

Article

Research on Open Circuit Fault Modeling and Fault Tolerant Control Strategy of Five-Phase Induction Motor

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Abstract: Five-phase induction motors have the advantages of high reliability and strong fault-tolerant performance, so its open circuit fault model and fault-tolerant control strategy are widely studied. Based on the normal operation of the five-phase induction motor, the mathematical model of the five-phase induction motor under the conditions of single-phase open circuits, adjacent two-phase open circuits, and non-adjacent two-phase open circuits are established by using the reduced order decoupling transformation. Based on the principle of constant magnetic potential, the relationship between magnetic potential and each phase current is analyzed by using the symmetrical component method (MSC). The fault-tolerant control strategy of a five-phase induction motor with the above three open-circuit faults is designed. Through simulation and prototype experiments, the phase current and speed conversion under three open-circuit faults are analyzed. The results show that after the open-circuit fault of a five-phase motor, the residual phase current is no longer balanced, the motor speed is decreased, and the vibration is increased significantly. After fault-tolerant control, the residual phase current is balanced, the rated speed can be reached, and the vibration of the motor is reduced. Thus, the validity and correctness of the fault-tolerant control strategy for a five-phase induction motor are verified.



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Keywords: five-phase induction motor; open circuit fault; mathematical model; fault tolerant control; simulation and experiment; method of symmetrical components

1. Introduction

The AC speed regulation system composed of a five-phase inverter and five-phase motor has outstanding advantages, such as high torque density, high efficiency, small torque ripple, and strong fault tolerance. Furthermore, it is widely used in low-voltage, high-power, high-performance, and high-reliability applications, such as ship propulsion, electric locomotives, and multi-electric aircraft [1–3]. Industrial investigation and research show that 30–40% of induction motor faults are caused by open circuits of stator winding or inverters [4,5]. A five-phase induction motor has redundant phases, so that it can still start normally and operate at reduced power in case of open-circuit or short-circuit fault in its stator winding (the number of remaining healthy phases is greater than or equal to 3). At the same time, appropriate control methods are adopted to balance the remaining healthy phase currents without manual maintenance and changing the motor topology, so as to realize the normal operation of the motor and improve the reliability of the motor system [6,7].

In recent years, with the improvement of the reliability requirements of motor systems, the fault modeling and fault-tolerant control strategy of five-phase induction motors have become the focus of experts and scholars. The mathematical model of a one-phase fault of an induction motor power supply is established by using the decoupling transformation method without reduction [8]. The mathematical model of a six-phase motor with an open circuit is established by using the same-level variable fault analysis method [9].

The mathematical model matrix representation method of a polyphase motor system is introduced, which provides the basis for realizing polyphase motor control and fault tolerance [10]. The basic principle and fault-tolerant control strategy based on Space Vector Pulse Width Modulation (SVPWM) and Current Hysteresis Bandwidth Pulse Width Modulation (chbpwm) are described [11]. In a d-q rotor reference system, a five-phase induction motor is controlled by field orientation to maximize torque efficiency and improve speed [12]. The air gap magnetic field of a five-phase induction motor is an indirect vector controlled by the constraints of the magnetic potential balance [13]; The voltage space vector asymmetry is redefined as the voltage space vector of a Brushless Direct Current Motor-Direct Torque Control (BLDCM-DTC) fed by Four-Switch, Three-Phase Inverter (FSTPI), and a DTC control principle without flux linkage observation is proposed [14–18]. The current prediction model is used for the fault-tolerant control of five-phase drives with a one-phase open circuit [19,20]. The application of the finite state model predictive controller in the current control of a polyphase motor is studied [21–23]. When an open-circuit fault occurs, the voltage vector diagram is reconstructed, and then the switching signal with an asymmetric waveform is selected in a sector. Based on it, an asymmetric SVPWM control theory is proposed [24–26]. No matter which fault-tolerant control mode is adopted, the main idea is to track the fault-tolerant current to realize the fault-tolerant control of the motor.

The mathematical model and fault-tolerant control strategy of an open-circuit fault of a five-phase cage induction motor are studied. The purpose is to improve the reliability and stability of a five-phase motor and reduce the motor current fluctuation after open-circuit fault. The mathematical model of the five-phase induction motor under the conditions of a one-phase open circuit, adjacent two-phase open circuit, and non-adjacent two-phase open circuit are established by using the reduced order decoupling transformation. Based on the principle of constant magnetic potential, the relationship between magnetic potential and each phase current is analyzed by using the Method of Symmetrical Components (MSC), the fault-tolerant control strategy of a five-phase induction motor when the above three open circuit faults occur is designed, and the constraints of fault-tolerant control are analyzed, so as to achieve the requirements of maximum speed and minimum torque ripple when the motor has open-circuit faults. The simulation and experimental results show that the fault-tolerant control strategy proposed in this paper has the advantages of simple calculation, constant magnetomotive force, low loss, and small current fluctuation.

The structure of this paper is as follows: In the first section, the research background, significance, and main work content are briefly described. In the second section, the mathematical model of an open-circuit fault of a five-phase induction motor is established. In the third section, the motor fault-tolerant control strategy is designed. In the fourth section, the theoretical part is simulated and verified by experiments, Last, in the fifth section, the work of this paper is summarized. The main research contents and methods of this paper are summarized in Figure 1.

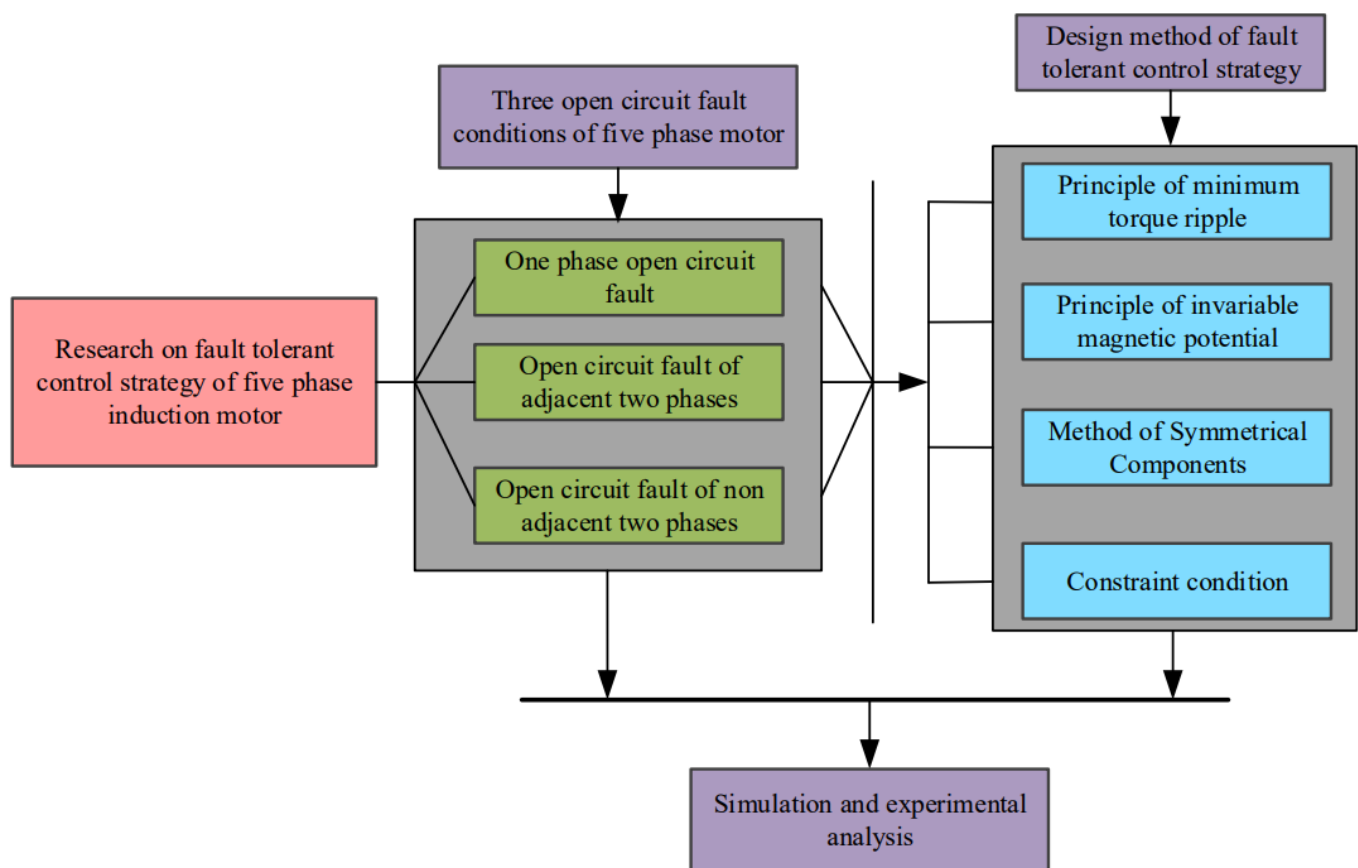


Figure 1. Summary of main research contents and methods in this paper.

2. Establishment of Mathematical Model for Open-Circuit Fault of Five-Phase Induction Motor

2.1. Mathematical Model of Normal Operation of Five-Phase Induction Motor

Considering the influence of fundamental wave and third harmonic, the mathematical model of a five-phase induction motor under normal operation in a $\alpha_1 - \beta_1 - \alpha_3 - \beta_3 - 0$ coordinate system is:

- (1) The matrix form of the stator and rotor flux linkage equation is [27]:

$$\begin{bmatrix} \psi_{s\alpha\beta} \\ \psi_{r\alpha\beta} \end{bmatrix} = \begin{bmatrix} C_s L_{ss} C_s^{-1} & C_s L_{sr1} C_r^{-1} \\ C_r L_{rs1} C_s^{-1} & C_r L_{rr} C_r^{-1} \end{bmatrix} \begin{bmatrix} I_{s\alpha\beta} \\ I_{r\alpha\beta} \end{bmatrix}, \quad (1)$$

where:

$[\psi_{s\alpha\beta}] = [\psi_{s\alpha1} \ \psi_{s\beta1} \ \psi_{s\alpha3} \ \psi_{s\beta3} \ \psi_{s0}]^T$ is the stator flux linkage equation;

$[\psi_{r\alpha\beta}] = [\psi_{r\alpha1} \ \psi_{r\beta1} \ \psi_{r\alpha3} \ \psi_{r\beta3} \ \psi_{r0}]^T$ is the rotor flux linkage equation;

$[I_{s\alpha\beta}] = [i_{s\alpha1} \ i_{s\beta1} \ i_{s\alpha3} \ i_{s\beta3} \ i_{s0}]^T$ is the stator current equation;

$[I_{r\alpha\beta}] = [i_{r\alpha1} \ i_{r\beta1} \ i_{r\alpha3} \ i_{r\beta3} \ i_{r0}]^T$ is the rotor current equation.

- (2) The voltage equation of the stator and rotor is [27]:

$$\begin{bmatrix} U_{dq} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} I_{s\alpha\beta} \\ I_{r\alpha\beta} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & -\omega_r \Gamma \end{bmatrix} \begin{bmatrix} \psi_{s\alpha\beta} \\ \psi_{r\alpha\beta} \end{bmatrix} + p \begin{bmatrix} \psi_{s\alpha\beta} \\ \psi_{r\alpha\beta} \end{bmatrix}, \quad (2)$$

where, $[U_{dq}] = [u_{d1} \ u_{q1} \ u_{d3} \ u_{q3} \ u_0]^T$ is the voltage vector in the rotating coordinate system.

- (3) The electromagnetic torque equation is [27]:

$$\begin{aligned}
 T_{em} &= n_p \left[I_{s\alpha\beta}^T C_s^T \frac{\partial}{\partial \theta_r} (L_{sr}) C_r I_{r\alpha\beta} \right] \\
 &= \frac{5}{2} n_p (L_{m1} (i_{s\beta 1} i_{r\alpha 1} - i_{r\beta 1} i_{s\alpha 1}))
 \end{aligned} \quad (3)$$

2.2. Mathematical Model of One-Phase Open-Circuit Fault

The establishment of an open-circuit fault mathematical model of a five-phase cage induction motor is the basis for the subsequent control and performance analyses of the motor. A phase A open circuit is taken as an example, wherein the mathematical model of a one-phase open-circuit fault of a five-phase motor is established. There is no current flowing in phase A of the motor. When the mathematical model is established, the rows and columns associated with phase A in the original five phase motor are removed, so the original stator self-inductance, stator leakage inductance, and stator rotor mutual inductance of the five-phase motor are changed, and the rotor self-inductance and leakage inductance are not changed.

According to the principle of constant magnetomotive force, the projection of the remaining four-phase current on the $\alpha_1 - \beta_1 - \alpha_3 - \beta_3 - 0$ axis is:

$$\begin{bmatrix} i_{s\alpha 1}' \\ i_{s\beta 1}' \\ i_{s\alpha 3}' \\ i_{s\beta 3}' \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{6\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) \\ \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{6\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) \\ \cos\left(\frac{6\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ \sin\left(\frac{6\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) \end{bmatrix} \begin{bmatrix} i_b \\ i_c \\ i_d \\ i_e \end{bmatrix}, \quad (4)$$

The projections of the above axes are orthogonal to each other, and the vectors corresponding to their axes are orthogonal to each other. When it is running without phase A, the decoupling transformation matrix of the five-phase motor is as follows:

$$T = \begin{bmatrix} \sqrt{\frac{2}{3}} \cos\left(\frac{2\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{4\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{6\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{8\pi}{5}\right) \\ \sqrt{\frac{2}{5}} \sin\left(\frac{2\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{4\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{6\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{8\pi}{5}\right) \\ \sqrt{\frac{2}{3}} \cos\left(\frac{6\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{2\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{8\pi}{5}\right) & \sqrt{\frac{2}{3}} \cos\left(\frac{4\pi}{5}\right) \\ \sqrt{\frac{2}{5}} \sin\left(\frac{6\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{2\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{8\pi}{5}\right) & \sqrt{\frac{2}{5}} \sin\left(\frac{4\pi}{5}\right) \end{bmatrix}, \quad (5)$$

2.3. Mathematical Model of Two-Phase Open-Circuit Fault

As in Section 2.2, according to the principle of constant magnetomotive force, when the adjacent two phases of the motor are an open circuit (taking the AB two-phase as an example), the projection of the CDE phase current on the $\alpha_1 - \beta_1 - \alpha_3 - \beta_3 - 0$ shaft is:

$$T_1 = \begin{bmatrix} \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{6\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) \\ \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{6\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) \\ \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) \end{bmatrix} \begin{bmatrix} i_c \\ i_d \\ i_e \end{bmatrix}, \quad (6)$$

Similarly, when the motor is not adjacent to a two-phase open circuit (taking the AC two-phase open circuit as an example), the projection of the BDE phase current on the $\alpha_1 - \beta_1 - \alpha_3 - \beta_3 - 0$ shaft is:

$$T_2 = \begin{bmatrix} \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{6\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) \\ \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{6\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) \\ \cos\left(\frac{6\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ \sin\left(\frac{6\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) \end{bmatrix} \begin{bmatrix} i_b \\ i_d \\ i_e \end{bmatrix}, \quad (7)$$

3. Fault Tolerant Strategy Analysis of Open-Circuit Fault of Five-Phase Induction Motor

3.1. Fault Tolerant Control Model of Five-Phase Motor Based on Magnetomotive Force Balance

Based on the principle of magnetomotive force balance, by using MSC, the state equation of the motor is decomposed into four sequence components and one zero sequence component, in which the first and third sequence components are positive sequence components and the second and fourth sequence components are negative sequence components. Based on the linear transformation theory, each phase of a group of five-phase systems can be written as the sum of n components, which are expressed as symmetrical components:

$$\begin{cases} \bar{I}_1 = \bar{I}_{10} + \bar{I}_{11} + \bar{I}_{12} + \cdots + \bar{I}_{1(n-1)} \\ \bar{I}_2 = \bar{I}_{20} + \bar{I}_{21} + \bar{I}_{22} + \cdots + \bar{I}_{2(n-1)} \\ \bar{I}_3 = \bar{I}_{30} + \bar{I}_{31} + \bar{I}_{32} + \cdots + \bar{I}_{3(n-1)} \\ \bar{I}_4 = \bar{I}_{40} + \bar{I}_{41} + \bar{I}_{42} + \cdots + \bar{I}_{4(n-1)} \\ \bar{I}_5 = \bar{I}_{50} + \bar{I}_{51} + \bar{I}_{52} + \cdots + \bar{I}_{5(n-1)} \end{cases} \quad (8)$$

where:

$$\begin{cases} \bar{I}_{2q} = \bar{I}_{1q} e^{-\frac{jq2\pi}{m}} \\ \bar{I}_{3q} = \bar{I}_{1q} e^{-\frac{j2q2\pi}{m}} \\ \vdots \\ \bar{I}_{mq} = \bar{I}_{1q} e^{-\frac{j(m-1)q2\pi}{m}} \end{cases}, \quad (9)$$

By substituting Equation (9) into Equation (8), the expression of each phase current component of a five-phase induction motor is as follows:

$$\begin{cases} \bar{I}_{1A} = \bar{I}_{10} + \bar{I}_{11} + \bar{I}_{12} + \bar{I}_{13} + \bar{I}_{14} \\ \bar{I}_{1B} = \bar{I}_{10} + a\bar{I}_{11} + a^2\bar{I}_{12} + a^3\bar{I}_{13} + a^4\bar{I}_{14} \\ \bar{I}_{1C} = \bar{I}_{10} + a^2\bar{I}_{11} + a^4\bar{I}_{12} + a\bar{I}_{13} + a^3\bar{I}_{14} \\ \bar{I}_{1D} = \bar{I}_{10} + a^3\bar{I}_{11} + a\bar{I}_{12} + a^4\bar{I}_{13} + a^2\bar{I}_{14} \\ \bar{I}_{1E} = \bar{I}_{10} + a^4\bar{I}_{11} + a^3\bar{I}_{12} + a^2\bar{I}_{13} + a\bar{I}_{14} \end{cases} \quad (10)$$

By ordering $a = e^{-2\pi/5}$, the MSC of a five-phase induction motor can be transformed into:

$$\begin{bmatrix} \bar{I}_{1A} \\ \bar{I}_{1B} \\ \bar{I}_{1C} \\ \bar{I}_{1D} \\ \bar{I}_{1E} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix} \begin{bmatrix} \bar{I}_{10} \\ \bar{I}_{11} \\ \bar{I}_{12} \\ \bar{I}_{13} \\ \bar{I}_{14} \end{bmatrix}, \quad (11)$$

That is to say, the MSC transformation matrix of a five-phase induction motor is:

$$C = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a & a^3 \\ 1 & a^3 & a & a^4 & a^2 \\ 1 & a^4 & a^3 & a^2 & a \end{bmatrix}, \quad (12)$$

According to the corresponding relationship between each phase current component and each phase magnetic potential, the MSC transformation relationship between each phase magnetic potential and each phase current can be obtained as follows:

$$\begin{bmatrix} \overline{\lambda_{1A}} \\ \overline{\lambda_{1B}} \\ \overline{\lambda_{1C}} \\ \overline{\lambda_{1D}} \\ \overline{\lambda_{1E}} \end{bmatrix} = \begin{bmatrix} 1 & a & a^2 & a^3 & a^4 \\ 1 & a^3 & a^6 & a^9 & a^{12} \\ 1 & a^6 & a^{12} & a^3 & a^9 \\ 1 & a^9 & a^3 & a^{12} & a^6 \\ 1 & a^{12} & a^9 & a^6 & a^3 \end{bmatrix} \begin{bmatrix} \overline{I_{10}} \\ \overline{I_{11}} \\ \overline{I_{12}} \\ \overline{I_{13}} \\ \overline{I_{14}} \end{bmatrix}, \quad (13)$$

According to MSC, in the steady state, assuming that the sinusoidal excitation has angular frequency, the instantaneous spatial phasor stator and rotor currents in the fundamental subspace can be expressed as a function of their root mean square symmetrical current components, as follows:

$$\begin{cases} \bar{i}_{s1}(t) = \sqrt{2} \left(\bar{I}_{11} e^{j\omega_s t} + \bar{I}_{14}^* e^{-j\omega_s t} \right) \\ \bar{i}_{r1}(t) = \sqrt{2} \left(\bar{I}_{11}^r e^{j\omega_s t} + \bar{I}_{14}^{r*} e^{-j\omega_s t} \right) \\ \bar{i}_{s1}^r(t) = \sqrt{2} \left(\bar{I}_{13} e^{j\omega_s t} + \bar{I}_{12}^* e^{-j\omega_s t} \right) \\ \bar{i}_{r1}^r(t) = \sqrt{2} \left(\bar{I}_{13}^r e^{j\omega_s t} + \bar{I}_{12}^{r*} e^{-j\omega_s t} \right) \end{cases}, \quad (14)$$

where: $\omega_s = 2\pi f_s$, f_s is 50 Hz.

The flux linkage equation of any subspace is as follows:

$$\begin{cases} \bar{\lambda}_{s1} = (l_s + L_{m1}) \bar{i}_{s1} + L_{m1} \bar{i}_{r1} \\ \bar{\lambda}_{r1} = L_{m1} \bar{i}_{s1} + (l_r + L_{m1}) \bar{i}_{r1} \\ \bar{\lambda}_{s1}^r = (l_s + L_{m3}) \bar{i}_{s1}^r + L_{m3} \bar{i}_{r1}^r \\ \bar{\lambda}_{r1}^r = L_{m3} \bar{i}_{s1}^r + (l_r + L_{m3}) \bar{i}_{r1}^r \end{cases}, \quad (15)$$

The electromagnetic torque equation of any subspace is as follows [23]:

$$T_e(t) = \frac{5}{2} PL_{m1} \Im \left\{ (i_{s1} + i_{r1}) \cdot (i_{s1}^r + i_{r1}^r) \cdot e^{-jp\omega_s t} \right\}, \quad (16)$$

By substituting Equation (13) into Equation (14), the synthetic magnetic potential with a fundamental current is:

$$\begin{aligned} \lambda_{st} &= \Delta\lambda_{14} + \Delta\lambda_{32} \\ &= \bar{\lambda}_{s1} + \bar{\lambda}_{r1} + \bar{\lambda}_{s1}^r + \bar{\lambda}_{s3}^r \end{aligned} \quad (17)$$

The fundamental magnetic potential and the third harmonic magnetic potential generated by the fundamental current can be obtained as follows:

$$\begin{cases} \Delta\lambda_{14} = 2\sqrt{2}L_{m1}[l_{s1} + l_{r1}] * \left((\bar{I}_{11} + \bar{I}_{11}^r) e^{j\omega_s t} + (\bar{I}_{14}^* + \bar{I}_{14}^{r*}) e^{-j\omega_s t} \right) \\ \Delta\lambda_{32} = 2\sqrt{2}L_{m3}[l_{s3} + l_{r3}] * \left((\bar{I}_{13} + \bar{I}_{13}^r) e^{j\omega_s t} + (\bar{I}_{12}^* + \bar{I}_{12}^{r*}) e^{-j\omega_s t} \right) \end{cases}, \quad (18)$$

According to the analysis Formula (18), the synthetic magnetic potential under the fundamental power supply of the motor is composed of the fundamental magnetic potential and the third harmonic magnetic potential generated by the fundamental wave, in which the fundamental magnetic potential $\Delta\lambda_{14}$ is determined by the first- and fourth-order components of the current, and the third magnetic potential $\Delta\lambda_{32}$ is determined by the second- and third-order components of the current. When the motor operates normally, only the fundamental magnetic potential generated by the fundamental current is not zero, that is $\bar{I}_{11} \neq 0$ and $\Delta\lambda_{et}^{32} = 0$. The sequence components of the resultant magnetic potential and current of the fundamental current are:

$$\begin{cases} \bar{\lambda}_{1A} = \frac{10A}{\pi} \bar{I}_{11} \cos(\phi - \omega_{e1}t) = \frac{5A}{\pi} \bar{I}_{11} (e^{j\phi} e^{-j\omega_{e1}t} + e^{-j\phi} e^{j\omega_{e1}t}) \neq 0 \\ \bar{I}_{11} \neq 0 \\ \bar{I}_{12} = \bar{I}_{13} = \bar{I}_{14} = 0 \end{cases}, \quad (19)$$

When a phase of the motor is open circuit, the invalid magnetic potential will increase significantly, and it will move relative to the synchronous rotating magnetic field and the torque pulsation of the motor will be increased. In this paper, the constraint conditions are set on the premise of the minimum change of the magnetic potential of the motor after phase loss. The fault-tolerant control of the motor after phase loss is carried out through the relationship between the magnetic potential and the current of each phase, and the optimal fault-tolerant current is solved by constraining the size of each harmonic magnetic potential, so that the speed of the motor after phase loss is maximal and the torque ripple is minimal. For this purpose, the following three conditions need to be met:

Condition 1: each compatible fault current needs to meet the following conditions:

$$I_{ntol} \leq I_{nrated}, \quad (20)$$

where, I_{ntol} is the fault-tolerant current and I_{nrated} is the rated current.

Condition 2: the constraint of the magnetic potential sequence component of each phase is:

$$\Delta\lambda_{14} = \frac{5A}{\pi} I_1 \left(e^{j\phi} e^{-j\omega_s t} + e^{-j\phi} e^{j\omega_s t} \right) = \min, \quad (21)$$

Condition 3: A five-phase induction motor is star connected. After the open-circuit fault occurs, the synthetic current of the remaining healthy phase is 0.

3.2. Fault Tolerant Strategy Analysis of One-Phase Open-Circuit Fault

According to the analysis in Section 3.1, the relationship between the magnetic potential of each phase of the five-phase motor and the current sequence component is:

$$\begin{cases} \overline{\lambda_{1A}} = a\overline{I_{11}} + a^2\overline{I_{12}} + a^3\overline{I_{13}} + a^4\overline{I_{14}} \\ \overline{\lambda_{1B}} = a^3\overline{I_{11}} + a^6\overline{I_{12}} + a^9\overline{I_{13}} + a^{12}\overline{I_{14}} \\ \overline{\lambda_{1C}} = a^6\overline{I_{11}} + a^{12}\overline{I_{12}} + a^3\overline{I_{13}} + a^9\overline{I_{14}} \\ \overline{\lambda_{1D}} = a^9\overline{I_{11}} + a^3\overline{I_{12}} + a^{12}\overline{I_{13}} + a^6\overline{I_{14}} \\ \overline{\lambda_{1E}} = a^{12}\overline{I_{11}} + a^9\overline{I_{12}} + a^6\overline{I_{13}} + a^3\overline{I_{14}} \end{cases}, \quad (22)$$

The relationship between each phase current and current sequence component is:

$$\begin{cases} \overline{I_{1A}} = \overline{I_{11}} + \overline{I_{12}} + \overline{I_{13}} + \overline{I_{14}} \\ \overline{I_{1B}} = a\overline{I_{11}} + a^2\overline{I_{12}} + a^3\overline{I_{13}} + a^4\overline{I_{14}} \\ \overline{I_{1C}} = a^2\overline{I_{11}} + a^4\overline{I_{12}} + a^1\overline{I_{13}} + a^3\overline{I_{14}} \\ \overline{I_{1D}} = a^3\overline{I_{11}} + a^1\overline{I_{12}} + a^4\overline{I_{13}} + a^2\overline{I_{14}} \\ \overline{I_{1E}} = a^4\overline{I_{11}} + a^3\overline{I_{12}} + a^2\overline{I_{13}} + a^1\overline{I_{14}} \end{cases} \quad (23)$$

When an open circuit fault occurs in phase A, the current and synthetic magnetic potential of phase A are 0. Therefore, in order to ensure the normal operation of the motor and minimize the invalid magnetic potential, it is necessary to make the invalid magnetic potential generated by the fundamental current 0. According to the constraints of motor fault-tolerant operation, the fundamental harmonic magnetic potential generated by the fundamental current should be minimized under the condition of ensuring the maximum torque and magnetic potential balance. Therefore, the following three conditions should be met in fault-tolerant control: (1) the fundamental magnetomotive force $\overline{I_{11}}$ remains unchanged; (2) $\overline{I_{14}} = 0$; (3) At least one of $\overline{I_{12}}$ and $\overline{I_{13}}$ is not 0.

Based on the above analysis, three control strategies for A, B, and C can be obtained, wherein Strategy A: $\overline{I_{11}} = I_{m1} \angle 0^\circ$, $\overline{I_{12}} = -\overline{I_{11}}$, $\overline{I_{14}} = 0$; Strategy B: $\overline{I_{11}} = I_{m1} \angle 0^\circ$, $\overline{I_{13}} = -\overline{I_{11}}$, $\overline{I_{14}} = 0$; and Strategy C: $\overline{I_{11}} = I_{m1} \angle 0^\circ$, $\overline{I_{12}} + \overline{I_{13}} = -\overline{I_{11}}$, $\overline{I_{14}} = 0$.

As shown in Figure 2, strategies A, B, and C are used to calculate the torque pulsation corresponding to different speeds under constant magnetic potential, and these values are standardized to obtain the comparison diagram of average torque and torque pulsation under the three strategies.

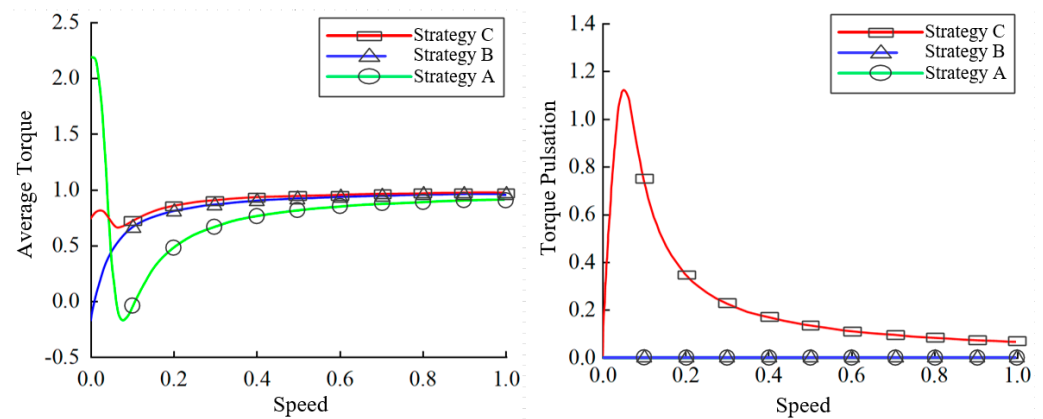


Figure 2. Performance comparison of three fault-tolerant strategies.

Considering the average torque and torque pulsation, the optimal error-tolerant control strategy obtained is strategy B. At this time, the amplitude and phase of the fault-tolerant current are:

$$\begin{cases} \overline{I_{1A}} = 0 \\ \overline{I_{2B}} = I_{m1} \cos\left(\omega t - \frac{3\pi}{10}\right) \\ \overline{I_{3C}} = I_{m1} \cos\left(\omega t - \frac{9\pi}{10}\right) \\ \overline{I_{4D}} = I_{m1} \cos\left(\omega t + \frac{9\pi}{10}\right) \\ \overline{I_{5E}} = I_{m1} \cos\left(\omega t + \frac{3\pi}{10}\right) \end{cases} \quad (24)$$

3.3. Mathematical Model Establishment and Fault Tolerance Strategy Analysis of Adjacent Two-Phase Open-Circuit Fault

The open circuit of adjacent two phases is analyzed in this section. Take the open circuit of A and B phases as an example, that is $I_A = I_B = 0$, according to Formulas (22) and (23), we get:

$$\begin{cases} \overline{\lambda_{1A}} = a\overline{I_{11}} + a^2\overline{I_{12}} + a^3\overline{I_{13}} + a^4\overline{I_{14}} = 0 \\ \overline{\lambda_{1B}} = a^3\overline{I_{11}} + a^6\overline{I_{12}} + a^9\overline{I_{13}} + a^{12}\overline{I_{14}} = 0 \\ \overline{I_{1A}} = \overline{I_{11}} + \overline{I_{12}} + \overline{I_{13}} + \overline{I_{14}} = 0 \\ \overline{I_{1B}} = a\overline{I_{11}} + a^2\overline{I_{12}} + a^3\overline{I_{13}} + a^4\overline{I_{14}} = 0 \end{cases} \quad (25)$$

In the case of magnetomotive force balance, in order to maintain the maximum torque and the minimum torque pulsation, the relationship of sequence components in the fault-tolerant control of adjacent two-phase open-circuit faults is the same as that of a one-phase open-circuit fault, that is: (1) the fundamental magnetomotive force $\overline{I_{11}}$ remains unchanged; (2) $\overline{I_{14}} = 0$; and (3) at least one of $\overline{I_{12}}$ and $\overline{I_{13}}$ is not 0.

The fault-tolerant control strategy is solved for the above three conditions, and the condition of maximum motor torque and uniform heating of each bridge arm after fault-tolerant control is met. The fault-tolerant current of the AB two-phase open-circuit operation of a five-phase motor is obtained as follows:

$$\begin{cases} \overline{I_{1A}} = 0 \\ \overline{I_{2B}} = 0 \\ \overline{I_{3C}} = 0.5092I_f \cos\left(\omega t - \frac{14\pi}{15}\right) \\ \overline{I_{4D}} = 0.5092I_f \cos\left(\omega t + \frac{4\pi}{5}\right) \\ \overline{I_{5E}} = 0.5092I_f \cos\left(\omega t + \frac{8\pi}{15}\right) \end{cases} \quad (26)$$

3.4. Mathematical Model Establishment and Fault Tolerance Strategy Analysis of Non-Adjacent Two-Phase Open-Circuit Fault

The open circuit operation of A and C phases of a five-phase motor is analyzed as an example. At this time, it should meet $I_A = I_C = 0$. According to Formulas (22) and (23), we get:

$$\begin{cases} \overline{\lambda_{1A}} = a\overline{I_{11}} + a^2\overline{I_{12}} + a^3\overline{I_{13}} + a^4\overline{I_{14}} = 0 \\ \overline{\lambda_{1C}} = a^6\overline{I_{11}} + a^{12}\overline{I_{12}} + a^3\overline{I_{13}} + a^9\overline{I_{14}} \\ \overline{I_{1A}} = \overline{I_{11}} + \overline{I_{12}} + \overline{I_{13}} + \overline{I_{14}} = 0 \\ \overline{I_{1C}} = a^2\overline{I_{11}} + a^4\overline{I_{12}} + a^1\overline{I_{13}} + a^3\overline{I_{14}} \end{cases}, \quad (27)$$

The analysis method is the same as that in Section 3.3, wherein the fault-tolerant current of the AC two-phase open-circuit operation of a five-phase motor is obtained as follows:

$$\begin{cases} \overline{I_{1A}} = 0 \\ \overline{I_{2B}} = 0.3959I_f \cos(\omega t - \frac{2\pi}{5}) \\ \overline{I_{3C}} = 0 \\ \overline{I_{4D}} = 0.3959I_f \cos(\omega t + \frac{14\pi}{15}) \\ \overline{I_{5E}} = 0.3959I_f \cos(\omega t + \frac{2\pi}{15}) \end{cases}, \quad (28)$$

4. Simulation and Experimental Discussion

4.1. Simulation Discussion

The block diagram of the fault-tolerant control system of rotor field orientation when the motor operates in an open circuit is shown in Figure 3.

As shown in Figure 2, the controller uses Clark transform and Parker transform modules. Clark and Parker transforms are usually used for field oriented control of three-phase alternating current motors. The time domain components of a three-phase system are transformed into an orthogonal stationary coordinate system by Clark transform. The coordinate system is converted into an orthogonal rotational coordinate system by Parker transform. The continuous realization of these two transformations can convert the alternating current and voltage waveforms into direct current signals, thus simplifying the calculation.

The basic parameters of a five-phase induction motor are shown in Table 1.

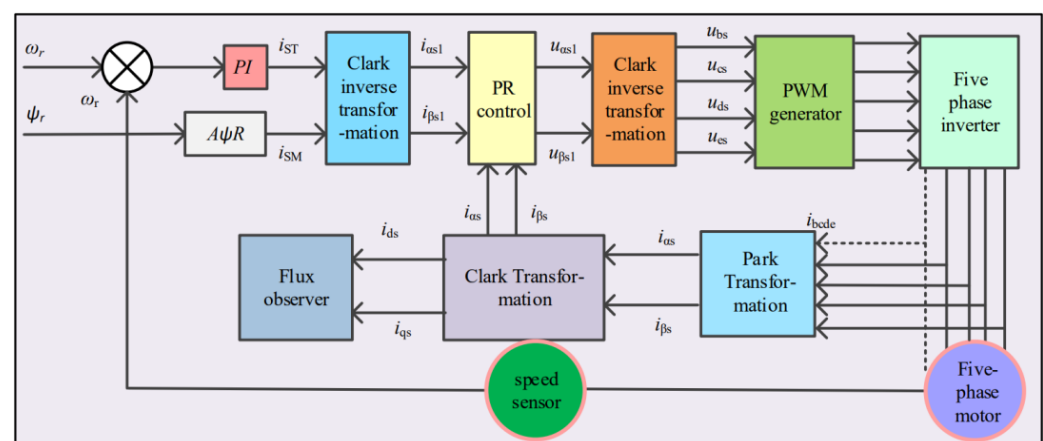
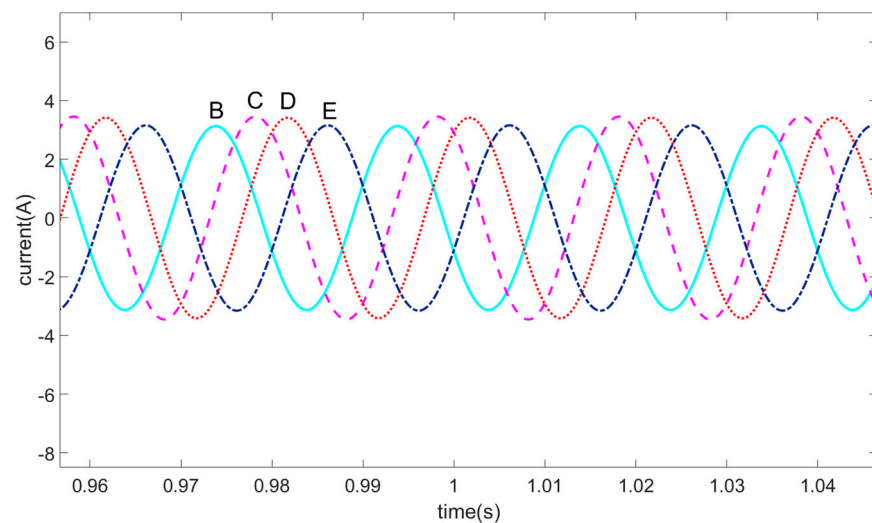
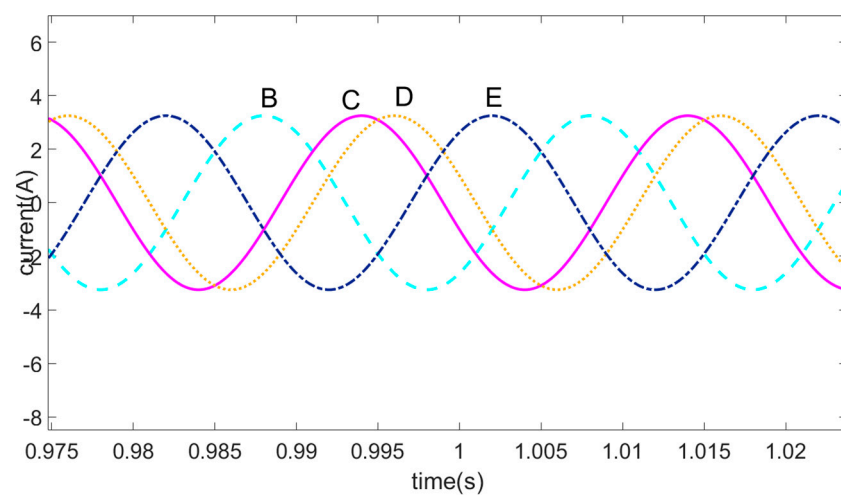


Figure 3. Five-phase induction motor fault-tolerant control block diagram.

Table 1. Parameters of five-phase induction motor.

Parameter	Unit	Value
Rated voltage	V	220
Stator resistance	Ω	4.3845
Rotor resistance	Ω	5.8266
Stator leakage inductance	H	0.0185
Excitation inductance	H	0.6575
Rotor leakage inductance	H	0.0319
Moment of inertia		0.0178

When phase A of a five-phase motor is an open-circuit fault, the schematic diagram for the other four-phase currents is shown in Figure 4. After being controlled by the fault-tolerant control strategy proposed in this paper, the schematic diagram of the remaining four-phase currents is shown in Figure 5.

**Figure 4.** Schematic diagram of remaining four-phase currents when phase A is an open-circuit fault.**Figure 5.** Schematic diagram of remaining four-phase currents after fault-tolerant control in case of open-circuit fault of phase A.

It can be seen from Figures 3 and 4 that when an open-circuit fault occurs in phase A of a five-phase motor, the remaining four-phase current is asymmetric, and the current

synthetic magnetic potential will be distorted at this time. After fault-tolerant control, the remaining four-phase current becomes the value with a similar amplitude and does not exceed the rated current. Comparing Figures 3 and 4, it can be seen that after fault-tolerant control, the current waveform of motor operation tends to be stable, the pulsation is small, and the motor can work normally.

When phase A and B of a five-phase motor are an open-circuit fault, the schematic diagram of the other three-phase currents is shown in Figure 6. After being controlled by the fault-tolerant control strategy proposed in this paper, the schematic diagram of the remaining three-phase currents is shown in Figure 7.

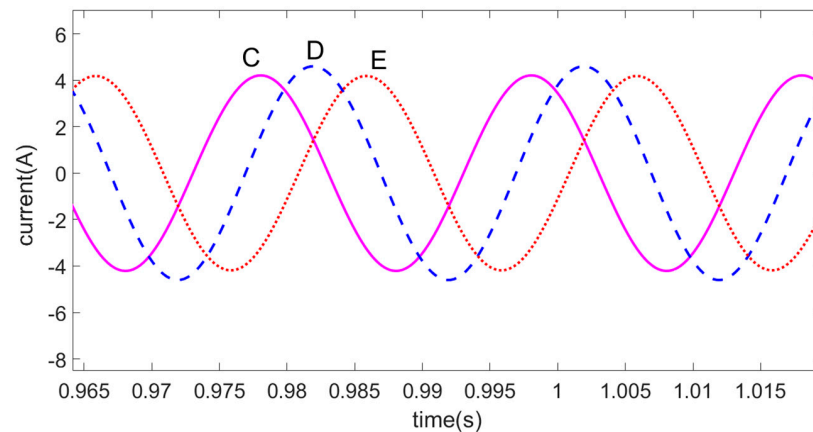


Figure 6. Schematic diagram of remaining three-phase currents when phase A and B are an open-circuit fault.

It can be seen from Figures 5 and 6 that when an open-circuit fault occurs in phase A and B of a five-phase motor, the stator phase currents are asymmetrical, and the currents of each phase are obviously increased. Moreover, the increase in the phase D current is obvious, and the increase in the phase C and E current is small. After being controlled by the fault-tolerant control strategy proposed in this paper, the residual healthy phase current amplitude of the five-phase motor is equal, and the current phase of each phase is consistent with the theoretical calculation. At this time, violent vibration and excessive noise are not generated during the operation of the motor.

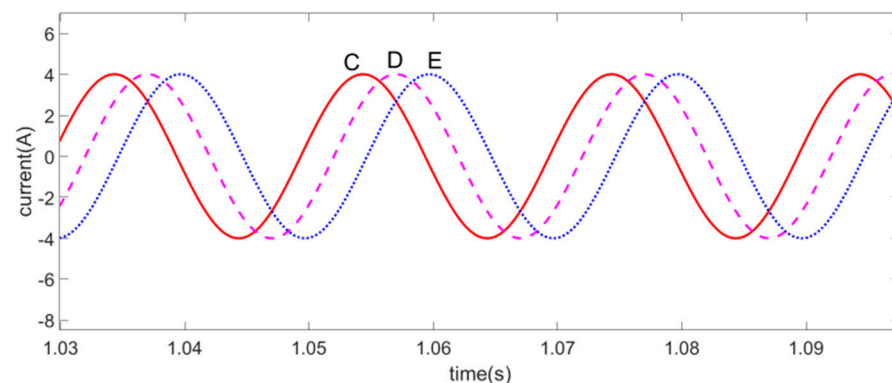


Figure 7. Schematic diagram of remaining three-phase currents after fault-tolerant control in case of open-circuit fault of phase A and B.

When phase A and C of the five-phase motor are open-circuit faults, the schematic diagram of the other three-phase currents is shown in Figure 8. After being controlled by the fault-tolerant control strategy proposed in this paper, the schematic diagram of the remaining three-phase currents is shown in Figure 9.

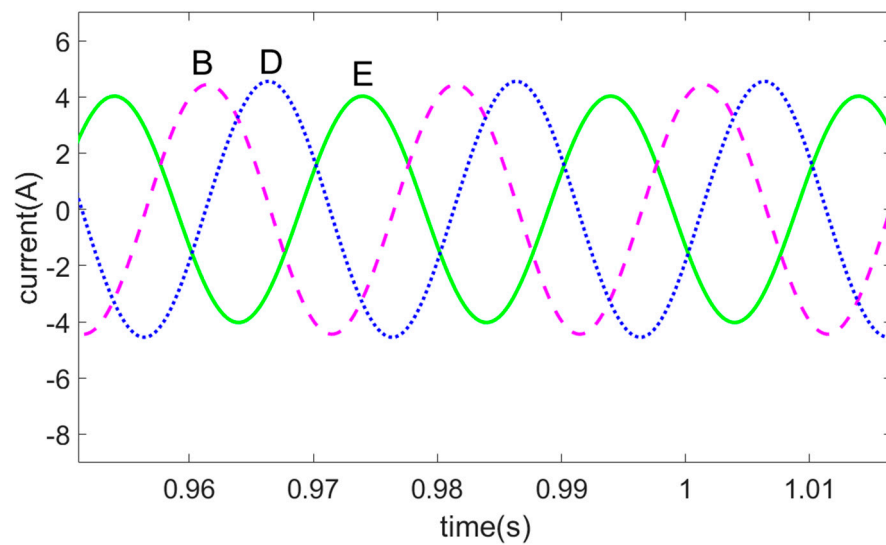


Figure 8. Schematic diagram of remaining three-phase currents when phase A and C are an open-circuit fault.

It can be seen from Figures 7 and 8 that when an open-circuit fault occurs in phase A and C of a five-phase motor, the stator phase currents are asymmetrical, and the currents of each phase are obviously increased. Moreover, the increase in the phase D and E current is obvious, and the increase in the phase B current is small. After being controlled by the fault-tolerant control strategy, the residual healthy phase current amplitude of the five-phase motor is equal, and the current phase of each phase is consistent with the theoretical calculation.

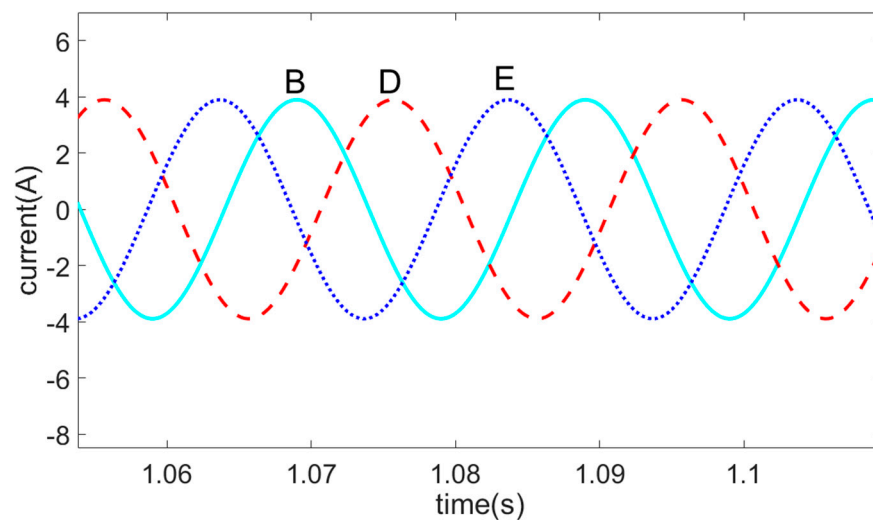


Figure 9. Schematic diagram of remaining threephase currents after fault-tolerant control in case of open-circuit fault of phase A and C.

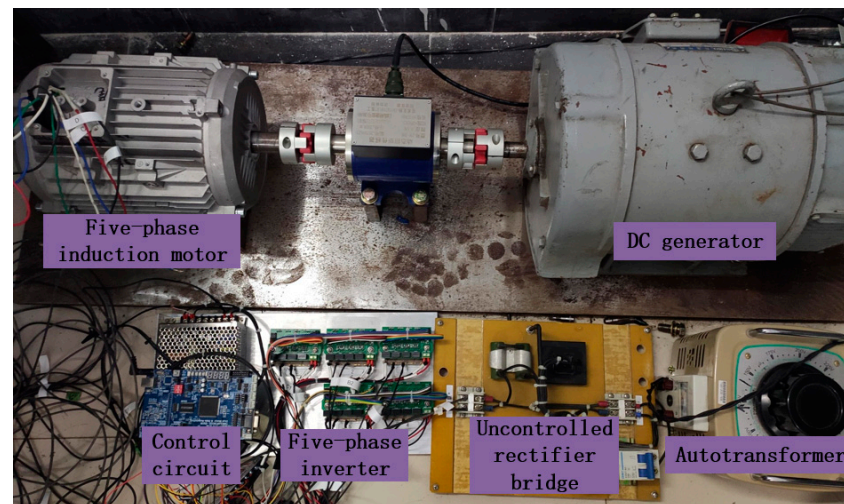
4.2. Experimental Discussion

A 2 kW five-phase cage induction motor is taken as an example to verify the effectiveness of the phase failure model and fault-tolerant control strategy in this paper. The motor parameters are shown in Table 2.

Table 2. Experimental parameters of five-phase induction motor.

Parameter	Unit	Value
Stator inner diameter	mm	98
Stator outer diameter	mm	175
Rotor inner diameter	mm	38
Rotor outer diameter	mm	97.5
Core length	mm	130
Number of stator slots		30
Number of slots of squirrel cage rotor		26
Number of conductors per slot of stator winding		57
Polar logarithm		1

The open circuit fault tolerance control experimental platform of a five-phase induction motor is shown in Figure 10.

**Figure 10.** Wiring diagram of open-phase experiment circuit.

The DC voltage obtained by connecting the autotransformer to the rectifier bridge is used to supply power to the five-phase inverter. DSP 28335 is used to design hardware circuits and output the five-phase SPWM control signal to control the IGBT of the five-phase inverter. When conducting the motor phase loss experiment, the input end of the five-phase induction motor is connected to a control switch. When the switch is closed, the circuit is conductive, and when the switch is open, the circuit is disconnected to realize the situation of a certain phase of the motor breaking, so as to obtain the phase loss current waveform when the motor suddenly loses phase.

The input voltage of the autotransformer is gradually increased from 30 V to 110 V (the stable voltage for normal operation of the motor). Experiments are carried out on three kinds of faults of the five-phase motor, such as an open circuit of phase A, an open circuit of adjacent A and B phases, and an open circuit of adjacent A and C phases. The current waveform and speed change after the open-circuit fault and fault-tolerant control are obtained.

When the input voltage is 80 V, the current waveform after the open-circuit fault and the current waveform after fault-tolerant control are shown in Figures 11–16. A, B, C, D and E in the figure are the representative of the current phase.

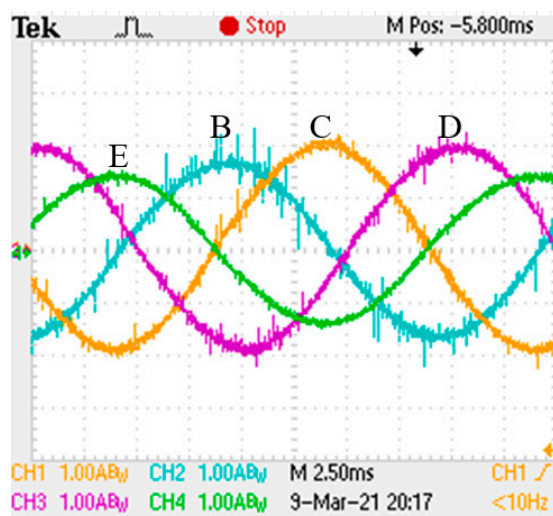


Figure 11. Waveform diagram of the lack of phase A current experiment.

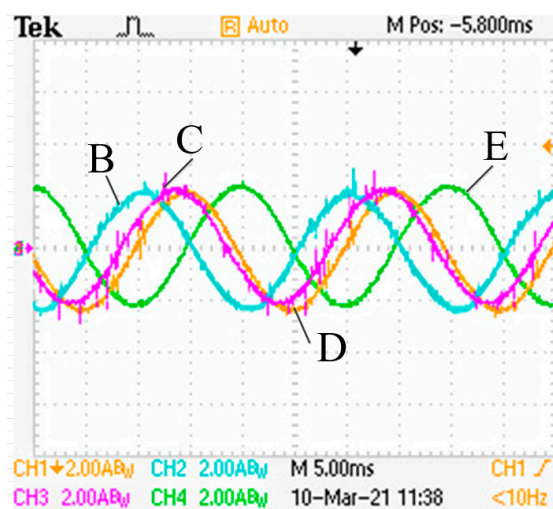


Figure 12. Lack of phase A fault-tolerant current waveform.

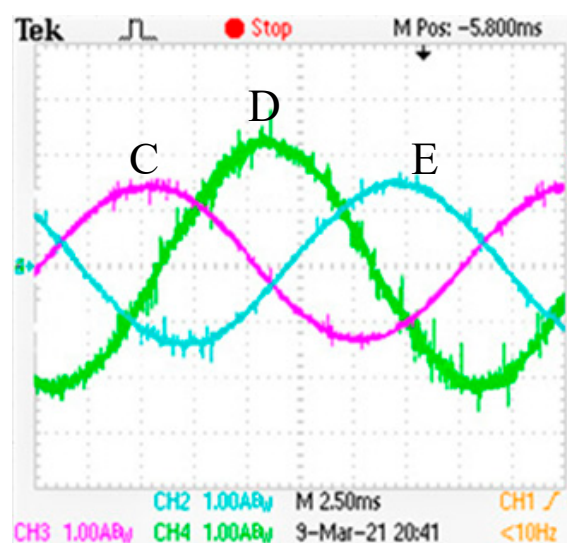


Figure 13. Waveform diagram of the lack of phase A and B current experiment.

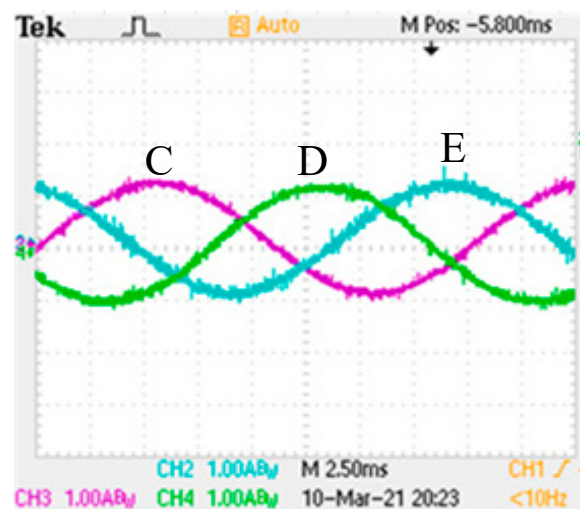


Figure 14. Lack of phase A and B fault-tolerant current waveform.

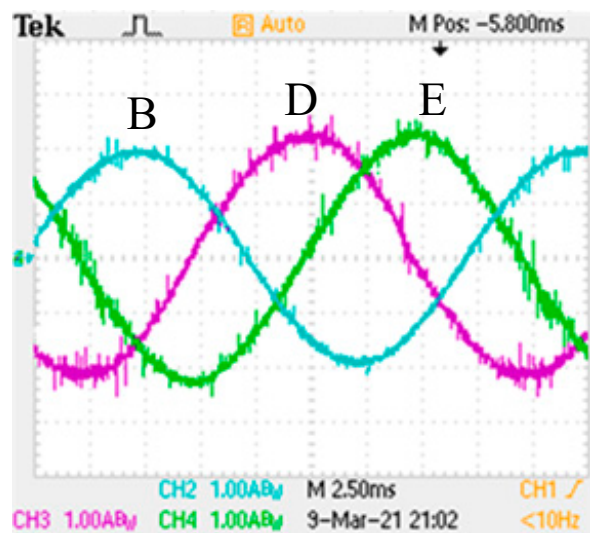


Figure 15. Waveform diagram of the lack of phase A and C current experiment.

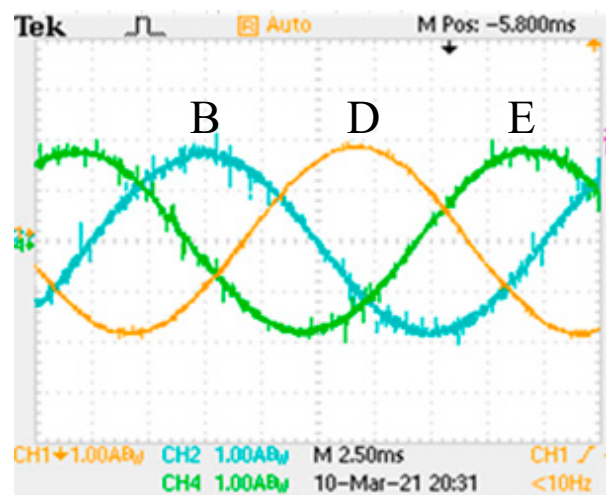


Figure 16. Lack of phase A and C fault-tolerant current waveform.

As can be seen from the above figure, after the open-circuit fault of the five-phase motor, the residual phase current is no longer balanced. After fault-tolerant control, the residual phase current is balanced and the motor can work normally. The comparison with a theoretical analysis and simulation verifies the effectiveness of the fault-tolerant control strategy in this paper.

The change in motor speed after an open-circuit fault and fault-tolerant control is measured in the experiment, as shown in Tables 3–5.

Table 3. Motor speed changes after open-circuit fault of phase A and fault-tolerant control.

Input Voltage (V)	Normal Operation (r/min)	Open Circuit Fault (r/min)	Fault Tolerant Control (r/min)
30 V	97	67	105
40 V	108	80	180
50 V	216	200	220
60 V	463	458	564
70 V	1385	588	600
80 V	1430	686	1356
90 V	1447	1273	1361
100 V	1465	1308	1459
110 V	1475	1259	1470

Table 4. Motor speed changes after open-circuit fault of phase AB and fault-tolerant control.

Input Voltage (V)	Normal Operation (r/min)	Open Circuit Fault (r/min)	Fault Tolerant Control (r/min)
30 V	97	0	0
40 V	108	0	0
50 V	216	0	0
60 V	463	0	50
70 V	1385	66	230
80 V	1430	105	588
90 V	1447	130	988
100 V	1465	149	1059
110 V	1475	150	1189

Table 5. Motor speed changes after open-circuit fault of phase AC and fault-tolerant control.

Input Voltage (V)	Normal Operation (r/min)	Open Circuit Fault (r/min)	Fault Tolerant Control (r/min)
30 V	97	60	80
40 V	108	90	110
50 V	216	108	189
60 V	463	220	260
70 V	1385	503	539
80 V	1430	514	917
90 V	1447	726	1262
100 V	1465	710	1436
110 V	1475	719	1466

It can be seen from Tables 3–5 that:

- (1) When the motor operates normally, the motor speed is increased with the increase of input voltage, and when it reaches 80 V, the motor works at the rated speed.
- (2) After the open-circuit fault of phase A occurs, the motor speed is increased for a certain time and cannot reach the expected value. However, after fault-tolerant control, the speed increases significantly faster and gradually reaches the rated value.

- (3) After the open-circuit fault of phase A and B occurs, the basic speed of the motor is extremely small. At this time, it is difficult to make up for the disturbance caused by the open-circuit fault and provide sufficient power to the motor. After fault-tolerant control, when the input voltage reaches 70 V, the motor speed is rapidly increased. It can be seen that the adjacent two-phase open-circuit fault has a great impact on the motor. When the input voltage reaches 110 V, the rotation speed of the motor tends to be stable. At this time, the motor does not reach the rated speed, but maintains low-speed operation at 1200 r/min.
- (4) After the open-circuit fault of phase A and C occurs, the speed of the motor is decreased. After fault-tolerant control, the speed of the motor is increased rapidly and operates at a stable speed of 1500 r/min. The two-phase open-circuit fault of A and C is more stable than that of A and B.
- (5) During normal operation, the motor vibration can be ignored. When an open-circuit fault occurs to the motor, the vibration is increased significantly. After fault-tolerant control, motor vibration is as follows: (a) The vibration is significantly reduced when a phase open-circuit fault occurs. (b) The motor vibration is small, and the operation is relatively stable when two non-adjacent phases fail. (c) The motor vibration is significantly reduced but still strong after fault-tolerant control when two adjacent phases of the motor fail.
- (6) The fault-tolerant control strategy proposed in this paper has the advantages of simple calculation, constant magnetomotive force, low loss, and small current fluctuation. The strategy takes the minimum torque ripple as the constraint condition and controls the amplitude and phase of the remaining healthy phase current to realize the normal operation of the five-phase induction motor in the event of an open-circuit fault. Compared with vector pulse width modulation technology, this strategy has less computations and simpler control [24]; Compared with the fault-tolerant control strategy in [28], which takes the balance of the magnetomotive force after the motor is out-of-phase as the constraint condition, this strategy can maintain the stability of the motor torque and has high working reliability. Compared with the full torque range efficiency optimization fault-tolerant control strategy, the control efficiency of this strategy is higher [14].

5. Conclusions

Based on the principle of invariable magnetic potential and symmetrical component method, a fault-tolerant control strategy for a five-phase motor is proposed in this paper. The research shows that:

- (1) When the five-phase motor has an open-circuit fault, the residual phase current is no longer balanced. After fault-tolerant control, the residual phase current is balanced again.
- (2) When the five-phase motor has an open-circuit fault, the motor speed decreases, so the rated speed cannot be reached. When the two adjacent phases of the motor have an open-circuit fault, the motor speed is almost zero, and the low-speed operation can be maintained after fault-tolerant control. When one phase or two non-adjacent phases of the motor have open-circuit faults, the rated speed can be reached after fault-tolerant control.
- (3) When the motor has an open-circuit fault, the vibration increases significantly. After fault-tolerant control, the vibration of the motor is reduced and the motor runs smoothly. However, when two adjacent phases fail, even after fault-tolerant control, the vibration of the motor is reduced, but it is still strong.

The future work directions of this study are as follows: (1) Research on speed, torque, vibration, and the residual performance of the motor under different load conditions after the open circuit fault of the motor occurs. (2) Research on motor fault diagnosis and automatic switching of control methods. (3) Finally, research on the influence of current higher harmonics on fault-tolerant control strategies.

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