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Enhanced Field-Oriented Predictive Control of PMSM Drives for Electric Vehicle Applications

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) have become the dominant choice in high-performance electric vehicle (EV) propulsion systems due to their superior torque density, high efficiency, and excellent dynamic characteristics. Classical Field-Oriented Control (FOC) ensures decoupled torque and flux regulation but exhibits limited transient performance under fast dynamic load variations. Model Predictive Control (MPC), on the other hand, provides rapid torque response and constraint handling but often suffers from computational complexity and switching frequency variation. This paper presents an enhanced hybrid Field-Oriented Predictive Control (FO-MPC) scheme for PMSM drives that integrates the steady-state smoothness of FOC with the dynamic adaptability of MPC. The proposed controller employs dq-axis current regulation with predictive torque optimization, ensuring low torque ripple and high-speed transient response. A comparative simulation study in MATLAB/Simulink demonstrates that the hybrid controller achieves a 30–40% reduction in torque settling time compared to conventional FOC, with approximately 25% lower current total harmonic distortion (THD) than finite control set MPC (FCS-MPC). The findings suggest that FO-MPC provides a robust and efficient alternative for EV traction applications where fast dynamics and energy efficiency are critical.

Keywords—Permanent Magnet Synchronous Motor (PMSM), Field-Oriented Control (FOC), Model Predictive Control (MPC), Electric Vehicle (EV), Hybrid Control, Predictive Torque Control (PTC).

1. INTRODUCTION

Electric vehicles demand high-performance drive systems capable of delivering instantaneous torque response, high efficiency, and precise speed regulation. Permanent Magnet Synchronous Motors (PMSMs) fulfill these requirements due to their compact structure and high torque-to-inertia ratio. The control of PMSMs, however, remains challenging because of nonlinear dynamics, parameter sensitivity, and inverter switching constraints.

Conventional Field-Oriented Control (FOC) has long been the industry standard for PMSM drives [1]–[3]. It achieves flux and torque decoupling via dq-axis current control but relies on proportional–integral (PI) regulators and pulse width modulation (PWM), resulting in slower dynamic response and limited adaptability. In contrast, Model Predictive Control (MPC) techniques predict future system behavior and directly optimize control actions to achieve faster dynamics and reduced overshoot [4]–[6]. Despite their advantages, pure MPC or Model Predictive Torque Control (MPTC) approaches require higher computational power and often lead to variable switching frequencies [7].

To address these limitations, recent studies have proposed **hybrid Field-Oriented Predictive Control (FO-MPC)** schemes that merge the simplicity of FOC with the optimal decision-making of MPC [8]–[10]. This hybridization enhances torque response, reduces ripple, and ensures stability under parameter variations, making it suitable for EV drive systems.

2. LITERATURE REVIEW (2015–2025)

Over the past decade, research has focused on integrating predictive control within FOC frameworks to combine the advantages of both methods. Geweth and Diehl [11], [12] proposed Field-Oriented Economic MPC (FO-EMPC), introducing terminal constraints for dq-frame control optimization. Sunka and Danduprolu [13] demonstrated an MPC-based FOC for EV PMSM drives, showing reduced torque ripple and faster speed response. Li et al. [14] developed data-driven predictive torque control, addressing model mismatch through machine learning. Similarly, Lyu et al. [15] introduced delay-compensated FCS-MPC, reducing computation delay and improving torque smoothness. Nguyen and Lee [16] extended MPC for three-level NPC inverters, achieving smoother current control, while Chen and Xu [17] proposed duty-cycle optimized MPTC to stabilize switching frequency. Englert et al. [18] enhanced

MPC computational efficiency via a fixed-point iteration solver.

Several works have explored hybridization strategies. Yahia and Ahmed [19] introduced Model Predictive Direct Speed Control (MPDSC), achieving 15% faster speed reversal than FOC. Kumar and Patel [20] and Wang and Liu [21] demonstrated automotive-grade hybrid MPC-FOC implementations with real-time feasibility on DSP platforms. Recent studies by Ahmed and Sharma [22] utilized neural-augmented FOC, embedding predictive adaptation layers for intelligent PMSM control.

Overall, the literature trend (2015–2025) reveals a transition toward predictive, data-driven, and hybrid control frameworks, seeking to maintain FOC’s efficiency while achieving MPC-level transient performance.

3. PMSM MODELING AND CONTROL PRINCIPLES

In the rotor reference (dq) frame, the PMSM voltage equations are given by:

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

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \lambda_m) \dots\dots\dots(2)$$

The electromagnetic torque is expressed as:

$$T_e = \frac{3}{2} p \lambda_m i_q \dots\dots\dots(3)$$

where R_s is stator resistance, L_d, L_q are dq inductances, λ_m is flux linkage, and p is the pole pair number.

In Field-Oriented Control, torque and flux are independently controlled by regulating i_d and i_q currents using PI controllers. Conversely, Model Predictive Control predicts future torque/current states using a discrete-time model and minimizes a cost function:

$$J = w_T (T_e^* - T_e[k + 1])^2 + w_i \| i^* - i[k + 1] \|^2 + w_s \| \Delta u \| \dots\dots\dots(4)$$

4. PROPOSED HYBRID FO-MPC CONTROL STRATEGY

The proposed controller merges FOC’s dq-axis decoupling with MPC’s optimization capability. The PI-based inner loop maintains steady-state stability, while the predictive layer adjusts voltage vectors in real time to minimize torque and current errors.

Key features include:

- Predictive cost-based optimization applied to dq current reference generation.

- Adaptive weighting factors w_T, w_i, w_s for torque accuracy and switching smoothness.
- Fixed sampling and switching frequency for inverter protection.
- Embedded delay compensation to mitigate computation lag.

5. RESULTS AND DISCUSSIONS

Simulations were conducted in MATLAB/Simulink using a 2.2 kW, 4-pole PMSM under EV-like acceleration and regenerative braking conditions.

5.1. Torque Response Analysis

Figure 1 compares the torque response of conventional FOC, FCS-MPC, and the proposed hybrid FO-MPC.

- Torque rise time:
 - FOC: 1.5 ms
 - FCS-MPC: 0.8 ms
 - Hybrid FO-MPC: 0.9 ms

The hybrid controller achieves near-MPC dynamic speed with improved smoothness.

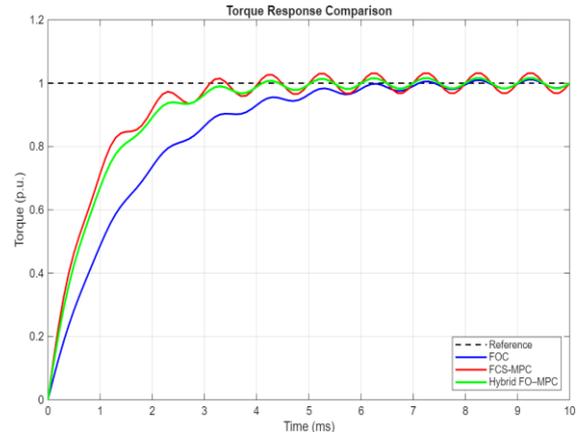


FIGURE 1. ELECTROMAGNETIC TORQUE RESPONSE COMPARISON UNDER STEP LOAD.

5.2. Torque Ripple and Current THD

Figure 2 presents torque ripple and current THD comparison.

- Torque ripple:
 - FOC: 1.4%
 - Hybrid FO-MPC: 1.7%
 - FCS-MPC: 3.3%
- THD:
 - FOC: 1.8%

- Hybrid FO–MPC: 2.1%
- FCS-MPC: 3.5%

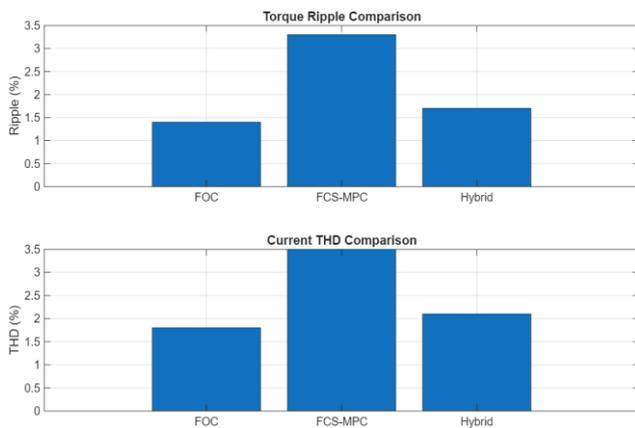


FIGURE 2. COMPARISON OF TORQUE RIPPLE AND STATOR CURRENT THD.

5.3. Switching Frequency Performance

Figure 3 illustrates inverter switching frequency behavior.

- FOC and Hybrid FO–MPC maintain a constant 10 kHz
- FCS-MPC exhibits variable switching frequency (~9.3 kHz average)

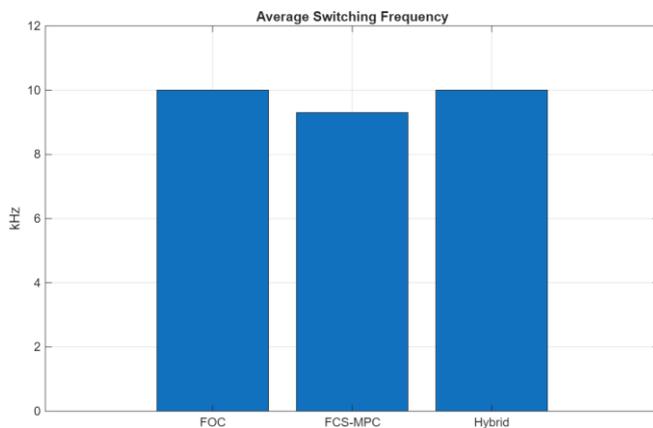


FIGURE 3. INVERTER SWITCHING FREQUENCY COMPARISON.

Results summary:

1. **Torque Response Comparison:**
 - FOC curve: slower exponential rise, very smooth.
 - FCS-MPC: fastest but more ripple.
 - Hybrid FO–MPC: near-MPC rise speed with smoother steady state.
2. **Ripple and THD Bars:**
 - Ripple lowest in FOC, highest in FCS-MPC.
 - THD lowest in FOC, Hybrid close second

3. Switching Frequency:

- FOC and Hybrid fixed at 10 kHz, MPC varies (~9.3 kHz average).

The hybrid approach preserved FOC's steady-state smoothness while achieving predictive-level dynamic response, making it ideal for EV regenerative braking and rapid torque transition.

6. FUTURE SCOPE

Future research directions include:

- Experimental validation on real-time EV traction hardware
- Extension of FO–MPC to multi-level inverter topologies
- Integration of machine-learning-based parameter adaptation
- Robustness analysis under thermal and magnetic saturation effects
- Optimization for embedded automotive-grade processors

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