Fault-Tolerant Operation of Five-Phase Permanent Magnet Synchronous Motor with Independent Phase Driving Control

Yongqing Wei, Mingzhong Qiao, and Peng Zhu

***Abstract*—The multi-phase motor drive system with multiple H-bridge power supply has high fault tolerance, which is widely used in aerospace, electric vehicle, ship integrated power system and other fields. In this paper, a fault-tolerant control strategy based on decoupling control and stator current compensation is proposed for the propulsion system of five-phase PMSM with independent neutrals. Firstly, the mathematical model of PMSM is established by using vector space decoupling method; Secondly, a stator current compensation method is adopted to carry out fault-tolerant control after the motor has single-phase and two-phase open-circuit faults and the fault-tolerant control system based on decoupling control is established; Finally, the decoupling control model and the fault-tolerant control of stator current compensation are verified by the simulation and experiment. The simulation and experiment results show that the method can reduce the torque ripple caused by the stator winding open-circuit fault, and the operation performance of the motor under fault condition is significantly improved.**

***Index Terms*—Five-Phase permanent magnet synchronous motor, H-bridge inverter, Fault-tolerant control, Vector space decoupling**

I. INTRODUCTION

THE multi-phase motor drive system has the advantages of high power density and high reliability, which is widely used in aerospace, electric vehicles, ship integrated power system and other fields[1]-[2]. If the each phase of the motor is independently supplied with power by an independent H inverter bridge, the multi-phase permanent magnet motor can realize open-phase operation under the condition of sudden failure, and the degree of control freedom of the motor can be improved. The main circuit topology of the five-phase H-bridge inverter with motor load is shown in Fig. 1. Compared with the traditional Y-connected inverter, the H-bridge inverter has the following obvious advantages: (1) the control of each phase is independent and flexible; (2) Each H-bridge of the inverter outputs a phase voltage, so that the voltage stress born by the power device is lower than that of a Y-type connection; (3) When a phase winding or a single inverter unit of the motor fails, the failure part does not affect other units and has good fault-tolerant performance; (4)The output level state of the inverter is increased, and the output voltage harmonic is small.

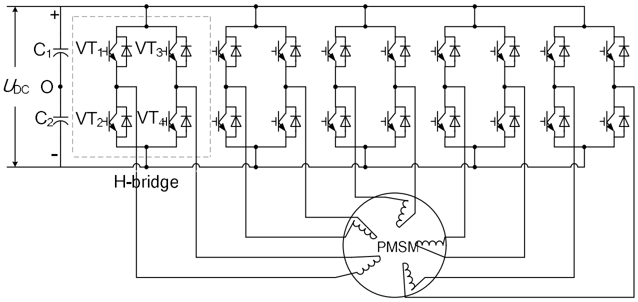

Fig. 1. Main circuit of the five-phase H-bridge inverter carried with PMSM.

For multi-phase speed control system, the most common faults include inverter power device damage and motor stator winding open circuit, which causes an open circuit in one or more of the stator windings of the motor. The fault-tolerant operation of multi-phase motor in the case of open-phase is generally through the effective control of the non-fault phase current. In recent years, some literatures have also studied the fault-tolerant current optimization of multi-phase motors with different winding structures, among which the full-bridge star-connected winding topology is more common and has more research results[3]-[6]. The reliability of the H-bridge inverter system is improved. However, any unbalanced state in the excitation current will have a greater impact on the motor performance, so the research of fault tolerant control is necessary to optimize the control strategy and modulation mode of the inverter and improve the performances in the open-phase working state. At present, there is little research on the current optimization control of H-bridge independent power supply propulsion system.

Taking into account different neutral connection models correspond to different current constraints, in this paper, a fault-tolerant control strategy based on the multi-dimensional decoupling transformation is proposed for H-bridge five-phase permanent magnet motor propulsion system with different neutral connection models. Firstly, the vector space decoupling mathematical model of the five-phase permanent magnet motor is established based on the generalized Park transformation. Secondly, when the motor has single-phase or two-phase open-circuit fault, the constraint control expression

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of motor current is derived by using the established decoupling mathematical model, and the fault-tolerant vector control strategy of the drive system is established, which provides a reference for the control strategy of the five-phase motor propulsion system.

II. SPACE DECOUPLING VECTOR MODEL OF FIVE-PHASE PMSM

A. Mathematical Model of PMSM

In order to simplify the analysis, the following assumptions are made when studying the mathematical model of the five-phase permanent magnet motor: (1) the five-phase windings *of the stator are symmetrically distributed in space, and the* electrical angle difference between two adjacent winding is 2pi/5; No damping windings are installed on the rotor; (2) The influence of saturation, hysteresis and eddy current of ferromagnetic material is neglected, and the skin effect of iron core and conductor is not considered; (3) only the fundamental and the third harmonics are considered in the air gap magnetic field, and the high order harmonics are ignored

$$\mathbf{T}(\theta_x)=\frac{2}{5}\begin{bmatrix} \cos\theta_x & \cos(\theta_x-\frac{2\pi}{5}) & \cos(\theta_x-\frac{4\pi}{5}) & \cos(\theta_x-\frac{6\pi}{5}) & \cos(\theta_x-\frac{8\pi}{5}) \\ -\sin\theta_x & -\sin(\theta_x-\frac{2\pi}{5}) & -\sin(\theta_x-\frac{4\pi}{5}) & -\sin(\theta_x-\frac{6\pi}{5}) & -\sin(\theta_x-\frac{8\pi}{5}) \\ \cos3\theta_x & \cos3(\theta_x-\frac{2\pi}{5}) & \cos3(\theta_x-\frac{4\pi}{5}) & \cos3(\theta_x-\frac{6\pi}{5}) & \cos3(\theta_x-\frac{8\pi}{5}) \\ -\sin3\theta_x & -\sin3(\theta_x-\frac{2\pi}{5}) & -\sin3(\theta_x-\frac{4\pi}{5}) & -\sin3(\theta_x-\frac{6\pi}{5}) & -\sin3(\theta_x-\frac{8\pi}{5}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{1}$$

Where, θ_x refers to the space electrical angle between the d axis and the a axis of the stator winding.

The first and second rows in the matrix correspond to the d_1-q_1 subspace. Fundamental and $10k\pm1(k=1,2,3,\ldots)$ subharmonics are projected into the subspace, the primary magnetomotive force rotation speed is the synchronous speed, which is related to the electromechanical energy conversion of the motor; The third and fourth rows in the matrix correspond to the d_3-q_3 subspace into which the third harmonic space is projected, and the third harmonic magnetomotive force has a synchronous rotation speed which is orthogonal to the d_1-q_1 subspace into which the third and $10k\pm3(k=1,2,3,\ldots)$ harmonics in the motor variables are projected, and They produce rotating electromotive force and constant torque with the third harmonic air-gap magnetic potential, which is related to the electromechanical energy conversion of the motor.

Using the transformation matrix of Equation (1), the voltage equation in the synchronous coordinate system can be obtained.

$$\begin{bmatrix} U_{d1} \\ U_{q1} \\ U_{d3} \\ U_{q3} \\ 0 \end{bmatrix} = R_s \begin{bmatrix} I_{d1} \\ I_{q1} \\ I_{d3} \\ I_{q3} \\ 0 \end{bmatrix} + \omega \begin{bmatrix} 0 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -3 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d3} \\ \psi_{q3} \\ 0 \end{bmatrix} + P \begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d3} \\ \psi_{q3} \\ 0 \end{bmatrix} \tag{2}$$

Where, U refers to the phase voltage of the motor stator winding; I refers to the phase current of the motor stator winding, and Ψ refers to the flux linkage of motor stator phase winding.

Because the electromagnetic torque generated by the third harmonic is very small, the electromagnetic torque can be approximated as

$$T_e = \frac{5}{2} n_P (\psi_m i_{q1} + (L_d - L_q) i_{d1} i_{q1}) \tag{3}$$

The motor torque is divided into two parts, if the motor is non-salient pole type, then $L_d=L_q$, the torque only includes the torque generated by the action of the flux linkage of the permanent magnet and the stator torque current component, which is proportional to i_{q1}, therefore, the motor torque can be controlled by controlling i_{q1}.

By establishing the multi-dimensional space vector decoupling transformation matrix of the five-phase permanent magnet motor, the decoupling model in d_1-q_1-d_3-q_3 rotating coordinate system is obtained, which provides a theoretical basis for the operation mechanism analysis of the five-phase PMSM speed control system.

If the stator phase current amplitude is I_m, the current expression of each phase of the stator winding is as the following:

$$\begin{cases} i_a = I_m \cos(\omega t) \\ i_b = I_m \cos(\omega t - \frac{2\pi}{5}) e^{j\frac{2\pi}{5}} \\ i_c = I_m \cos(\omega t - \frac{4\pi}{5}) e^{j\frac{4\pi}{5}} \\ i_d = I_m \cos(\omega t - \frac{6\pi}{5}) e^{j\frac{6\pi}{5}} \\ i_e = I_m \cos(\omega t - \frac{8\pi}{5}) e^{j\frac{8\pi}{5}} \end{cases} \tag{4}$$

Thus, the motor stator current composite vector is expressed as the following:

$$I = i_a + i_b + i_c + i_d + i_e = \frac{5}{2} I_{\mathrm{m}} (\cos \omega t + j \sin \omega t) \quad (5)$$

In stable operation, the magnetomotive force space vector formed by the five-phase winding currents can be equivalent to a rotating composite vector whose amplitude is 2.5 times of the phase current.

B. Influence of Phase Failure on Motor Equation

In the topology shown in Fig. 1, the two terminals of each stator phase winding are connected to the two terminals of an independent inverter H-bridge. Since there is no direct electrical connection between the individual networks, damage to a single drive unit does not affect the normal operation of the remaining four units. Thereby, the reliability of the entire system is improved. However, the system has electromagnetic coupling of five motor stator windings, and any unbalanced state in the excitation current will have a greater impact on the motor performance.

Assuming that the a-phase winding in the five-phase motor is open, it is known from the decoupling transformation matrix in Equation (1) that i_{q1} and i_{q3} are not affected by the lack of phase a, while i_{d1}, i_{d3} and 0 axes are affected by the lack of phase a, and changed to the following.

$$\begin{cases} i_{d1} = \cos(\theta_x - \frac{2\pi}{5}) i_{b1} + \cos(\theta_x - \frac{4\pi}{5}) i_{c1} + \cos(\theta_x - \frac{6\pi}{5}) i_{d1} + \cos(\theta_x - \frac{8\pi}{5}) i_{e1} \\ i_{d3} = \cos(3(\theta_x - \frac{2\pi}{5})) i_{b1} + \cos(3(\theta_x - \frac{4\pi}{5})) i_{c1} + \cos(3(\theta_x - \frac{6\pi}{5})) i_{d1} + \cos(3(\theta_x - \frac{8\pi}{5})) i_{e1} \\ i_0 = \frac{1}{5}(i_{b1} + i_{c1} + i_{d1} + i_{e1}) \end{cases} \quad (6)$$

From Equation (6), it can be found that each harmonic current satisfies the following relationship:

$$i_0 = -(i_{d1} + i_{d3}) \quad (7)$$

As can be seen from equation (7), i_0 is no long an independent variable, Only four degrees of freedom remain for the phase currents.

For the multi-phase motor independently powered by an H-bridge inverter, When the motor has a phase failure, the degree of freedom of the motor current is reduced, but because the motor is not affected by physics[7], if the decoupling transformation matrix is kept unchanged, the voltage equation, the flux linkage equation and the torque equation are not affected, only the current is affected, and only the current of the missing phase is set to be zero.

III. FAULT-TOLERANT OPERATION CONTROL

In the case of missing phase, the stator current vector is no longer symmetrical in space, so even if it continues to operate in the fault state, the torque ripple is relatively large, at this time, it is necessary to reconstruct the phase current to maintain the torque constant. In order to keep the air-gap MMF unchanged before and after the fault and minimize the copper loss, it is necessary to adjust the current of the residual phase to compensate the stator current of the missing phase, which can effectively reduce the output torque ripple of the motor[8]-[10].The amplitude and phase of the residual phase current can be solved as a nonlinear programming problem with constraints, which can be solved by iterative optimization. The current constraints are as follows:

(1) The stator flux linkage remains unchanged.

(2) The current amplitude of each phase is equal or the copper loss of winding is minimum.

It is stipulated that the residual effective value of each phase current shall not exceed the rated value after the motor is out of phase. The fault-tolerant current calculation when one-phase winding open and two-phase windings open is analyzed respectively.

A. One-phase Open Circuit Fault

Assuming that phase a is open circuit, the phase angle and amplitude of the residual phase current are changed to ensure that the circular rotating magnetic field before and after the fault is basically unchanged, so as to ensure the fault-tolerant operation of the motor. According to the principle that the front and back magneto motive force is constant, the formula (5) is expanded by using Euler formula, the real part and the imaginary part are equal, and the amplitude and phase of the residual phase current are derived as the following:

$$\begin{cases} i_b = -i_d = \dfrac{5I_{\mathrm{m}}}{4\sin^2 \dfrac{2\pi}{5}} \cos(\omega t - \dfrac{\pi}{5}) = 1.38 I_{\mathrm{m}} \cos(\omega t - \dfrac{\pi}{5}) \\ i_c = -i_e = \dfrac{5I_{\mathrm{m}}}{4\sin^2 \dfrac{2\pi}{5}} \cos(\omega t - \dfrac{4\pi}{5}) = 1.38 I_{\mathrm{m}} \cos(\omega t - \dfrac{4\pi}{5}) \end{cases} \quad (8)$$

The residual fault-tolerant current amplitudes of all phases are equal, and the residual four-phase current needs to be increased to 1.38 times of the rated value in order to maintain the rotating magneto motive force before the fault and output the rated torque.

After phase a is open-circuited, the space vector diagram corresponding to the remaining 4-phase current is as shown in the Fig.2. It can be seen that the residual phase current amplitudes are equal and the space vectors are symmetric.

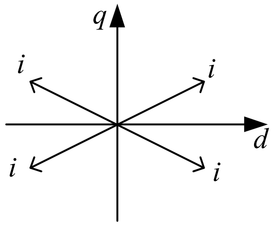

Fig. 2. Phase diagram of phase currents with phase a open fault

If it is specified that the effective value of the residual current of each phase not exceed the rated values, then the fundamental current i_{q1} will be limited, which will cause the maximum output torque of the system to be limited.

B. Two-phase Open Circuit Fault

When phase a and phase b of the motor are open-circuited simultaneously, the amplitude and phase of the remaining three-phase current are derived according to the same constraint conditions as the following:

$$\begin{cases} i_c = \dfrac{5I_{\mathrm{m}}\cos\dfrac{\pi}{5}}{4\sin^2\dfrac{2\pi}{5}}\cos(\omega t-\dfrac{2\pi}{5}) = 1.1I_{\mathrm{m}}\cos(\omega t-\dfrac{2\pi}{5}) \\ i_d = \dfrac{5I_{\mathrm{m}}\cos^2\dfrac{\pi}{5}}{\sin^2\dfrac{2\pi}{5}}\cos(\omega t+\dfrac{4\pi}{5}) = 3.5I_{\mathrm{m}}\cos(\omega t+\dfrac{4\pi}{5}) \\ i_e = \dfrac{5I_{\mathrm{m}}\cos\dfrac{\pi}{5}}{4\sin^2\dfrac{2\pi}{5}}\cos(\omega t) = 1.1I_{\mathrm{m}}\cos(\omega t) \end{cases} \tag{9}$$

The space vectors corresponding to the remaining 3-phase currents are shown in Figure 3. It can be seen that when the five-phase motor works with two phases missing, the current amplitudes of each phase are no longer equal if the stator flux linkage is kept unchanged and the copper loss is minimized[11]-[12]. When the maximum amplitude of the phase current RMS reaches the rated value of the inverter power devices, the output torque will reach the upper limit.

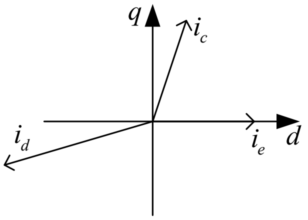

Fig. 3. Phase diagram of phase currents with phase a and phase b open fault

To sum up, the current expression of the remaining phase can be derived by taking the equal amplitude of each phase current or the minimum winding copper loss as the control target and keeping the stator flux unchanged. The fault-tolerant control strategy adopted in this paper adopts the same decoupling transformation in the normal operation and fault-tolerant operation of the system, and the implementation of the fault-tolerant control strategy is simplified.

C. Fault-tolerant Control Based Decoupling Model

Fig. 4 is the structure diagram of the vector control system in the space decoupling coordinate system. When the motor is in normal operation, the fundamental rotating magnetic potential and torque are mainly determined by i_{d1} and i_{q1}, and when a phase loss occurs, i_{d3} and i_{q3} can provide additional degrees of freedom for fault-tolerant control[13]-[15].

For the vector control of the surface-mounted PMSM, the direct axis current is still set to zero, that is, $i_{d1}=i_{d3}=i_0=0$. Without loss of generality, $i_{q3}=k_i*i_{q1}$. The third harmonic current injected into the five-phase permanent magnet synchronous motor can effectively reduce the saturation degree of the iron core and improve the utilization rate of the ferromagnetic material.

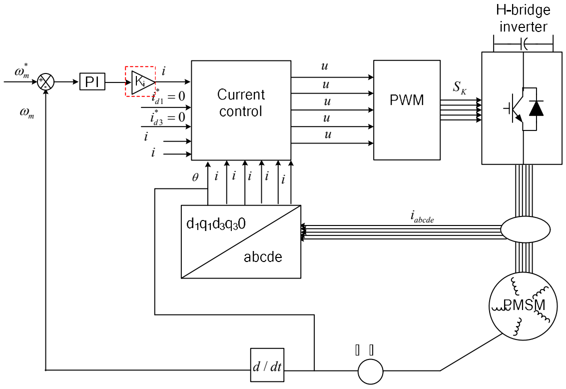

Fig. 4. Vector control block diagram of five-phase PMSM

The zero-sequence current is no longer an independent variable, and its given value is determined according to equation (7). In order to track the zero-sequence current, the proportional resonant (PR) control algorithm is adopted.

When the motor has open-phase fault, the current optimization control is adopted to adjust the open-circuit fault. If the fault-tolerant current is limited not to exceed the rated current, the torque current setpoint value is multiplied by the torque derating coefficient k_i on the basis of the rated value in Figure 4, then the maximum input torque of the motor will be limited, and the motor will be derated.

IV. SIMULATION AND EXPERIMENTAL ANALYSIS OF FAULT TOLERANT CONTROL

In order to verify the above fault-tolerant control strategy, the current and torque waveforms under different open-phase conditions are simulated. At t = 0.06 s, phase a is disconnected and at the moment of t = 0.12 s, phase b is disconnected again. When the fault-tolerant control is not adopted, the current waveform output by the motor is as shown in Fig.5.

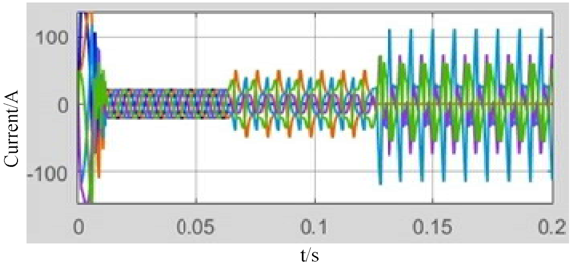

Fig. 5 Current simulation waveforms under no fault-tolerant control with one open phase

When the phase loss occurs, the waveform of the remaining phase currents are distorted, and the amplitudes of the phase currents increase, especially when the two phases of the motor are missing. The remaining phase currents are no longer symmetrical, the loss increases, and even times of the fundamental frequency appear in the torque ripple, which in turn increases motor vibration and noise.The corresponding speed and torque waveforms are shown in Fig.6.

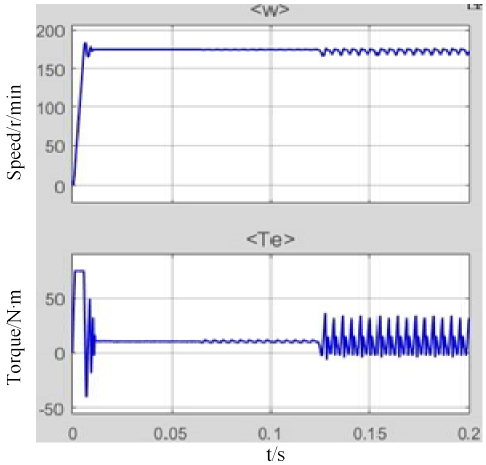

Fig. 6 Speed and torque simulation waveforms under no fault-tolerant control with one open phase

It can be seen that the torque ripple of the motor is larger when the two-phase missing phase is compared with the single-phase missing phase. Therefore, the adjacent two-phase open circuit has a great impact on the motor, which directly affects the normal operation of the motor.

In the original motor vector control strategy, if the fault-tolerant control method is used to compensate the current. the current waveforms of single-phase and two-phase open are respectively shown in the Fig.7.and Fig.8.

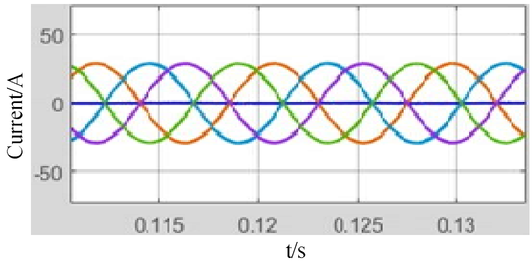

Fig. 7. Current simulation waveforms under fault-tolerant control with one open phase

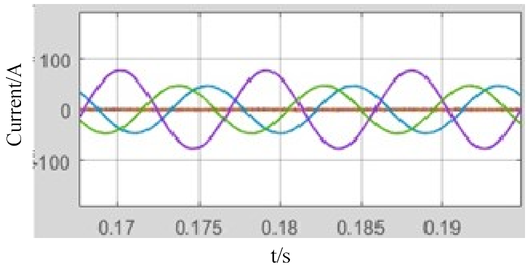

Fig. 8. Current simulation waveforms under fault-tolerant control with two open phases

From Fig.7 and Fig.8, the actual output currents of the remaining phase are consistent with the given values of the optimization current, and the fault tolerant operation of the motor is realized after adopting fault-tolerant control. The speed and torque waveforms of the motor are shown in the Fig.9 when single-phase and two-phase open-phase faults occur respectively.

It can be seen that the torque ripple of the motor is almost the same as that before the fault under the fault tolerant control. The torque ripple is greatly reduced, and the motor can continue to work stably.

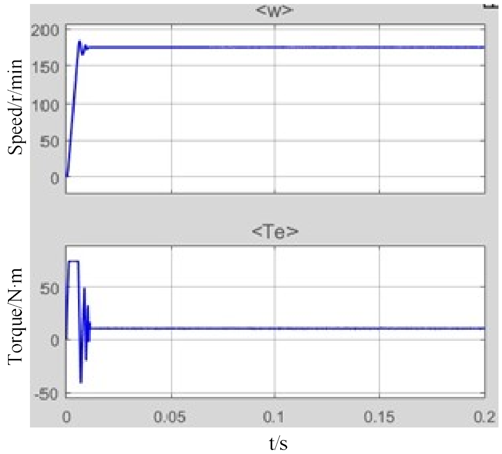

Fig. 9 Speed and torque simulation waveforms under fault-tolerant control

In order to further verify the correctness of the proposed method, experiments are carried out on a five-phase permanent magnet motor platform. When the motor works at light load, and phase a winding is open circuit, after the fault-tolerant control strategy is put into effect, the measured output phase currents of other channels of the motor are shown in Fig.10.

When the system is in normal operation, the waveforms of the dynamic process of a certain phase without fault-tolerant control and with fault-tolerant control are as shown in the Fig.11. From top to bottom are the fundamental torque current, the fundamental excitation current and the electromagnetic torque waveform.

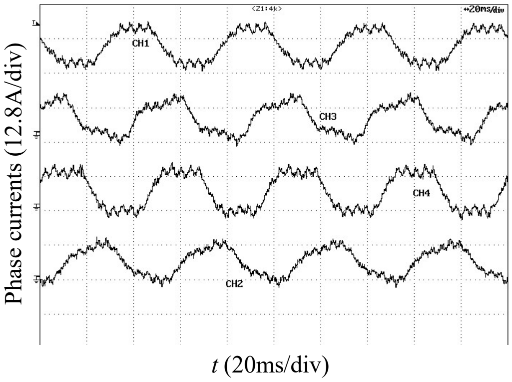

Fig. 10. Phase current experiment waveforms in the phase open control process

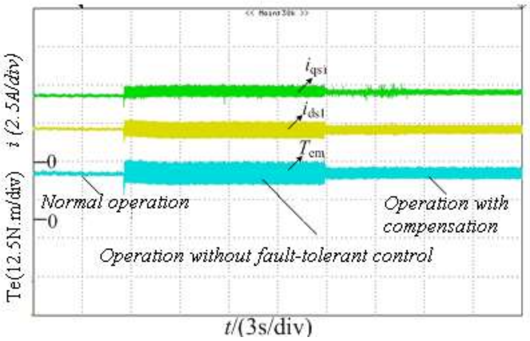

Fig. 11. Fundamental direct and quadrate currents components and electromagnetic torque experiment wavefoms in the phase open control process

It can be seen from the Fig.10 that after the open-phase fault occurs, the output current of the fault phase becomes zero and stops working, and the other phases continue to work normally and share the load current equally. From Fig.11, with the fault-tolerant control, the oscillation of the current and the electromagnetic torque is reduced obviously. It also can be seen that when the motor works in a light load state and the motor is supplied by a PWM inverter, the motor current contains more high-frequency harmonics, which cause the output currents to be less sinusoidal.

V. CONCLUSIONS

The multi-phase permanent magnet propulsion system fed by five-phase H-bridge inverter is widely used in high performance and high reliability propulsion system. A fault-tolerant current control strategy is proposed for the open-circuit fault in the drive system. By setting the current constraints of the independent circuit for neutral point, the corresponding vector control method is obtained. The results show that this method can reduce the torque ripple caused by the stator winding open-circuit fault, and the operation performance of the motor under fault condition can be significantly improved. Because the maximum output current is not allowed to exceed the rated value of the winding, the maximum output torque will be suppressed, and the motor will take derating operation.

Each phase winding of the multi-phase motor is independently powered by an H-bridge. When a phase loss fault occurs, the motor transformation matrix can still adopt a non-reduced order matrix, but the degree of freedom of the current is reduced.

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