

A Survey of Several Control Methods for Multiphase PMSMs: A Comparative Assessment

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Abstract: Multiphase permanent magnet synchronous machines (PMSMs) are widely applied in high-power and high-reliability systems such as electric vehicles, more electric aircraft, and marine propulsion. However, controlling these systems poses significant challenges due to the increased degrees of freedom, the requirement for harmonic suppression in the x - y subspace, and fault-tolerant capability. This paper presents a comprehensive and comparative overview of control strategies for multiphase PMSMs, including classical methods (FOC, DTC), model predictive control (MPC), sensorless control, fault-tolerant control (FTC), and advanced hybrid approaches. A quantitative comparison is conducted based on key performance indicators such as total harmonic distortion (THD), torque ripple, computational complexity, fault tolerance capability, and position sensor requirements. The results indicate that MPC with virtual vectors achieves low THD (2–4%) and low torque ripple (3–5%), while effectively suppressing harmonic currents in the x - y subspace; however, it still faces challenges related to computational burden and weighting factor tuning. Sensorless methods eliminate mechanical sensors but remain limited in the low-speed region. FTC enables continued operation at 70–80% of rated power under open-phase faults, making it a critical feature for safety-critical systems. Based on these findings, a three-layer integrated control framework (MPC core – hybrid sensorless observer – fault diagnosis and reconfiguration) is proposed. In addition, future research directions are outlined, including real-time MPC with reduced complexity, deep learning-based sensorless control, and self-adaptive drive systems.

Keywords: Multiphase PMSM, Model predictive control, Sensorless control, Fault-tolerant control, Integrated control framework.

Date Of Submission: 07-04-2026

Date of Acceptance: 20-04-2026

I. INTRODUCTION

In recent years, electrification has been rapidly developed in sectors such as road transportation, maritime systems, and aviation. Electric vehicles (EVs), electric ships, and more electric aircraft (MEA) are being increasingly deployed, leading to a growing demand for drive systems that offer both high power density and high reliability [1]. However, conventional three-phase permanent magnet synchronous machines (PMSMs) have revealed several inherent limitations: high phase currents impose significant stress on power semiconductor devices, limited fault tolerance means that even a minor fault can disable the entire system, and torque ripple is difficult to completely eliminate [2, 3]. In recent years, electrification has been rapidly developed in sectors such as road transportation, maritime systems, and aviation. Electric vehicles (EVs), electric ships, and more electric aircraft (MEA) are being increasingly deployed, leading to a growing demand for drive systems that offer both high power density and high reliability [1]. However, conventional three-phase permanent magnet synchronous machines (PMSMs) have revealed several inherent limitations: high phase currents impose significant stress on power semiconductor devices, limited fault tolerance means that even a minor fault can disable the entire system, and torque ripple is difficult to completely eliminate [2, 3].

To address these challenges, multiphase PMSMs have been investigated as a promising alternative [4]. Increasing the number of phases allows current to be more evenly distributed, thereby reducing the stress on individual phases and power devices. Moreover, the additional degrees of freedom provide enhanced fault-tolerant capability. In the event of one or two open-phase faults, the machine can continue operating—albeit with reduced performance—instead of a complete shutdown [5]. In addition, torque ripple and current harmonics can be significantly mitigated [6].

Several prominent control approaches have been developed, including model predictive control (MPC) [6, 7], sensorless control [8], and fault-tolerant control (FTC) [9]. However, most existing review papers tend to focus on only one of these approaches. For instance, some works concentrate solely on MPC for multiphase systems, others address sensorless control for dual three-phase configurations [10], while some focus

exclusively on fault diagnosis [11]. Few studies provide a comprehensive comparison across these methods or propose a unified control framework [12].

This paper makes the following main contributions. First, it provides a more comprehensive overview based on recent research published from 2020 to the present [12-15]. Second, it develops a detailed classification of control strategies, divided into five main categories: classical control (FOC, DTC), model predictive control (MPC), sensorless control, fault-tolerant control (FTC), and advanced hybrid methods [14]. Third, a quantitative comparison among these approaches is conducted based on key performance indicators such as total harmonic distortion (THD), torque ripple, computational complexity, fault tolerance capability, and position sensor requirements. Finally, the paper proposes a novel integrated control framework combining MPC, sensorless observers, and fault-tolerant control (MPC + Sensorless + FTC) [12, 15].

The remainder of this paper is organized as follows. Section 2 provides an overview of multiphase machine structures, advantages, and mathematical modeling. Section 3 presents a detailed classification of control strategies. Section 4 offers a comparative analysis of their advantages and limitations. Section 5 discusses challenges, research gaps, and future development trends. Section 6 concludes the paper.

II. OVERVIEW OF MULTIPHASE PMSM DRIVE SYSTEMS

This section presents common machine topologies, mathematical modeling based on vector space decomposition (VSD), and inverter configurations along with their associated challenges.

2.1. Machine Structure and Mathematical Modeling

Multiphase permanent magnet synchronous machines (PMSMs) extend the conventional three-phase structure. They can be classified by number of phases and winding arrangements. Five-phase PMSMs are commonly used as benchmark systems because they offer two additional degrees of freedom without significantly increasing inverter complexity [8]. Six-phase PMSMs include symmetrical (60° shift) and asymmetrical (dual three-phase, DTP, 30° shift) types; the latter is widely adopted due to compatibility with standard three-phase inverters and elimination of 5th- and 7th-order harmonics [2, 4]. Higher-phase machines (7, 9, 12 phases) appear in specialized high-power or extreme fault-tolerance applications, but their cost and complexity increase with phase count [16].

Winding configuration also affects control. Three common configurations are: (i) single neutral – simple but allows zero-sequence current; (ii) isolated neutrals – each three-phase set has its own neutral, suppressing circulating currents (typical in DTP) [8, 17]; (iii) series-connected windings – two three-phase sets in series, fully utilizing DC-link voltage but introducing coupling challenges between inverters [18].

The mathematical modeling approach adopted in this paper is based on vector space decomposition (VSD). The core idea is to transform the original high-dimensional system into multiple orthogonal subspaces, as illustrated in Fig. 1

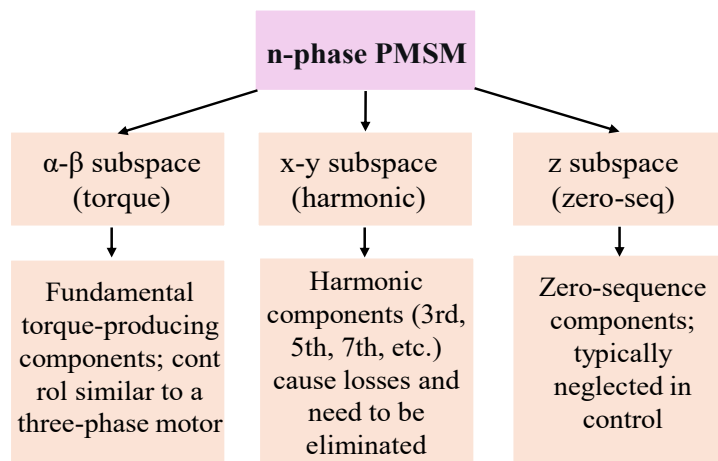


Fig. 1 Principle of vector space decomposition (VSD)

According to the vector space decomposition (VSD) approach, the current and voltage equations of the machine in the rotating dq reference frame for the α - β subspace are identical to those of a conventional three-phase system. In contrast, the x - y and z subspaces exhibit predominantly resistive-inductive (RL) characteristics with negligible back electromotive force (EMF) [2, 19].

This property enables designers to reuse well-established control techniques developed for three-phase machines, while incorporating additional control loops to suppress harmonic currents in the x - y subspace. Specifically, the transformation can be expressed as given in (1)-(6).

$$\underline{x}_{dq} = [T_{Park}] \underline{x}_{\alpha\beta} = [T_{Park}] [T_{Clarke}] \underline{x} \quad (1)$$

Trong đó:

$$\underline{x} = [x_1 \ x_2 \ x_3 \ \dots \ x_N]^T \quad (2)$$

$$\underline{x}_{\alpha\beta} = [x_\alpha \ x_\beta \ x_{x2} \ x_{y2} \ \dots \ x_{xk} \ x_{yk} \ x_{z1} \ x_{z2}]^T \quad (3)$$

$$\underline{x}_{dq} = [x_{d1} \ x_{q1} \ x_{d2} \ x_{q2} \ \dots \ x_{dk} \ x_{qk} \ x_{z1} \ x_{z2}]^T \quad (4)$$

$$T_{Clarke} = \sqrt{\frac{2}{n}} \begin{bmatrix} 1 & \cos(\sigma) & \cos(2\sigma) & \dots & \cos((n-1)\sigma) \\ 0 & \sin(\sigma) & \sin(2\sigma) & \dots & \sin((n-1)\sigma) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & \cos(k\sigma) & \cos(2k\sigma) & \dots & \cos(k(n-1)\sigma) \\ 0 & \sin(k\sigma) & \sin(2k\sigma) & \dots & \sin(k(n-1)\sigma) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \dots & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \dots & -\frac{1}{\sqrt{2}} \end{bmatrix} \quad (5)$$

$$[T_{Park}] = \begin{bmatrix} \cos(h_1\theta) & \sin(h_1\theta) & \dots & 0 & 0 & 0 & 0 \\ -\sin(h_1\theta) & \cos(h_1\theta) & \dots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & 0 \\ 0 & 0 & \dots & \cos(h_k\theta) & \sin(h_k\theta) & 0 & 0 \\ 0 & 0 & \dots & -\sin(h_k\theta) & \cos(h_k\theta) & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 1 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Where \underline{x} is the n -dimensional vector of variables in the natural (phase) reference frame; $\underline{x}_{\alpha\beta}$ is the n -dimensional vector in the stator reference frame; $k=(n-1)/2$ nếu n lẻ, và $k=(n-2)/2$ for even n ; x_{z1} and x_{z2} denote the components associated with the zero-sequence subspaces (z_1, z_2); and the last row of the Clarke and Park transformation matrices exists only for even-phase systems.

2.2. Inverter Configurations and Modulation Techniques

Multiphase machines are typically supplied by multi-leg voltage source inverters (VSIs), with each phase driven by an independent leg. Multilevel inverters are also used in medium- to high-voltage applications to reduce dv/dt stress and improve current quality. Regarding modulation, two major challenges arise. First, harmonic currents in the x - y subspace can be excited by basic voltage vectors; virtual voltage vectors [4] or advanced PWM strategies [20] are common solutions. Second, in high-speed or high-power operation, the low carrier ratio (LCR) can drop below 15, causing delays and voltage distortion. Techniques such as multistep MPC or optimal pulse pattern (OPP) modulation have been proposed to address this [13, 21].

III. CLASSIFICATION OF CONTROL METHODS (TAXONOMY)

This section presents various control strategies that have been developed for multiphase PMSM drive systems, ranging from classical approaches to more advanced techniques. Fig. 2 illustrates the overall classification framework of the six groups of methods discussed in this paper.

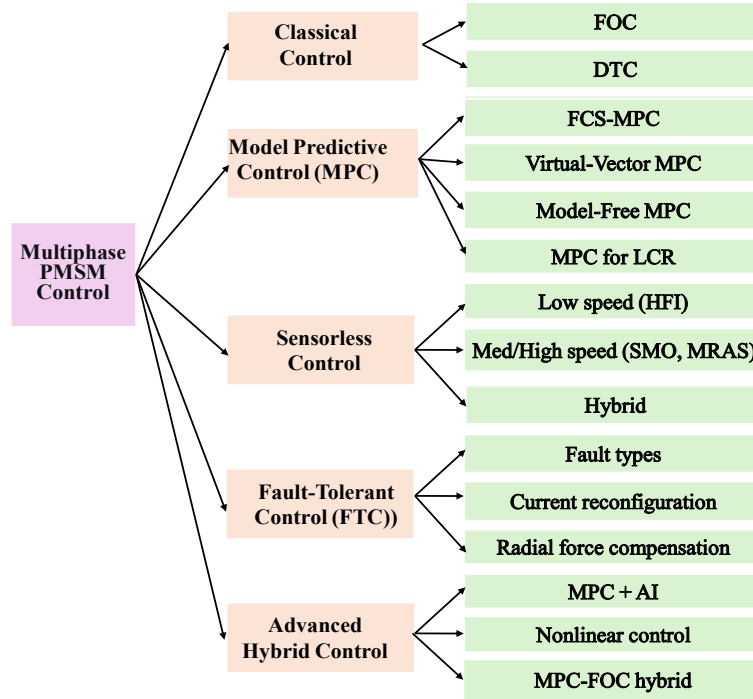


Fig. 2 Classification of Control Strategies for Multiphase PMSM Drives

3.1. Classical Control Methods (FOC and DTC)

Two classical approaches—Field-Oriented Control (FOC) and Direct Torque Control (DTC)—have been extended from three-phase systems to multiphase configurations due to their simplicity and operational reliability.

FOC (Field-Oriented Control): In multiphase FOC, based on vector space decomposition (VSD), the α - β subspace (torque-producing components) is regulated using PI controllers similarly to conventional three-phase systems, while the x - y subspaces (harmonic components) are controlled by additional PI loops to suppress low-order harmonic currents. This structure ensures stable steady-state operation and achieves near-sinusoidal currents with low distortion, making it suitable for high-precision industrial applications [22]. However, FOC exhibits three main limitations: (i) strong dependence on accurate machine parameters (stator resistance, inductance, and permanent magnet flux); (ii) increased control complexity due to multiple PI controllers and cross-coupling compensation among subspaces; and (iii) limited fault-tolerant capability, as open-phase faults require complex reconfiguration and do not always guarantee stable operation.

DTC (Direct Torque Control): Unlike FOC, DTC directly controls stator torque and flux using hysteresis comparators and a switching lookup table, without intermediate current control loops. In multiphase systems, the number of available voltage vectors is significantly higher than in three-phase systems (e.g., 32 vectors for a five-phase inverter compared to 8 in three-phase systems), which contributes to improved current quality and reduced torque ripple. Nevertheless, DTC still suffers from two major drawbacks: high torque ripple, particularly at low speeds, and variable switching frequency, which complicates filter design and increases switching losses. Enhancements such as combining DTC with PWM or employing virtual voltage vectors [23] can mitigate torque ripple and stabilize the switching frequency; however, these improvements increase algorithmic complexity and reduce the inherent simplicity of DTC.

Table 1. Qualitative comparison between FOC and DTC for multiphase PMSM drives.

Criteria	FOC	DTC
Torque ripple	Low (when switching frequency is sufficiently high)	High (especially at low speeds)
Computational complexity	Moderate (requires coordinate transformations)	Low (only lookup tables and comparators required)
Model parameter requirement	High (dependent on R_s, L_d, L_q, ψ_{PM})	Low (mainly requires R_s)
Fault tolerance capability	Poor (requires complex reconfiguration)	Moderate (lookup table can be adjusted)

Switching frequency	Constant (due to PWM)	Variable (state-dependent)
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3.2. Model Predictive Control (MPC)

FCS-MPC (Finite Control Set MPC): FCS-MPC exploits the discrete nature of voltage source inverters. At each sampling instant, it predicts future values of controlled variables (current, torque, flux) for all possible voltage vectors and selects the optimal one by minimizing a cost function. A typical cost function includes reference/predicted state vectors, prediction horizon, weighting matrix, and switching penalty factor [23, 24]. The main advantages are natural handling of nonlinear constraints and fast dynamic response, outperforming FOC and DTC [4]. However, in multiphase systems, two major challenges arise. First, computational burden grows rapidly with phase number (8 vectors in 3-phase, 32 in 5-phase, 64 in 6-phase). Solutions include geometric preselection [25] and reduced candidate sets (e.g., only five virtual vectors), which can cut computational effort by up to 80% [24]. Second, tuning weighting factors is difficult because different cost terms have different physical units [6]. Automatic tuning based on optimization or machine learning has been explored, but an alternative approach eliminating weighting factors via virtual vector sets (virtual FCS) is promising [22].

Virtual-Vector MPC: A specific issue in multiphase systems is low-order harmonic currents in the x-y subspace, which cause **copper** losses and waveform distortion without contributing to torque. Conventional vectors excite these harmonics. The virtual voltage vector (V^3) technique combines two or more basic vectors within one sampling period to create a virtual vector with zero average in the x-y subspace, suppressing harmonics. Results in [23] show phase current THD below 3%. Multi-step virtual vectors (combining three or more basic vectors) further reduce steady-state current ripple by about 30% [23]. A modulated virtual-vector-based predictive current control for DTP-PMSM drives also significantly improves steady-state performance [25].

Model-Free MPC (MFPC): Model-based MPC strongly depends on the accuracy of machine parameters (e.g., resistance and inductance), which may vary due to temperature changes and magnetic saturation, leading to degraded control **performance**. To address this issue, model-free predictive control (MFPC) replaces the complex mathematical model of the machine with a simplified ultralocal model of the form:

$$\frac{dx}{dt} = F(t) + \alpha u(t) \tag{7}$$

where $F(t)$ represents all unknown **dynamics**, including disturbances, nonlinearities, and parameter variations, and is updated online using past measurement data.

As a result, MFPC can tolerate **parameter** deviations of up to 50%, whereas FCS-MPC experiences significant performance degradation when the mismatch exceeds 20%. Another development trend of MFPC is its integration with nonlinear disturbance observers to enhance the accuracy of the ultralocal model [7]. Instead of relying solely on past data, disturbance observers enable more accurate estimation of $F(t)$, particularly in the presence of measurement noise or external disturbances. Simulation and experimental results have demonstrated that this enhanced MFPC approach achieves significantly improved current quality (THD) and harmonic suppression capability compared to conventional MPC methods.

MPC Under Low Carrier Ratio (LCR) Conditions: In high-power applications (e.g., marine propulsion and wind energy systems), the switching frequency is inherently limited, resulting in a low ratio between the switching frequency and the **fundamental** frequency (carrier ratio), which can fall below 15 (LCR region). Under such conditions, conventional control methods encounter difficulties due to computational delays and voltage distortion.

Three main approaches have been proposed to address this issue: (i) **multistep MPC**, where the prediction horizon $N > 1$ is used to **compensate** for computational delays; (ii) **optimal pulse pattern (OPP)** techniques, which compute optimal switching sequences offline while only adjusting amplitude and phase angle online [13]; (iii) **MPC with an implicit modulator**, which enables a constant switching frequency operation [4]. Comparative studies [21] indicate that each approach is suitable for different power ranges and technical requirements.

3.3. Sensorless Control

The elimination of mechanical position and speed sensors offers several advantages, including reduced system cost, improved reliability (by removing failure-prone components), and decreased size and weight. Sensorless control methods for multiphase PMSM drives can be classified according to their operating speed range.

Saliency-Based Methods for Low-Speed Operation: At low speeds (0–10% of rated speed), the back-EMF remains insufficient, thus saliency-based methods are employed. A high-frequency signal (0.5–2 kHz) is injected into the machine, and the resulting current response is analyzed to estimate the rotor position. In multiphase systems, a common approach is to inject signals into the α - β subspace (with a 90° phase shift) and

observe the response in the x -ysubspace.

According to [26], for dual three-phase PMSMs (DTP-PMSMs), discontinuous injection reduces acoustic noise by 10–15 dB compared to continuous injection, while maintaining estimation errors below 2 electrical degrees. Another improvement is to utilize the inverter switching frequency as the injection signal, eliminating the need for an additional source, reducing losses, and simplifying hardware implementation.

However, these methods suffer from several drawbacks, including additional losses, acoustic noise, and degraded performance in machines with low saliency (e.g., surface-mounted PMSMs – SPM).

Model-Based Methods for Medium- and High-Speed Operation: At higher speeds, the back electromotive force (back-EMF) becomes significant and can be utilized for rotor position estimation. Common approaches include the sliding mode observer (SMO), model reference adaptive system (MRAS), and extended Kalman filter (EKF).

Among these, SMO is widely adopted due to its simplicity and strong robustness against disturbances and parameter uncertainties. SMO employs a switching (bang-bang) observer structure to compensate for the error between measured and estimated currents, thereby reconstructing the back-EMF and estimating the rotor position. In [8], SMO was applied to a five-phase PMSM, where the third-order harmonic component of the back-EMF was exploited to enhance estimation accuracy. Experimental results demonstrated an average position error below 1 electrical degree over a speed range from 20% to 100% of the rated speed.

Although EKF offers higher estimation accuracy and the capability to estimate multiple states simultaneously (e.g., position, speed, and parameters), it suffers from high computational complexity, especially as the state dimension increases (which can reach 10–12 in multiphase systems). Therefore, EKF is typically suitable only for systems with high-performance processors or applications requiring extremely high accuracy.

Hybrid Methods: To achieve sensorless control over the entire speed range (from standstill to rated speed), current research trends focus on combining saliency-based methods for low-speed operation with model-based methods for high-speed regions. The key challenge lies in ensuring a smooth transition between these two modes within the transition speed region (typically 5–15% of rated speed), as abrupt switching may lead to instability or torque transients [10].

To address this issue, several techniques have been proposed:

Low-pass filtering: smoothing the estimated signals during the transition. Recent studies have proposed two-stage filters with adaptive cutoff frequencies to improve estimation accuracy [27].

Confidence-based weighting: combining estimates from multiple observers by assigning weights based on their respective confidence levels, followed by a voting mechanism to determine the control mode [28].

Hysteresis-based switching: employing two distinct speed thresholds (upper threshold ω_m and lower threshold ω_n) to prevent chattering when the speed fluctuates around the transition point, thereby ensuring reliable mode switching [28].

3.4. Fault-Tolerant Control – FTC

Fault tolerance is one of the most significant advantages of multiphase machines compared to conventional three-phase systems. In the presence of faults affecting one or more phases (e.g., open-circuit or short-circuit faults) or inverter faults (e.g., switch open-circuit), the redundant degrees of freedom in multiphase systems enable current reconfiguration and continued operation at reduced power, rather than complete shutdown as in three-phase systems.

Common fault types in multiphase PMSM drive systems include:

Phase Open-Circuit Fault (POCF): This is the most common fault, occurring due to winding disconnection or fuse operation. The current in the faulty phase drops to zero.

Phase Short-Circuit Fault (PSCF): More severe than POCF, as the short-circuit current can be very large, leading to braking torque and excessive thermal stress. Rapid isolation of the faulty phase is required, typically using thyristors or semiconductor fuses.

Switch Open-Circuit Fault (SOCF): One or more IGBT switches in the inverter fail to conduct. The impact depends on the location of the faulty switch; in some cases, the corresponding phase can still be partially controlled (e.g., only during the positive or negative half-cycle).

Current Reconfiguration Strategies: Upon fault detection, the FTC controller recalculates the reference currents for the remaining healthy phases to maintain the desired torque and flux, while satisfying thermal and voltage constraints. In five-phase machines, the two remaining degrees of freedom are exploited for current reconfiguration.

In [5], an optimization-based approach was proposed with a cost function that includes torque error, copper losses, and radial force. Experimental results showed that the machine can continue operating at approximately 80% of its rated power under a single open-phase fault, while torque ripple increases from 5% to 12%.

More recently, the concept of universal fault-tolerant control (universal FTC) for dual three-phase

PMSMs (DTP-PMSMs) has been introduced [9]. This approach provides a unified control structure capable of handling all single open-circuit faults by simply updating the transformation matrix and current controller parameters, thereby simplifying implementation and reducing memory requirements.

Radial Force Compensation: A commonly overlooked issue in conventional FTC studies is the radial force. Under asymmetrical operating conditions (e.g., after a fault), the magnetic forces between the rotor and stator become unbalanced, leading to increased vibration and acoustic noise, as well as reduced bearing lifetime.

Recent studies [5, 29] have incorporated radial force compensation into the FTC cost function, in addition to conventional terms such as torque error and losses. Experimental results on five-phase machines demonstrate that, with radial force compensation, vibration amplitude can be reduced by approximately 40–50% compared to controllers optimizing only torque and losses, while the average torque and torque ripple remain nearly unchanged.

3.5. Advanced and Hybrid Methods

Integration of MPC with AI (ANN, Reinforcement Learning): Artificial intelligence (AI) introduces new opportunities for drive control, particularly by replacing the vector selection stage in FCS-MPC with artificial neural networks (ANNs). ANNs are trained to directly predict the optimal voltage vector from the system states (e.g., currents, speed, and errors), instead of evaluating the cost function for each candidate vector. This significantly reduces computational burden—by an order of magnitude—enabling MPC implementation on low-cost microcontrollers.

In [30], a hybrid approach combining MPC with ANN and fuzzy logic for PMSMs driven by multilevel inverters demonstrated a reduction of approximately 70% in computation time compared to conventional FCS-MPC, while maintaining current quality and dynamic performance. Another promising direction is reinforcement learning (RL), which learns the control policy directly from system states to control actions without requiring an explicit mathematical model. RL benefits from learning based on real operational data and can adapt to system variations without complete retraining.

Nonlinear Control (Backstepping, SMC): Nonlinear control techniques, such as backstepping and sliding mode control (SMC), have also been applied to multiphase drive systems. Backstepping designs controllers recursively based on Lyapunov functions, ensuring global stability of the closed-loop system. SMC employs a switching (bang-bang) structure to drive the system trajectories onto a predefined sliding surface, offering strong robustness against disturbances and parameter uncertainties.

However, conventional SMC suffers from the chattering phenomenon (high-frequency oscillations around the sliding surface), which may excite unmodeled dynamics and generate acoustic noise. Advanced variants, such as higher-order SMC, have been developed to mitigate chattering effects.

Hybrid MPC–FOC Control: Several studies have proposed hybrid control schemes that utilize MPC during transient conditions (for fast dynamic response) and switch to FOC during steady-state operation (for stable current quality and constant switching frequency). A smooth transition mechanism—such as low-pass filtering or fading techniques—is required to avoid system disturbances during mode switching. In [31], a hybrid MPC–FOC controller was compared with pure FOC and MPC in a six-phase PMSM drive. The results showed a balanced performance: transient response was improved by approximately 30% compared to FOC, while steady-state current ripple was reduced by about 40% compared to MPC. Table 2 summarizes a qualitative comparison among MPC, sensorless control, FTC, and classical methods using a five-level evaluation scale

Table 2. Qualitative comparison of control strategies for multiphase PMSM drives.

Criteria	FOC	DTC	MPC	Sensorless	FTC	Hybrid (MPC–FOC)
Transient response (speed, torque)	Good	Excellent	Excellent	Poor–Moderate	Moderate	Excellent
Steady - state current quality (THD)	Excellent	Poor	Good	Moderate	Poor–Moderate	Excellent
Computational complexity	Low	Very low	High	Moderate	High	Moderate–High
Fault tolerance capability (open - phase)	Poor	Poor	Good (extendable)	Poor (requires sensors)	Excellent	Good
Position sensor requirement	Required	Required	Required	Not required	Required	Required (can be hybrid)
Harmonic current suppression (x–y subspace)	Moderate (requires additional PI loops)	Poor	Excellent (virtual vectors)	Not applicable	Moderate	Good
Suitability for low carrier ratio (LCR)	Poor	Moderate	Good (with multistep/OPP)	Not applicable	Moderate	Good

The three major groups of advanced control strategies—MPC, sensorless control, and fault-tolerant control (FTC)—each exhibit distinct strengths and are actively being developed. MPC stands out for its multi-objective optimization capability and effective harmonic suppression; however, it faces challenges related to computational burden and model dependency. Sensorless control offers significant advantages in terms of cost reduction and reliability, but its performance remains limited in the low-speed region. FTC represents a key competitive advantage of multiphase systems, yet it requires complex control structures and fast, accurate fault detection mechanisms. The inevitable future trend is the integration of these approaches, aiming toward a unified control framework capable of automatically adapting to varying operating conditions and fault scenarios.

IV. COMPARATIVE ANALYSIS AND IDENTIFICATION OF RESEARCH GAPS

This section provides a comprehensive and quantitative overview of the control methods classified in Section 3. Rather than merely listing advantages and disadvantages, comparative tables are constructed based on key technical criteria, accompanied by observations derived from experimental results reported in reliable references. Table 3 summarizes the qualitative evaluation of the five main groups of control strategies based on six key criteria. The assessments are synthesized from comparative studies [5, 22, 32] and review papers [2, 10, 13].

Table 3. Qualitative comparison of control strategies for multiphase PMSM drives.

Method	THD	Torque ripple	Computational Complexity	Fault Tolerance Capability	Position Sensor Requirement	Harmonic Suppression Capability (x-y subspace)
FOC	Very low (<3%)	Low	Low	Poor	Required	Moderate (requires additional PI control loop)
DTC	Medium (5–8%)	High (8–12%)	Very low	Poor	Required	Poor
MPC (FCS-MPC)	Low (2–4%)	Low (3–5%)	High	Good (extendable)	Required	Good (with virtual vector techniques)
Sensorless (HFI+SOMO)	Medium (4–6%)	Medium (5–7%)	Medium	Poor (requires backup sensing for reliability)	Not required	Not applicable
FTC	Dependent (typically increases by 2–3% under fault conditions)	Increased (up to 10–12%)	High	Excellent (maintains 70–80% rated power)	Required (unless combined with sensorless techniques)	Moderate
Hybrid (MPC-FOC)	Very low (<3%)	Low (2–4%)	Medium–High	Good	Required	Good

4.1. Analysis based on each criterion

Phase current THD – a key indicator of current quality and associated losses. In multiphase systems, low-order harmonic currents in the x-y subspace contribute significantly to THD. FOC achieves the lowest THD (typically below 3%) due to dedicated PI control loops, while MPC with virtual vectors also attains very low THD (2–3%). In contrast, DTC exhibits the highest THD (5–8%) due to discrete voltage vector selection and variable switching frequency [2]. Sensorless methods generally show moderate THD levels (4–6%), mainly due to disturbances introduced by high-frequency signal injection [10].

Torque ripple – affecting smooth operation and mechanical lifetime. DTC suffers from the highest ripple (8–12%) because of its hysteresis-based control [2]. MPC achieves lower ripple (3–5%), which can be reduced below 3% when combined with modulation techniques [4]. FOC also provides low ripple (below 5%) when the switching frequency is sufficiently high. Under fault conditions, without radial force compensation, FTC may result in increased ripple up to 10–12% [5].

Computational complexity – determining feasibility for implementation on low-cost microcontrollers. DTC is the simplest (requiring only lookup tables and comparators), while FOC has moderate complexity (coordinate transformations and PI controllers). MPC is the most computationally demanding, especially in high-phase systems. Improvements such as preselection [25] reduce the number of evaluated vectors; for instance, the method in [24] evaluates only five virtual vectors, reducing computation time by approximately 80%.

Fault tolerance capability – a major advantage of multiphase systems. FTC can maintain 70–80% of

rated power under a single open-phase fault [5]. MPC can be extended to support FTC by modifying the cost function and voltage vector set [33]. In contrast, FOC and DTC inherently lack fault tolerance. Sensorless control alone is not fault-tolerant but can be integrated with FTC to enhance system reliability [34].

Position sensor requirement – only sensorless methods eliminate the need for mechanical sensors, reducing cost and improving reliability [10]. Other methods typically require encoders or resolvers unless combined with sensorless estimation. However, in hybrid systems, sensors are often retained for startup or backup purposes.

4.2. Key Insights from the Comparative Analysis

No universal solution: Each control strategy has its own strengths and is suited to specific application domains. FOC and DTC are appropriate for low-cost systems with moderate reliability requirements; MPC is preferable for high-performance, multi-objective control; and FTC is essential for safety-critical applications (e.g., electric vehicles and aerospace systems).

Integration as an inevitable trend: The boundaries between control methods are increasingly blurred. MPC is progressively incorporating concepts from FOC (e.g., hybrid MPC–FOC [31]), while sensorless and FTC functionalities are being directly integrated into MPC frameworks [33]. This trend is leading to the emergence of unified control architectures.

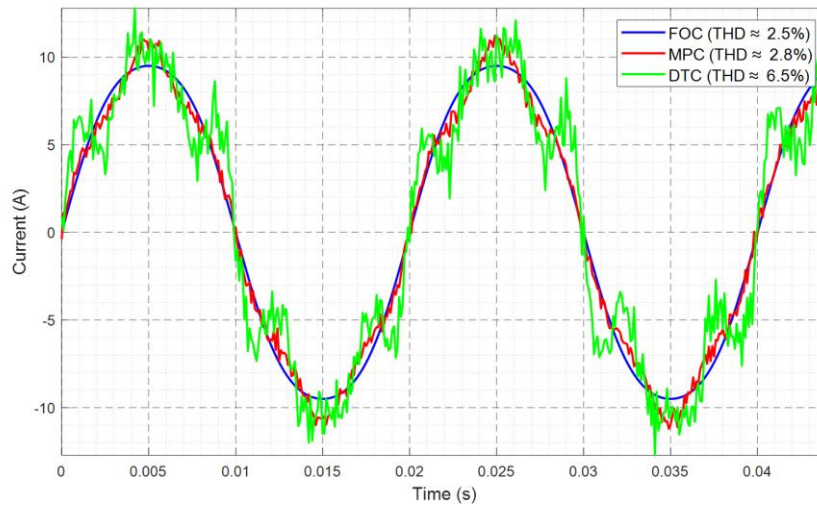


Fig. 3 The phase current waveforms of FOC, MPC, and DTC for a six-phase PMSM

Fig. 3 illustrates typical phase current waveforms of FOC, MPC, and DTC for a six-phase PMSM (at 50% rated power and a switching frequency of 5 kHz), synthesized from [4, 22]: **FOC**-Nearly sinusoidal current, THD \approx 2.5%; **MPC (virtual vector)**-Sinusoidal current, THD \approx 2.8%, with faster dynamic response under load variations; **DTC** - Highly rippled current, THD \approx 6.5%.

In summary, MPC is emerging as a leading solution for applications requiring high overall performance; FOC remains a simple and reliable choice for systems without stringent dynamic requirements; and FTC is essential for safety-critical applications. The integration of these approaches is expected to be the dominant future direction.

4.3. Research Gaps

Computational complexity of MPC: Real-time implementation remains challenging due to the rapid growth of voltage vectors with the number of phases (e.g., 32 for five-phase and 64 for six-phase systems) and the prediction horizon. Techniques such as preselection [25] and virtual vectors [24] have been proposed, but no general solution achieves an optimal trade-off.

Lack of standardized benchmarks: There is no unified evaluation framework to fairly compare FOC, MPC, sensorless, and FTC methods under identical conditions [10].

Low-speed sensorless limitations: High-frequency injection (HFI) methods introduce acoustic noise, additional losses, and reduced accuracy in low-saliency machines. Improvements such as discontinuous injection [26] mitigate noise but do not fully eliminate these drawbacks.

Limited validation under progressive faults: Most FTC studies focus on abrupt faults under laboratory conditions, whereas real faults often evolve gradually [5]. Integrated frameworks combining fault detection (observer- or AI-based) with FTC are still lacking.

Absence of an integrated control framework: The most significant gap is the lack of a unified architecture combining MPC, sensorless, and FTC. Although partial integrations exist (e.g., MPC with sensorless [8] and MPC with FTC [33]), a complete framework incorporating all three components has not yet been fully developed [12]

V. CONCLUSION

This paper presents a comprehensive and quantitative analysis of control strategies for multiphase permanent magnet synchronous motor (PMSM) drives, based on more than 70 high-quality publications from 2020 to 2025. The results show that FOC achieves the lowest THD ($\approx 2.5\%$) and torque ripple ($\approx 3\%$) due to its decoupled control structure, but suffers from limited fault tolerance and strong parameter dependency. DTC offers fast dynamic response but exhibits higher THD ($\approx 6.5\%$) and torque ripple (8–12%) due to discrete voltage vector selection. MPC with virtual vectors achieves THD of about 2.8% and torque ripple around 4%, while enabling harmonic suppression in the x - y subspace without additional control loops; however, it faces challenges in computational burden (5–10 times higher than FOC in five-phase systems) and weighting factor tuning.

For sensorless control, hybrid HFI–SMO methods enable position estimation with errors below 2 electrical degrees across the full speed range, although the transition region still poses stability risks. In fault-tolerant control, modern reconfiguration strategies can maintain 75–85% of rated power under a single open-phase fault, with torque ripple increasing from about 5% to 10–12% when radial force compensation is considered.

Based on these findings, a three-layer integrated control framework (MPC Core – Hybrid Sensorless Observer – Fault Diagnosis and Reconfiguration) is proposed to overcome the limitations of individual methods and move toward intelligent, sensorless, and fault-adaptive drive systems. Future work includes simulation under various fault scenarios, experimental validation on a 2–5 kW test bench, and the integration of reinforcement learning for automatic tuning of weighting factors and observer parameters.

This work aims to provide a comprehensive and up-to-date reference while opening new research directions for multiphase drives in applications requiring high reliability, efficiency, and cost-effectiveness, such as electric vehicles, more electric aircraft, and high-power systems.

Conflict of interest

There is no conflict to disclose.

ACKNOWLEDGEMENT

This research was supported by a university research grant from Thai Nguyen University of Technology (TNUT). We thank our colleagues at TNUT for their valuable insights and expertise that greatly assisted this research.

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