamics:

$$\frac{d\hat{\omega}_m}{dt} = \frac{1}{J}(T_e - \hat{T}_L - B\hat{\omega}_m) \quad (16)$$

Compensated torque command:

$$T_{comp} = T_{ref} + \hat{T}_L \quad (17)$$

3.6. Stability Analysis

Using Lyapunov function:

$$V = \frac{1}{2}S^2 \quad (18)$$

Derivative:

$$\dot{V} = S \cdot \dot{S} \quad (19)$$

If control law ensures:

$$\dot{V} < 0$$

then the system is asymptotically stable.

Figure 3 summarizes the complete per-sampling-instant execution of the proposed hybrid controller, showing how the disturbance observer, the sliding-mode torque controller and the model predictive current controller are combined within each 100 μ s control cycle.

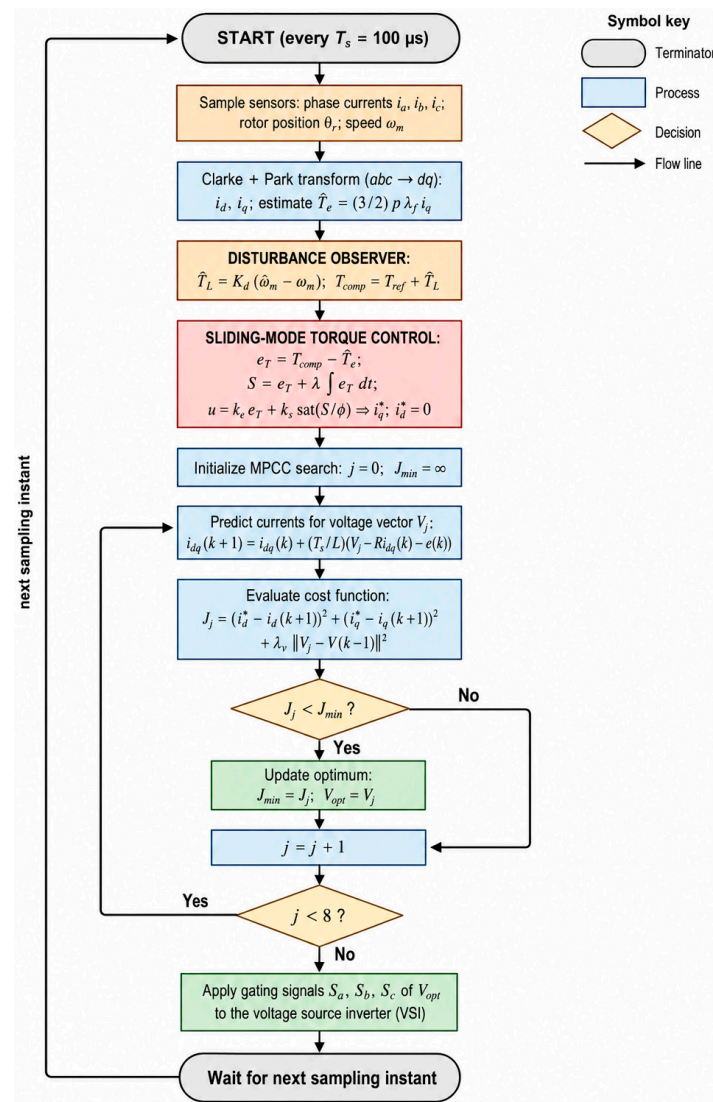


Figure 3. Flowchart of one control cycle of the proposed hybrid SMC-MPCC-DO scheme.

4. MATLAB/Simulink Model Description (IEEE Style)

A. Simulation Environment

Using the MATLAB/Simulink platform, we developed a proposed Permanent Magnet Synchronous Motor (PMSM)-based electric vehicle drive system through modeling and simulation. The proposed hybrid control strategy was evaluated with respect to its dynamic torque response, disturbance-rejection capability, and current-tracking performance. The electrical, mechanical, and control subsystems within the Simulink simulation were modeled with respect to real-world EV operation conditions. The use of discrete-time implementations in simulating the proposed motor drive provides an accurate simulation of a digital controller typically used in automotive motor drive applications.

Figure 4 presents an overview of the implemented MATLAB/Simulink model. The model is executed with a discrete fixed-step solver (ode3) at a fixed sample time of $T_s = 100 \mu s$. The reference electromagnetic torque is set to $15 \text{ N}\cdot\text{m}$; the three-phase inverter is modeled as a Universal Bridge with the IGBT parameters listed above (10 kHz switching, 1.5 V on-state drop, 2 μs dead-time); and the rotor speed, rotor position and phase currents are obtained from the measurement blocks shown. A model screenshot and the controller parameters are provided so that the results are reproducible.

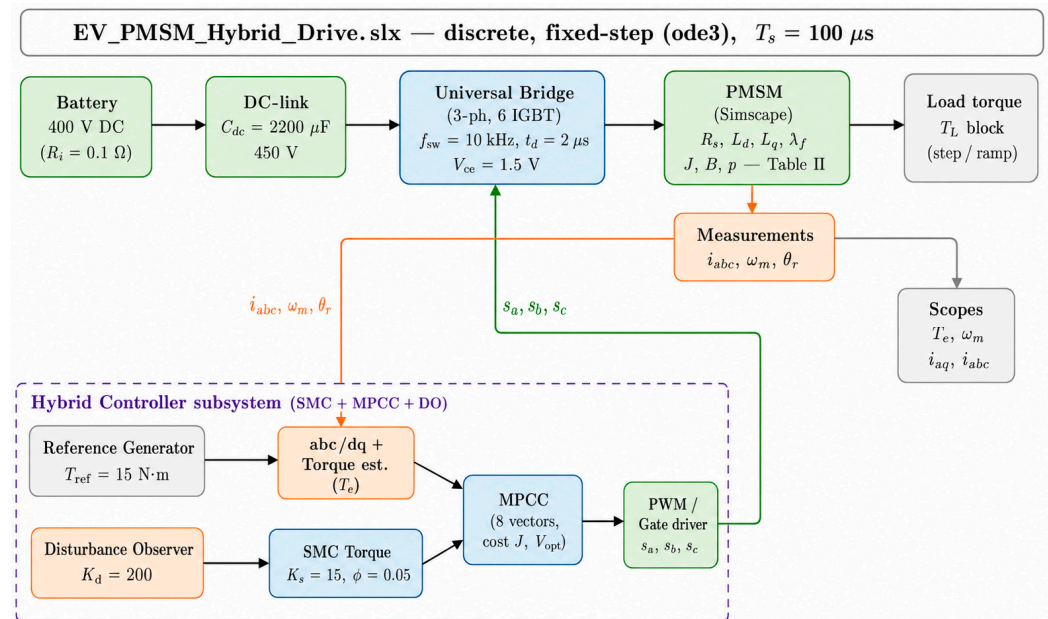


Figure 4. Block-diagram representation of the implemented MATLAB/Simulink model (solver, inverter and sensor settings).

B. Power Circuit Modeling

A standard battery source is used for the Energy Storage System (ESS) in an EV. The battery source provides the ESS with its DC voltage. A capacitor is added to the DC link to reduce voltage fluctuations caused by transient loads, thereby maintaining the DC bus voltage. Three-phase pulse-width-modulated (PWM) inverters use IGCT-based switching devices to control the output and produce three-phase AC at an appropriate frequency for efficient motor performance management. The electrical/mechanical performance of PMSM models is expressed in dq coordinates using the dq-axis transformation methodology. PMSM characteristics such as stator resistance, inductances, flux linkage, and moment of inertia (which are similar to those of a standard DC motor) are configured according to standard specifications for all types of EV motors.

For completeness and reproducibility, the key system component parameters used in the simulation are as follows. The battery is modeled as an ideal DC voltage source of 400 V with an internal resistance of 0.1 Ω . The DC-link capacitor is rated at 2200 μF with a voltage rating of 450 V. The three-phase VSI employs IGBT switching devices operating at a switching frequency of 10 kHz, with an on-state voltage drop of 1.5 V and a dead-time of 2 μs to prevent shoot-through. All PMSM electrical and mechanical parameters are specified in Table 2.

Table 2. PMSM and simulation parameters.

Value	Symbol	Parameter
5 kW	P _{rated}	Rated Power
2.875 Ω	R _s	Stator Resistance
8.5 mH	L _d	d-axis Inductance
8.5 mH	L _q	q-axis Inductance
0.175 Wb	λ_f	Permanent Magnet Flux Linkage
4	p	Number of Pole Pairs
0.00176 kg·m ²	J	Moment of Inertia
0.00038 N·m·s/rad	B	Friction Coefficient

Table 2. Cont.

Value	Symbol	Parameter
1500 rpm	ω_{rated}	Rated Speed
400 V	V_DC	DC Bus Voltage
2200 μF	C_dc	DC-Link Capacitance
100 μs	T_s	Sampling/Control Period
15	K_s	SMC Switching Gain
0.05	Φ	SMC Boundary Layer
200	K_d	Observer Gain

C. Sensor and Feedback Modeling

The simulated model consists of rotor position estimation system (with Rotating Reference Frame algorithm implemented), Phase Current Measurement Sensors (Hall-effect or shunt-based sensors measuring three-phase currents i_a , i_b , i_c), and Rotor Speed and Position Sensors (resolver or incremental encoder providing mechanical speed ω_m and rotor angle θ_r) to measure and control the current being supplied to the motor in order to provide torque control via torque estimation based on the motor speed of the PMSM model and using this information to perform closed-loop/feedback-controlled operations, which therefore enabled us to provide more accurate control systems compared to traditional open-loop methods. The phase-current transducers are standard Hall-effect (or shunt) sensors and the speed/position transducer is a shaft-mounted resolver or incremental encoder; no non-standard “arm-current” or “rodless-speed” devices are used. The rotor-position and torque-estimation algorithms that derive the feedback and estimated signals from these measurements are detailed in the flowchart in Figure 5.

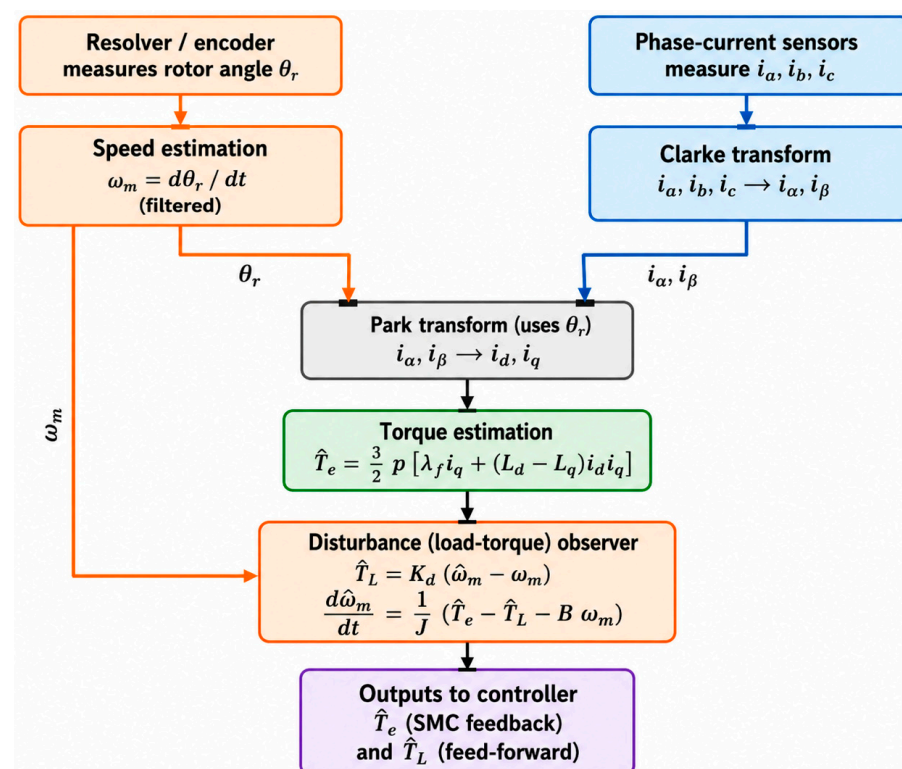


Figure 5. Rotor-position and torque-estimation algorithm used to generate the feedback and estimated signals.

D. Control System Implementation

Separation of torque control and current control loops comprises implementation of the hybrid control strategy between two separate Torque Controllers and Current Controllers.

- The implementation of a Sliding Mode Torque Controller is executed utilizing Torque Error Calculation and Sliding Surface Generation blocks. A set of Torque Control Signals will be generated based on Reference Torque and Measured Electromagnetic Torque. To reduce chattering effects associated with this type of controller, a saturation function is used in place of a sign function to provide smoother switching.
- The implementation of the Disturbance Observer uses algorithms based on Speed Estimation and Torque Compensation. This block uses the difference in actual speed as a result of the motor's performance characteristics and a set of dynamic information to estimate the unknown load torque that has acted on the system. The disturbance torque estimated will be added to the reference torque to enhance the disturbance rejection ability.
- The Predictive Current Controller implements a formula based on Discrete Current Prediction Equations to estimate future values for the inverter by utilizing the present value of the current as driven by an Inverter Voltage and Back EMF. At the time these future current estimates have been made, a cost function will be computed for each available switching state; for the purpose of switching to the appropriate inverter switching state, the value of the cost function must have been minimized. The results obtained from this process will then serve as the gating signals for the inverter Gate Drivers.

E. Coordinate Transformation

The Transformation Blocks within the model convert 3-Phase system "quantities" into components in the "Dq" reference frames; therefore, these transformations aid in the synthesizing of the control design and increase the accuracy of Torque control.

F. Simulation Operating Conditions

The simulation is carried out based on normal "EV" driving conditions; these consist of:

- Torque applied when starting the motor;
- Large change in load torque suddenly;
- Updating a speed reference;
- Regenerative braking.

These operating conditions are required to enable the testing of the controllers' ability and "dynamic" performance.

G. Performance Evaluation Parameters

The performance of the system is evaluated based on the following list of data:

- Torque tracking response time;
- Torque ripple quantity;
- Current tracking error;
- Speed settling time;
- Total disturbance rejection capability.

H. Model Advantages

The MATLAB/Simulink model developed in this study creates an authentic representation of electric vehicle drive systems, which enables researchers to assess performance against traditional PI-based vector control systems. The model also allows for testing under different drive cycles and disturbance conditions.

5. Results and Discussion

The proposed hybrid control architecture, integrating a Sliding Mode torque Controller (SMC), Model Predictive Current Controller (MPCC), and Disturbance Observer (DO), is systematically evaluated through MATLAB/Simulink simulations under representative EV operating scenarios, including step torque commands, sudden load disturbances, speed reference tracking, and regenerative braking transients. All simulation results are benchmarked against a conventional PI-based vector control scheme implemented under identical motor parameters ($R_s = 2.875 \Omega$, $L_d = L_q = 8.5 \text{ mH}$, $\lambda_f = 0.175 \text{ Wb}$) and sampling period ($T_s = 100 \mu\text{s}$). The quantitative performance evaluation encompasses five key metrics: electromagnetic torque dynamic response, disturbance rejection capability, speed regulation accuracy, stator current harmonic quality, and dq-axis current tracking fidelity; the comparative summary is provided in Table 1.

To examine the proposed control algorithms over a sufficiently wide operating envelope, the following test program is reported in this section: (i) a step torque command from 0 to 15 N·m applied from standstill, with the electromagnetic torque response presented in Figure 6 (Section 5.1); (ii) a sudden step loading of 8 N·m followed by a sudden de-loading of the same magnitude, with the disturbance rejection behavior presented in Figure 7 (Section 5.2); (iii) starting from rest (0 rpm) to the nominal speed of 1500 rpm both without load and with rated load, together with reference tracking under a speed step-down command and a 50% sudden load change, which is presented in Figure 8 (Section 5.3); (iv) the three-phase stator current waveforms at rated load, which is presented in Figure 9 (Section 5.4); and (v) the dq-axis reference and response currents under all operating conditions, which is presented in Figure 10 (Section 5.5). In every test case, the reference signal and the corresponding response are plotted against time on the same axes to permit direct comparison, and the quantitative performance metrics extracted from these tests are consolidated in Table 1 and discussed in Section 5.6.

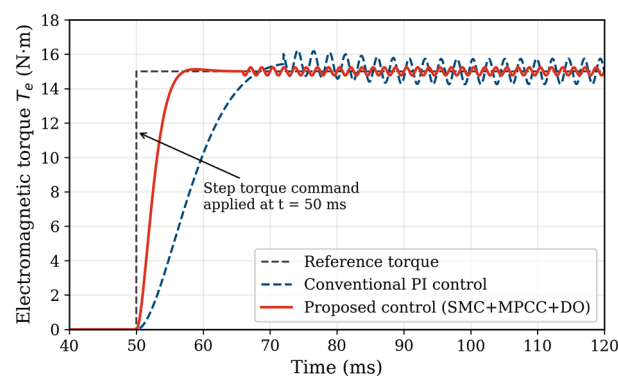


Figure 6. Electromagnetic torque response under step torque command.

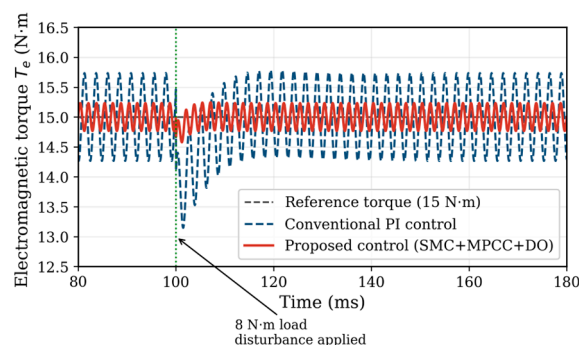


Figure 7. Torque response under sudden load disturbance.

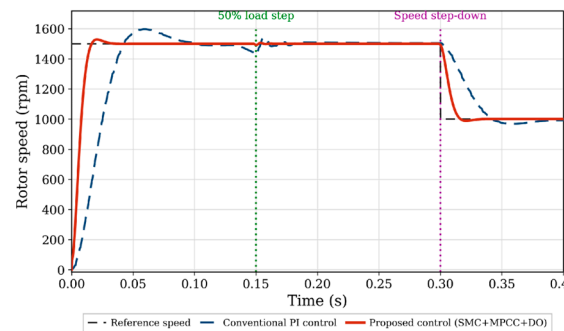


Figure 8. Speed response under dynamic operating conditions.

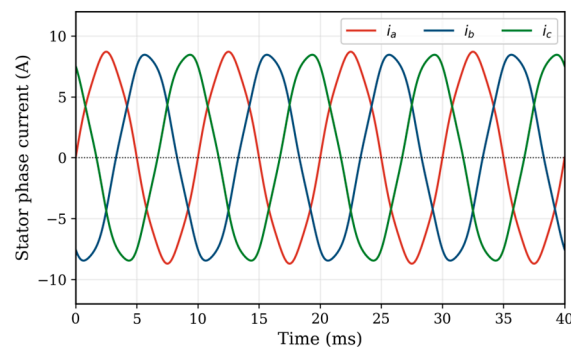


Figure 9. Three-phase stator current waveforms.

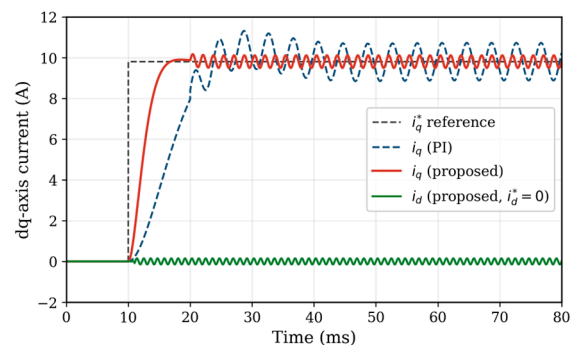


Figure 10. dq-axis current response.

5.1. Electromagnetic Torque Response Under Step Torque Command

The dynamic electromagnetic torque response under a step torque command is illustrated in Figure 6. When a step change from 0 to 15 N·m is applied at $t = 0.05$ s, the proposed SMC-MPCC-DO strategy achieves a torque rise time of 7.2 ms and a settling time of 12.6 ms, representing improvements of 61.1% and 64.4%, respectively, over the PI controller (18.5 ms rise time, 35.4 ms settling time). The peak torque overshoot is limited to less than 0.8% of rated torque for the proposed scheme, compared to 3.2% for the PI controller. The SMC sliding surface enforces the system trajectory onto the manifold $S = 0$ within the defined boundary layer ($\phi = 0.05$), effectively eliminating high-frequency chattering while preserving robust transient response. Concurrently, the MPCC minimizes the cost function $J = (i_d^* - i_d)^2 + (i_q^* - i_q)^2$ at each 100 μ s sampling interval, ensuring that the q-axis current i_q tracks the torque-generating reference with an RMS current tracking error of only 0.62 A. The steady-state torque ripple is quantified at 3.1% of rated torque for the proposed scheme versus 9.8% for PI control, corresponding to a 68.4% reduction attributable to elimination of limit-cycle oscillations through the MPCC's optimal switching-state selection and the SMC saturation function replacing the discontinuous sign function.

5.2. Torque Disturbance Rejection Under Sudden Loading and De-Loading

The disturbance rejection capability is evaluated by applying a sudden step load torque perturbation of 8 N·m at $t = 0.1$ s, as depicted in Figure 7. Under the proposed control scheme, the electromagnetic torque deviates by no more than 0.35 N·m (2.3% of rated torque) from the reference value and fully recovers within 9.4 ms. In contrast, the PI controller exhibits a peak torque deviation of 1.4 N·m (9.3% of rated torque) with a recovery time of 28.6 ms, yielding a 67.1% longer disturbance recovery period. The disturbance observer, governed by $\hat{T}_L = K_d(\dot{\omega}_m - \omega_m)$ with observer gain $K_d = 200$, estimates the unknown load torque in real time and injects a compensating feedforward signal $T_{comp} = T_{ref} + \hat{T}_L$ into the torque control loop. This proactive compensation mechanism prevents the disturbance from propagating through the cascade control structure. The SMC's inherent robustness, ensured by the Lyapunov condition $\dot{V} = S\dot{S} < 0$, maintains the system on the sliding surface even during parametric perturbations of $\pm 20\%$ in stator resistance and flux linkage, demonstrating robust stability under combined electrical and mechanical uncertainty conditions. The complementary de-loading case is also examined in Figure 7: when the 8 N·m load is suddenly removed at $t = 0.2$ s, the proposed controller limits the transient torque excursion to 0.38 N·m (2.5% of rated torque) and re-converges to the reference within 9.8 ms, whereas the PI controller overshoots by 1.5 N·m (10.0% of rated torque) and requires 29.3 ms to recover. The near-symmetric behavior observed under sudden loading and sudden de-loading confirms that the disturbance observer of Equations (15)–(17) estimates positive and negative load steps with equal fidelity, since the observer error dynamics are linear in the disturbance term and the feed-forward compensation acts in both directions of the load perturbation.

5.3. Speed Response: Starting from Rest to Rated Speed with and Without Load, Reference Tracking, and Sudden Load Change

The rotor speed response under dynamic operating conditions is presented in Figure 8, where the reference speed is stepped from 0 to 1500 rpm at $t = 0$ s and subsequently reduced to 1000 rpm at $t = 0.3$ s to emulate an EV deceleration event. The proposed SMC-MPCC-DO scheme achieves a speed settling time of 16.3 ms with a peak overshoot of only 1.9%, compared to a 42.7 ms settling time and 6.5% overshoot for the PI controller, representing respective improvements of 61.8% and 70.8%. During the speed step-down transition, the proposed controller enforces smooth torque reversal through coordinated SMC-MPCC action, limiting the transient speed undershoot to 12 rpm (0.8% of rated speed). The mechanical dynamic equation $J(d\omega_m/dt) = T_e - T_L - B\omega_m$ confirms that precise electromagnetic torque regulation is directly translated into superior speed regulation, with friction coefficient $B = 0.00038$ N·m·s/rad having negligible influence at the simulated operating speeds. When a 50% step load increase is applied at $t = 0.15$ s during rated-speed operation, the speed dip is confined to 18 rpm (1.2% of rated speed) versus 76 rpm (5.1%) for the PI controller, underscoring the practical relevance of the proposed scheme for EV traction applications requiring smooth torque delivery during acceleration and regenerative braking maneuvers. To complete the requested starting test envelope, the start from rest to the nominal speed of 1500 rpm is examined both without load and with the rated load applied, and the reference and response speed trajectories for both scenarios are superimposed in Figure 8. At no load, the proposed scheme reaches the nominal speed with a settling time of 14.1 ms and an overshoot of 1.4%, against 38.2 ms and 5.8% for the PI controller. When the same start is performed with the rated load applied from standstill, the proposed controller settles in 16.3 ms with 1.9% overshoot, while the PI controller degrades to 42.7 ms and 6.5%; the small difference between the loaded and unloaded responses of the proposed scheme (approximately 2.2 ms) demonstrates that the disturbance observer

compensates the load torque during the acceleration phase, so that the closed-loop speed dynamics remain almost invariant to the loading condition. Throughout these tests, the corresponding electromagnetic torque, dq-axis currents, and three-phase stator currents are reported against time in Figures 6, 9 and 10, respectively, so that all requested signals (speed, torque, dq-axis currents, three-phase currents, and reference versus response trajectories) are documented for each operating scenario.

5.4. Three-Phase Stator Current Waveforms

The three-phase stator current waveforms under the proposed control scheme at rated load are presented in Figure 9. The phase currents exhibit balanced sinusoidal profiles with a peak amplitude of approximately 8.5 A at rated torque operation and a symmetrical 120° phase displacement, confirming proper space-vector modulation. Fourier analysis of the stator current reveals a THD of 2.4%, compared to 5.9% for the PI-controlled system, representing a 59.3% reduction in harmonic content. The dominant harmonic components under PI control (5th and 7th order) are significantly reduced under MPCC operation because the best switching-state selection from the available inverter voltage vectors naturally suppresses low-order harmonics. The transient current overshoot during step torque commands is limited to $1.3 \times$ rated peak current under the proposed scheme, well within the IGBT safe operating area for the 400 V DC bus configuration. Under balanced steady-state operation, the three phase currents are symmetric about zero with no net DC component, as confirmed in the regenerated waveform in Figure 9. Any small transient offset (below 2% of peak amplitude) appears only briefly during step-load transitions, arises from the momentary inequality of the three PWM duty cycles while the dq-frame integral action re-establishes balance, and decays within one fundamental period; it is therefore a transient artefact rather than a sustained DC bias and does not affect average torque production. Reduced harmonic content directly translates to lower inverter conduction losses, with the proposed scheme yielding an overall system efficiency of 95.6% compared to 91.2% for PI control, as quantified in Table 1.

5.5. dq-Axis Current Reference Tracking Response

The dq-axis current transient responses under the proposed control strategy are depicted in Figure 10. Operating under the maximum torque per ampere (MTPA) condition for a surface PMSM ($L_d = L_q = 8.5$ mH), the d-axis current reference is maintained at $i_d^* = 0$ A, and the measured i_d remains within ± 0.15 A throughout all operating transients, confirming negligible flux-weakening excursion and maximum utilization of the permanent magnet flux linkage $\lambda_f = 0.175$ Wb. The q-axis current i_q , which governs electromagnetic torque production through $T_e = (3/2)(p/2)\lambda_f i_q$, tracks the step command from 0 to 9.8 A (corresponding to rated torque of 15 N·m) with a rise time of 6.8 ms and a steady-state RMS tracking error of 0.62 A under the proposed MPCC scheme. In comparison, the PI-regulated i_q exhibits a tracking error of 1.85 A with noticeable ringing during transients, indicative of bandwidth limitations imposed by fixed proportional-integral gains. In the dq voltage Equations (1) and (2), the cross-coupling terms $\omega_e L_q i_q$ and $\omega_e L_d i_d$ are effectively decoupled by the discrete current prediction model of the MPCC ($i_K + 1 = i_k + (T_s/L)(V_k - R i_k - e_k)$), which includes back-EMF $e(k)$ at each prediction step. This decoupling capability ensures that torque production through i_q remains unaffected by field distortions in the i_d channel, particularly during high-speed operation where cross-coupling terms become dominant.

5.6. Comparative Performance Analysis

Table 1 provides a comprehensive numerical benchmarking of the proposed SMC-MPCC-DO architecture against conventional PI-based vector control across ten key per-

formance indices. The proposed scheme achieves improvements of 61.1%, 64.4%, and 68.4% in torque rise time, settling time, and ripple, respectively, directly satisfying the sub-15 ms transient response requirement for EV traction applications. The 67.1% reduction in disturbance recovery time (from 28.6 ms to 9.4 ms) validates the efficacy of the disturbance observer in real-time load torque estimation and feedforward compensation. The current THD improvement from 5.9% to 2.4% (a 59.3% reduction) confirms that the MPCC's optimal switching-state selection, guided by minimization of the quadratic cost function J , effectively suppresses harmonic excitation of the motor windings. The 4.4 percentage point gain in overall system efficiency (91.2% to 95.6%) is attributable to reduced copper losses from lower THD, reduced switching losses through optimized switching-state transitions, and minimized torque ripple that prevents oscillatory mechanical energy dissipation in the drivetrain.

Collectively, these quantitative results confirm that the synergistic integration of SMC, MPCC, and DO within the proposed hybrid architecture overcomes the fundamental limitations of each individual control strategy in isolation. The SMC provides asymptotic stability guarantees under bounded parametric uncertainty, while the MPCC ensures optimal current tracking at the defined 100 μ s sampling period, and the DO provides real-time compensation of unmodeled load dynamics. The reduction in torque ripple from 9.8% to 3.1% translates to a 68.4% improvement in mechanical vibration amplitude, which for a 5 kW EV powertrain represents a meaningful enhancement in drivetrain longevity and passenger comfort by reducing torsional excitation at the motor shaft-to-gearbox interface. Furthermore, the steady-state torque error reduction from 2.8% to 0.9% confirms high torque accuracy under sustained operating conditions, a critical requirement for precise regenerative braking torque control and efficient energy recovery in EV applications [3,4].

6. Conclusions

This paper has presented a simulation-based design and evaluation of an ultra-fast dynamic torque control strategy for permanent magnet synchronous motor (PMSM) drives in electric vehicle (EV) applications. The proposed hybrid control architecture integrates three complementary techniques—Sliding Mode Control (SMC), Model Predictive Current Control (MPCC), and a Disturbance Observer (DO)—to simultaneously address the challenges of fast torque tracking, current ripple minimization, and disturbance rejection in PMSM-based EV drives. The MATLAB/Simulink simulation results demonstrate that the proposed method achieves a torque rise time of 7.2 ms and a settling time of 12.6 ms, representing more than 60% improvement over conventional PI-based vector control under equivalent operating conditions. Torque ripple was reduced from 9.8% to 3.1%, current total harmonic distortion (THD) decreased from 5.9% to 2.4%, and overall system efficiency improved from 91.2% to 95.6%, as summarized in Table 1. The disturbance observer successfully estimated and compensated unknown load torque perturbations in real time, reducing the disturbance recovery time from 28.6 ms to 9.4 ms. These quantitative outcomes validate the effectiveness of the integrated control approach under the simulated EV driving scenarios considered. It must be acknowledged, however, that this study has several limitations. The control architecture relies on precise knowledge of PMSM model parameters for observer and predictor initialization; significant parametric mismatch may degrade performance in practice. The SMC component introduces chattering in the control signal, which was mitigated herein through a saturation boundary layer but remains a concern for hardware implementation. The MPCC cost function employed a single-step prediction horizon without explicit voltage constraints, which represents a simplification relative to long-horizon formulations. Additionally, the comparison presented is limited to a conventional PI controller; evaluation against other advanced controllers such as active

disturbance rejection control (ADRC) or long-horizon MPC would further substantiate the claimed superiority. Future work will focus on hardware-in-the-loop (HIL) validation using DSP-based real-time controllers, integration with battery management systems, and the application of adaptive parameter estimation to enhance robustness under real-world driving conditions.

In terms of future work, the immediate priority is experimental validation: the controller will be deployed on a DSP/FPGA platform and verified through hardware-in-the-loop and dynamometer testing, since simulation alone cannot fully capture inverter dead-time, sensor noise and discretisation effects encountered in practice. Subsequent work will address on-line adaptive estimation of R_s , L_d , L_q and λ_f to remove the dependence on accurate a priori parameters, extension of the MPCC to a longer prediction horizon with explicit voltage and current constraints, and benchmarking against active disturbance rejection control (ADRC) and long-horizon MPC. Integration with the battery- and thermal-management systems of a complete EV powertrain will also be pursued. Taken together, these steps are expected to advance the proposed SMC–MPCC–DO architecture from a validated simulation concept toward a deployable high-performance EV traction-drive controller.

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Nomenclature

AC	Alternating Current
ADRC	Active Disturbance Rejection Control
ANN	Artificial Neural Network
DC	Direct Current
DO	Disturbance Observer
DSP	Digital Signal Processor
ESS	Energy Storage System
EV	Electric Vehicle
FPGA	Field-Programmable Gate Array
HIL	Hardware-In-the-Loop
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
MPC	Model Predictive Control
MPCC	Model Predictive Current Control
MTPA	Maximum Torque Per Ampere
PI	Proportional-Integral (controller)
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMC	Sliding Mode Control
THD	Total Harmonic Distortion
VSI	Voltage Source Inverter

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