Unified Decoupling Vector Control of Five-Phase Permanent-Magnet Motor With Double-Phase Faults

CHENG CHEN¹, HUAWEI ZHOU⁰¹, (Member, IEEE), GUANGHUI WANG², (Member, IEEE), AND GUOHAI LIU¹, (Senior Member, IEEE)

¹Department of Electrical and Information Engineering, Jiangsu University, Zhenjiang 212013, China
²China North Vehicle Research Institute, Beijing 100072, China

Corresponding author: Guanghui Wang (ghwang201@163.com)

This work was supported by the Beijing Natural Science Foundation of China under Project 3182041.

ABSTRACT Multi-phase permanent-magnet (PM) motor is a competitive candidate for application where uninterrupted operation is demanded under fault condition. However, double-phase open-circuit or short-circuit faults result in serious problems, such as high fluctuating-torque, deteriorated dynamic performance, even breakdown. This paper proposes a novel unified decoupling vector control strategy to restrain torque fluctuations and improve dynamic performance for a five-phase PM motor with arbitrary double-phase failures. The novelty of the proposed strategy is the development of reduced-order orthogonal transformation matrices and remedies voltages, and then the smooth operation with vector control strategy can be achieved under double-phase open-circuit or short-circuit fault condition. The decoupled motor model in the synchronous rotating frame is achieved by the combination of the reduced-order orthogonal transformation matrices deduced from the optimal fault-tolerant currents and the remedy voltages. The torque fluctuations cancellation is achieved by the remedy voltages. This control strategy exhibits the improved dynamic performance with smooth torque of the faulty PM motor. The experimental results are presented to verify the feasibility of the proposed strategy.

INDEX TERMS Five-phase permanent-magnet motor, fault-tolerant control, reduced-order orthogonal transformation matrix, remedy voltage, double-phase faults, vector control.

I. INTRODUCTION

Multiphase permanent-magnet (PM) motors have attracted considerable attention in high reliability applications due to their main merits [1], [2]. Compared with three phase ones, they have lower pulsating torque, more effective mitigation in both the voltage and current stress, lower dc-link current harmonics and more degrees of freedom for restraining the impact of fault phases [2], [3]. Continued operation is critical requirement in safety-critical cases because the shutdown of the motor may not be admissible even under the most serious fault scenarios [4], [5]. Clearly, fault-tolerance is very important to the motor drives.

Open-circuit and short-circuit faults of stator windings are the most common fault types. By special design with no magnetic coupling between stator windings, the fault in one phase can have little impact on other phases during the operation [5]–[7]. However, if appropriate fault-tolerant control (FTC) strategy is not adopted after fault occurrence, the deteriorated currents would cause serious torque fluctuations and vibrations, even resulting in breakdown of the motor drive.

The FTC can be achieved by the preserving magnetic motive force (MMF) value equal to the healthy one, thus eliminating torque fluctuations caused by faults [8]. To achieve it, a simple method is that the currents are controlled separately to track the fault-tolerant currents in the remaining healthy phases [8], [9]. The controller structure remains unchanged under the healthy and fault conditions. However, the controller design is challenging due to the time-varying references. Some FTC strategies were adopted to improve the torque performance of multi-phase motor with open-circuit or short-circuit fault combined with direct torque control (DTC) [2], [10], [11]. However, they suffer from...
The model-predictive control strategy is utilized to deal with the fault-tolerant operation [12]–[14]. However, some problems still exist such as current distortion and complex calculation. It is well known that the vector control (VC) strategy has good steady-state and dynamic performance. It can solve the aforementioned problems. In order to achieve the VC operation of multi-phase motor, the theory of vector space decomposition (VSD) is favorable. By using the traditional transformation matrix, the VSD splits the variables into several subspaces that can be controlled independently [15]. However, when the faults occur, the different subspaces are no longer independent. In order to realize the VC operation of five-phase motor under fault condition, some transformation matrices were mainly investigated, such as the reduced-order transformation matrices [16], [17] and the reduced-order orthogonal transformation matrices [18]–[20]. By using these matrices, the motor with VC strategy achieves disturbance-free operation under the fault condition. Nevertheless, these FTC strategies are only suitable for single-phase fault. Reduced-order non-orthogonal transformation matrices were adopted in five-phase PM motor with double-phase open-circuit faults [21]–[23]. Combined with VC strategy, they completed the purpose of smoothing torque. However, these FTC approaches are unable to be applied in the five-phase PM motor with double-phase short-circuit faults.

The purpose of this paper is to mitigate torque fluctuations and improve dynamic response of the FTPM motor with arbitrary double-phase open-circuit or short-circuit faults. Hence a unified decoupling VC strategy based on reduced-order orthogonal transformation matrices is newly proposed. The main contributions are as follows:

1) The realization of the unified decoupling VC for the FTPM motor with arbitrary double-phase open-circuit or short-circuit faults not only smooths the torque but also improves its dynamic performance.

2) The decoupled motor model in synchronous rotating frame is obtained by the incorporation of the new reduced-order orthogonal transformation matrices and remedy voltages.

3) The remedy voltages are generated to eliminate the impact of double-phase short-circuit faults.

The rest of the paper is organized as follows. A five-phase PM motor drive will be briefly presented in Section II. In Section III, the new reduced-order orthogonal transformation matrices and remedy voltages under double-phase faults will be derived, and the decoupled model will be built, then the development of unified VC strategy under double-phase fault condition will be discussed. In Section IV, the experimental results will be presented to verify the proposed VC strategy. Finally, the conclusions will be summarized in Section V.

II. FTPM MOTOR DRIVE

The topology of the 20-slot/22-pole five-phase fault-tolerant PM (FTPM) motor with V-shaped PMs is shown in Fig. 1. The alternate-teeth-wound fractional-slot concentrated windings are adopted. The fault-tolerant teeth interleaving the armature teeth are introduced to achieve electrical, magnetic, thermal, and mechanical isolation between phases [24]. Therefore, the inter phase coupling can be ignored, and the mutual inducances and associated effects can be neglected. The value of self-inductance is nearly constant. Thus the phase inductance $L_s$ can be supposed as constant. The back electromotive forces (EMFs) are supposed as fundamental. This five-phase FTPM motor is a standard star-connected machine.

The five-phase FTPM motor can be considered as a set of two fictitious motors in different reference frames. The orthogonal reference frames can simplify the controller design. Hence, the phase variables can be divided into two orthogonal reference frames named $\alpha$-$\beta$ and $x$-$y$ by using the traditional transformation matrix (1), which group different harmonic components [25]. The fundamental components that contribute to the electromechanical energy conversion are mapped in $\alpha$-$\beta$, while the third harmonic components that have no contribution to the torque produce are distributed into $x$-$y$, which have to be controlled to zero. The traditional VC strategy for FTPM is shown in Fig. 2. Therefore, the phase current references of the healthy motor can be expressed as (2).

$$\begin{align*}
T_C &= \begin{bmatrix}
1 & \cos \gamma & \cos 2\gamma & \cos 3\gamma & \cos 4\gamma \\
0 & \sin \gamma & \sin 2\gamma & \sin 3\gamma & \sin 4\gamma \\
1 & \cos 3\gamma & \cos 6\gamma & \cos 9\gamma & \cos 12\gamma \\
0 & \sin 3\gamma & \sin 6\gamma & \sin 9\gamma & \sin 12\gamma
\end{bmatrix} \\
\begin{align*}
i_A &= -i_y^* \sin(\theta) + i_y^\alpha \cos(\theta) \\
i_B &= -i_y^* \sin(\theta - \gamma) + i_y^\beta \cos(\theta - \gamma) \\
i_C &= -i_y^* \sin(\theta - 2\gamma) + i_y^\alpha \cos(\theta - 2\gamma) \\
i_D &= -i_y^* \sin(\theta - 3\gamma) + i_y^\beta \cos(\theta - 3\gamma) \\
i_E &= -i_y^\alpha \cos(\theta - 4\gamma) + i_y^* \cos(\theta - 4\gamma)
\end{align*}
\end{align*}$$
where \( i_A, i_B, i_C, i_D, i_E \) are the phase currents, \( i_d \) and \( i_q \) are the stator currents in the synchronous rotating frame \( d-q \), \( \gamma \) is the electrical angle between \( d \)-axis and \( A \)-axis, \( \gamma \) is equal to \( 0.4\pi \).

Although the fault-tolerant technology has been adopted in the design of FTPM motor, the motor with traditional VC still offers seriously deteriorated torque due to its coupling between phases after fault occurrence [16], [26]. Two failure phases can be either nonadjacent or adjacent. According to Fig. 2, when double-phase short-circuit or open-circuit faults occur in nonadjacent-phases (phase-B and phase-E) or adjacent-phases (phase-C and phase-D), the relation among the currents in the fault phases and the currents in \( \alpha-\beta \) and \( x-y \) can be expressed as

\[
\begin{align*}
0.5 (i_B + i_E) &= i_d \cos \gamma + i_q \cos 2\gamma \\
0.5 (i_B - i_E) &= i_d \sin \gamma - i_q \sin 2\gamma \\
0.5 (i_C + i_D) &= i_d \cos 2\gamma + i_q \cos \gamma \\
0.5 (i_C - i_D) &= i_d \sin 2\gamma + i_q \sin \gamma
\end{align*}
\]

(3)

Since the short-circuit current stems from the corresponding phase back EMF, when short-circuit faults occur, the values in the left sides of (2) and (3) are not controllable, then the relation between \( i_d \) and \( i_q \) is fixed and the relation between \( i_d \) and \( i_q \) is also constant. Therefore, they are in serious coupling with each other and cannot be controlled independently. When double-phase open-circuit faults occur, the currents in the fault phases are zero, the values in the left sides of (2) and (3) are zero. Thus, the currents in \( \alpha-\beta \) are in conflict with the currents in \( x-y \) after double-phase open-circuit faults occurrence. Hence, the traditional transformation matrix would cause coupling model and deteriorated torque after double-phase fault occurrence. It goes against the VC purpose, so the traditional transformation matrix cannot be used under fault conditions.

III. POST-FAULT DECOUPLING VC OPERATION

A. FAULT-TOLERANT CURRENTS

Due to immunity of healthy phases to fault phases, the impact on healthy phase currents can be ignored. When double-phase short-circuit faults occur, the impact on torque can be divided into two parts: the impact of the open-circuit faults on torque and the impact of short-circuit currents on torque when the remaining healthy phase currents are zero. When double-phase open-circuit faults occur, the impact on torque is only caused by open-circuit faults. Suppose the short-circuit current is zero, the impact of short-circuit current on torque will be zero, so the short-circuit fault can be recognized as open-circuit fault. Hence, the open-circuit fault can be supposed as a special type of short-circuit faults. In order to ensure the continuous operation, the fault-tolerant current references are the sum of the fault-tolerant current references obtained from the open-circuit faults and the remedial current references used to eliminate the impact of short-circuit currents. Therefore, the process of optimizing fault-tolerant current references includes two steps.

1) NONADJACENT-PHASE OPEN-CIRCUIT FAULTS

Without loss of generality, the nonadjacent-phase open-circuit faults are assumed to occur in phase-B and phase-E. Due to PM rotor MMF is constant, the constant stator MMF can generate constant torque [1]. Thus, to achieve the disturbance-free operation, the healthy phase currents should satisfy the following constraints: 1) the fault-tolerant currents in phase-C and phase-D need to satisfy the mirror symmetry principle with respect to the axis of phase-A; 2) the healthy phase currents should only contain the fundamental components due to the sinusoidal back EMFs; 3) the sum of healthy phase currents should be zero according to the windings being star connected; 4) the stator MMF, which is produced by the remaining healthy phase windings, should be maintained the same as that in healthy operation [8], [27]. Thus the constraints can be expressed as

\[
\begin{align*}
\dot{i}_A^e &= I_0 \cos (\theta + \theta_1) \\
\dot{i}_C^e &= I_1 \cos (\theta + \theta_1 - \theta_2) \\
\dot{i}_D^e &= I_1 \cos (\theta + \theta_1 + \theta_2) \\
\dot{i}_A^q + \dot{i}_C^q + \dot{i}_D^q &= 0 \\
N_i^A + a^2 N_i^C + a^3 N_i^D &= N_i^A + a N_i^B + a^2 N_i^C + a^3 N_i^D + a^4 N_i^E
\end{align*}
\]

(5)

where \( \theta_1 = \arccos \left( \frac{1}{\sqrt{a^2 + 1}} \right) \), \( a = e^{\theta y} \), \( N \) is the total number of turns for each phase, \( \theta_2 \) is the angle between the currents in phase-C and phase-A, \( I_0 \) and \( I_1 \) are the amplitudes of phase-A and phase-C currents. Therefore, according to (2) and (5), the fault-tolerant current references can be calculated as

\[
\begin{align*}
\dot{i}_A^e &= 1.382 \left( -\dot{i}_q^e \sin (\theta) + \dot{i}_q^e \cos (\theta) \right) \\
\dot{i}_C^e &= 2.236 \left( -\dot{i}_q^e \sin (\theta - 1.5\gamma) + \dot{i}_q^e \cos (\theta - 1.5\gamma) \right) \\
\dot{i}_D^e &= 2.236 \left( -\dot{i}_q^e \sin (\theta + 1.5\gamma) + \dot{i}_q^e \cos (\theta + 1.5\gamma) \right)
\end{align*}
\]

(6)

It can be noticed that phasor-C and phasor-D currents have the same amplitudes and their amplitudes enlarge to \( 2.236 \) times, and the angle between them becomes \( 2\gamma \), but phasor-A current is in the same position and its amplitude enlarge to 1.382 times.
2) NONADJACENT-PHASE SHORT-CIRCUIT FAULTS

The nonadjacent-phase short-circuit faults are assumed to occur in phase-B and phase-E. The short-circuit currents cannot be directly restrained due to stemming from their phase back EMFs. Thus, the remaining healthy phases need to generate extra currents named remedial currents to eliminate the impact of short-circuit currents. To derive the remedial currents, it needs to follow two constraints: 1) the sum of the stator MMF generated by the remedial currents and short-circuit currents should be zero; 2) the sum of the remediial currents should be zero. Hence, the constraints can be expressed as

\[
\begin{align*}
N_i''_A + aN_iB + a^2N_i''_C + a^3N_i''_D + a^4N_iE &= 0 \\
i'_A + i''_C + i''_D &= 0
\end{align*}
\]  

where \(i'_A\), \(i''_C\), and \(i''_D\) are the short-circuit currents in phase-A, phase-C, and phase-D, respectively; \(i_B\), \(i_E\) are the sum of healthy phase currents in phase-B and phase-E, respectively.

Then, according to (7), the remedial currents can be calculated as

\[
\begin{align*}
i''_A &= -0.1708 (k_1 i_B + k_2 i_E) \\
i''_C &= -0.7236 k_1 i_B + 0.8944 k_2 i_E \\
i''_D &= -0.7236 k_2 i_B + 0.8944 k_1 i_E
\end{align*}
\]

where \(k_1\) and \(k_2\) are the coefficients of phase-B and phase-E, respectively. The coefficients \(k_1 = 1\) and \(k_2 = 1\) denote that phase-B and phase-E are short-circuited, respectively; \(k_1 = 0\) and \(k_2 = 0\) denote that phase-B and phase-E are open-circuited, respectively, so the remedial currents in the remaining healthy phases are zero. It can be noticed that the remedial currents in phase-C and phase-D have equal amplitude.

3) ADJACENT-PHASE OPEN-CIRCUIT FAULTS

The adjacent-phase open-circuit faults are assumed to occur in phase-C and phase-D. To achieve the disturbance-free operation, the healthy phase currents should satisfy the following constraints: 1) the fault-tolerant currents in phase-B and phase-E need to satisfy the mirror symmetry principle with respect to the axis of phase-A; 2) the healthy phase currents should only contain the fundamental components; 3) the sum of healthy phase currents should be zero according to the windings being star connected; 4) the stator MMF produced by the remaining healthy phase windings should be kept the same as that in healthy operation. Thus, the constraints can be expressed as

\[
\begin{align*}
i''_A &= I_2 \cos(\theta + \theta_1) \\
i''_B &= I_2 \cos(\theta + \theta_1 - \theta_2) \\
i''_E &= I_2 \cos(\theta + \theta_1 + \theta_2) \\
i''_A + i''_B + i''_E &= 0
\end{align*}
\]

\[
N_i''_A + aN_iB + a^2N_i''_C + a^3N_i''_D + a^4N_iE = 0
\]

where \(\theta_1\) is the angle between the currents in phase-B and phase-A, \(I_2\) and \(I_3\) are the amplitudes of phase-A and phase-B currents. Hence, according to (2) and (9), the fault-tolerant currents for the open-circuit faults can be expressed as

\[
\begin{align*}
i''_A &= 1.171 (k_3 i_c + k_4 i_d) \\
i''_B &= -0.895 k_3 i_c - 0.276 k_4 i_d \\
i''_E &= -0.895 k_4 i_d - 0.276 k_3 i_c
\end{align*}
\]

where \(k_3\) and \(k_4\) are the coefficients of phase-C and phase-D, respectively. If \(k_3 = 1\) and \(k_4 = 1\), then phase-C and phase-D are short-circuited; if \(k_3 = 0\) and \(k_4 = 0\), then phase-C and phase-D are open-circuited, so the remedial currents in the remaining healthy phases are zero. It can be observed that the remedial currents in phase-B and phase-E have the same amplitudes. Additionally, the tolerant-tolerant current in phase-A under adjacent-phase short-circuit fault condition is the biggest one among all the fault conditions.

B. REDUCED-ORDER ORTHOGONAL TRANSFORMATION MATRICES

1) NONADJACENT-PHASE FAULTS

When the FTPM motor has double-phase faults, it only remains three healthy phases and becomes a three-phase PM motor, so it has only two degrees of freedom. The only two degrees of freedom can be mapped in one reference frame.
Thus, the reduced-order orthogonal transformation matrix remaining healthy phase currents should be equal to zero.

The only two degrees of freedom can be derived as

\[ T_{post1} = \begin{bmatrix} 0.483 & 0.781 \cos 1.5\gamma & 0.781 \cos (-1.5\gamma) \\ 0 & 0.247 \sin 1.5\gamma & 0.247 \sin (-1.5\gamma) \\ 0.386 & 0.386 & 0.386 \end{bmatrix} \]  

And its inverse matrix is

\[ T_{post1}^{-1} = 2.236 \begin{bmatrix} 0.618 & 0 & 0.386 \\ \cos 1.5\gamma & \sin 1.5\gamma & 0.386 \\ \cos (-1.5\gamma) & \sin (-1.5\gamma) & 0.386 \end{bmatrix} \]

The last line of (14) is used as a constraint about sum of healthy phase currents being zero, so the Park transformation matrix can be defined as

\[ C_{post} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

2) ADJACENT-PHASE FAULTS

When the FTPM motor has double-phase faults, it has only two degrees of freedom. The only two degrees of freedom can be mapped in \( \alpha_f - \beta_f \) by using the transformation matrix. According to (10), the two orthonormal basis \( T_3 \) and \( T_4 \) in \( \alpha_f - \beta_f \) can be defined as

\[ T_3 = \begin{bmatrix} 1.618 \cos 2\gamma & \cos (-2\gamma) \\ 0 & \sin 2\gamma & \sin (-2\gamma) \end{bmatrix} \]

According to the production of transformation matrix and its inverse matrix being an identity matrix, and the sum of the remaining healthy phase currents being equal to zero, the reduced-order orthogonal transformation matrix and its inverse matrix under adjacent-phase fault condition can be derived as

\[ T_{post2} = \begin{bmatrix} 0.184 & 0.114 \cos 2\gamma & 0.114 \cos (-2\gamma) \\ 0 & 0.647 \sin 2\gamma & 0.647 \sin (-2\gamma) \\ 0.386 & 0.386 & 0.386 \end{bmatrix} \]

\[ T_{post2}^{-1} = 2.236 \begin{bmatrix} 0.184 & 0.114 \cos 2\gamma & 0.114 \cos (-2\gamma) \\ 0 & 0.647 \sin 2\gamma & 0.647 \sin (-2\gamma) \\ 0.386 & 0.386 & 0.386 \end{bmatrix} \]

C. DECOUPLED MODEL UNDER DOUBLE-PHASE FAULTS

1) NONADJACENT-PHASE FAULTS

Due to the fault-tolerant design, the five-phase back EMFs are not affected by the double-phase faults. However, the back EMFs are time-variables when they are transformed into the synchronous rotating frame \( d_l-q_l \) by using (14) and (16). Hence, when the FTPM motor is modeled, the back EMFs have to be shifted to the phase voltage items. Then the FTPM motor model with phase-B and phase-D faults can be built as (19). If the short-circuit faults occur in phase-B and phase-E, \( u_B \) and \( u_E \) are equal to zero, \( i_B = i_R \), and \( i_E = i_E \),

\[
\begin{align*}
    u_{Ae} &= u_A - e_A = Ri_A + L_s \frac{di_A}{dt} \\
    u_{Be} &= u_B - e_B = Ri_B + L_s \frac{di_B}{dt} \\
    u_{Ce} &= u_C - e_C = Ri_C + L_s \frac{di_C}{dt} \\
    u_{De} &= u_D - e_D = Ri_D + L_s \frac{di_D}{dt} \\
    u_{Ee} &= u_E - e_E = Ri_E + L_s \frac{di_E}{dt}
\end{align*}
\]

According to (8) and (20), the remedial voltages can be derived to generate remedial currents in the remaining healthy phases. When they are transformed into \( \alpha_f - \beta_f \) by using (14), they can be expressed as

\[ \begin{bmatrix} u'_{af} \\ u''_{af} \end{bmatrix} = 0.124 (k_1 e_B + k_2 e_E) \]

\[ \begin{bmatrix} u'_{\beta f} \\ u''_{\beta f} \end{bmatrix} = 0.381 (k_1 e_B - k_2 e_E) \]

It should be noticed that if phase-B and phase-E are open-circuited, then \( k_1 = 0 \) and \( k_2 = 0 \), thus the remedial voltages are zero. When the remedial voltages are added in the remaining healthy phases, the phases would generate remedial currents to eliminate the impact of faults. Then according to (14), (20) and (21), the faulty FTPM motor in \( \alpha_f - \beta_f \) can be expressed as

\[
\begin{align*}
    u'_a + u'_f &= R (i'_a + i'_f) + L_s \frac{d (i'_a + i'_f)}{dt} \\
    u'_\beta + u''_f &= R (i'_\beta + i''_f) + L_s \frac{d (i'_\beta + i''_f)}{dt}
\end{align*}
\]

where \( i'_a \) and \( i'_f \) are the remedial currents in \( \alpha_f - \beta_f \), and they can be derived from (8) and (14).

\[
\begin{align*}
    i'_a &= -0.124 (k_1 i_B + k_2 i_E) \\
    i'_\beta &= -0.381 (k_1 i_B - k_2 i_E)
\end{align*}
\]

It should be noticed that if phase-B and phase-E are open-circuited, then \( k_1 = 0 \) and \( k_2 = 0 \), thus the remedial currents are zero. It can be noticed from (21) that the remedial voltages are related to the back EMFs of short-circuited phases. Meanwhile, the short-circuit currents are also directly related to their phase back EMFs, and back EMFs are time-variable in \( d_l-q_l \). Hence, the remedial currents and voltages are time-variables in \( d_l-q_l \). Additionally, the remedial currents are employed to cancel the torque fluctuations caused by short-circuit currents, and they are not related to the average torque. Therefore, to achieve the VC operation, they should be subtracted from the currents in the remaining healthy phases. According to (21)-(23), by using (16), the decoupled
model of FTPM motor with phase-B and phase-E faults in \( d_1-q_1 \) can be derived as

\[
\begin{align*}
\dot{u}_d &= R_i \dot{i}_d + L_s \frac{d i_d}{dt} - \omega L_s i_q \\
\dot{u}_q &= R_i \dot{i}_q + L_s \frac{d i_q}{dt} + \omega L_s i_d
\end{align*}
\]  

(24)

The torque can be derived from the derivative of the magnetic co-energy with respect to the rotor position [28] by using (6), (8) and (14)-(16), and then it can be expressed as

\[
T_c = 2.5p \lambda_m i_d
\]

(25)

where \( \lambda_m \) is the permanent magnet flux-linkage, \( p \) is the pole-pair number.

It can be noticed from (24) and (25) that the FTPM motor model with either nonadjacent-phase open-circuit or short-circuit faults is completely decoupled in \( d_1-q_1 \) and it nearly has the same voltage and torque equations as the healthy one.

2) ADJACENT-PHASE FAULTS

According to the aforementioned method, when short-circuit or open-circuit faults occur in phase-C and phase-D, the remedial voltages and currents in \( \alpha' - \beta' \) can be derived as

\[
\begin{align*}
\dot{u}_{d'} &= -0.324 (k_3 e_C + k_4 e_D) \\
\dot{u}_{q'} &= 0.236 (k_3 e_C - k_4 e_D) \\
\dot{i}_{d'} &= 0.324 (k_3 i_C + k_4 i_D) \\
\dot{i}_{q'} &= -0.236 (k_3 i_C - k_4 i_D)
\end{align*}
\]  

(26)

The decoupled model of FTPM motor with phase-C and phase-D faults in \( d_{\text{post}1}-q_{\text{post}1} \) is the same as (24), and the output torque is the same as (25). It should be noticed that if phase-C and phase-D are open-circuited, then \( k_3 = 0 \) and \( k_4 = 0 \), thus the remedial voltages and currents are zero.

D. PROPOSED VC STRATEGY

According to (20)-(25), when the controller outputs the voltages (28), the fault-tolerant currents (6) and (8) are generated in the remaining healthy phases after open-circuit or short-circuit faults occurrence to non-adjacent double-phase faults. According to (5) and (7), the equalizing stator MMF before and after fault can be achieved. Then, the constant stator MMF and rotor MMF can generate invariable torque. Thus, the torque fluctuations caused by fault can be restrained, and almost the same torque as that under healthy condition can be maintained. Therefore, the FTPM motor can eliminate the impacts of nonadjacent double-phase faults. It can be seen from (24) that the decoupled model in \( d_{\text{post}1}-q_{\text{post}1} \) is the same as healthy one. Hence, when the nonadjacent double-phase faults occur, the VC strategy can be still adopted as shown in Fig. 3. When the adjacent-phase faults occur, the output voltages of the controller are illustrated in (29), and then the fault-tolerant currents (10) and (12) can be generated in the remaining healthy phases. According to (9) and (11), the equalizing stator MMF before and after fault is also achieved. Thus, the same torque as in healthy operation can be obtained, and then the impacts of adjacent double-phase faults can be eliminated. Fig 4 shows the proposed VC under adjacent double-phase fault condition. It can be seen from (25) that when the double-phase faults occur, the torque equation is also the same as that of the healthy motor. Hence, if \( i_d \) is kept the same value as \( i_q \) under healthy condition. Therefore, the FTPM motor can achieve disturbance-free operation after double-phase faults occurrence. It can be seen that the proposed VC shown in Figs. 3 and 4 almost has the same control block diagram as Fig. 2, except the transformation matrices and imposition of remedial voltages. It should be noted that although the motor are fault-tolerant designed, the short-circuit phase should be still isolated from the bridge of voltage source inverter. The fault phases under short-circuit faults are isolated by normally closed relays. When the motor operates under healthy condition, there is no signal to control the relays, and the relays are on-state. When the short-circuit faults are detected, the relays are controlled to be off-state, and then the faulty phases are isolated from the bridges of the voltage source inverter.

\[
\begin{align*}
\begin{bmatrix}
\dot{u}_{A} \\
\dot{u}_{B} \\
\dot{u}_{C}
\end{bmatrix} &= T_{\text{post}1}^{-1} \begin{bmatrix}
C_{\text{post}1} & 0 \\
0 & C_{\text{post}1}
\end{bmatrix} \begin{bmatrix}
\dot{u}_{d} \\
\dot{u}_{q}
\end{bmatrix} + \begin{bmatrix}
\dot{e}_A \\
\dot{e}_C
\end{bmatrix} + \begin{bmatrix}
e_A \\
\epsilon_C
\end{bmatrix} \\
\begin{bmatrix}
\dot{u}_{A} \\
\dot{u}_{B} \\
\dot{u}_{C}
\end{bmatrix} &= T_{\text{post}2}^{-1} \begin{bmatrix}
C_{\text{post}2} & 0 \\
0 & C_{\text{post}2}
\end{bmatrix} \begin{bmatrix}
\dot{u}_{d} \\
\dot{u}_{q}
\end{bmatrix} + \begin{bmatrix}
\dot{e}_A \\
\dot{e}_B
\end{bmatrix} + \begin{bmatrix}
e_A \\
\epsilon_B
\end{bmatrix}
\end{align*}
\]  

(28)
When the non-adjacent faulty phases are phase-B and phase-E, phase-C and phase-A, phase-D and phase-B, phase-E and phase-C, or phase-A and phase-D, the corresponding \( k_5 \) is 0, 1, 2, 3, or 4, respectively. Then the only thing to do is that \( \theta \) in (16) is replaced by \( \theta - 0.4k_5\pi \).

When the adjacent faulty phases are phase-C and phase-D, phase-D and phase-E, phase-E and phase-A, phase-A and phase-B, or phase-B and phase-C, the corresponding \( k_6 \) is 0, 1, 2, 3, or 4, respectively. Then the only thing to do is that \( \theta \) in (16) is replaced by \( \theta - 0.4k_6\pi \). Meanwhile, the back EMFs in the remedial voltages are replaced by the back EMFs of faulty phases; the phase currents in the remedial currents are replaced by the currents in the faulty phases. Therefore, they can be easily achieved by permutation when either open-circuit or short-circuit faults occur in other double-phases. Therefore, the FTPM motor can achieve disturbance-free operation after arbitrary double-phase faults occurrence.

IV. EXPERIMENTAL RESULTS

An experimental platform was designed to verify the feasibility of the proposed VC strategy as shown in Fig. 5. The five-phase FTPM motor shown in Fig. 1, torque sensor and a DC generator are mounted coaxially. The FTPM motor is driven by a voltage source inverter with five bridges that is mainly composed of two conventional three-phase intelligent power modules PM100CVA120 and a controller based on TMS320F2812 DSP. The rotor position is obtained by using a digital incremental encoder with 2048 pulses per resolution and DSP QEP peripheral. The load is provided by a DC generator connected to a resistance. The current waveforms are shown in a YOKOGAWA DLM2034 oscilloscope connected with Tek A622 current clamps. The currents and speed in the synchronous rotating frame can be obtained by a D/A converter TLV5614 connected to the DSP SPI peripheral.

The FTPM motor operates in torque mode with the strategies shown in Figs. 2-4. The carrier-based pulse width modulation (CPWM) technique in [29] is adopted under both healthy and fault conditions. To avoid saturation of flux density in iron and demagnetization of PMs, the limitation of \( q \)-axis current reference is set as 5 A.

A. TORQUE FLUCTUATIONS CANCELLATION

Fig. 6 shows the torque and phase current responses under both healthy and double-phase fault conditions. When the double-phase open-circuit faults occur in either nonadjacent-phase (phase-B and phase-E) or adjacent-phase (phase-C and phase-D), the currents in the remaining healthy phases are deteriorated and the torque fluctuations are high. The main reason is that the coupling of \( i_a \) and \( i_y \) and the coupling of \( i_b \) and \( i_y \) according to (3) and (4). Compared with nonadjacent-phase open-circuit faults, when adjacent-phase open-circuit faults occur, the torque fluctuations are much
larger, the currents in the remaining healthy phases are more seriously distorted, and the amplitudes of currents in phase-B and phase-E under adjacent-phase faults are higher than that in phase-C and phase-D under nonadjacent-phase faults. When short-circuit faults occur in either nonadjacent-phase (phase-B and phase-E) or adjacent-phase (phase-C and phase-D), the currents in the remaining healthy phases are seriously distorted. According to (3) and (4), $i_a$ and $i_x$ are coupling, thus $i_x$ cannot be controlled to zero by adopting the traditional VC strategy. And according to (1), the phase-A current is equal to $i_a + i_x$. Thus, the phase-A current contains third harmonics. Thus, the torque fluctuations are seriously deteriorated, and the pulsating amplitudes of torque are larger than the average torque in healthy operation. Compared with nonadjacent-phase short-circuit faults, adjacent-phase short-circuit faults cause more serious pulsating torque. Compared with open-circuit fault, the short-circuit faults cause much higher fluctuating torque. Hence, the adjacent-phase short-circuit faults cause the highest fluctuating torque, thus resulting in the most dangerous and harmful impact on FTPM motor drive.

To evaluate the online control reconfiguration and steady-state performance of the proposed VC strategy, the process from healthy to fault-tolerant operation was tested. The proposed VC strategy was activated at once when the double-phase faults were injected. Fig. 7 shows the torque and current responses under both healthy condition with traditional VC strategy and double-phase fault condition with proposed VC strategy. It can be noticed that during the transition from healthy to fault-tolerant operation, the currents in the healthy phases are a little larger than the steady-state currents in fault-tolerant operation, and small torque fluctuations are existed. The main reason is the control reconfiguration and current PI controllers. Thus, there is a little impact to FTPM motor during the process of the control reconfiguration. When open-circuit faults occur in phase-B and phase-E (nonadjacent double-phases), the amplitudes of fault-tolerant currents in the healthy phases enlarge, and the amplitudes of phase-C and phase-D currents are larger than that of phase-A current. The angle between phase-C and phase-D currents shifts to the double angle of that in healthy operation. Thus, the phase currents are in accordance with (6). The torque fluctuations caused by the open-circuit faults are restrained effectively, and the average torque is equal to that in healthy operation. When phase-C and phase-D (adjacent double-phases) are open-circuited, the amplitudes of fault-tolerant currents in healthy phases increase, and the amplitude of phase-A current is larger than that of phase-B and phase-E currents. The angle between phase-B and phase-E currents enlarges to the double angle of that in healthy operation. Thus, the currents in the remaining healthy phases are consistent with (10). The fluctuating torque caused by the fault is cancelled, and the torque ripples are almost the same as that in healthy operation. When nonadjacent-phase short-circuit faults occur in phase-B and phase-E, the currents in phase-B and phase-E are determined by their phase back EMFs, resistors and inductances, so their amplitude increases suddenly and then attenuates in exponent to constant value later. The amplitude of phase-A current becomes larger. Fortunately, the pulsating torque caused by the fault is restrained effectively, and the torque is smooth. When adjacent-phase short-circuit faults occur in phase-C and phase-D, the amplitudes of phase-C and phase-D currents also enlarge suddenly and then attenuates in exponent to constant value later. The amplitude of phase-A current becomes much bigger, but it is in accordance with the sum of (10) and (12). Fortunately, the pulsating torque caused by the fault is restrained, and the torque ripples are almost the same as that in healthy operation. Therefore, when double-phase open-circuit or short-circuit
faults occur in either nonadjacent-phases or adjacent-phases, the FTPM motor with the proposed VC strategy can continue operation with smooth torque and almost the same torque ripples as that in healthy operation. Therefore, safe and reliable operation is achieved under fault condition. Fig. 7 also reveals that the fault-tolerant currents under adjacent-phase short-circuit fault condition is the biggest among those under the fault conditions. And the largest currents may lead to saturation of flux density in iron and demagnetization of PMs. Hence, the adjacent-phase short-circuit faults will result in the most dangerous impact on FTPM motor. Fortunately, the fault-tolerant currents are in accordance with aforementioned analysis, the proposed VC can restrain the impact of double-phase faults under the limited value of phase currents. Therefore, the FTPM motor with the proposed VC can operate for a short time after the double-phase faults occurrence, and the healthy dynamic performance is employed as the reference. Fig. 9 shows the current responses when the torque steps between 2 Nm and 4 Nm under healthy condition. The waveforms in zoom are magnified. The response time is 1 ms. Fig. 10 shows the response time with the proposed VC strategy under nonadjacent-phase open-circuit fault condition. It can be observed that the response time is still 1 ms no matter whether the torque steps up or down with the same changes. Fig. 11

**FIGURE 8.** Torque and current responses to transition from healthy to fault-tolerant operations (12 Nm/div, 20 A/div, 500 ms/div, 50 ms/div in zoom1 and zoom2). (a) Nonadjacent-phase (phase-B and phase-E) open-circuit faults. (b) Adjacent-phase (phase-C and phase-D) open-circuit faults.

**FIGURE 9.** Current responses to step changes in torque reference with traditional VC under healthy condition (20 A/div, 50 ms/div, 2 ms/div in the zoom). (a) Torque reference up-steps. (b) Torque reference down-steps.

**FIGURE 10.** Current responses to step changes in torque references with proposed VC under phase-B and phase-E open-circuit fault condition (20 A/div, 50 ms/div, 2 ms/div in the zoom). (a) Torque reference up-steps. (b) Torque reference down-steps.

**FIGURE 11.** Current responses to step changes in torque references with proposed VC under nonadjacent-phase (phase-B and phase-E) open-circuit fault condition. (a) Torque reference up-steps. (b) Torque reference down-steps.

**B. DYNAMIC PERFORMANCE**

To test dynamic performance of the FTPM motor drive, the current response is analyzed during the torque steps after the
shows the response time with the proposed VC strategy under adjacent-phase (phase-C and phase-D) open-circuit fault condition. It can be noticed that the response time is 1 ms with the same torque steps. Fig. 12 shows the response time with the proposed VC strategy under nonadjacent-phase (phase-B and phase-E) short-circuit fault condition. It can be seen that the response time is 1 ms when the same torque steps change. Fig. 13 shows the response time with the proposed VC strategy under adjacent-phase (phase-C and phase-D) short-circuit fault condition. It reveals that the response time is 1 ms with the same torque steps. Therefore, the response time of the FTPM motor with proposed VC strategy is equal to that of healthy one. It should be noted that the same PI controllers are used in the current loops. Hence, the proposed VC strategy can maintain the same dynamic performance as that of the healthy motor with traditional VC method.

The speed performance of the FTPM motor with proposed VC strategy under the double-phase faults is also analyzed, and the speed response in healthy operation is
FIGURE 15. Speed and current responses to step changes in speed references with proposed VC under phase-B and phase-E open-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 16. Speed and current responses to step changes in speed references with proposed VC under phase-C and phase-D open-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 17. Speed and current responses to step changes in speed references with proposed VC under phase-B and phase-E short-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 18. Speed and current responses to step changes in speed references with proposed VC under phase-C and phase-D short-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 14. Speed and current responses to step changes in speed references with proposed VC under phase-B and phase-E open-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 15. Speed and current responses to step changes in speed references with proposed VC under phase-B and phase-E open-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 16. Speed and current responses to step changes in speed references with proposed VC under phase-C and phase-D open-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 17. Speed and current responses to step changes in speed references with proposed VC under phase-B and phase-E short-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

FIGURE 18. Speed and current responses to step changes in speed references with proposed VC under phase-C and phase-D short-circuit fault condition (400 r/min/div, 20 A/div, 200 ms/div). (a) Speed reference up-steps. (b) Speed reference down-steps.

used as reference. Figs. 14-18 show the speed and current responses during the speed reference steps. The output of speed controller is \( q \)-axis current reference, and the steps in the speed are between 100 r/min and 200 r/min. It can be observed that the FTPM motor under double-phase faults almost has the same speed regulating characteristic as that in healthy operation during the speed reference steps. The \( q \)-axis currents are nearly the same as that in healthy operation. It should be noted that all speed controllers have the same PI parameters. The fault-tolerant currents in double-phase fault operation are larger than that in healthy operation, and they are in consistent with (6), (8), (10) and (12). The short-circuit currents have quite different variation tendency from healthy phase currents. The main reason is that the short-circuit current is related to its phase back EMF and impedance. Fortunately, the torque is only related to the \( q \)-axis current with the proposed VC. Hence, the double-phase faults with
the proposed VC strategy have little impact on the torque. Therefore, the proposed VC strategy is effective when the arbitrary double-phase faults occur.

V. CONCLUSION

This paper has newly proposed a unified decoupling VC strategy based on reduced-order orthogonal transformation matrices for a five-phase FTPM motor with arbitrary double-phase faults. The key conclusions are summarized as follows.

1) Among all the faults, the adjacent-phase short-circuit faults cause the most serious impact on motor drive.

2) Based on the derivation of reduced-order orthogonal transformation matrices and remedial voltages, the decoupled motor model is achieved in the synchronous rotating frame, which allows VC strategy to be suitable for fault-tolerant operation and minimal reconfiguration after double-phase faults occurrence.

3) It has been verified that the FTPM motor with the proposed VC strategy can deliver smooth torque, improve its dynamic performance and achieve disturbance-free operation under double-phase fault condition.

Therefore, the unified decoupling VC strategy is a promising solution to restrain the impact of double-phase open-circuit or short-circuit faults and is easy to implement. However, it is not suitable for single-phase open-circuit or short-circuit fault.

REFERENCES

[1] Q. Chen, G. Xu, G. Liu, W. Zhao, L. Liu, and Z. Lin, “Torque ripple reduction in five-phase IPM motors by lowering interactional MMF,” IEEE Trans. Ind. Electron., vol. 65, no. 11, pp. 8520–8531, Nov. 2018.

[2] M. Bermudez, I. Gonzalez-Prieto, F. Barrero, H. Guzman, X. Kestelyn, and M. J. Duran, “An experimental assessment of open-phase fault-tolerant virtual-vector-based direct torque control in five-phase induction motor drives,” IEEE Trans. Power Electron., vol. 33, no. 3, pp. 2774–2784, Mar. 2018.

[3] Q. Chen, G. Liu, W. Zhao, L. Qu, and G. Xu, “Asymmetrical SVPWM fault-tolerant control of five-phase PM brushless motors,” IEEE Trans. Energy Convers., vol. 32, no. 1, pp. 12–22, Mar. 2017.

[4] G. Choi and T. M. Jahns, “Investigation of key factors influencing the response of permanent magnet synchronous machines to three-phase symmetrical short-circuit faults,” IEEE Trans. Energy Convers., vol. 31, no. 4, pp. 1488–1497, Dec. 2016.

[5] W. Zhao, K. Du, and L. Xu, “Design considerations of fault-tolerant permanent magnet Vernier machine,” IEEE Trans. Ind. Electron., vol. 67, no. 9, pp. 7290–7300, Sep. 2020.

[6] W. Zhao, X. Pan, J. Ji, L. Xu, and J. Zheng, “Analysis of PM eddy current loss in four-phase fault-tolerant flux-switching permanent-magnet machines by air-gap magnetic field modulation theory,” IEEE Trans. Ind. Electron., vol. 67, no. 7, pp. 5369–5378, Jul. 2020.

[7] F. Wu, H. Ge, A. M. El-Rafeia, M. Farshadnia, A. Pouramin, and R. Dutta, “Partially-coupled d–q–0 components of magnetically-isolated FSCW IPM machines with Open-End-Winding drives,” IEEE Trans. Ind. Appl., vol. 56, no. 2, pp. 1397–1407, Mar/Apr. 2020.

[8] M. J. Duran and F. Barrero, “Recent advances in the design, modeling, and control of multiphase machines—Part II,” IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 456–468, Jan. 2016.

[9] B. Sen and J. Wang, “Stationary frame fault-tolerant current control of polyphase permanent-magnet machines under open-circuit and short-circuit faults,” IEEE Trans. Power Electron., vol. 31, no. 7, pp. 4684–4696, Jul. 2016.

[10] M. Bermudez, I. Gonzalez-Prieto, F. Barrero, H. Guzman, M. J. Duran, and X. Kestelyn, “Open-phase fault-tolerant direct torque control technique for five-phase induction motor drives,” IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 902–911, Feb. 2017.

[11] Y. Wang, L. Geng, W. Hao, and W. Xiao, “Improved control strategy for fault-tolerant flux-switching permanent-magnet machine,” IEEE Trans. Power Electron., vol. 34, no. 5, pp. 4536–4557, May 2019.

[12] T. Tao, W. Zhao, Y. Du, Y. Cheng, and J. Zhu, “Simplified fault-tolerant model predictive control for a five-phase permanent-magnet motor with reduced computation burden,” IEEE Trans. Power Electron., vol. 35, no. 4, pp. 3850–3858, Apr. 2020.

[13] A. Kiselev, G. R. Cataoquino, A. Kuznietsov, and R. Leidhold, “Finite-control-set MPC for open-phase fault-tolerant control of PM synchronous motor drives,” IEEE Trans. Ind. Electron., vol. 67, no. 6, pp. 4444–4452, Jun. 2020.

[14] G. Liu, C. Song, and Q. Chen, “FCS-MPC-based fault-tolerant control of five-phase IPM motor for MTPA operation,” IEEE Trans. Power Electron., vol. 35, no. 3, pp. 2882–2894, Mar. 2020.

[15] Z. Wang, Y. Jiang, and Y. Hu, “Decoupled vector space decomposition based space vector modulation for dual three-phase three-level motor drives,” IEEE Trans. Power Electron., vol. 33, no. 12, pp. 10683–10697, Dec. 2018.

[16] H. Guzman, M. J. Duran, F. Barrero, L. Zarri, B. Bogado, I. G. Prieto, and M. R. Arahal, “Comparative study of predictive and resonant controllers in fault-tolerant five-phase induction motor drives,” IEEE Trans. Ind. Electron., vol. 63, no. 1, pp. 606–617, Jan. 2016.

[17] L. Cheng, Y. Sui, P. Zheng, P. Wang, and F. Wu, “Implementation of postfault decoupling vector control and mitigation of current ripple for five-phase fault-tolerant PM machine under single-phase open-circuit fault,” IEEE Trans. Power Electron., vol. 33, no. 10, pp. 8623–8636, Oct. 2018.

[18] H. Zhou, W. Zhao, G. Liu, R. Cheng, and Y. Xie, “Remedial field-oriented control of five-phase fault-tolerant permanent-magnet motor by using reduced-order transformation matrices,” IEEE Trans. Ind. Electron., vol. 64, no. 1, pp. 169–178, Jan. 2017.

[19] Q. Chen, W. Zhao, G. Liu, and Z. Lin, “Extension of virtual-signal-injection-based MTPA control for five-phase IPMMSM into fault-tolerant operation,” IEEE Trans. Ind. Electron., vol. 66, no. 2, pp. 944–955, Feb. 2019.

[20] Q. Chen, L. Gu, Z. Lin, and G. Liu, “Extension of space-vector-signal-injection-based MTPA control into SVPWM fault-tolerant operation for five-phase IPMMSM,” IEEE Trans. Ind. Electron., vol. 67, no. 9, pp. 7321–7333, Sep. 2020.

[21] B. Tian, Q.-T. An, J.-D. Duan, D. Semenov, D.-Y. Sun, and L. Sun, “Cancellation of torque ripples with FOC strategy under two-phase failures of the five-phase PM motor,” IEEE Trans. Power Electron., vol. 32, no. 7, pp. 5459–5472, Jul. 2017.

[22] G. Liu, Z. Lin, W. Zhao, Q. Chen, and G. Xu, “Third harmonic current injection in fault-tolerant five-phase permanent-magnet motor drive,” IEEE Trans. Power Electron., vol. 33, no. 8, pp. 6970–6979, Aug. 2018.

[23] C. Xiong, T. Guan, P. Zhou, and H. Xu, “A fault-tolerant FOC strategy for five-phase SPMSM with minimum torque ripples in the full torque operation range under double-phase open-circuit fault,” IEEE Trans. Ind. Electron., vol. 67, no. 11, pp. 9059–9072, Nov. 2020.

[24] Q. Chen, G. Liu, W. Zhao, L. Sun, M. Shao, and Z. Liu, “Design and comparison of two fault-tolerant interior-permanent-magnet motors,” IEEE Trans. Ind. Electron., vol. 61, no. 12, pp. 6615–6623, Dec. 2014.

[25] H. Guzman, M. J. Duran, F. Barrero, B. Bogado, and S. Toral, “Speed control of five-phase induction motors with integrated open-phase fault operation using model-based predictive current control techniques,” IEEE Trans. Ind. Electron., vol. 61, no. 9, pp. 4474–4484, Sep. 2014.

[26] H. Zhou, G. Liu, W. Zhao, X. Yu, and M. Gao, “Dynamic performance improvement of five-phase permanent-magnet motor with short-circuit fault,” IEEE Trans. Ind. Electron., vol. 65, no. 1, pp. 145–155, Jan. 2018.

[27] G. Liu, L. Qu, W. Zhao, Q. Chen, and Y. Xie, “Comparison of two SVPWM control strategies of five-phase fault-tolerant permanent-magnet motor,” IEEE Trans. Power Electron., vol. 31, no. 9, pp. 6621–6630, Sep. 2016.

[28] A. Gaeta, G. Scelba, and A. Consoli, “Modeling and control of three-phase PMSMs under open-phase fault,” IEEE Trans. Ind. Appl., vol. 49, no. 1, pp. 74–83, Jan./Feb. 2013.

[29] O. Dordovic, M. Jones, and E. Levi, “A comparison of carrier-based and space vector PWM techniques for three-level five-phase voltage source inverters,” IEEE Trans. Ind. Appl., vol. 9, no. 2, pp. 609–619, May 2013.

[30] H. Zhou, C. Zhou, W. Tao, J. Wang, and G. Liu, “Virtual-stator-flux-based direct torque control of five-phase fault-tolerant permanent-magnet motor with open-circuit fault,” IEEE Trans. Power Electron., vol. 35, no. 5, pp. 5007–5017, May 2020.
CHENG CHEN received the B.Sc. degree in electrical engineering from the Yancheng Institute of Technology, Yancheng, China, in 2017. He is currently pursuing the M.Sc. degree in electrical engineering with Jiangsu University, Zhenjiang, China. His current research interests include drive and control of PM motors.

HUAWEI ZHOU (Member, IEEE) received the B.Sc. and M.Sc. degrees in control engineering from Jiangsu University, Zhenjiang, China, in 2003 and 2006, respectively, and the Ph.D. degree in electrical engineering from the Graduate University of Chinese Academy of Sciences, Beijing, China, in 2012.

He has been with Jiangsu University, since 2003, where he is currently a Professor with the School of Electrical and Information Engineering. From 2017 to 2018, he was a Visiting Academic with the Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield, U.K. His teaching and research interests include electric machines design, PM motor drives for electric vehicles and electromagnetic suspension, fault-tolerance analysis, and intelligent control.

GUANGHUI WANG (Member, IEEE) received the B.S. degree in electronic information engineering from the China University of Geosciences, Beijing, China, in 2005, and the Ph.D. degree in pattern recognition and intelligent system from the Beijing Institute of Technology, Beijing, in 2013.

He has been a Researcher with the China North Vehicle Research Institute, since 2013. From 2017 to 2018, he was a Visiting Academic with the Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield, U.K. His research interests include the development of electrical machine, servo control, and artificial intelligence.

GUOHAI LIU (Senior Member, IEEE) received the B.Sc. degree from Jiangsu University, Zhenjiang, China, in 1985, and the M.Sc. and Ph.D. degrees from Southeast University, Nanjing, China, in 1988 and 2002, respectively, all in electrical engineering and control engineering.

He has been with Jiangsu University, since 1988, where he is currently a Professor and the Dean of the School of Electrical and Information Engineering. From 2003 to 2004, he was a Visiting Professor with the Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield, U.K. His teaching and research interests include electrical machines, motor drives for electric vehicles, and intelligent control. He has authored or coauthored over 200 technical articles and four textbooks, and holds 30 patents in these areas. Dr. Liu is a Fellow of IET.