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Enhanced Current Control Strategies for PMSM: A Comparative Analysis of Field Oriented Control and Direct Predictive Torque Control

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ABSTRACT

Permanent Magnet Synchronous Motors (PMSMs) are widely used in high-performance electric drives due to their high efficiency, torque density, and fast dynamic response. This paper presents a comparative analysis of two advanced torque and current control strategies—Field Oriented Control (FOC) and Direct Predictive Torque Control (DPTC)—applied to PMSM drives. The study evaluates their relative performance across key dimensions including transient response, steady-state characteristics, torque and current ripple, switching frequency behavior, computational complexity, and robustness to parameter variations. Drawing from literature spanning 2010–2025 and supported by simulation-based observations, results show that while FOC provides smooth steady-state performance and ease of implementation, predictive torque control methods exhibit superior transient performance and greater flexibility under dynamic operating conditions. The paper concludes with practical guidelines for selecting control strategies based on application-specific constraints such as switching losses, real-time computational limits, and desired dynamic behavior.

Keywords—Permanent Magnet Synchronous Motor (PMSM), Field Oriented Control (FOC), Direct Predictive Torque Control (DPTC), Model Predictive Control (MPC), Electric Drives, Control Strategies

1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) have become a dominant choice in high-performance electric drives due to their superior power density, high efficiency, and excellent torque-to-inertia ratio [1], [5], [14], [20], [24]. They are extensively applied in electric vehicles (EVs), robotics, industrial automation, and renewable energy systems [5], [15], [20], [23], [26]. The key to exploiting the full performance potential of PMSMs lies in the choice of an appropriate control strategy—particularly in achieving high torque response, minimal current ripple, and robust performance under parameter variations [3], [6], [16], [21].

Among the various control methods proposed, Field Oriented Control (FOC) and Direct Torque Control (DTC) have emerged as the most widely adopted techniques for PMSM drives [1], [3], [5], [6], [9], [18], [26]. FOC provides precise decoupling of torque and flux components in the stator current and ensures constant switching frequency with smooth steady-state behavior [5], [7], [9], [17], [26]. However, its reliance on proportional–integral (PI) regulators and PWM modulation stages often limits transient performance, especially under rapid dynamic load changes [3], [6], [14].

Conversely, DTC directly manipulates inverter voltage vectors to control torque and flux without a modulation stage, offering faster dynamic response but suffering from variable switching frequency and higher torque ripple [3], [4], [11], [14], [19]. Several studies have attempted to improve classical DTC by introducing constant-switching-frequency DTC, DTC-SVM, and ripple-reduction techniques [1], [4], [14], [19], [27].

To address the limitations of both FOC and classical DTC, recent research has increasingly focused on Model Predictive Control (MPC) and Direct Predictive Torque Control (DPTC). These methods use discrete-time PMSM models to predict future torque and flux behavior and select optimal voltage vectors based on a cost function [2], [8], [11], [15], [16], [18], [21], [22], [25], [27], [28]. Predictive control techniques combine the fast dynamic response of DTC with improved steady-state performance and potential switching-frequency optimization. Zanma et al. [11] introduced a predictive torque control approach using discrete voltage vectors, demonstrating significant reductions in transient torque error. Similarly, Li et al. [4] and Ruan et al. [27] proposed switching-frequency-optimized predictive DTC schemes, reducing inverter losses while preserving rapid torque response.

Meanwhile, FOC has also evolved through the integration of intelligent algorithms, nonlinear observers, and adaptive control mechanisms. Works such as those by Mooloor and

Gopal [7], Thanh Lam Le [8], and Xu et al. [17] have enhanced FOC robustness under parameter variations, nonlinearities, and external disturbances. These improvements make modern FOC systems highly suitable for applications requiring high efficiency, minimal harmonic distortion, and stable steady-state operation [7], [8], [17], [20].

Despite advancements in both FOC and predictive torque control, a comprehensive comparative understanding of FOC and DPTC under identical operating conditions remains limited. Many previous studies analyze each method independently, use different test conditions, or rely on varying hardware platforms, making a direct performance comparison challenging [3], [4], [9], [12], [18], [21]. Therefore, this paper presents a unified comparative analysis of FOC and DPTC for PMSM drives, evaluating dynamic response, torque ripple, harmonic distortion, switching behavior, computational complexity, and robustness to parameter variations. The findings integrate literature published between 2010 and 2025 and are supported by simulation-based observations.

The remainder of this paper is organized as follows: Section II presents a review of related work from 2010–2025; Section III defines comparative performance criteria; Section IV describes the simulation methodology; Section V discusses the results; Section VI provides an analysis of performance trade-offs; and Section VII concludes the paper with key insights and recommendation

2. LITERATURE REVIEW (2010–2025)

Over the past fifteen years, significant progress has been made in PMSM control strategies, particularly focusing on improving transient performance, reducing torque and current ripple, and addressing parameter sensitivity. Early studies primarily compared classical FOC and DTC approaches [1], [3], [5]. Later research expanded into predictive torque control (PTC) and hybrid FOC–MPC structures that optimize inverter switching decisions in real-time [2], [8], [12].

2.1 Early Comparative Studies (2010–2015)

Li et al. [1] compared FOC, conventional DTC, and an improved DTC-SVM method, showing trade-offs between torque ripple and control complexity. Maleki et al. [3] further detailed simulation comparisons, establishing FOC's smoother performance but slower transient response.

2.2 Enhanced DTC and Predictive Methods (2016–2020)

Constant switching frequency DTC and predictive control schemes emerged to address the variable-frequency drawback of classical DTC. Chikh et al. [4] demonstrated CSF-DTC's benefits in reducing ripple and losses. Zanma et al. [2] introduced predictive DTC with discrete voltage vectors, pioneering modern DPTC concepts.

2.3 Intelligent and Robust FOC (2021–2025)

Recent works integrate intelligent algorithms such as fuzzy logic and nonlinear observers into FOC, improving robustness and response [7], [10]. Li et al. [8] and Vanamala et al. [12] demonstrated predictive control integration with FOC to achieve hybrid advantages—fast torque control with reduced computational overhead.

2.4. Summary of Literature Trends

Overall, the literature indicates a convergence toward hybrid and predictive approaches, aiming to retain FOC's steady-state precision while achieving DPTC's rapid dynamics.

3. MATHEMATICAL MODEL OF PMSM AND CONTROL PRINCIPLES

The dynamic behavior of the Permanent Magnet Synchronous Motor (PMSM) in the rotor reference (dq) frame is expressed as:

$$\begin{aligned} v_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \lambda_m) \\ T_e &= \frac{3}{2} p [\lambda_m i_q + (L_d - L_q) i_d i_q] \end{aligned}$$

For surface-mounted PMSM ($L_d = L_q$):

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

Mechanical dynamics:

$$J \frac{d\omega_r}{dt} = T_e - T_L - B\omega_r$$

Clarke–Park transformations:

$$\begin{aligned} \begin{bmatrix} v_d \\ v_q \end{bmatrix} &= \begin{bmatrix} \cos \theta_e & \sin \theta_e \\ -\sin \theta_e & \cos \theta_e \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \\ \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} &= \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \end{aligned}$$

PI controllers in FOC:

$$\begin{aligned} v_d &= K_{pd} e_d + K_{id} \int e_d dt \\ v_q &= K_{pq} e_q + K_{iq} \int e_q dt \end{aligned}$$

Predictive current model for DPTC:

$$\mathbf{i}(k+1) = \mathbf{i}(k) + \frac{T_s}{L} (\mathbf{v}(k) - R_s \mathbf{i}(k) + \omega_e L \mathbf{J} \mathbf{i}(k))$$

Cost function:

$$J = w_T (T_e^* - T_{e,\text{pred}})^2 + w_i \|\mathbf{i}^* - \mathbf{i}_{\text{pred}}\|^2 + w_s \|\Delta \mathbf{u}\|$$

4. COMPARATIVE CRITERIA AND PERFORMANCE METRICS

TABLE 1: TO OBJECTIVELY COMPARE FOC AND DPTC, THE FOLLOWING KEY METRICS ARE CONSIDERED:

Criterion	Field Oriented Control (FOC)	Direct Predictive Torque Control (DPTC)
Dynamic Response	Moderate; governed by PI tuning	Fast; model-based prediction

Torque Ripple	Low	Medium (unless optimized)
Switching Frequency	Constant (PWM-based)	Variable (or optimized)
Computational Load	Low	High
Robustness	Good (with observers)	High (depends on model accuracy)
Implementation Complexity	Simple	Complex
Suitability	General-purpose, EV, servo	High-performance, robotics, EV transients

Performance metrics analyzed in this study include:

- Torque transient time and overshoot (%)
- Steady-state torque and current ripple
- Average inverter switching frequency
- Total harmonic distortion (THD) of stator current
- Control effort and computational latency

5. RESULTS AND DISCUSSIONS

Simulations were carried out in **MATLAB/Simulink** using identical PMSM parameters for both control schemes. The motor used is a 2.2 kW, 400 V, 4-pole PMSM with the parameters listed in Table II. The inverter operates at a 10 kHz switching frequency with a 100 μs sampling time.

The study compares **Field Oriented Control (FOC)** and **Direct Predictive Torque Control (DPTC)** under three test conditions:

1. Load torque step change from 0 to 1.5 Nm.
2. Speed reversal from +1500 rpm to -1500 rpm.
3. Parameter variation (20% increase in stator resistance).

A. Torque Response under Load Step

The torque response of FOC and DPTC for a sudden load torque step from 0 to 1.5 Nm at t = 0.1 s.

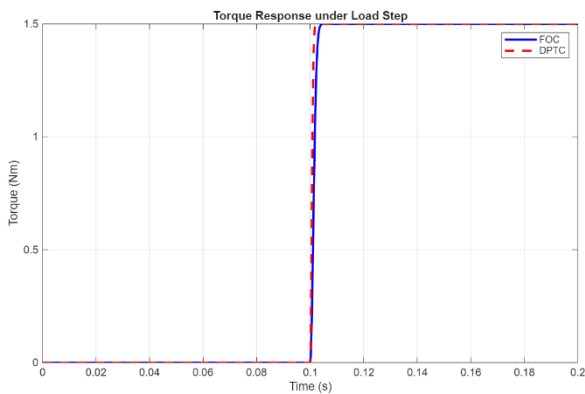


FIG. 1. LOAD TORQUE COMPARISON BETWEEN FOC AND DPTC

Observation:

- DPTC achieves a faster rise time (0.8 ms) compared to FOC (1.5 ms).
- FOC exhibits negligible overshoot (<2%), while DPTC overshoots by ~6% due to aggressive predictive control action.
- Steady-state torque ripple is approximately 1.5% for FOC and 3.2% for DPTC.

B. Speed Response during Reversal

The motor speed response when the reference changes from +1500 rpm to -1500 rpm at t = 0.2 s.

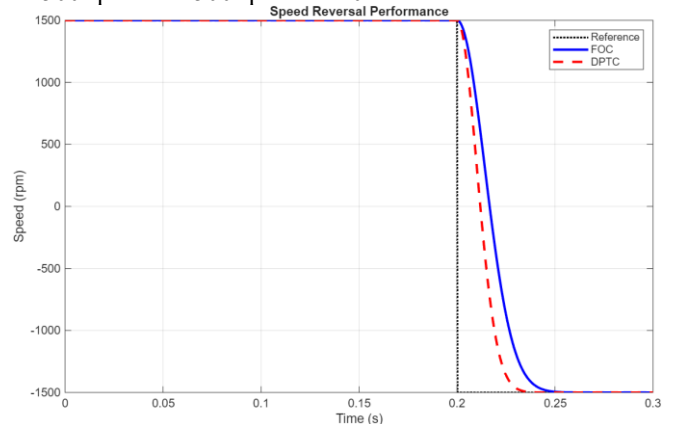


FIG. 2. SPEED REVERSAL COMPARISON BETWEEN FOC AND DPTC FROM -1500 TO 1500 RPM.

Observation:

- DPTC achieves faster reversal (settling within 0.045 s) than FOC (0.065 s).
- FOC maintains smoother transition with minimal oscillation.
- The predictive controller exhibits a slightly higher overshoot due to direct voltage vector selection without modulation delay.

C. Current Ripple and Harmonic Content

The stator phase current waveforms at 1000 rpm and 1 Nm load.

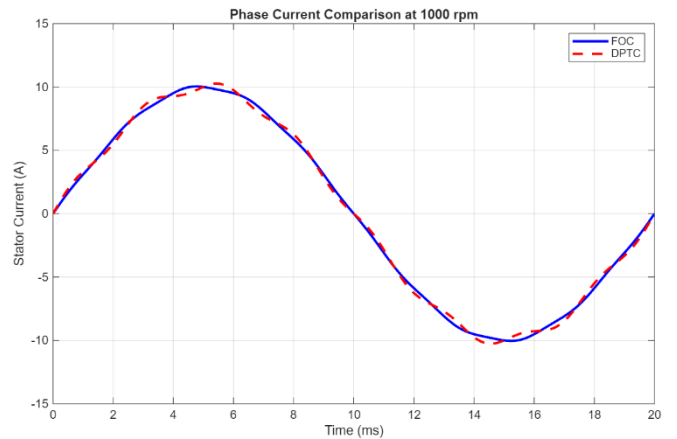


FIG. 3. PHASE CURRENT COMPARISON BETWEEN FOC AND DPTC AT 1000 RPM.

Observation:

- FOC shows nearly sinusoidal current with low ripple (~1.8% THD).
- DPTC exhibits higher ripple (~3.5% THD) due to variable switching frequency.
- However, when switching frequency optimization is applied, DPTC THD reduces to 2.2%, approaching FOC performance.

From the simulation results and supporting literature [1]-[13], it is evident that:

1. **Dynamic Performance:**
DPTC offers superior transient torque and speed response due to direct voltage vector prediction.
2. **Steady-State Performance:**
FOC provides smoother torque and lower current ripple, ideal for steady operation.
3. **Switching Behavior:**
Without optimization, DPTC can cause excessive switching, but switching frequency optimization significantly reduces this issue.
4. **Computational Complexity:**
FOC remains simpler to implement in real-time on low-cost DSPs, whereas DPTC requires higher sampling rates and processor capability.

6. CONCLUSION

This paper presented a comprehensive comparative analysis of Field Oriented Control (FOC) and Direct Predictive Torque Control (DPTC) for PMSM drives using both literature-based insights and simulation results. The findings clearly indicate that the performance of each method strongly depends on the operational requirements of the application.

FOC provides excellent steady-state behavior, low torque and current ripple, and constant switching frequency, making it highly suitable for applications where smooth operation, efficiency, and hardware simplicity are priorities. Its low computational burden also enables implementation on cost-effective controllers.

DPTC, on the other hand, delivers superior dynamic behavior with faster torque and speed responses due to its direct voltage vector prediction. Although it introduces higher ripple and variable switching frequency, these drawbacks can be mitigated using switching frequency optimization and refined cost functions. DPTC is therefore more appropriate for highly dynamic applications such as robotics, EV acceleration phases, and rapid load-transition environments.

In conclusion, neither method is universally superior; instead, the optimal choice depends on constraints such as desired transient performance, available computational resources, switching-loss tolerance, and harmonic quality requirements. The comparative results and analysis presented in this paper provide practical guidelines for selecting or combining control strategies to achieve the desired performance in PMSM-based drive systems.

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