

Article

Multi-Plane Virtual Vector-Based Anti-Disturbance Model Predictive Fault-Tolerant Control for Electric Agricultural Equipment Applications

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Abstract

This paper proposes an anti-disturbance model predictive fault-tolerance control strategy for open-circuit faults of five-phase flux intensifying fault-tolerant interior permanent magnet (FIFT-IPM) motors. This strategy is applicable to electric agricultural equipment that has an open winding failure. Due to the rich third-harmonic back electromotive force (EMF) content of five-phase FIFT-IPM motors, the existing model predictive current fault-tolerant control algorithms fail to effectively track fundamental and third-harmonic currents. This results in high harmonic distortion in the phase current. Hence, this paper innovatively proposes a multi-plane virtual vector model predictive fault-tolerant control strategy that can achieve rapid and effective control of both the fundamental and harmonic planes while ensuring good dynamic stability performance. Additionally, considering that electric agricultural equipment is usually in a multi-disturbance working environment, this paper introduces an adaptive gain sliding-mode disturbance observer. This observer estimates complex disturbances and feeds them back into the control system, which possesses good resistance to complex disturbances. Finally, the feasibility and effectiveness of the proposed control strategy are verified by experimental results.



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Keywords: model prediction; fault-tolerance; sliding mode disturbance observer; flux-intensifying motor

1. Introduction

Traditional agricultural machinery exhibits high fossil energy dependence [1,2], with inherent drawbacks including excessive energy consumption, heavy pollution, and operational instability [3–5]. To meet modern agriculture’s demand for high-quality harvesting [6], the industry now prioritizes green, high-efficiency development [7], driving trends toward equipment electrification [8–10] and intelligentization [11–13]. Motor-driven agricultural machinery [14] demonstrates distinct advantages: energy efficiency [15,16], operational effectiveness [17], superior control performance [18], high power density, and low noise [19].

The application scenarios of electric agricultural machinery equipment are diverse [20–22] and need to face complex operating environments [23–26] such as variable soils [27–29], crop heterogeneity [30,31], and field obstacles [32]. Continuous operation requirements [33] further heighten demands for high-reliability motor drive systems critical to agricultural

safety [34]. The five-phase permanent magnet synchronous motor (PMSM) has high efficiency, high power density, high reliability, excellent speed regulation performance [35–38], and higher control freedom, which can achieve fault-tolerant operation and has broad application prospects in the field of agricultural electrification. Among them, the five-phase Flux-Intensifying Fault-Tolerant Interior Permanent Magnet (FIFT-IPM) motor leverages inherent inverse-saliency characteristics ($L_d > L_q$) [39,40] to deliver robust overload capacity. Combined with its strong fault tolerance, superior torque output, low torque ripple, and high efficiency/power density [41], this motor proves exceptionally suitable as the central drive unit for electric agricultural equipment in complex farming environments.

The complex and diverse working conditions in agricultural production put forward strict requirements on the control strategy of motors [42]. For multi-phase motors such as five-phase FIFT-IPM motors, when a phase fault occurs in the motor [43], no hardware circuit needs to be changed; only appropriate fault-tolerant control strategies need to be selected, such as fault-tolerant control strategies based on vector control [44], direct torque control [45], or model predictive control (MPC), etc., that can realize fault-tolerant operation. Model prediction of fault-tolerant control strategies is becoming a hot spot in the field of fault-tolerant control strategy research because of its advantages, such as good steady-state performance and fast dynamic response [46].

In recent years, much research on MPC fault-tolerant control has been produced. Ref. [47] proposed a fault-tolerant model predictive current control (MPCC) strategy that simplifies control set and duty cycle optimization. The method improves dynamic performance by optimizing voltage vector selection, reducing computational load, and suppressing zero-sequence currents, significantly enhancing the control accuracy and robustness of multi-phase motor systems. However, single-phase faults can lead to increased current harmonic distortion. Ref. [48] further proposed a fault-tolerant control strategy based on the prediction control of a finite control set model. This method introduces a z -subspace perpendicular to the fundamental space, effectively reducing the current harmonic distortion under single-phase faults and improving the fault-tolerant capacity and stability of the system. However, the control accuracy problem caused by too few effective vectors within a unit period needs to be solved urgently. Ref. [49] proposes that MPCC is based on a preselected method and duty cycle control technology and applies two effective vectors during the control cycle, which can effectively improve the control effect. Additionally, refs. [50–52] employs a model predictive fault-tolerant control strategy using virtual voltage vectors as the control set. Such algorithms take the principle of eliminating the y -axis voltage in the x - y harmonic space as the virtual vector synthesis principle so that torque and magnetic link pulsation can be reduced, and multiple basic voltage vectors are involved in the control period. However, such a method is equivalent to using open-loop control for harmonic space, which is not suitable for controlling the third-harmonic plane of a non-sine back electromotive force five-phase FIFT-IPM motor. Therefore, it is urgent to find an MPC fault-tolerant control strategy based on multi-plane precision control to improve the reliability of control and obtain excellent steady-state and dynamic performance.

Moreover, in light of the complex and harsh working environments confronting electrified agricultural equipment, drive motor systems are persistently exposed to multifaceted interference during operation, while the requirements for high reliability in continuous operation become particularly stringent under specific operating conditions involving winding open-circuit faults. In recent years, ref. [53] proposed a fault-tolerant control strategy based on decoupling control and stator current compensation. This method can reduce torque pulsation caused by open-circuit faults of stator windings and significantly improve the operating performance of the motor under fault conditions. However, it fails to account for the impact of external disturbances on control performance. This requires a disturbance

observer (DOB). In [54], the DOB was introduced into the fault-tolerant control method based on direct torque control to suppress the fluctuating torque caused by short-circuit current. In [55], multiple disturbances in permanent magnet synchronous motors were divided into modeling loads and norm-bounded disturbances. It estimated the load by designing a disturbance observer and applying an adaptive controller to compensate for norm-bounded disturbances. However, the application of the above-mentioned observer in the open-circuit fault-tolerant control system of electric agricultural equipment windings needs further research.

This study introduces a multi-plane virtual vector model predictive fault-tolerant control strategy. Compared with the existing studies, the main contribution of this article can be summarized as follows. Firstly, due to the relatively high third-harmonic back EMF content in five-phase FITF-IPM motors, existing model predictive current fault-tolerant control algorithms fail to effectively track both fundamental and third-harmonic currents. Therefore, the proposed multi-plane virtual vector model predictive fault-tolerant control strategy can effectively and rapidly track both fundamental and third-harmonic currents simultaneously under open-circuit fault conditions while ensuring good dynamic stability performance. Secondly, after partitioning the traversal sectors, the proposed algorithm can significantly reduce computational load compared to the original algorithm, which ensures the rapid execution of the control strategy and conserves the processor's computing resources. Finally, with the design of the adaptive gain sliding-mode disturbance observer, its gain is able to be dynamically adjusted according to the system's real-time state, which can significantly enhance the system's ability to resist complex disturbances in agricultural application environments under fault conditions.

In Section 2, the topology and characteristics of the five-phase FIFT-IPM motor are introduced. Section 3 presents a multi-plane mathematical model for open-circuit faults. The proposed multi-plane virtual vector model predictive fault-tolerant control strategy based on an adaptive gain disturbance observer is described in Section 4. Section 5 presents the overall control strategy. Finally, Section 6 verifies the feasibility and superiority of the proposed strategy through experiments.

2. Motor Topology Structure and Characteristics

Figure 1 depicts the topological structure of the five-phase FIFT-IPM motor. In order to realize the high stability of inverse saliency characteristics, a slot pole combination of 20-slots/12-poles is adopted. For the stator part, to effectively improve the fault operating capability and the reliability of operation, fractional-slot concentrated windings [56] and an unequal stator width design are applied. In the rotor part, an innovative “flux-barrier guidance” design concept is implemented, featuring larger q-axis magnetic barriers to achieve enhanced inverse-saliency characteristics [39]. This effectively reduces cross-coupling effects within the magnetic circuit [35]. The inductive characteristics of the five-phase FIFT-IPM motor are depicted in Figure 2, showcasing stable parameter variations and pronounced inverse-saliency characteristics [57], thereby validating the design concept's correctness.

It is worth noting that the five-phase FIFT-IPM motors' stable parameter characteristics compensate for the MPC algorithms' reliance on precise motor parameters to some extent. Furthermore, as detailed in the back EMF harmonic analysis diagram in Figure 1, the five-phase FIFT-IPM motor fully retains the third-harmonic content in the back EMF during its design and optimization [41], accounting for approximately 17.5%. This effectively enhances torque output while reducing magnetic saturation effects. The parameters of the five-phase FIFT-IPM motor are listed in Table 1.

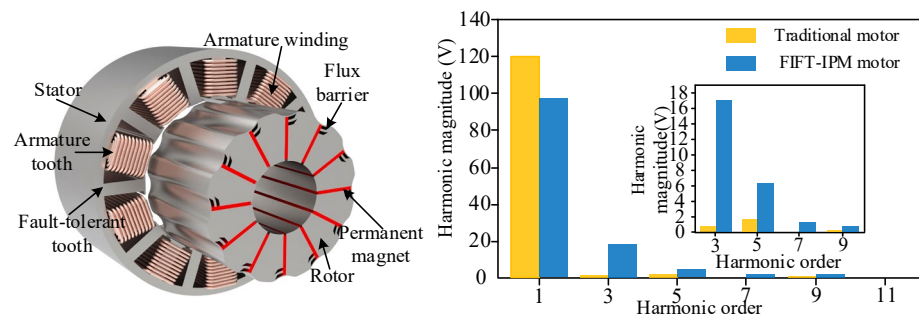


Figure 1. Topology and back EMF harmonic analysis of the five-phase FIFT-IPM motor.

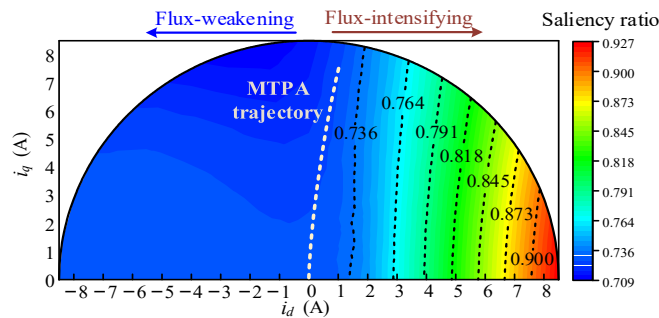


Figure 2. Saliency characteristics of FIFT-IPM motor.

Table 1. Parameters of the five-phase FIFT-IPM.

Parameter	Value	Parameter	Value
Fundamental flux linkage	0.103 Wb	3rd harmonic flux linkage	0.006 Wb
Fundamental d-axis inductance	17.29 mH	Fundamental q-axis inductance	12.60 mH
3rd d-axis inductance	12.83 mH	3rd q-axis inductance	12.81 mH
Polar of poles	6	Rated speed	1200 rpm
Rated current	5.98 A	Rated torque	12 N·m
Rated output power	2 kW	Resistance	0.69 Ω

3. Multi-Plane Mathematical Model Under Open-Circuit Fault

Assuming that the phase-A open-circuit fault occurs in the five-phase FIFT-IPM motor, the A phase winding will no longer participate in the electromechanical energy conversion, and the motor is in an asymmetric operation state after the fault. The voltage equation of the remaining four phase windings of the stator after the fault under the ideal state is expressed as

$$\begin{bmatrix} u_B \\ u_C \\ u_D \\ u_E \end{bmatrix} = R_s \begin{bmatrix} i_B \\ i_C \\ i_D \\ i_E \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_B \\ i_C \\ i_D \\ i_E \end{bmatrix} + \begin{bmatrix} e_B \\ e_C \\ e_D \\ e_E \end{bmatrix} \quad (1)$$

where $u_B, u_C, u_D, u_E, i_B, i_C, i_D, i_E, e_B, e_C, e_D, e_E$ are the phase voltage, phase current, and back EMF of the remaining normal phases; R_s is the phase winding resistance; and L_s is the phase inductance of each phase winding.

To achieve fault-tolerant control of the FIFT-IPM motor, it is necessary to make corresponding adjustments to the current in the remaining normal phase. By controlling the fundamental and harmonic currents in this phase and adjusting their amplitude and phase, smooth torque can be obtained, ensuring disturbance-free operation. When a single-phase open-circuit fault occurs in a five-phase FIFT-IPM motor, the control degrees of freedom de-

crease. The reduced-order Clarke transform matrix, primarily controlling the fundamental plane, can be reconstructed as follows:

$$T_{A1} = \frac{2}{5} \begin{bmatrix} \cos \alpha + m & \cos 2\alpha + m & \cos 3\alpha + m & \cos 4\alpha + m \\ \sin \alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \sin 12\alpha \\ 1 & 1 & 1 & 1 \end{bmatrix} \quad (2)$$

where α represents the angle between the axes of two adjacent phase windings, and m is the correction factor to ensure that the reverse electromotive force remains constant before and after the fault. The value of m is typically -1 , and $\alpha = 2\pi/5$.

In order to accurately control the third-harmonic plane, a reduced-order Clarke transformation matrix is established with the third-harmonic plane as the main control:

$$T_{A3} = \frac{2}{5} \begin{bmatrix} \cos 3\alpha - 1 & \cos 6\alpha - 1 & \cos 9\alpha - 1 & \cos 12\alpha - 1 \\ \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \sin 12\alpha \\ \sin \alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ 1 & 1 & 1 & 1 \end{bmatrix} \quad (3)$$

To sum up, when the open-circuit fault occurs in the five-phase FIFT-IPM motor, the stator voltage equation in the rotating coordinate system obtained by the reduced-order transformation matrix (2) can be expressed as:

$$\begin{cases} u_{d1} = R_s i_{d1} + L_{d1} \frac{di_{d1}}{dt} - \omega_e L_{q1} i_{q1} \\ u_{q1} = R_s i_{q1} + L_{q1} \frac{di_{q1}}{dt} + \omega_e L_{d1} i_{d1} + \omega_e \Psi_{m1} \\ u_{z1} = R_s i_{z1} + L_{z1} \frac{di_{z1}}{dt} + 3\Psi_{m3} \omega_e \cos 3\theta_e \end{cases} \quad (4)$$

where R_s represents stator resistance; ω_e is the electrical angular velocity; θ_e is the electrical angle; L_{d1} and L_{q1} are the inductances of the dq -axis on the fundamental plane; L_{z1} is the inductor on the $q3$ -axis; Ψ_{m1} and Ψ_{m3} are the fundamental and third-harmonic components of the stator flux linkage, respectively; u_{d1} , u_{q1} , i_{d1} , and i_{q1} are the voltages and currents in the d_1 - q_1 coordinate system, respectively; and u_{z1} and i_{z1} are the third-harmonic voltages and currents, respectively.

When a five-phase motor is in a healthy state, there are 32 voltage vectors in both the fundamental and third-harmonic spaces. However, after an open-circuit fault occurs, the number of voltage vectors in both the fundamental and harmonic spaces is reduced to 16. Figure 3 illustrates spatial distributions of voltage vectors in two subspaces. Different from normal operation, each space plane is divided into 12 sectors under OCF conditions. The remaining unaffected phase voltages are transformed using the first two rows of the reduced-order Clarke matrix shown in Equation (2), resulting in the voltage vector distribution shown in Figure 3a. Similarly, using the first two rows of the reduced-order matrix shown in Equation (3), the voltage vector distribution in the third-harmonic space can be obtained, as shown in Figure 3b. Moreover, the amplitudes of these voltage vectors are classified into six types: 0 , $0.145 U_{dc}$, $0.325 U_{dc}$, $0.441 U_{dc}$, $0.447 U_{dc}$, and $0.616 U_{dc}$, where U_{dc} is the dc-link voltage.

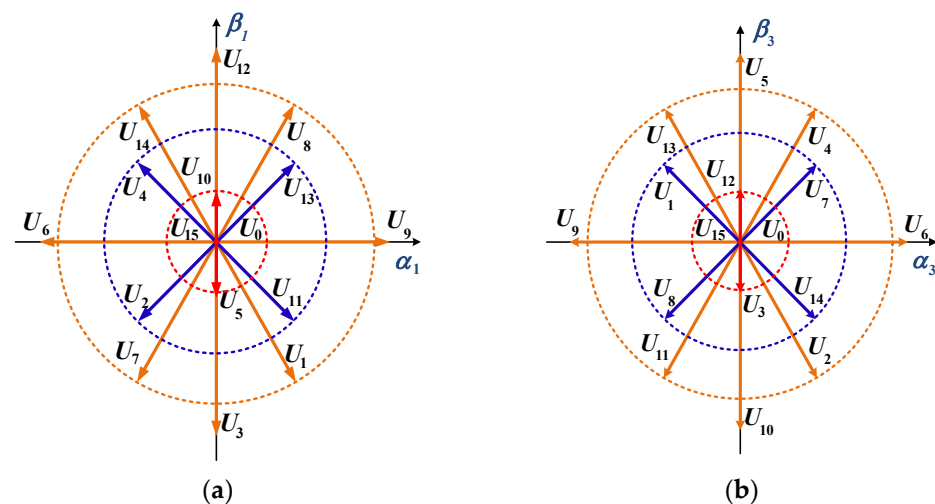


Figure 3. Space voltage vector distribution under phase-A open-circuit fault. (a) Distribution in fundamental subspace and (b) distribution in third-harmonic subspace.

4. Fault-Tolerant Control Strategy for Model Prediction of Multi-Plane Virtual Vector

To address the issue that existing MPC fault-tolerant control strategies cannot effectively track fundamental and third-harmonic currents while maintaining good dynamic and steady-state performance, this paper proposes a multi-plane virtual vector model predictive fault-tolerant control (MPVV-MPFTC) strategy. Additionally, a vector control strategy based on a disturbance observer is introduced, which enhances the resistance of the motor drive system of agricultural electrical equipment to complex environmental disturbances during fault tolerance, ensuring that the steady-state and dynamic performance under fault conditions matches that of normal operation.

4.1. Virtual Vector Model Prediction Fault-Tolerant Control

This paper introduces the MPVV-MPFTC strategy for addressing open-circuit faults in five-phase FIFT-IPM motors. A key feature of this strategy is that the virtual voltage vectors selected through traversal optimization are equivalent to the sum of three adjacent valid voltage vectors and a zero vector. To meet the requirement of generating standard PWM waveforms, i.e., symmetric PWM waveforms—the fundamental voltage space vector diagram in Figure 3 is referenced. The candidate vector groups listed in Table 2 are designed to generate centrally symmetric pulses, as shown in Figure 4. These six candidate vector groups can synthesize six virtual voltage vectors with variable direction and amplitude, effectively covering any direction and amplitude. Consequently, the proposed strategy achieves more precise tracking of fundamental and third-harmonic currents.

Table 2. Voltage vector combination of virtual vectors.

Virtual Vector	Basic Vector I	Basic Vector II	Basic Vector III	Basic Vector IV
U_{vv1}	U_9 (1001)	U_{13} (1101)	U_8 (1000)	$U_{0,15}$
U_{vv2}	U_8 (1000)	U_{12} (1100)	U_{14} (1110)	$U_{0,15}$
U_{vv3}	U_{14} (1110)	U_4 (0100)	U_6 (0110)	$U_{0,15}$
U_{vv4}	U_6 (0110)	U_2 (0010)	U_7 (0111)	$U_{0,15}$
U_{vv5}	U_7 (0111)	U_3 (0011)	U_1 (0001)	$U_{0,15}$
U_{vv6}	U_1 (0001)	U_{11} (1011)	U_9 (1001)	$U_{0,15}$

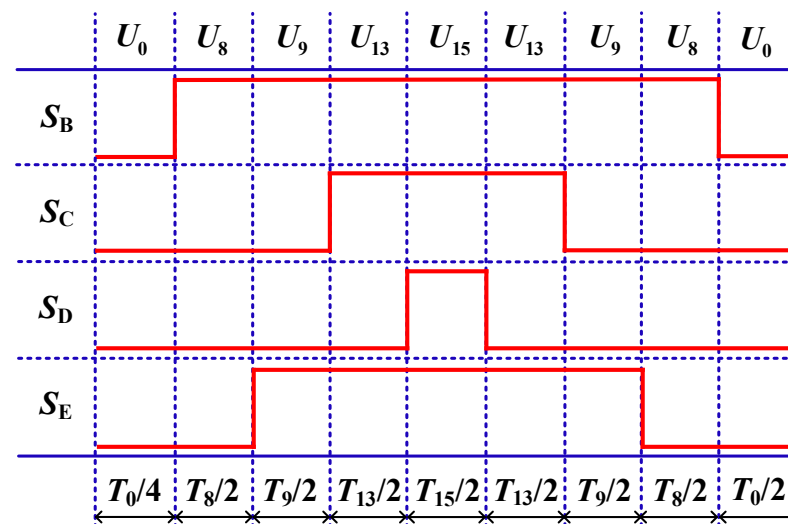


Figure 4. Switch sequence diagram.

In addition to the three basic voltage vectors shown in Table 2, the pre-synthesized virtual vector also contains a zero vector, and its synthesis formula is

$$T_s U_{vvn} = T_1 U_I + T_2 U_{II} + T_3 U_{III} + T_0 U_{IV} \quad (5)$$

where n ranges from 1 to 6, and U_I , U_{II} , U_{III} , and U_{IV} represent the basic voltage vectors I, II, III, and IV, respectively. T_1 , T_2 , T_3 , and T_0 are the times of the three basic vectors and the time of the zero vector, respectively, and T_s is a control period.

4.2. Computational Optimization of Multi-Plane Virtual Vector Model Prediction Fault Tolerance Control

The computational load of the proposed control strategy primarily involves calculating the action time for each vector group. To avoid wasting computational resources, the reference voltage is derived from the reference current to determine the position of the target voltage vector, thereby defining the traversal sectors. This approach reduces traversal steps and optimizes computation time. The reference voltage $u_{\alpha 1}$, $u_{\beta 1}$ in the stationary coordinate system is obtained using the feedback current and the given current. By referencing the voltage sectors in Table 3, the traversal sectors for the expected voltage vector in the next moment can be quickly identified, as illustrated in Figure 5. Each sector contains three candidate virtual vectors, reducing the original six traversal optimization calculations to just three. This significantly lightens the computational load while maintaining algorithm speed. As shown in Table 4, the improved algorithm expands the total number of virtual vectors to ten, which enhances tracking accuracy.

Table 3. Quadrant selection.

$U_{\alpha 1}$	$U_{\beta 1}$	Ergodic Quadrant	Contained Virtual Vectors
≥ 0	> 0	I	Uvv1, Uvv7, Uvv2
< 0	≥ 0	II	Uvv3, Uvv2, Uvv8
≤ 0	< 0	III	Uvv4, Uvv5, Uvv9
> 0	≤ 0	IV	Uvv10, Uvv6, Uvv5

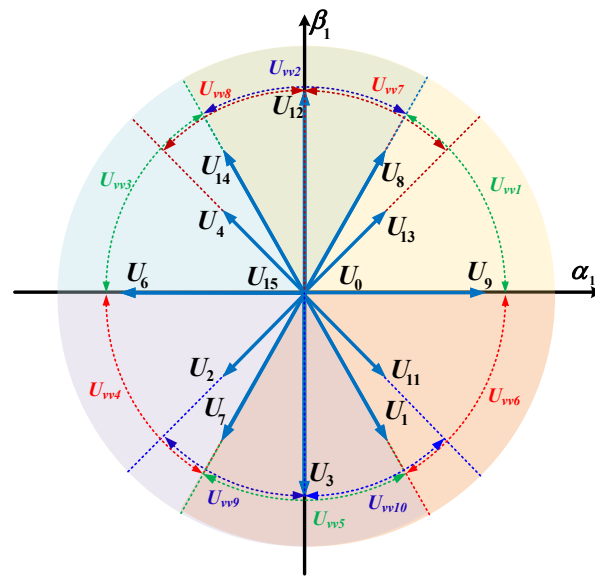


Figure 5. Distribution of vector groups.

Table 4. Extended vector groups.

Virtual Vector	Basic Vector I	Basic Vector II	Basic Vector III	Basic Vector IV
U_{vv7}	U_{13} (1101)	U_8 (1000)	U_{12} (1100)	$U_{0,15}$
U_{vv8}	U_{12} (1100)	U_{14} (1110)	U_4 (0100)	$U_{0,15}$
U_{vv9}	U_2 (0010)	U_7 (0111)	U_3 (0011)	$U_{0,15}$
U_{vv10}	U_3 (0011)	U_1 (0001)	U_{11} (1011)	$U_{0,15}$

4.3. Calculation of Vector Action Time

The MPVV-MPFTC strategy proposed in this paper uses the principle of no difference beat to calculate the vector action time. When the traversing sector is determined, the action time of each basic vector and zero vector in the three vector groups within the sector will be calculated according to the given current and feedback current. The expression for action time calculation is

$$\begin{bmatrix} i_{d1}(k+1) \\ i_{q1}(k+1) \\ i_{z1}(k+1) \end{bmatrix} = \begin{bmatrix} i_{d1}(k) \\ i_{q1}(k) \\ i_{z1}(k) \end{bmatrix} + \begin{bmatrix} \Delta_{d1_1} & \Delta_{d1_2} & \Delta_{d1_3} & \Delta_{d1_0} \\ \Delta_{q1_1} & \Delta_{q1_2} & \Delta_{q1_3} & \Delta_{q1_0} \\ \Delta_{z1_1} & \Delta_{z1_2} & \Delta_{z1_3} & \Delta_{z1_0} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_0 \end{bmatrix} = \begin{bmatrix} i_{d1}^* \\ i_{q1}^* \\ i_{z1}^* \end{bmatrix} \quad (6)$$

where $i_{d1}(k+1)$, $i_{q1}(k+1)$, and $i_{z1}(k+1)$ represent the predicted values of the current for the next moment on the d_1 axis, q_1 axis, and z_1 axis, respectively; i_{d1}^* , i_{q1}^* , and i_{z1}^* are the reference values of the current; $i_{d1}(k)$, $i_{q1}(k)$, and $i_{z1}(k)$ are the feedback values of the current at this moment; Δ_{d1_n} ($n = 0,1,2,3$), Δ_{q1_n} ($n = 0,1,2,3$), and Δ_{z1_n} ($n = 0,1,2,3$) are the rates of increase in current on the d_1 -axis, q_1 -axis, and z_1 -axis, respectively, for different basic voltage vectors in the candidate vector group.

In addition, the vector action time satisfies the following relation:

$$T_s = T_1 + T_2 + T_3 + T_0 \quad (7)$$

Substituting Equation (7) into Equation (6), we can get the action time of each basic vector in the preselected vector group:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \begin{bmatrix} \Delta_{d1_1} - \Delta_{d1_0} & \Delta_{d1_2} - \Delta_{d1_0} & \Delta_{d1_3} - \Delta_{d1_0} \\ \Delta_{q1_1} - \Delta_{q1_0} & \Delta_{q1_2} - \Delta_{q1_0} & \Delta_{q1_3} - \Delta_{q1_0} \\ \Delta_{z1_1} - \Delta_{z1_0} & \Delta_{z1_2} - \Delta_{z1_0} & \Delta_{z1_3} - \Delta_{z1_0} \end{bmatrix}^{-1} \begin{bmatrix} i_{d1}^* - i_{d1}(k) - \Delta_{d1_0}T_s \\ i_{q1}^* - i_{q1}(k) - \Delta_{q1_0}T_s \\ i_{z1}^* - i_{z1}(k) - \Delta_{z1_0}T_s \end{bmatrix} \quad (8)$$

When the zero vector acts, the slope of the axial current for the d_1 -axis, q_1 -axis, and z_1 -axis is expressed as

$$\begin{cases} \Delta_{d1_0} = \frac{1}{L_d}(\omega_e L_{q1} i_{q1} - R_s i_{d1}) \\ \Delta_{q1_0} = \frac{1}{L_q}(-\omega_e L_{d1} i_{d1} - R_s i_{q1} - \omega_e \psi_{m1}) \\ \Delta_{z1_0} = \frac{1}{L_{z1}}(-R_s i_z - 3\omega_e \psi_{m3} \cos 3\theta_e) \end{cases} \quad (9)$$

When the basic vector U_n ($n = \text{I, II, III, IV}$) acts on the d_1 -axis, q_1 -axis, and z_1 -axis, the expression for the current slope of the axis is

$$\begin{cases} \Delta_{d1_n} = \Delta_{d1_0} + \frac{u_{d1_n}}{L_d} \\ \Delta_{q1_n} = \Delta_{q1_0} + \frac{u_{q1_n}}{L_q} \\ \Delta_{z1_n} = \Delta_{z1_0} + \frac{u_{z1_n}}{L_{z1}} \end{cases} \quad (10)$$

where u_{d1_n} , u_{q1_n} , and u_{z1_n} represent the basic vectors for the uncorrelated d_1 -axis, q_1 -axis, and z_1 -axis voltage.

After obtaining the action times of each basic vector in the three preselected vector groups within the traversed sector, the vectors are synthesized to form three virtual vectors. These virtual vectors are then sequentially substituted into the model for prediction at the next moment, and optimization based on a cost function is performed. This process selects the candidate virtual voltage vectors that most closely match the desired voltage vector, thereby achieving the optimal control effect. The prediction model is as follows:

$$\begin{cases} i_{d1}(k+1) = i_{d1}(k) + \frac{T_s}{L_d}(u_{vv_d} + \omega_e L_{q1} i_{q1}(k) - R_s i_{d1}(k)) \\ i_{q1}(k+1) = i_{q1}(k) + \frac{T_s}{L_q}(u_{vv_q} - \omega_e L_{d1} i_{d1}(k) - R_s i_{q1}(k) - \omega_e \psi_f) \\ i_{z1}(k+1) = i_{z1}(k) + \frac{T_s}{L_{z1}}(u_{vv_z1} - R_s i_{z1}(k) - 3\omega_e \psi_{f3} \cos 3\theta) \end{cases} \quad (11)$$

where u_{vv_d} , u_{vv_q} , and u_{vv_z} represent the voltage vectors corresponding to the d_1 -axis, q_1 -axis, and z_1 -axis, respectively.

In order to achieve accurate tracking of the current, and due to the existence of the third-harmonic, it is necessary to strictly control the z_1 -axis component, so the general cost function is set as

$$J = \sqrt{(i_{d1}^* - i_{d1}(k+1))^2} + \sqrt{(i_{q1}^* - i_{q1}(k+1))^2} + \sqrt{(i_{z1}^* - i_{z1}(k+1))^2} \quad (12)$$

Since the candidate virtual vector to be traversed is reduced to three, after three traverses in Equation (11), the three groups of predicted currents are substituted into the value function for optimization. Finally, select the optimal virtual voltage vector U_{vvn} , which is closest to the expected voltage vector U_0 .

4.4. Sliding-Mode Disturbance Observer

To improve the resistance of fault-tolerant control systems of electrical agricultural equipment to interference under the MPVV-MPFTC strategy, this paper innovatively proposes a novel sliding mode disturbance observer (SMDOB) with adaptive gain. By

introducing an adaptive factor into SMDOB, it can effectively eliminate current harmonics caused by faults. At the same time, compared to traditional disturbance observers, the accuracy of estimated parameters has been significantly improved. The key to the proposed SMDOB with adaptive gain lies in estimating complex disturbances and feeding them back into the control system.

When the interference signal appears, its time-domain differential equation can be expressed as

$$\dot{x} = Ax + B_0u + B_1d \quad (13)$$

where u and d represent the standard model signal and interference signal, respectively. A , B_0 , and B_1 are the corresponding coefficient matrices.

Suppose the system disturbance changes slowly:

$$\dot{d} = 0 \quad (14)$$

where d represents the disturbance to be observed in the control system.

In the context of a fault-tolerant control system experiencing a fault state, the tracking error attributable to torque pulsation is observed to escalate. Consequently, the tracking error of the q_1 -axis current can be classified as a disturbance, which in turn can be denoted as variable x .

$$x = \tilde{i}_q - i_q \quad (15)$$

It is imperative to recognize that the discontinuity inherent in the switching function of conventional linear sliding surfaces can result in pronounced jitter, which may degrade the dynamic performance of the system and potentially lead to instability and collapse. To mitigate this challenge, an integral term is incorporated into the traditional sliding surface, thereby creating an integral sliding surface. The formulation of this surface is as follows:

$$S(x) = x + c \int_0^x x d\tau \quad (16)$$

where c is the integral factor. It should be noted that if the value of c is too large, the jitter of the sliding mode controller will increase. After incorporating the integral term, the steady-state error is reduced, the jitter is mitigated, and the stability of the controller can be enhanced.

To enhance the robustness of the fault-tolerant control system, in accordance with the strong robust law, a function $x/(|x| + \delta)$ is introduced to construct the sliding mode control rate of the SMDOB with adaptive gain, which can be expressed as

$$G(s) = \dot{S} = -\varepsilon_1 \frac{x}{|x| + \delta} \text{sign}(S) - \varepsilon_2 S \quad (17)$$

where ε_1 and ε_2 are the isokinetic approach coefficient and exponential reaching coefficient. When ε_1 and ε_2 increase, the sliding mode surface becomes faster. δ is the adjustment factor, satisfying the condition $0 \leq \delta \leq 1$.

$$\eta(s) = \mu(s) = E - k|G(s)| \quad (18)$$

where k represents the gain factor, and E denotes the ideal gain.

The control rate of the control system can be described as

$$\Delta f_{k+1}(t) = \lambda \Delta f_k(t) + \mu(t) \tilde{i}_{e,k}(t) + \eta(t) \tilde{i}_{e,k+1}(t) \quad (19)$$

where the parameter λ is the forgetting factor, which represents a periodic harmonic transformation. According to Equation (19), the control block diagram of the SMDOB module with adaptive gain is shown in Figure 6.

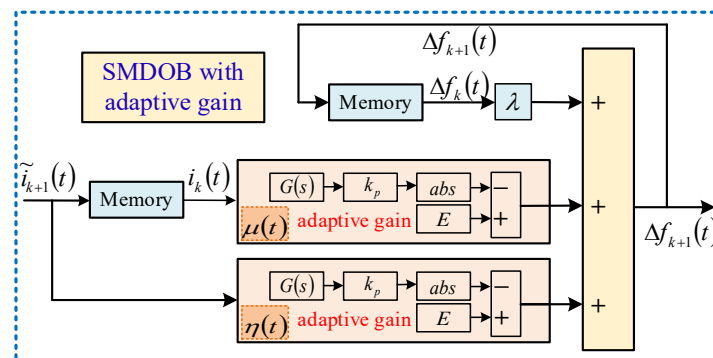


Figure 6. SMDOB with adaptive gain.

From Equations (16) and (17), it can be seen that the adaptive gain SMDOB is designed based on the concept of dynamic compensation. This reduces current harmonics and enhances the fault-tolerant control systems' disturbance rejection capability and dynamic performance. Compared to conventional solutions, the linear DOB suffers from accuracy degradation under parameter perturbations due to its reliance on a nominal model; the Extended State Observer (ESO) has limited bandwidth; the fixed-gain SMO tends to induce chattering. The proposed SMDOB integrates the robustness of sliding mode control with an adaptive gain mechanism: By dynamically adjusting gains through the reaching law, it achieves an optimal balance between rapid disturbance estimation and chattering suppression. In summary, the proposed controller exhibits good robustness under faulty conditions.

5. Overall Control Strategy

For the single-phase open-circuit fault in FIFT-IPM motors, the overall control block diagram of the proposed MPVV-MPFTC strategy is illustrated in Figure 7. Unlike traditional MPC approaches that neglect or apply open-loop processing to harmonic plane control, our fault-tolerant strategy utilizes independent reduced-order transformation matrices for both fundamental and harmonic planes. This achieves synchronous closed-loop precise control of fundamental and harmonic currents. Furthermore, computational load optimization is implemented for the traversal optimization process within the MPVV-MPFTC module, enabling rapid and effective control of both planes. On the other hand, to adapt to the multi-disturbance agricultural environment, the strategy incorporates an adaptive-gain SMDOB. This provides dynamic compensation through feedforward action, while its adaptive gain mechanism adjusts observer gains in real-time based on system states. These significantly enhance the system's ability to withstand complex environmental disturbances during faults, ensuring robust operation of the fault-tolerant control system in agricultural applications.

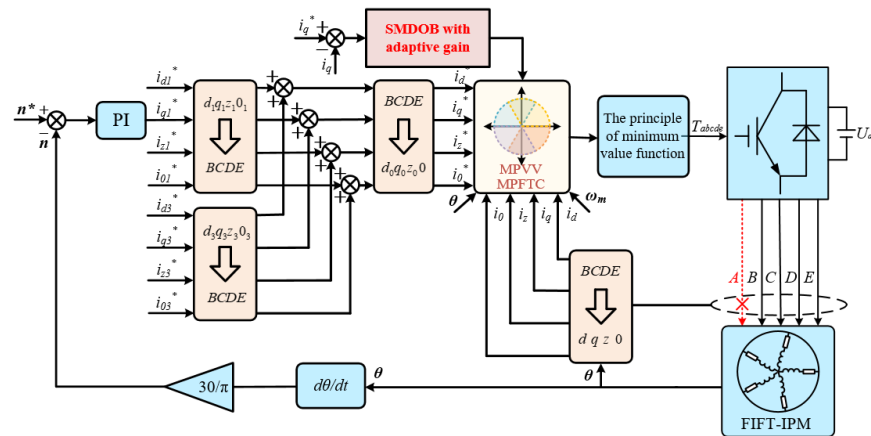


Figure 7. Diagram of system control.

6. Experimental Verification

To verify the feasibility of the proposed model predictive fault-tolerant control strategy and the accuracy of the disturbance observer theory analysis, this paper constructs an experimental platform for a five-phase FIFT-IPM motor. The experimental platform is shown in Figure 8, which mainly includes an inverter and a magnetic powder brake. The switching commands are generated by the dSPACE 1007 (dSPACE Mechatronic Control Technology, Paderborn, Germany), with the sampling frequency and inverter switching frequency both set to 10 kHz. The magnetic powder brake acts as a load, while the torque sensor is used to obtain the torque signal. To validate the improvement of the steady-state performance of the proposed anti-disturbance multi-plane virtual vector model predictive fault-tolerant control strategy, the experimental results of the MPVV-MPFTC strategy and the traditional single-vector MPFTC strategy under duty cycle optimization were analyzed and compared, and they are, respectively, referred to as Method A and Method B.

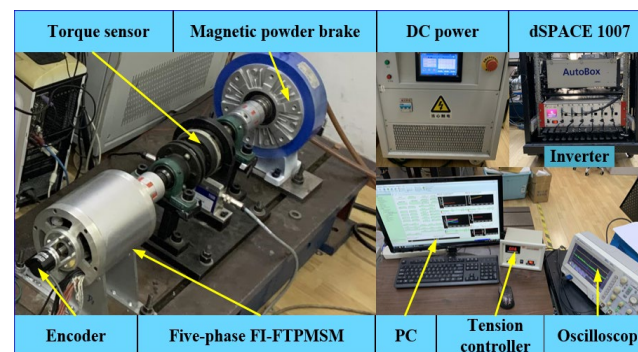


Figure 8. Experimental platform of the five-phase FIFT-IPM motor.

6.1. Fault-Tolerant Control Switching Experiment of Motor Drive System

Figures 9a and 10 present the performance comparison between Method A and Method B during the transition from a healthy state to a fault-tolerant state. The experimental results show that under normal operating conditions, torque and speed remain relatively stable, with phase currents exhibiting standard sine waveforms. After implementing fault-tolerant control, Figure 9a shows that the remaining phase currents quickly return to sine waveforms, the speed rapidly recovers, and torque pulsation is significantly reduced. Meanwhile, the harmonic components of i_{q1} and i_{d1} in Figure 9b drop sharply after fault tolerance. The fault-tolerant control switching experiments have demonstrated that the proposed Scheme A can ensure continuous operation of the motor without shutdown under fault conditions. Compared to Method B, Scheme A exhibits higher sinusoidal quality in its

fault-tolerant phase currents, which can be attributed to its implementation of the deadbeat principle for calculating the action durations of multiple voltage vectors. This approach demonstrates superior advantages in current tracking performance.

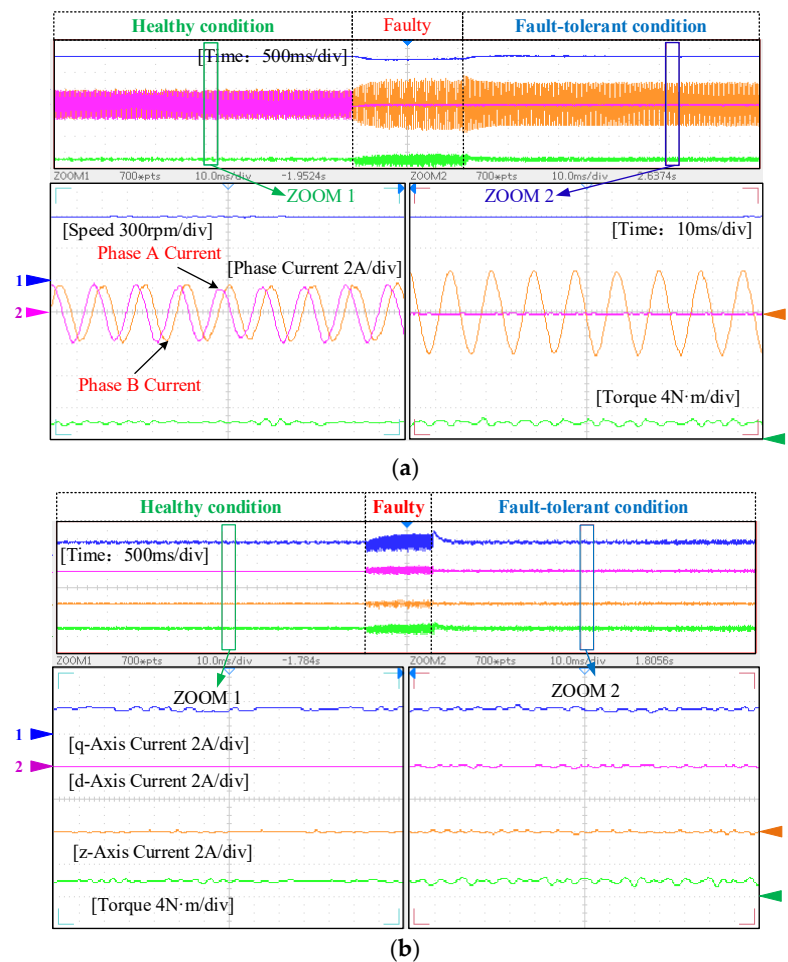


Figure 9. Switching experiment from healthy operation to fault-tolerant operation. (a) Method A speed, phase current, and torque online switching diagram. (b) Current online switching diagram of axis i_{q1} , i_{d1} , and i_{z1} in Method A.

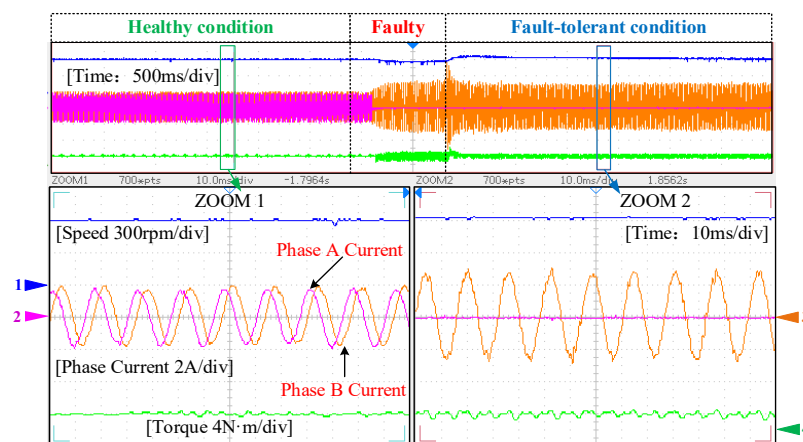


Figure 10. Method B online switching of speed, phase current, and torque.

6.2. Steady State Performance Test of Motor Drive System

To comprehensively evaluate the performance of the proposed strategy under stable conditions, Figure 11 presents a comparison chart of the d_1 -axis, q_1 -axis, and z_1 -axis currents

as well as the electromagnetic torque of the motor at 600 r/min speed. The experimental results show that Method A significantly outperforms Method B in suppressing harmonic currents in the fundamental wave space, i.e., i_{z1} , which leads to smaller pulsations of i_{q1} and i_{d1} after fault tolerance. Figure 12 further reveals the comparison of phase currents C, D, and E with electromagnetic torque when the motor operates at 400 r/min. Other experimental data sampling analyses are detailed in Table 5. It is evident that the proposed fault-tolerant control strategy A achieves an average reduction of 55% in phase current distortion rate and a 10.88% decrease in torque ripple compared to conventional Method B.

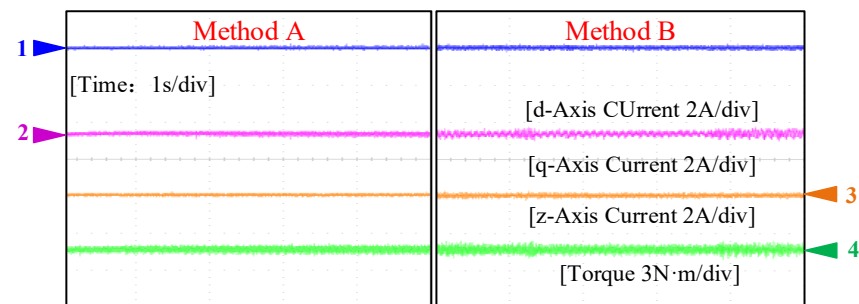


Figure 11. Comparison of $q1$ -axis, $d1$ -axis, and $z1$ -axis current under fault tolerance.

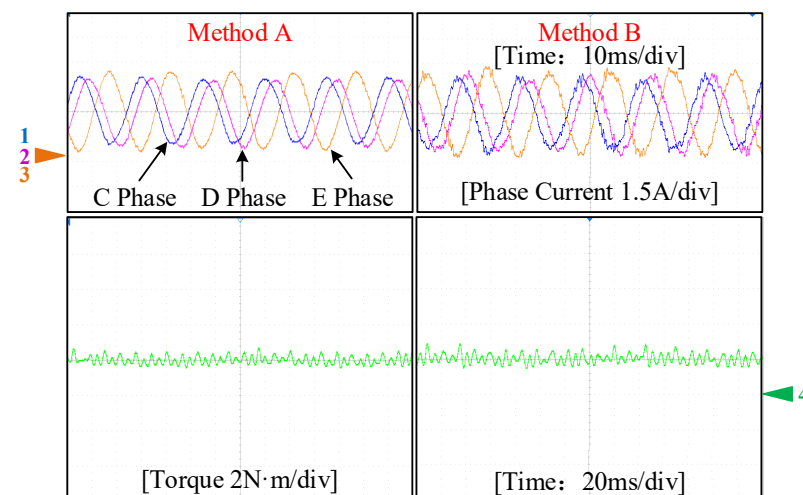


Figure 12. Comparisons of phase current and torque under fault-tolerant operation.

Table 5. Experimental results under different methods and different operations.

Speed (r/min)/ Experimental Load (N·m)	Fault-Tolerant Strategy	Current Distortion Rate (%)			Torque Ripple (%) $\frac{T_{\max}-T_{\min}}{T_{\text{avg}}} \times 100\%$
		C	D	E	
200/1.831	Method A	2.90	3.74	4.45	34.95
200/1.792	Method B	10.51	10.06	8.76	36.71
400/1.984	Method A	4.63	3.52	4.83	36.29
400/2.212	Method B	10.41	9.48	8.35	43.40
600/2.198	Method A	6.50	4.15	5.31	40.03
600/2.317	Method B	11.89	10.04	9.83	45.01

After a comprehensive analysis of the experimental data, it can be concluded that the proposed strategy has significant advantages in stability performance, effectively reducing current distortion rates and torque pulsations, thereby enhancing the stable operation quality of the motor.

6.3. Dynamic Performance Test of Motor Drive System

To verify the dynamic stability performance of the proposed fault-tolerant control strategy, Figure 13 shows the experimental waveforms for speed response and variable load response. In the speed response test, Figure 13a presents the waveform of speed versus torque. This experiment demonstrates that the actual speed can quickly follow the set speed reference value, whether accelerating or decelerating, with a response time controlled below 0.2 s. The speed curve maintains good smoothness, which proves the excellent performance of the MPVV-MPFTC strategy in speed response. In the variable load response test, Figure 13b illustrates the speed response under varying loads. Specifically, when the load decreases, the speed can recover to the reference value within about 0.35 s, with an overshoot of only 1.4%; whereas when the load increases, the response time is approximately 0.3 s, with an overshoot of about 1.7%. These experimental results indicate that the fault-tolerant control strategy has good robustness against load disturbances, ensuring stable operation of the motor under load variations.

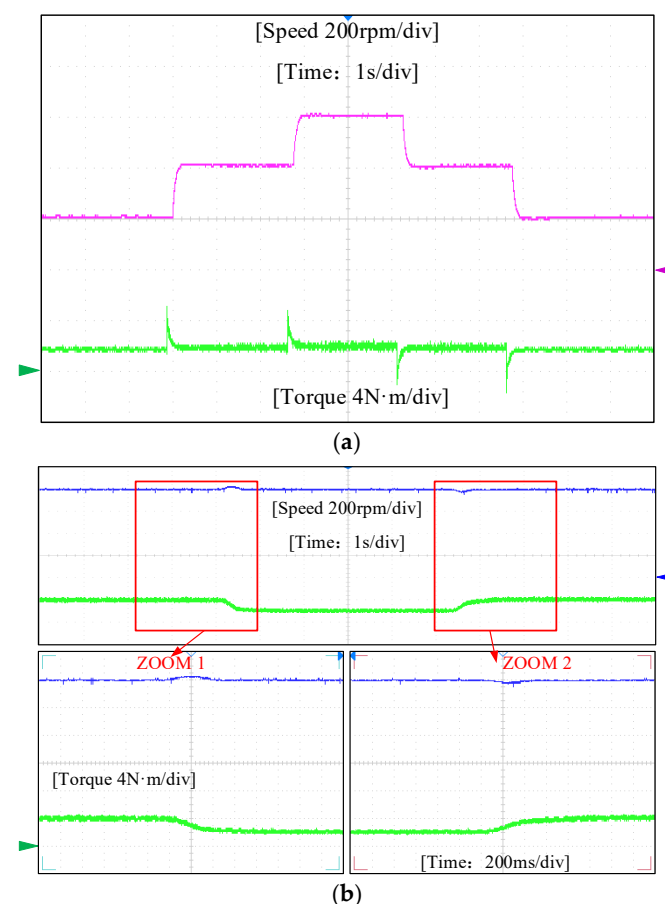


Figure 13. Dynamic response experiment. (a) Speed response test chart. (b) Load response test diagram.

6.4. Analysis of Calculation Amount of Motor Drive System

The computational load of control strategies in drive systems critically determines their operational speed and practical applicability. To intuitively evaluate the computational load of the proposed fault-tolerant control strategy, this paper adopts the single-vector MPFTC strategy with duty ratio optimization as a reference benchmark. A normalized processing of computation time was implemented to explicitly reveal the relative computational complexity among different algorithms, with detailed data presented in Figure 14. The enhanced algorithm demonstrates a 33.3% reduction in computational load compared to the original methodology presented in this work, achieved through refined traversal optimization

procedures and streamlined computational workflows, thereby significantly accelerating algorithmic execution. Although exhibiting a 52.94% increase in computation time relative to duty-cycle-optimized fault-tolerant control methods, the substantial improvements in control performance justify this computational trade-off. In practical implementations, the superior control efficacy sufficiently compensates for the additional computational resource allocation, validating its high cost-effectiveness in industrial applications.

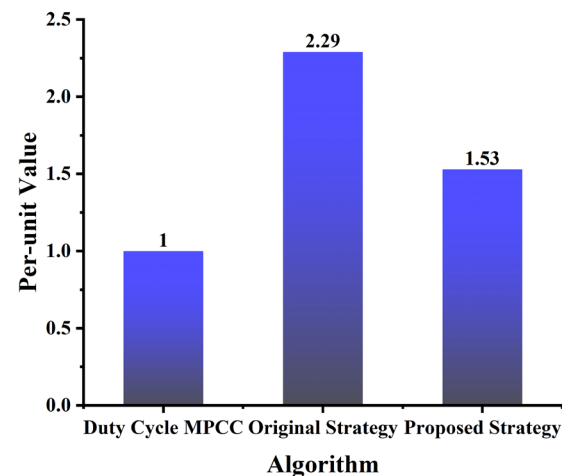


Figure 14. Quantitative graph of running time of fault-tolerant strategy.

7. Conclusions

In light of single-phase open-circuit faults of five-phase FIFT-IPM motors used in electrical agricultural equipment, this paper proposes a multi-plane virtual vector model predictive fault-tolerant control strategy to achieve better control performance. In addition, a sliding-mode disturbance observer based on adaptive gain is proposed, which dynamically adjusts the gain according to the real-time state of the system so that it can better operate in a multi-disturbance agricultural application environment under fault conditions and effectively guarantees the good robustness of the fault-tolerant control system in fault conditions. This fault tolerance strategy has the following advantages:

- (1) The proposed MPVV-MPFTC strategy contains multiple basic voltage vectors during the control period, and the modulation range can cover any direction and any amplitude and is calculated using the principle of no-beat. Vector action time can track multi-plane current more effectively and has a good control effect. Compared with traditional duty-cycle-optimized single-vector MPFTC, the proposed strategy achieves a 55% average reduction in current distortion rate and a 10.88% decrease in torque ripple;
- (2) After dividing the traversal sectors in the proposed algorithm, the computational load is reduced by 33.3% compared to the original algorithm, thereby saving the processor's computing resources;
- (3) The sliding mode disturbance observer based on adaptive gain can better resist disturbances under fault conditions, effectively ensuring that the fault-tolerant control system has good robustness in agricultural application environments.

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