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Fault Diagnosis and Fault-Tolerant Control of Five-Phase Motor Drives: Methods, Comparisons, and Future Directions

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ABSTRACT: *Five-phase drive systems, which belong to the class of multiphase systems (i.e., systems with more than three phases), have attracted increasing attention as a promising alternative to conventional three-phase systems due to their higher power density, lower torque ripple, and inherently improved fault-tolerant capability. To highlight and fully exploit the fault-tolerant advantages of five-phase systems in particular, and multiphase systems in general, this paper presents the main fault diagnosis (FD) and fault-tolerant control (FTC) techniques for five-phase drive systems, provides quantitative comparisons among different FTC strategies, and discusses future development trends.*

Common fault types are classified, and FD techniques are categorized into signal/model-based methods, machine learning-based approaches, and hybrid techniques. FTC strategies are reviewed based on control approaches, including field-oriented control (FOC), direct torque control (DTC) with virtual vectors, and model predictive control (MPC), along with emerging topologies and sensorless control schemes. Quantitative comparisons extracted from experimental studies indicate that DTC with virtual vectors reduces torque ripple from approximately 20% to 8–10%, while model-free MPC maintains it below 5%.

Finally, three key research directions are identified: simultaneous handling of multiple faults, reduction of computational complexity, and deep integration of artificial intelligence into closed-loop control systems.

Keywords: *Five-phase drive systems, fault diagnosis, fault-tolerant control, FOC, DTC, MPC, virtual vectors, sensorless control, electric vehicles*

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I. INTRODUCTION

Five-phase drive systems have emerged as an effective alternative to conventional three-phase systems due to their advantages, including higher power density, improved efficiency, lower torque ripple, and inherent fault-tolerant capability [1], [2]. These features make them particularly suitable for applications requiring high reliability and safety. In particular, the ability to continue operation under phase fault conditions is considered a key advantage of multiphase systems [2], [3], [13].

To fully exploit these advantages, effective fault diagnosis (FD) and fault-tolerant control (FTC) strategies are required. FD is responsible for fault detection, localization, and classification, while FTC reconfigures the system to maintain stable operation after a fault occurs [2], [3]. The integration of FD and FTC is especially critical in safety-critical applications such as electric vehicles and aerospace systems [2], [13].

Common fault types include open-phase faults [7], [10], inter-turn short-circuit (ITSC) faults [4], [5], open-switch faults in power converters [14], [15], and sensor faults [6]. Each type of fault affects current, torque, and thermal behavior differently, requiring corresponding FD and FTC strategies. In recent years, numerous studies have proposed FD techniques based on signal processing, model-based approaches, and machine learning, along with FTC strategies belonging to FOC, DTC, and MPC families, as well as emerging topologies and sensorless control schemes [4], [7], [10], [13], [14].

Existing survey papers often focus on a narrow aspect (e.g., only induction motors [1] or only electric vehicle applications [2]) and do not fully reflect recent developments in 2024–2025. Therefore, this paper focuses on three main aspects: (i) modern FD and FTC methods; (ii) quantitative comparisons among different FTC strategies; and (iii) future research trends.

To conduct this study, a comprehensive literature search was performed across major academic databases, including IEEE Xplore, ScienceDirect, MDPI, SpringerLink, and the IET Digital Library. The search employed combinations of keywords such as “five-phase motor drive,” “fault diagnosis,” “fault-tolerant control,” “FOC,” “DTC,” “MPC,” “virtual vector,” “inter-turn short circuit,” “sensorless control,” "open-phase fault," and "electric vehicle." Only publications from 2016 to 2025 were considered, with priority given to peer-reviewed journals and reputable conferences. Both theoretical and experimental studies were included to enable in-depth analysis. Quantitative data (e.g., torque ripple and diagnosis accuracy) were directly extracted from experimental results reported in the original studies.

The remainder of this paper is organized as follows. Section 2 presents fault classification. Section 3 describes FD methods. Section 4 analyzes FTC strategies. Section 5 provides comparisons and evaluations of FTC methods. Section 6 discusses applications and future trends. Finally, Section 7 concludes the paper.

II. FAULT CLASSIFICATION IN FIVE-PHASE DRIVE SYSTEMS

Fault classification is essential for designing appropriate fault diagnosis and fault-tolerant control strategies. In five-phase drive systems, faults can occur in all three main components: the motor, the inverter, and the sensor system. Based on their physical mechanisms and system-level impacts, these faults can be categorized into four main groups, as described below.

Open-phase fault: This fault occurs when one phase of the motor is disconnected or open-circuited. Common causes include cable failure, winding breakage inside the motor, or an open-switch fault in the inverter [7], [10]. Under this condition, the remaining phase currents must increase to maintain torque production, leading to higher copper losses and torque oscillations at twice the fundamental frequency. Recent studies have shown that injecting third-harmonic currents or reconfiguring the transformation matrix can significantly mitigate these adverse effects, as discussed in [13], [14].

Inter-turn short-circuit (ITSC) fault: This is considered one of the most severe faults, as it typically originates from insulation degradation and can rapidly escalate if not detected early [4], [5]. The ITSC fault is characterized by a short circuit between turns within the same phase, resulting in large circulating currents and localized overheating. Current detection methods are mainly based on stator current waveform analysis, utilizing disturbance observers or multiscale convolutional neural networks, achieving high accuracy and the ability to estimate fault severity [4], [8].

Power switch fault: This type of fault occurs in voltage source inverters and is also quite common. Open-switch faults are typically caused by device failures (e.g., IGBT) or gate driver malfunctions, leading to the complete loss of switching capability in the affected device [14], [15]. When a switch is open, the corresponding phase current is disrupted, causing severe current distortion and large torque oscillations. In contrast, short-circuit faults can result in extremely high fault currents and must be handled using fast protection mechanisms such as fuses or system shutdown. FTC strategies based on MPC or DTC have been proposed to maintain operation under single or multiple open-switch fault conditions [14], [15].

Sensor fault: These faults primarily affect rotor position/speed sensors and current sensors. They may arise from electromagnetic interference, hardware failure, or calibration drift [6]. In sensorless control systems, current sensor faults can be compensated using adaptive observers, while position sensor faults often require control law reconfiguration or a transition to voltage-based estimation methods [13], [16].

Table 1 summarizes the main fault types, their typical causes, and their primary impacts.

Fault Type	Typical Causes	Main Effects	References
Open-phase fault	Cable failure, switch fault, winding break	Increased phase currents, torque oscillation at 2f	[7], [10]
ITSC	Insulation degradation, overheating	Large circulating currents, local heating, efficiency loss	[4], [5], [8]
Open-switch fault	Device failure, gate driver malfunction	Current distortion, large torque oscillations	[14], [15]
Sensor fault	Noise, hardware failure, drift	Speed/position errors, system instability	[6], [13]

III. FAULT DIAGNOSIS METHODS

Based on the fault analysis presented in Section 2, it is evident that fault diagnosis plays a crucial role in early fault detection, fault localization, and severity assessment, thereby enabling the activation of appropriate fault-tolerant control (FTC) strategies. Fault diagnosis (FD) methods for five-phase drive systems in particular, and multiphase systems in general, can be broadly classified into three main categories.

Signal- and Model-Based Methods

Traditional FD techniques typically exploit characteristic features of current, voltage, or speed signals. An effective approach is the use of a disturbance observer to estimate abnormal components caused by inter-turn short-circuit (ITSC) faults, enabling fault detection without requiring additional sensors or auxiliary parameters [4]. This method was experimentally validated by Chen et al. [4] on a five-phase PMSM, demonstrating the capability to detect ITSC faults within 0.5 ms with a false positive rate below 2%.

In addition, an online detection method based on the product of the shorted-turn ratio and the short-circuit current has been proposed for surface-mounted five-phase PMSMs [5]. Furthermore, a unified algorithm capable of detecting and diagnosing multiple electrical faults, including ITSC, phase-to-phase faults, ground faults, and open-circuit faults, has been developed based on discrete wavelet transform (DWT) and fuzzy logic. The detection and diagnosis process is completed in less than two stator current cycles [9].

Machine Learning-Based Methods

Artificial intelligence and machine learning techniques have been widely applied to improve the accuracy of FD. A representative approach employs a multiscale convolutional neural network combined with Bayesian optimization for early ITSC fault diagnosis, achieving an accuracy of 98.7% on a dataset of 5000 samples [8].

Another method utilizes Gaussian process regression (GPR) to estimate stator resistance online, enabling ITSC fault detection without requiring speed or load information [8]. More recently, a fault diagnosis approach based on residual current fusion and a probabilistic neural network (PNN) has been proposed for five-phase PMSM drives. By analyzing the residual current using max and min functions, a health index is constructed; its fundamental frequency component is compared with a threshold for fault detection, and the PNN is subsequently used to identify the fault type and the affected phase [7].

Hybrid Methods

To leverage the advantages of both approaches, hybrid methods combining signal processing techniques with fuzzy logic or neural networks have been developed. A hybrid algorithm using DWT to extract features from stator currents, followed by fuzzy logic for ITSC fault classification in five-phase PMSMs, has been experimentally validated [9]. This approach provides effective noise suppression while reducing computational burden. Table 2 summarizes the accuracy of the main FD methods.

Table 2 – Accuracy of fault diagnosis methods

FD Method	Target Fault	Accuracy	Test Conditions	References
Disturbance observer	ITSC	>95% (early detection)	Load variation, measurement noise	[4]
Multiscale CNN + Bayesian	ITSC	98.7%	Experimental data (five-phase PMSM)	[8]
DWT + Fuzzy logic	ITSC	94.5%	Simulation and experiment	[9]
Residual current fusion + PNN	ITSC + open-phase	96.2% (average)	Five-phase motor	[7]

IV. FAULT-TOLERANT CONTROL STRATEGIES

After a fault is detected, the next objective is to maintain stable system operation. Fault-tolerant control (FTC) strategies for five-phase drive systems can be broadly classified into three main categories: field-oriented control (FOC), direct torque control (DTC), and model predictive control (MPC). In addition, emerging topologies such as open-end winding configurations and six-leg inverters, as well as sensorless control schemes, are becoming important research directions.

FOC-Based FTC

In FOC schemes, when an open-phase fault occurs, the Clarke and Park transformation matrices must be reconfigured to exclude the faulty phase. A typical approach involves redesigning the current reference vector to optimally redistribute currents among the remaining healthy phases, thereby maintaining torque production and reducing copper losses, while incorporating decoupling compensation [10]. Experimental results on five-phase PMSMs indicate that, after reconfiguration, the torque ripple increases by no more than 30% compared to the healthy condition [10].

The injection of third-harmonic currents into the FOC scheme allows the exploitation of trapezoidal back-EMF characteristics, improving torque density and enabling sensorless control operation [11].

DTC-Based FTC with Virtual Vectors

DTC features a simple structure, fast dynamic response, and low sensitivity to parameter variations. The first fault-tolerant DTC scheme for five-phase induction motors employed a modified switching table [12]. However, this approach results in relatively high torque ripple (approximately ±20%).

To address this issue, the concept of virtual vectors (VVs) has been introduced. By combining basic voltage vectors within a switching period, VVs produce a more accurate average voltage, reducing torque ripple to approximately ±8–10% [1]. An improved approach utilizes a dynamic duty cycle ratio to directly regulate currents in the xy subspace, instead of using fixed values, thereby extending the operating speed range [1]. Notably, a fault-tolerant switching table that does not require explicit fault diagnosis has been developed for five-phase PMSMs, enabling automatic transition to a safe operating mode without precise identification of the faulty phase [1].

MPC-Based FTC

MPC has gained increasing attention due to its capability to handle constraints and perform multi-objective optimization. A recent approach is model-free predictive flux control (MFPFC), which inherently exhibits fault-tolerant characteristics. This method employs an ultra-local model together with an extended state observer (ESO) to estimate disturbances caused by arbitrary open-phase faults, thereby maintaining smooth operation without explicit system reconfiguration [14]. Experimental results show that torque ripple can be maintained below 5% and flux deviation below 2% across the entire speed range [14].

A parameter-free MPC scheme based on dynamic mode decomposition with control (DMDc) has also been proposed for five-phase PMSMs under both healthy and ITSC fault conditions. This method does not require prior knowledge of motor parameters and is capable of compensating torque ripple induced by ITSC faults, reducing copper losses by up to 12% compared to conventional MPC [15]. Furthermore, generalized MPC strategies for handling one or two open-switch faults have also been developed [14], [15].

Emerging Topologies and Sensorless Control

Open-end winding configurations, which utilize two inverters, enable independent control of current components and enhance fault-tolerant capability. The five-phase six-leg inverter topology eliminates neutral current constraints and extends FTC capability to handle up to three-phase faults [16].

In terms of sensorless control, back-EMF observers, second-order generalized integrator (SOGI) filters, and hybrid adaptive robust observers (HARO) have been integrated with FTC schemes to enable operation over a wide speed range, even under open-phase fault conditions [13], [16].

V. COMPARISON AND EVALUATION OF FTC METHODS

The selection of an appropriate fault-tolerant control (FTC) strategy depends on several factors, including control performance, computational resources, implementation complexity, and robustness to fault detection delay. The following comparisons are based on quantitative results reported in experimental studies.

A comparison between direct torque control (DTC) and rotor field-oriented control (RFOC) under open-phase fault conditions shows that DTC has a simpler structure, lower parameter dependency, and faster torque response. However, it exhibits higher current and torque ripple in steady-state operation. In contrast, RFOC achieves smoother current waveforms and lower torque ripple but is more complex and highly dependent on the accuracy of rotor parameters [17].

A comparison between proportional–integral resonant (PI-resonant) controllers and predictive control within FTC frameworks indicates that predictive control provides superior dynamic response, particularly at low speeds. However, it is highly sensitive to fault detection delay—if the delay exceeds 2 ms, the system may become unstable. In contrast, PI-resonant control is slower but more robust to such delays [18]. More recently, the integration of artificial neural networks (ANN) with MPC has significantly improved speed tracking performance and reduced torque ripple under open-phase fault conditions, with speed tracking error reduced from 3.5% to 1.2% compared to PI-based MPC [19]. Table 3 summarizes the quantitative comparison of different FTC methods.

Table 3 – Performance comparison of FTC methods

Method	**Torque Ripple**	**Response Time**	**Complexity**	**Parameter Dependency**	**Fault Diagnosis Requirement**
FOC (RFOC)	±5%	Slow	Medium	High	Fault location required
Classical DTC	±20%	Very fast	Low	Very low	Not required
DTC + VVs	±8–10%	Fast	Low	Low	Not required or minimal
MPC (FCS-MPC)	±3–5%	Fast	High	Medium	Fault information required
Model-free MPC	±4%	Very fast	High	Very low	Not required
Parameter-free MPC	±5%	Fast	High	None	Not required

The data are compiled from [1, 12, 14, 15, 17, 18].

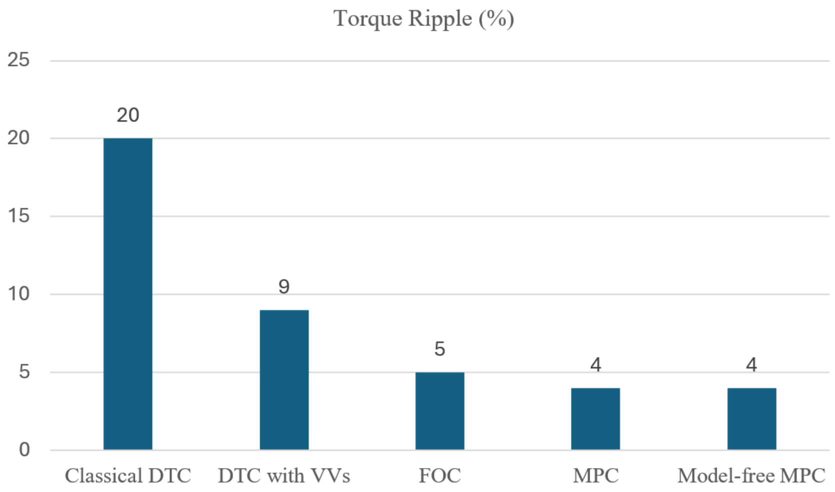

Fig. 1 Comparison of torque ripple (%) among fault-tolerant control (FTC) methods.

VI. APPLICATIONS AND FUTURE DEVELOPMENT TRENDS

Typical Applications

Five-phase drive systems have been applied in various fields requiring high reliability. In electric vehicles, the five-phase configuration enables continued operation in a degraded mode under fault conditions [6], [19]. In aerospace applications, five-phase motors with wide-speed-range sensorless control are used in actuators such as control surfaces and fuel pumps [13]. In marine and agricultural applications, FTC strategies have also been successfully implemented [16].

Future Development Trends

Based on the reviewed studies, several key trends are expected to shape future research in the coming decade.

First, artificial intelligence and deep learning will continue to play an increasingly significant role. Multiscale convolutional neural networks [8] and probabilistic neural networks [7] have already demonstrated high diagnostic accuracy. Transfer learning and reinforcement learning are expected to reduce the need for large training datasets.

Second, model-free and parameter-independent control strategies are likely to gain further attention. Approaches such as DMDc-based model predictive current control (MPCC) [15] and model-free predictive flux control (MFPFC) using extended state observers (ESO) [14] have demonstrated stable operation without requiring precise motor parameters.

Third, the simultaneous handling of multiple faults (multi-fault scenarios) will become a central challenge. Most existing studies focus on single fault conditions, and there is a need for FD and FTC algorithms capable of addressing complex fault combinations [14], [16].

Fourth, reducing computational complexity is a critical requirement for practical implementation. Techniques such as condition-based extreme vector selection [15] have shown promising results. The integration of MPC with embedded FPGA or GPU platforms is expected to facilitate real-time industrial deployment.

Finally, digital twin technology and the Internet of Things (IoT) are expected to be integrated for remote monitoring and predictive maintenance.

VII. CONCLUSION

This paper has presented the main fault diagnosis (FD) and fault-tolerant control (FTC) methods for five-phase drive systems, provided quantitative comparisons among different FTC strategies, and discussed future development trends.

First, existing methods have demonstrated effectiveness in handling various common fault types. Open-phase faults can be addressed using reconfigured FOC [10], DTC with virtual vectors (VVs) [1], and reconfiguration-free MPC approaches [14]. ITSC faults can be detected with high accuracy (up to 98.7%) [8]. Power switch faults can be handled using generalized MPC strategies [14], [15], while sensor faults can be mitigated through sensorless control techniques [13].

Second, quantitative comparisons indicate that DTC with VVs reduces torque ripple from approximately 20% to 8–10%, whereas model-free MPC maintains it below 5% [1], [14]. MPC provides superior dynamic response but is sensitive to fault detection delay, while DTC offers a simpler structure and greater robustness [17], [18].

Third, future research should focus on three main directions: (i) simultaneous handling of multiple faults; (ii) reduction of computational complexity for implementation on low-cost embedded platforms; and (iii) deep integration of artificial intelligence into closed-loop control systems, aiming toward fully adaptive, model-free intelligent controllers.

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REFRENCES

[1] B. Chikondra, A. G. Yepes, O. Al Zaabi, K. Al Hosani, J. Doval Gandoy, and R. K. Behera, “Open-phase fault-tolerant DTC technique for three-level NPC VSI-fed five-phase induction motor drives,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 11, no. 2, pp. 2114–2125, 2023.

[2] M. A. Frikha, J. Croonen, K. Deepak, Y. Benômar, M. El Baghdadi, and O. Hegazy, "Multiphase motors and drive systems for electric vehicle powertrains: State of the art analysis and future trends," Energies, vol. 16, no. 2, 2023.

[3] A. G. Yepes, O. Lopez, I. Gonzalez-Prieto, M. J. Duran, and J. Doval-Gandoy, "A comprehensive survey on fault tolerance in multiphase ac drives, part 1: General overview considering multiple fault types," Machines, vol. 10, no. 3, 2022.

[4] Q. Chen, X. Han, G. Liu, et al., "Inter-Turn Fault Diagnosis and Control for Five-Phase PMSMs by Disturbance Observer," IEEE Trans. Ind. Electron., vol. 71, no. 11, pp. 13901–13909, 2024.

[5] Fan, Puyi, and Yichen Zhang. "A Detection Method for Interturn Short-Circuit Fault of Five-Phase Surface Mounted PMSM." 2023 26th International Conference on Electrical Machines and Systems (ICEMS). IEEE, 2023.

[6] Y. Bensalem, A. Kouzou, R. Abbassi, H. Jerbi, R. Kennel, and M. Abdelrahem, "Sliding-mode-based current and speed sensors fault diagnosis for five-phase PMSM," PSE Community, 2023.

[7] Wang, Quan, et al. "Fault diagnosis for five-phase PMSM drive using residual current fusion and probabilistic neural network." Journal of Power Electronics 26.4 (2026): 781-793.

[8] Chen, Qian, et al. "ITSC fault diagnosis for five phase permanent magnet motors by attention mechanisms and multiscale convolutional residual network." IEEE Transactions on Industrial Electronics 71.8 (2023): 9737-9746.

[9] S. Moosakunju and V. P., "A hybrid fault detection and diagnosis algorithm for five-phase PMSM drive," Arabian Journal for Science and Engineering, 2022.

[10] Plugaru, Tudor-Ştefan, et al. "One Phase Open-Circuit Fault-Tolerant Vector Control For A Five Phase PMSM Machine." 2024 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR). IEEE, 2024.

[11] F. Wilczyński and P. Strankowski, "Sensorless field oriented control for five-phase induction motors with third harmonic injection and fault insensitive feature," Bulletin of the Polish Academy of Sciences, 2019.

[12] M. Bermudez, I. Gonzalez-Prieto, F. Barrero, et al., "Open-Phase Fault-Tolerant Direct Torque Control Technique for Five-Phase Induction Motor Drives," IEEE Trans. Ind. Electron., 2016.

[13] I. Assoun, L. Idkhajine, B. Nahid-Mobarakeh, et al., "Wide-Speed Range Sensorless Control of Five-Phase PMSM Drive under Healthy and Open Phase Fault Conditions for Aerospace Applications," MDPI Energies, vol. 16, no. 1, p. 279, 2023.

[14] Chen, Cheng, et al. "Natural fault-tolerant model-free predictive flux control in five-phase PMSM drives under any-phase open-circuit fault." IEEE Access (2025).

[15] Y. Huang, W. Huang, K. Ru, and D. Xu, "Parameter-Free Model Predictive Control of Five-Phase PMSM Under Healthy and Inter-Turn Short-Circuit Fault Conditions," MDPI Energies, vol. 18, no. 17, p. 4549, 2025.

[16] Wu, Lijian, et al. "Fault-tolerant operation for five-phase permanent magnet synchronous machine drives with five-phase six-leg inverter." IET Electric Power Applications 18.5 (2024): 489-502.

[17] Bermudez, Mario, et al. "Comparative study of DTC and RFOC methods for the open-phase fault operation of a 5-phase induction motor drive." IECON 2015-41st Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2015.

[18] H. Guzman et al., "Comparative study of predictive and resonant controllers in fault-tolerant five-phase induction motor drives," IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 606–617, 2016.

[19] Hassan, Ahmed M., and Mohamed Eladly Metwally. "Improving performance of electric vehicle drive system based a five-phase PMSM under fault using ANN and MPC." Scientific Reports (2025).

[20] Kulandaivel, Gobikannan, et al. "Five-phase induction motor drive-A comprehensive review." Frontiers in Energy Research 11 (2023): 1178169.