PMSM Open-Phase Fault-Tolerant Control Strategy Based on Four-Leg Inverter

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***Abstract*—Open-phase fault is a common failure in permanent magnet synchronous motor (PMSM), which would degrade motor performance and increase its loss due to the unbalanced phase currents. However, conventional fault-tolerant strategies suffer from the tracking problem of sinusoidal current references. In this paper, different from previous fault-tolerant strategies, a new fault-tolerant method for open-phase PMSM is proposed by designing a novel transformation matrix for current/voltage references. With the new transformation matrix, the voltage/current references in the *d–q* frame can be transformed to the phase voltage/current references of the two remaining phases. With the proposed method, open-phase fault-tolerant implementation can be much easier (proportional-integral controller is enough) and its performance can be much higher. Besides, as the tolerant method is designed based on the four-leg inverter, stronger fault-tolerance capability can be obtained compared with the three-phase inverter-based method. Finally, the experimental results confirm the validity of the proposed fault-tolerant method.**

***Index Terms*—Fault tolerance, open-phase fault, permanent magnet synchronous motor (PMSM), reference frame transformation.**

I. INTRODUCTION

In SOME applications, such as aircraft, spacecraft, automotive, and transportation, the reliability of the motor control system is very important and critical. However, different types of faults may occur in its motor drive. Some of them are related to the machine (e.g., interturn short-circuit and open-phase) and others to the power converter (short/open power switch faults) [1]. Although the short-circuit case has been studied [2], [3], the open-phase fault has received more attention in recent years [4]–[9]. The open-phase faults are one of the main fractions of overall machine drive faults, which can account for up to 38% in industrial drives [10]. It typically appears when either one phase of the machine or one leg of inverter switch is completely disconnected. Under open-phase fault, motor performance and efficiency degrade due to the unbalanced phase currents, and it may lead to the unrecoverable damage in extreme situation. To guarantee the high reliability in these situations, open-phase fault-tolerance for the motor drive is indispensable.

Various investigations have been conducted on the fault-tolerance of the open-phase motor. According to the number of motor phase, the fault-tolerant methods can be classified as multiphase motor fault-tolerances [11]–[14] and three-phase motor fault-tolerances [15]–[17]. The multiphase motor has advantages over the conventional three-phase machine for fault-tolerant operation as it can continue operations using the remaining healthy phases without additional hardware. However, the design and control of the multiphase motor are complicated, and the application range of the multiphase motor is narrower. Hence, it is significant and meaningful to study the open-phase fault-tolerant strategy for three-phase permanent magnet synchronous motor (PMSM) in industrial applications.

The open-phase fault-tolerant strategies for the three-phase PMSM consist in reformulating the current references so that the magnetic motive forces (MMFs) and the electromagnetic torque can keep unchanged. It mainly refers to fault-tolerant inverter topology and fault-tolerant control algorithm. For the three-phase PMSM, several fault-tolerant topologies have been proposed. The topologies mainly include three-phase inverter with an extra-leg split capacitor (named ELSC for short) [18], [19] and three-phase inverter with an extra inverter leg (named four-leg inverter or ELES for short) [20]–[25]. Hoang *et al*. compared the current vector control performances of different fault tolerant inverter topologies for the three-phase motor with one phase open fault [26]. In the ELSC topology, the negative torque, which usually occurs when the machine operates with one phase opened, can be eliminated. However, the maximum speed of the machine in the postfault operation region is reduced to half of its nominal value because the applied voltage on the machine terminals is decreased to half of its original value in this reconfiguration topology [26]. For the ELES topology, it can deal with the stator windings fault and power switch fault [27]. Most of the solutions proposed in the past to alleviate drive and/or machine faults need at least the accessibility to the neutral point of the stator windings.

To carry out the motor drive with an open phase, current references have to change to keep a suitable rotating stator field, and the controller reconfiguration is required to track the new current references. To maintain the same rated torque as a

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normal condition, the healthy phase currents have to increase by $\sqrt{3}$ times with a 60° phase shift to each other, while the neutral current has to be a sinusoidal waveform with three times amplitude [30], [31]. Due to the increased current amplitude, the current rating of the switching device needs to be increased also during motor postfault operation. Under the restriction of maximum current in inverter leg, the maximum torque of the open-phase motor reduces to 1/3 of the maximum torque in health condition. Besides, it can be found that tracking the modified sinusoidal current references is a challenging task for the current controller in practice (phase difference is not 120°, but 60°), especially it is position-dependent.

In [28] and [29], the hysteresis current controller in the *a-b-c* reference frame is adopted to realize the tracking control of phase currents and neutral current references. However, this kind of control system suffers from the inconstant switch frequency and its control accuracy is limited. In order to improve the controllability of the system, an innovative remedial scheme is proposed based on unbalanced voltage feedforward compensation [20], [21]. This kind of remedial strategy is a simple and easy operation. It does not require the reconfiguration of *d–q* current proportional-integral (PI) controllers when the failure occurs, and it works well if the motor parameters do not have distinct variations. However, in some special applications, such as aircraft, spacecraft, and automotive, the environment temperature of the motor changes in large scale during it operates. Thus, the motor winding resistance may vary accordingly. Besides, in some industrial applications, the large winding current may leads to the change of motor inductance. If the motor parameters can be estimated and updated in real-time, the effect of voltage feedforward compensation can be preserved. Otherwise, open-phase motor performance would degrade. It can be found that the previous fault-tolerant methods for open-phase PMSM mainly focus on the controller design. However, the controller robustness to cope with parameters' perturbation still needs to be improved.

After that, a modeling and field-oriented control method of a three-phase induction motor under open-phase fault is proposed in [18] and [19]. It is realized by exploiting suitable reference frame transformations to establish a new model of the open-phase machine, and it can also be used for field orientation. This fault-tolerant scheme is designed for the ELSC topology, in which the neutral point of the stator winding is connected to the middle point of dc bus. It can be found that the procedure of open-phase motor modeling and reference frame transformation presented in [19] are very complicated. Furthermore, the analysis and model are not suitable for ELES topology which is extensively employed in the three-phase PMSM fault-tolerant system. Therefore, it is necessary to simplify the frame transformation procedure and establish a model that is suitable for the ELES-topology-based three-phase PMSM system.

This paper proposes an accurate formulation of a new model for three-phase PMSM in case of an open-phase fault. With the new transformation matrix, the voltage/current references in the *d–q* frame can be transformed to the phase voltage/current voltage references of the two healthy phases, and the current controllers (PI controller) can be switched to the postfault state directly without controller's redesign. The proposed open-phase fault-tolerant system possesses stronger fault-tolerance capability compared with the ELSC-topology-based system. It can deal with the stator winding fault and power switch fault simultaneously. This paper is organized as follows. In Section II, the new fault tolerant control strategy based on a new transformation matrix is introduced for four-leg inverter PMSM system. Section III develops experiments. Finally, Section IV concludes this paper.

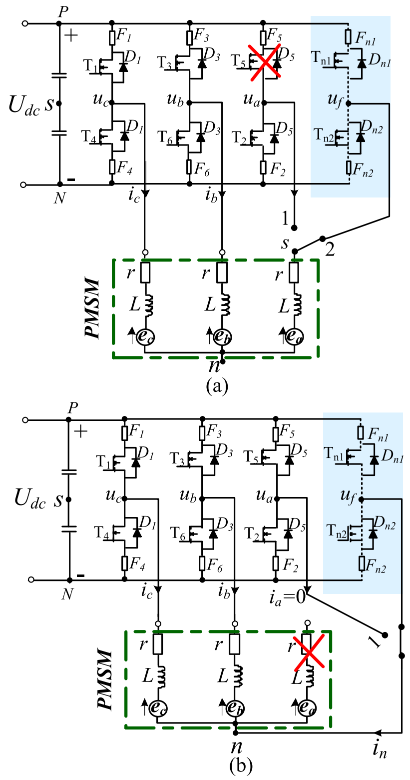


Fig. 1. Open-phase fault-tolerant topology for three-phase PMSM.

II. Fault-Tolerant Control Strategy

A. Open-Phase Fault PMSM Operation

Usually, in the open-phase motor, the neutral wire should be available. In normal condition, the motor drive operates with a three-leg inverter, the neutral wire is not connected. When there is a power switch fault, the phase corresponding to the fault leg can be connected to the fourth leg directly [see Fig. 1(a)]. If there is stator winding open-phase fault, the fault-tolerance capability can be achieved by connecting the neutral point of the stator winding to the fourth leg or to the leg corresponding to the open phase [see Fig. 1(b)]. The open-phase fault-tolerant topology for three-phase PMSM is shown in Fig. 1.

Working in healthy conditions, PMSM model in *a-b-c* stationary reference frame is given by

$$u_{abc} = R \cdot i_{abc} + L_s \cdot p \cdot i_{abc} + e_{abc} \tag{1}$$

where $u_{abc} = [u_{an}\, u_{bn}\, u_{cn}]^T$, u_{an}, u_{bn}, and u_{cn} are the three-phase terminal voltages in *a-b-c* frame, $i_{abc} = [i_a\, i_b\, i_c]^T$, i_a, i_b, and i_c are motor phase currents in *a-b-c* frame, p is differential operator, *R* is the resistance matrix, $R = [r\,0\,0;\,0\,r\,0;\,0\,0\,r]$, and L_s is the inductance matrix, $L_s = [L\,M\,M;\ M\,L\,M;\ M\,M\,L]$, $e_{abc} = [e_a\,e_b\,e_c]^T$ is phase back-electromotive forces (EMFs), respectively.

In normal condition, through Clarke and Park transformations, the phase currents in three-phase stationary frame (i_a, i_b, and i_c) can be transformed to dc variables in synchronous frame (i_d and i_q). PI controller can be used to regulate the motor current. Then, the outputs of the PI controller, i.e., voltage references u_d^* and u_q^*, are transformed to u_α^* and u_β^* to drive the three-phase inverter (or transformed to u_{an}^*, u_{bn}^*, and u_{cn}^* in carrier-based PWM). All of the transformations can be achieved through Clarke and Park transformations and their inverse matrixes

$$i_{dq} = T_{\text{park}} \cdot T_{\text{clarke}} \cdot i_{abc} = P \cdot i_{abc} \tag{2}$$

$$u_{dq} = T_{\text{park}} \cdot T_{\text{clarke}} \cdot u_{abc} = P \cdot u_{abc} \tag{3}$$

$$P = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{4}$$

where $i_{dq} = [i_d\,i_q]^T$, i_d, and i_q are motor currents in *d–q* coordinate, $u_{dq} = [u_d\,u_q]^T$, u_d, and u_q are motor voltages in *d–q* coordinate, $T_{\text{clarke}} = 2/3[1\ -1/2\ -1/2;\ 0\ \sqrt{3}/2\ -\sqrt{3}/2]$ is the Clarke transformation matrix; $T_{\text{park}} = [\cos(\theta)\ \sin(\theta);\ -\sin(\theta)\ \cos(\theta)]$ is the Park transformation matrix, *P* is the transformation matrix from *a-b-c*→*d–q* frame, θ is the rotor position, respectively.

The inverse transformation from the *d–q* frame to *a-b-c* frame is given by

$$i_{abc}^* = T_{\text{clarke}}^{-1} \cdot T_{\text{park}}^{-1} \cdot i_{dq}^* = P^{-1} \cdot i_{dq}^* \tag{5}$$

$$u_{abc}^* = T_{\text{clarke}}^{-1} \cdot T_{\text{park}}^{-1} \cdot u_{dq}^* = P^{-1} \cdot u_{dq}^* \tag{6}$$

$$P^{-1} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \tag{7}$$

where superscript "$*$" denotes the references value, ${T_{\text{clarke}}}^{-1} = [1\ 0;\ -1/2\ \sqrt{3}/2;\ -1/2\ -\sqrt{3}/2]$ is the inverse Clarke transformation matrix; ${T_{\text{park}}}^{-1} = [\cos(\theta)\ -\sin(\theta);\ \sin(\theta)\ \cos(\theta)]$ is the inverse Park transformation matrix, P^{-1} is the transformation matrix from *d–q*→*a-b-c* frame, respectively.

Supposing that phase A is open, at this instant $i_a = 0$. Phase A cannot generate electromagnetic torque when open-phase fault appears. Removing the terms related to phase A, (2) and (3) can be rewritten as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T_a \begin{bmatrix} i_b \\ i_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = T_a \begin{bmatrix} u_b \\ u_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} u_b \\ u_c \end{bmatrix} \tag{9}$$

where T_a is the transform matrix from *b-c*→*d–q* frame, and $T_a = [\cos(\theta - 2\pi/3)\cos(\theta + 2\pi/3);\ -\sin(\theta - 2\pi/3) - \sin(\theta + 2\pi/3)]$.

Similarly, the inverse transformation from *d–q*→*b-c* frame can be obtained by neglecting the terms related to phase A in (5) and (6)

$$\begin{bmatrix} i_b^* \\ i_c^* \end{bmatrix} = T_{av}^{-1} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} u_{bn}^* \\ u_{cn}^* \end{bmatrix} = T_{av}^{-1} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} = \begin{bmatrix} \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} \tag{11}$$

where T_{av}^{-1} is the virtual transformation matrix from *d–q*→*b-c* frame, which is obtained by removing the terms relate to phase A in matrix P^{-1} directly, and $T_{av}^{-1} = [\cos(\theta - 2\pi/3)\ -\sin(\theta - 2\pi/3);\ \cos(\theta + 2\pi/3)\ -\sin(\theta + 2\pi/3)]$.

When open-phase fault occurs in phase A, the voltage equation [see (1)] reduces to

$$\begin{bmatrix} u_{bn} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M \\ M & L \end{bmatrix} p \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_b \\ e_c \end{bmatrix} \tag{12}$$

where u_{bn}, u_{cn}, and i_b, i_c are the phase voltages and currents of the two remaining phases, e_b and e_c are the corresponding phase back-EMFs, respectively.

If the nonlinearity of the PWM voltage source inverter can be ignored, it is expected that the motor voltages are equal to their references under open-phase condition

$$\begin{bmatrix} u_{bn} \\ u_{cn} \end{bmatrix} = \begin{bmatrix} u_{bn}^* \\ u_{cn}^* \end{bmatrix}. \tag{13}$$

Replacing motor voltages in (12) by their reference values, (12) can be rewritten as

$$\begin{bmatrix} u_{bn}^* \\ u_{cn}^* \end{bmatrix} = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M \\ M & L \end{bmatrix} p \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_b \\ e_c \end{bmatrix}. \tag{14}$$

In order to analyze the relationship between voltage and current in *d–q* coordinate, reference frame transformation is conducted for the open-phase PMSM with conventional transformation matrixes (T_a and T_{av}^{-1}). Substituting the voltage u_{bc}^* in (14) by (11) and substituting current i_{bc} in (14) by (8), the input–output equation of the generalized open-phase PMSM (see Fig. 2) can be derived as

$$\begin{aligned} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} &= rT_{av}{T_a}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{3L}{2} T_{av}{T_a}^{-1} p \begin{bmatrix} i_d \\ i_q \end{bmatrix} \\ &\quad + \frac{3L}{2} T_{av}(p{T_a}^{-1}) \begin{bmatrix} i_d \\ i_q \end{bmatrix} + T_{av} \begin{bmatrix} e_b \\ e_c \end{bmatrix}. \end{aligned} \tag{15}$$

From (8) and (10), it can be noted that the product of the matrixes T_a and T_{av}^{-1} is not unit matrix. If the conventional Clarke and Park transformations are applied to the open-phase motor, the voltage equation [see (15)] for the generalized open-phase PMSM will be very complicated and strong nonlinear will be

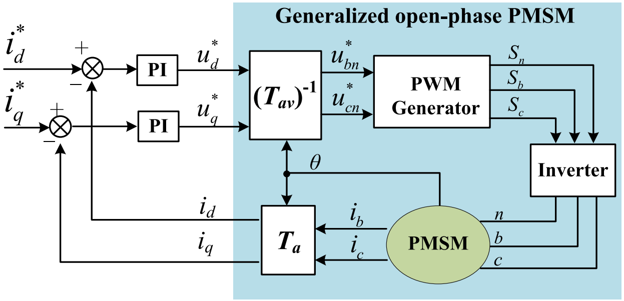


Fig. 2. PMSM control system under open-phase fault.

induced. In addition, the control performance would degrade distinctly if PI controller is applied. Therefore, a new transformation matrix for the voltage/current references is necessary under the open-phase fault condition.

B. New Transformation Matrix for Voltage/Current References

It can be noticed that to keep MMFs and electromagnetic torque of the open-phase PMSM unchanged, the *dq*-axes currents should be preserved as prefault. Therefore, the remaining two healthy phases have to produce the same *dq*-axes currents after the open-phase fault occurs.

Assuming that the open-phase fault presents in phase A [see Fig. 1(b), the analyses of phases B and C are similar], then the motor works in the unbalanced condition ($i_a = 0$). In this case, i_a is uncontrollable, and only phase B and phase C can produce effective torque. Therefore, in order to obtain the same *d*–*q* currents as prefault, the expected phase currents in remained phases B and C should be modified. According to (8), the corrected current commands in phases B and C can be obtained by inversing matrix T_a

$$\begin{bmatrix} i_b^* \\ i_c^* \end{bmatrix} = \sqrt{3} \begin{bmatrix} -\cos(\theta + \pi/6) & \sin(\theta + \pi/6) \\ -\cos(\theta - \pi/6) & \sin(\theta - \pi/6) \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = T_a^{-1} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix}. \tag{16}$$

Similarly, the corrected phase voltages references in *b-c* frame can be obtained as

$$\begin{aligned} \begin{bmatrix} u_{bn}^* \\ u_{cn}^* \end{bmatrix} &= \sqrt{3} \begin{bmatrix} -\cos(\theta + \pi/6) & \sin(\theta + \pi/6) \\ -\cos(\theta - \pi/6) & \sin(\theta - \pi/6) \end{bmatrix} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} \\ &= T_a^{-1} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix}. \end{aligned} \tag{17}$$

With the new transformations matrixes (T_a and T_a^{-1}), (15) can be simplified as

$$\begin{aligned} u_{dq}^* &= \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} i_{dq} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p i_{dq} \\ &\quad + \omega \begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix} i_{dq} + \omega \psi_m \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} \end{aligned} \tag{18}$$

where $k_1 = \sin(2\theta)/3$, $k_2 = (2 + \cos(2\theta))/3$, respectively.

For the healthy PMSM control system, the *dq*-axes voltage equation can be written as

$$\begin{aligned} u_{dq}^* &= \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} i_{dq} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p i_{dq} \\ &\quad + \omega \begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix} i_{dq} + \omega \psi_m \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \end{aligned} \tag{19}$$

Compared (18) with (19), it can be found that the voltage equation under the fault condition is similar to that under healthy condition. The main differences between (18) and (19) are the back-EMF terms. The last two terms of (18) and (19) can be regarded as interference. Hence, the interference terms of the healthy motor can be written as

$$\begin{bmatrix} f_{dh} \\ f_{qh} \end{bmatrix} = \begin{bmatrix} -\omega L_q i_d \\ \omega L_d i_q + \omega \psi_m \end{bmatrix}. \tag{20}$$

While the interference terms of the open-phase motor can be written as

$$\begin{bmatrix} f_{df} \\ f_{qf} \end{bmatrix} = \begin{bmatrix} -\omega L_q i_q + k_1 \omega \psi_m \\ \omega \cdot L_d i_d + k_2 \omega \cdot \psi_m \end{bmatrix}. \tag{21}$$

From (20) and (21) it can be found that the forms of these two interferences terms are similar before and after the fault, and they have almost the same order of magnitudes. Although the amplitude of interferences is slightly larger after fault, it is acceptable. Therefore, the current controller can be designed as a PI controller without modification. If necessary, these interferences can be removed by feedforward compensation.

Similarly, the transformation matrixes under phases B and C open-fault can be obtained. The unified expression for the transformations can be described as

$$\begin{aligned} \begin{bmatrix} i_x^* \\ i_y^* \end{bmatrix} &= T_z^{-1} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \\ &= \sqrt{3} \begin{bmatrix} \sin(\theta - \frac{\pi - 2k\pi}{3}) & \sin(\theta + \frac{\pi + 4k\pi}{6}) \\ -\sin(\theta + \frac{\pi + 2k\pi}{3}) & \sin(\theta - \frac{\pi - 4k\pi}{6}) \end{bmatrix} \cdot \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \end{aligned} \tag{22}$$

$$\begin{aligned} \begin{bmatrix} u_{xn}^* \\ u_{yn}^* \end{bmatrix} &= T_z^{-1} \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} \\ &= \sqrt{3} \begin{bmatrix} \sin(\theta - \frac{\pi - 2k\pi}{3}) & \sin(\theta + \frac{\pi + 4k\pi}{6}) \\ -\sin(\theta + \frac{\pi + 2k\pi}{3}) & \sin(\theta - \frac{\pi - 4k\pi}{6}) \end{bmatrix} \cdot \begin{bmatrix} u_d^* \\ u_q^* \end{bmatrix} \end{aligned} \tag{23}$$

where subscripts *x* and *y* denote the remaining phases, subscript *z* denotes the open-phase, *k* is phase adjustment coefficient. When $z = a$, then $x = b$, $y = c$, $k = 0$; while $z = b$, then $x = c$, $y = a$, $k = 2$; and when $z = c$, then $x = a$, $y = b$, $k = 1$.

It should be noticed that when open-phase fault appears, $i_z = 0$. The frame transformation results yield by matrix P (*a*-*b*-*c*→*d*–*q*) and by matrix $T_a(x - y \rightarrow d - q)$ are same in the feedback-loop. $i_z = 0$ can be regarded as a special case of normal Clarke and Park transformations, therefore the transformation matrix *P* can be used in feedback-loop of the open-phase PMSM system as well.

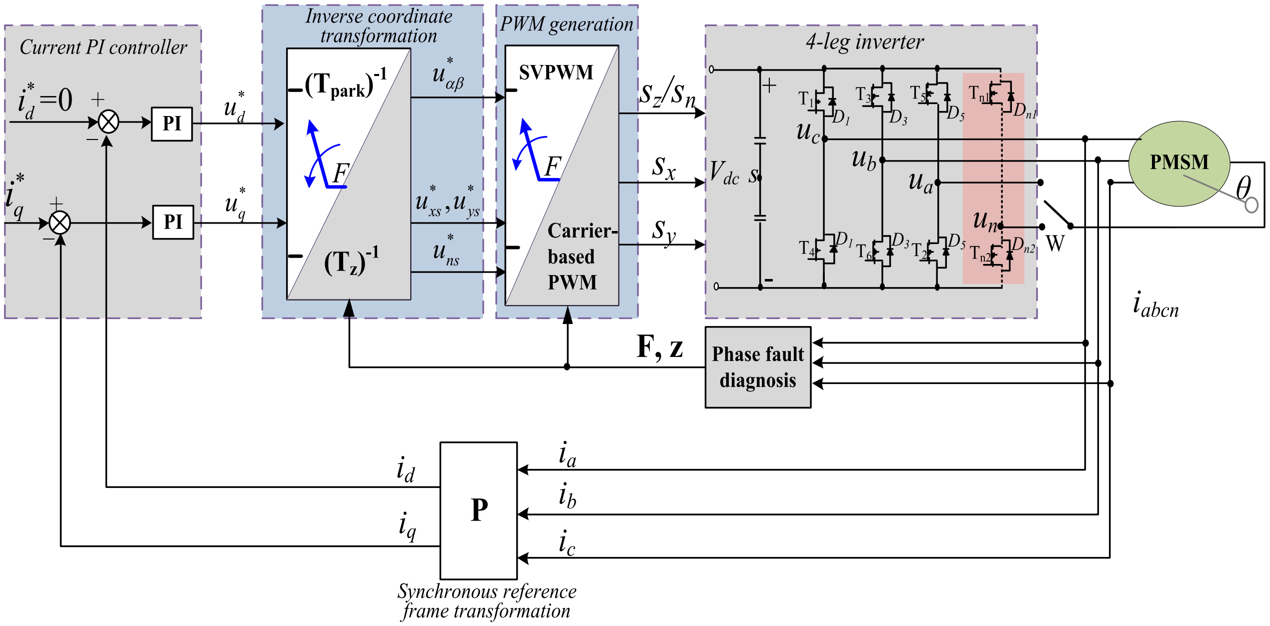


Fig. 3. Proposed fault-tolerant control scheme.

However, the transformation matrix P^{-1} in the forward path of the current loop should be replaced by matrix T_z^{-1} to avoid strong nonlinear under open-phase fault as described in Part A. Since the frame transformation in feedback-loop is unchanged, the expression of electromagnetic torque can be maintained in case of an open-phase fault.

C. Open-Phase PMSM Drive With Carrier-Based PWM Method

Under stator winding open-phase fault, one of the three-phase windings is unavailable. Therefore, three independent voltages cannot be obtained with the conventional SVPWM method. Considering that the carrier-based PWM method can produce three independent voltages, it is employed in this paper. Its principle and operation method is shown in detail in [33]–[35].

For normal PMSM with carrier-based PWM, the references of three-phase terminal voltages and neutral voltage can be obtained as

$$\begin{cases} u_{ns}^* = -(\max(u_{abc}^*) + \min(u_{abc}^*))/2 \\ u_{as}^* = u_{an}^* + u_{ns}^* \\ u_{bs}^* = u_{bn}^* + u_{ns}^* \\ u_{cs}^* = u_{cn}^* + u_{ns}^* \end{cases} \tag{24}$$

where $u_{abc}^* = [u_{an}^*, u_{bn}^*, u_{cn}^*]$, $\max(u_{abc}^*)$, and $\min(u_{abc}^*)$ are the maximum and minimum values of three-phase voltage references (u_{an}^*, u_{bn}^*, and u_{cn}^*), u_{as}^*, u_{bs}^*, and u_{cs}^* are the motor terminal to dc-link midpoint voltage commands, which are given to PWM module directly, u_{ns}^* is motor neutral point to dc-link midpoint voltage commands, respectively.

Under the open-phase condition, the power switches corresponding to the open phase are controlled turn-OFF, and the terminal voltage references u_{xn}^* and u_{yn}^* for the remaining phases should be modified as (23). Considering that the design principle of the offset voltage u_{ns}^* is to maximize the voltage utilization of voltage source, offset voltage command can be set as

$$u_{ns}^* = -\frac{u_{xn}^* + u_{yn}^*}{2}. \tag{25}$$

The proposed open-phase fault-tolerant method can be utilized in the general PMSM system. Applying the proposed transformation matrixes to the system, it is possible to control the postfault electromagnetic torque with superior performance without controller reconfiguration. Fig. 3 is the block diagram of the PMSM control system that can deal with the normal condition and open-phase fault condition. This control system mainly includes seven modules: current PI controller, synchronous reference frame transformation, PWM generation, four-leg inverter, PMSM, phase fault diagnosis, and inverse coordinate transformation. The phase fault diagnosis module outputs the fault symbol (F) and the fault location (z) by monitoring phase currents. If the motor operates in healthy condition, conventional transformation matrix P (*a-b-c*→*d–q*) is used for motor currents transformation to obtain *dq*-axes currents feedbacks. Through the regulation of the PI current controller, the *dq*-axes voltage control efforts (u_d^* and u_q^*) are generated, and then transformed to voltage control efforts u_α^* and u_β^* with transformation matrix $T_{\text{park}}{}^{-1}$. After that, the voltage control efforts are modulated through SVPWM to drive the motor. When the open phase fault occurs, the new inverse transformation matrix T_z^{-1}(*d–q*→*x-y*) is adopted to obtain the voltage control efforts (u_{xn}^* and u_{yn}^*), and the carrier-based PWM is utilized for generating the inverter driving signals. It can be found that the main differences between the two vector controllers are the inverse transformation matrixes in the forward path of the current loop and the PWM modulation method. Other modules are the same in normal condition and in an open-phase fault condition.

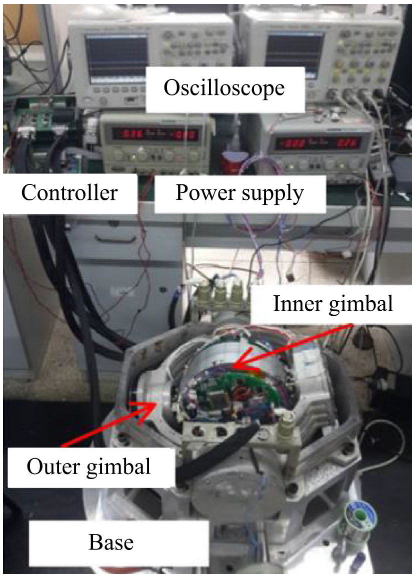


Fig. 4. DGCMGs experimental system.

TABLE I
DGCMGS OUTER GIMBAL MOTOR PARAMETERS

Paremeters	Value
DC power supply Vdc (V)	28
Moment of Inertia J (kg·m^2)	0.173
Back-EMF Coefficient K_e (N·m/A)	2.22
Phase Resistance R (Ω)	6
Phase Inductance L (mH)	9
Angular momentum H (N·ms)	10

III. SURFACE PERMANENT MAGNET SYNCHRONOUS MOTOR EXPERIMENTAL RESULTS

A. Experimental Setup

To evaluate the performance of the proposed method, comparative experiments using the proposed coordinate transformation method are developed. The platform for this study is a double gimbal control moment gyros (DGCMGs) prototype as shown in Fig. 4. The gimbals are driven by surface PMSM. Its main parameters are shown in Table I. The gimbal motor torque control system adopts $i_d = 0$ control mode.

B. Experiment 1: Open-Phase Fault-Tolerant Methods Comparison

In order to verify the superiority of the proposed open-phase fault-tolerant method, phase A is forced to be disconnected from the inverter during motor operation. Thus, it is unavailable after that. Comparative experiments are conducted among the systems without fault-tolerant, with voltage feedforward compensation, and with the proposed method. The obtained motor voltage and current waveforms are illustrated in Fig. 5. From Fig. 5(I) it can be observed that after open-phase fault, the current in phase A decreases to zero at once, while the detected voltage in phase A is not zero due to the back-EMF. It can be seen that although the fourth leg can provide the neutral current flowing circuit, *d*–*q* currents present distinct fluctuation during motor postfault operation.

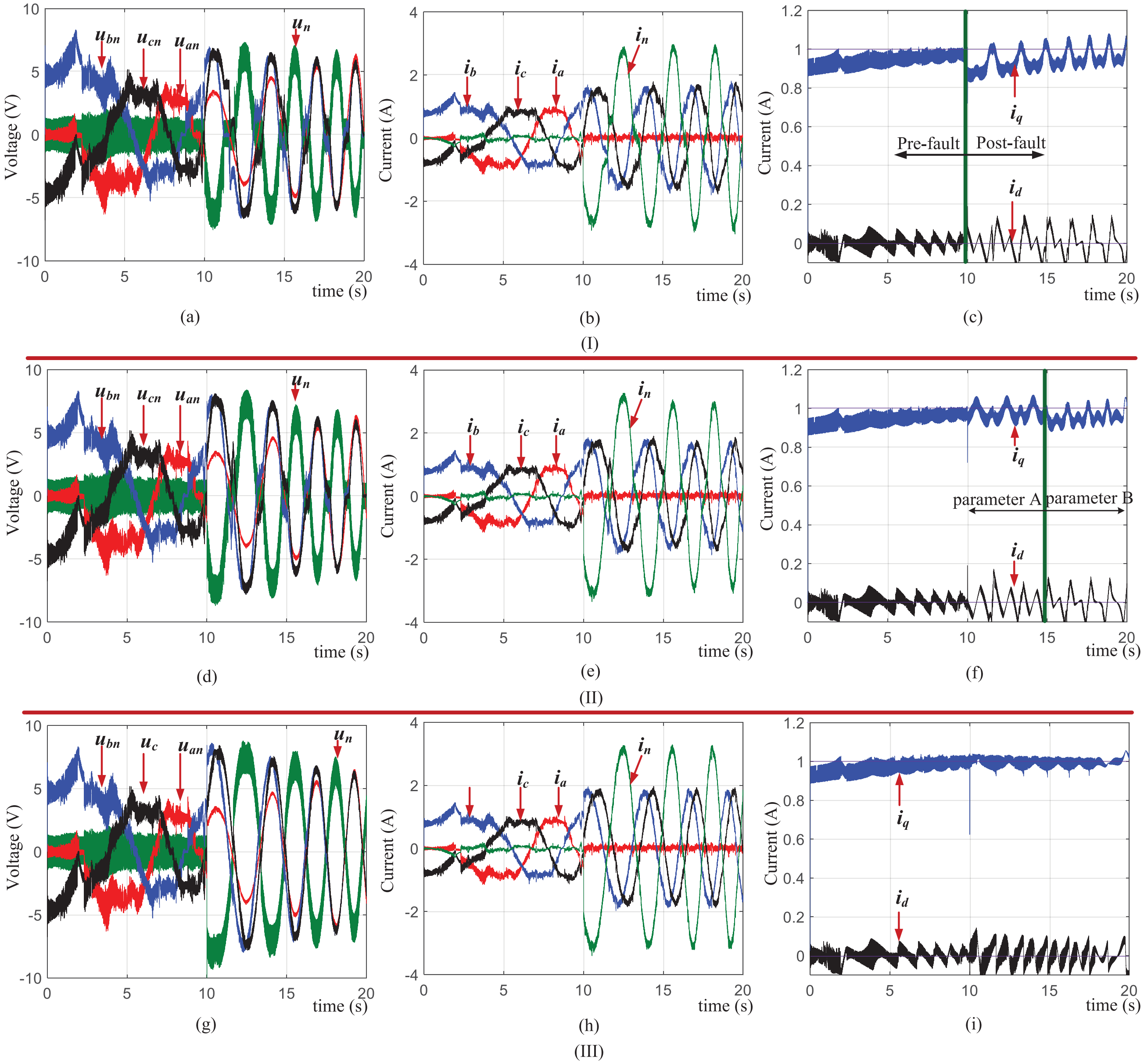
In order to improve the open-phase PMSM performance, voltage feedforward compensation-based fault-tolerant method is applied into the system. The feedforward voltage is calculated according to [20] and [21]. To obtain the accurate feedforward voltage, the motor parameters such as permanent-magnet flux linkage λ_m, stator direct, quadrature and leakage inductance l_d, l_q, l_σ should be acquired in advance. In the experiment, the accurate motor parameters are employed in feedforward voltage compensation first. The corresponding phase voltages and currents waveforms are described in Fig. 5(II). From Fig. 5(II), we can observe that *d*–*q* current performance improves through feedforward compensation, and the *q*-axis current fluctuation decreases from 0.185 to 0.156 A [parameter A in Fig. 5(f)]. But its effect is limited, as the change of inductances and phase resistance are neglected in the compensation. And then, the feedforward voltage compensation with inaccurate parameters has been tested. When the motor parameters are inaccurate, the compensation effect degrades. As shown in Fig. 5(f), the errors of the *dq*-axes currents increase when motor parameters change 50% (parameter B). It can be found that the performance of the voltage feedforward compensation-based method would be influenced by the accuracy of the motor parameters estimation.

After that, the proposed fault-tolerant method based on reference frame transformation is applied to the system. The corresponding waveforms are described in Fig. 5(III). From Fig. 5(III), it can be seen that the *q*-axis current fluctuation decreases obviously compared with that of the open-phase motor system and feedforward voltage compensation system. Although some fluctuations exist in *d*-axis current waveforms, they will not influence motor performance, as *d*-axis current coefficient is zero in torque expression of surface PMSM $(L_d = L_q)$.

C. Experiment 2: Accelerating and Speed Reversal Performance Tests

In this experiment, the performances of the proposed fault-tolerant method are tested under open-phase PMSM accelerating and speed reversal operation. First, the accelerating performance is tested. In the test, the current references are given as $i_d^* = 0$ A and $i_q^* = 0.3$ A before *t* = 15 s, and then the current references are given as $i_d^* = 0$ A and $i_q^* = 0.7$ A. At *t* = 8 s, phase A is forced to be disconnected, and the proposed fault-tolerant scheme is applied to the system. In a healthy condition, the motor is driven by a three-phase inverter. Once the stator winding of phase A is disconnected, the fourth leg is activated. The obtained phase currents, *d*–*q* currents and speed of the open-phase PMSM are presented in Fig. 6. From Fig. 6, it can be found that when the open-phase motor is accelerating, the fluctuations superimposed in motor current are small, and motor speed waveform is smooth.

And then, the speed reversal performance of the open-phase motor is tested. In the test, the current references are given as $i_d^* = 0$ A and $i_q^* = -0.4$ A before *t* = 15 s, and then the current references are given as $i_d^* = 0$ A and $i_q^* = -0.8$ A. At *t* = 8 s, phase A is forced to be disconnected, and the proposed fault



(a) (b) (c)

(I)

(d) (e) (f)

(II)

(g) (h) (i)

(III)

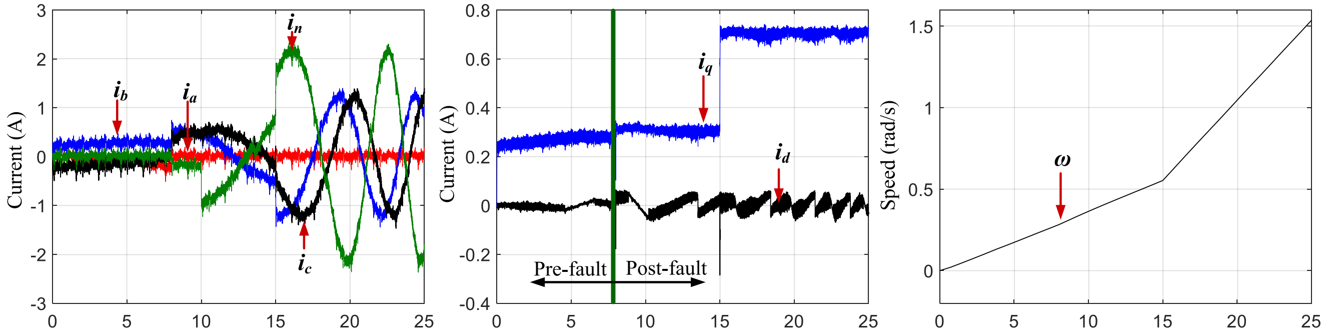
Fig. 5. Different open-phase fault-tolerant methods comparison. (I) open-phase fault without fault-tolerant compensation. (a) Actual voltages detected in the motor terminal. (b) Motor phase currents and neutral current. (c) *d*–*q* currents transformed by *a*-*b*-*c* currents. (II) Open-phase fault with voltage feedforward compensation. (d) Actual voltages detected in the motor terminal. (e) Motor phase currents and neutral current. (f) *d*–*q* currents transformed by *a*-*b*-*c* currents. (III) Open-phase fault with proposed new coordinate transformation. (g) Actual voltages detected in the motor terminal. (h) Motor phase currents and neutral current. (i) *d*–*q* currents transformed by *a*-*b*-*c* currents.

-tolerant scheme is applied to the system. The phase currents, *d*–*q* currents and speed of the open-phase PMSM are presented in Fig. 7.

From Fig. 7, it can be found that although there is small speed fluctuation at the instant of fault occurrence, the open-phase motor works well during its speed reversal operation.

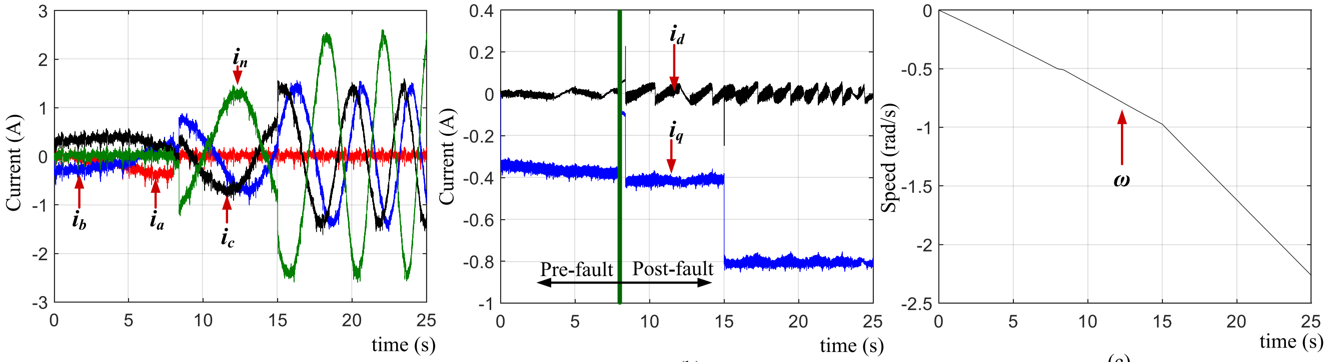
D. Experiment 3: Steady-State Performance Tests and Fast Fourier Transform Analysis

In this experiment, the steady-state performance and fast Fourier transform (FFT) analysis are conducted for the proposed fault-tolerant method. As the rated speed and rated current of the DGCMGs gimbal are relatively low, another PMSM with larger power is used for the test. In this experiment, phase A is disconnected, and the current references are given as $i_d^* = 0\,\text{A}$ and $i_q^* = 10\,\text{A}$ before $t = 5$ s, and then the current references are given as $i_d^* = 0\,\text{A}$ and $i_q^* = 20\,\text{A}$. The yielded three-phase currents waveforms and *dq* current waveforms are shown in Fig. 8(a) and (b). From the current waveforms, it can be found that the proposed open-phase fault tolerant method has acceptable steady-state performance. And then, FFT analysis is conducted for the *dq* currents as shown in Fig. 8(c). According to the harmonic characteristic of the *dq*-axes currents, it can be found



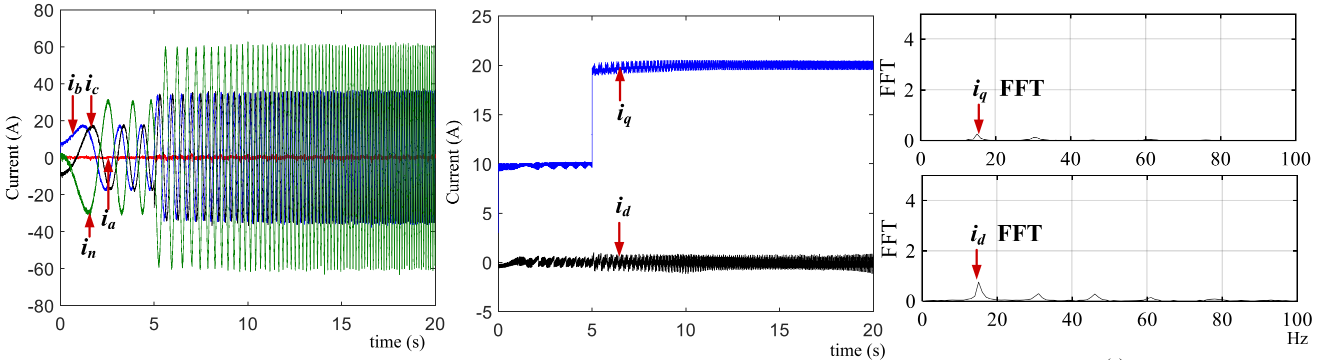
(a) (b) (c)

Fig. 6. Open-phase PMSM accelerating performance. (a) Motor three-phase currents. (b) *d*–*q* currents transformed by *b*-*c*-*n* currents. (c) Motor speed.



(a) (b) (c)

Fig. 7. Open-phase PMSM speed reversal performance. (a) Motor three-phase currents. (b) *d*–*q* currents transformed by *a*-*b*-*c* currents. (c) Motor speed.



(a) (b) (c)

Fig. 8. Steady-state performance tests and FFT analysis. (a) MOTOR phase currents and neutral current. (b) *d*–*q* currents transformed from *a*-*b*-*c* currents. (c) *d*–*q* currents FFT analysis.

that the proposed fault tolerant method has low total harmonic distortion.

IV. CONCLUSION

In order to improve motor performance after open-phase fault, a new motor model is established based on a novel coordinate transformation. Different from previous fault-tolerant strategies, this kind of open-phase fault-tolerant method does not need reconfiguration of the controller or voltage feedforward compensation. Particularly, the PI controller parameters can be kept unchanged when the open-phase fault occurs. With the new fault-tolerant control strategy, the performance of the open-phase motor system can be improved obviously. In addition, as the tolerant method is designed based on a four-leg inverter, stronger fault-tolerant capability can be obtained compared with the three-phase inverter-based method. It can deal with power switch fault and stator winding open-phase fault simultaneously.

The validity and the superiority of the proposed new open-phase fault-tolerant method have been verified by experiments on the surface PMSM in DGCMGs.

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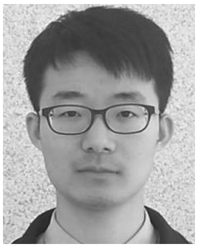

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