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Control strategy for dual three-phase PMSM based on reduced order mathematical model under fault condition due to open phases

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Abstract: The high fault-tolerance ability is one important application characteristic of multiphase motors. At present, researches on fault-tolerant control of multiphase motors are focused on open-phase faults. When an open-phase fault occurs for the dual three-phase machine, the α–β subspace and $z1$–$z2$ subspace currents are no longer decoupled, so the mathematical model with open phases should be set up. In this study, the mathematical model of the dual three-phase permanent-magnet synchronous motor (PMSM) with one open phase is set up by the vector space decomposition modelling method, and two optimal current control modes of minimum stator loss and maximum torque output are achieved by vector control strategy. The experimental results demonstrate the effectiveness and feasibility of the proposed strategy.

1 Introduction

Multiphase motors are suited for application fields such as electric vehicles, wind power generation, and aerospace applications [1–3]. One important application characteristic of multiphase motors is the good fault-tolerant ability. By the way of fault isolation, various open circuit and short-circuit faults in the motor drive system can be converted into open-phase faults. Therefore, researches on fault-tolerant control of multiphase motors are focused on open-phase faults.

At present, the researches on multiphase motors are mainly focused on five-phase and six-phase motors. The dual three-phase machine is a favourable choice among various multiphase machine structures. It has two sets of three-phase stator windings spatially shifted by 30 electrical degrees. It is also known as the asymmetrical six-phase machine, double-star machine or split-phase machine. With the special winding structure, the dual three-phase motor can eliminate sixth harmonic torque pulsations which always exist in conventional three-phase motors [4, 5].

The purpose of the fault-tolerant control is to maintain normal torque output and minimise torque pulsations. The fault-tolerant control strategy based on magnetic motive force (MMF) balance principle for three-phase motors is proposed in [6], but the neutral point of the motor must be connected to the midpoint of the DC bus voltage. This fault-tolerant control strategy has been extended to multiphase motors [7], and the optimised phase current references can be obtained according to optimisation goals such as minimum stator loss and maximum torque output. However, the mathematical model of open-phase faults is not established, and only the hysteresis current control can be adopted. Therefore, the above fault-tolerant control strategy lacks versatility.

The mathematical model of the dual three-phase motor with one open phase has been established in [8, 9], and the vector control and pulse-width modulation (PWM) strategies under fault condition are proposed. The reduced order mathematical model for the five-phase permanent-magnet synchronous motor (PMSM) with one open phase is established in [10], but there is a strong coupling between d-axis and q-axis. By introducing the additional transformation matrix, the mathematical model is transformed into a constant equation with disturbance. The feed forward control strategy is used to compensate for the disturbance, and the currents proportional–integral (PI) control under fault condition is achieved. The fault-tolerant control strategy based on normal decoupling transformation for multiphase motors with an odd number of phases is purposed in [11], the theoretical analysis proves that this strategy can guarantee the same MMF under a fault condition, and the seven-phase motor is taken as an example to verify the experiment. This strategy is applied to the dual three-phase induction motor in [12].

In this paper, the mathematical model of the dual three-phase PMSM (DT-PMSM) with one open phase is set up by the vector space decomposition modelling method, and two optimal current control modes of minimum stator loss and maximum torque output are achieved by vector control strategy. The experimental results demonstrate the effectiveness and feasibility of the proposed strategy.

2 Mathematical model of the DT-PMSM in the fault mode

The DT-PMSM system fed by six-phase voltage source inverter is shown in Fig. 1.

Two isolated neutrals are usually adopted for the DT-PMSM on the healthy operation. This configuration prevents the flow of zero-sequence currents and simplifies the structure of the control system. Take F phase as an example, the dual three-phase motor drive system with the single open-phase fault is shown in Fig. 2.

2.1 Mathematical model in the natural coordinate system

It is assumed that the stator current and the flux-linkage are sinusoidally distributed. The voltage and flux equations are

$$U_{\mathrm{s}} = \boldsymbol{R}_{\mathrm{s}}\boldsymbol{I}_{\mathrm{s}} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}} \tag{1}$$

$$\boldsymbol{\psi}_{\mathrm{s}} = \boldsymbol{L}_{\mathrm{s}}\boldsymbol{I}_{\mathrm{s}} + \gamma_{\mathrm{s}}\psi_{\mathrm{m}} \tag{2}$$

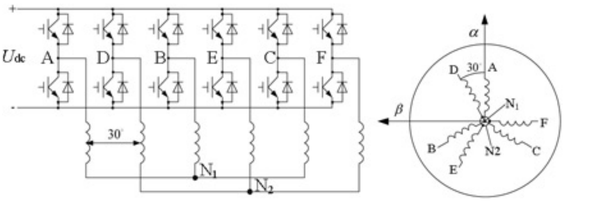

Fig. 1 *Dual three-phase motor system fed by six-phase voltage source inverter*

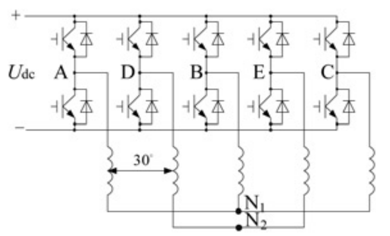

Fig. 2 *Dual three-phase motor drive system with single open-phase fault*

where

$$
\begin{aligned}
\boldsymbol{U}_{\mathrm{s}} &= [u_{\mathrm{A}} \quad u_{\mathrm{B}} \quad u_{\mathrm{C}} \quad u_{\mathrm{D}} \quad u_{\mathrm{E}}]^{\mathrm{T}} \\
\boldsymbol{I}_{\mathrm{s}} &= [i_{\mathrm{A}} \quad i_{\mathrm{B}} \quad i_{\mathrm{C}} \quad i_{\mathrm{D}} \quad i_{\mathrm{E}}]^{\mathrm{T}} \\
\boldsymbol{\psi}_{\mathrm{s}} &= [\psi_{\mathrm{A}} \quad \psi_{\mathrm{B}} \quad \psi_{\mathrm{C}} \quad \psi_{\mathrm{D}} \quad \psi_{\mathrm{E}}]^{\mathrm{T}} \\
\boldsymbol{R}_{\mathrm{s}} &= R_{\mathrm{s}}\boldsymbol{I}_5 \\
\boldsymbol{\gamma}_{\mathrm{s}} &= \left[\cos\theta \;\; \cos\left(\theta-\frac{2\pi}{3}\right) \;\; \cos\left(\theta-\frac{\pi}{6}\right) \;\; \cos\left(\theta-\frac{5\pi}{6}\right) \;\; \cos\left(\theta+\frac{\pi}{2}\right)\right]^{\mathrm{T}}
\end{aligned}
$$

ψ_{m} is the permanent magnet flux linkage amplitude; γ_{s} is the flux coefficient matrix.

For the surface mounted PMSM without considering saturation, $\boldsymbol{L}_{\mathrm{s}}$ is a constant matrix

$$
\boldsymbol{L}_{\mathrm{s}} = L_{\mathrm{aal}}\boldsymbol{I}_5 + L_0 \begin{bmatrix}
1 & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{4\pi}{3}\right) & \cos\left(\frac{\pi}{6}\right) & \cos\left(\frac{5\pi}{6}\right) \\
\cos\left(\frac{4\pi}{3}\right) & 1 & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{3\pi}{2}\right) & \cos\left(\frac{\pi}{6}\right) \\
\cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{4\pi}{3}\right) & 1 & \cos\left(\frac{5\pi}{6}\right) & \cos\left(\frac{3\pi}{2}\right) \\
\cos\left(\frac{\pi}{6}\right) & \cos\left(\frac{3\pi}{2}\right) & \cos\left(\frac{5\pi}{6}\right) & 1 & \cos\left(\frac{2\pi}{3}\right) \\
\cos\left(\frac{5\pi}{6}\right) & \cos\left(\frac{\pi}{6}\right) & \cos\left(\frac{3\pi}{2}\right) & \cos\left(\frac{4\pi}{3}\right) & 1
\end{bmatrix} \tag{3}
$$

where L_{aal} is the stator self-leakage inductance and L_0 is the main self-inductance average.

2.2 Determination of the transformation matrix

Similar to the normal operation of the DT-PMSM, the static decoupling transformation matrix under open-phase faults can be expressed as

$$
\boldsymbol{T}_{5\mathrm{s}} = [\boldsymbol{\alpha} \quad \boldsymbol{\beta} \quad z1 \quad z2 \quad z3]^{\mathrm{T}}
$$

where the α–β components are related to the electromechanical energy conversion, while the $z1$–$z2$–$z3$ components produce stator losses. According to the winding space distribution, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ can be obtained

$$
\begin{aligned}
\boldsymbol{\alpha}^{\mathrm{T}} &= \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \\
\boldsymbol{\beta}^{\mathrm{T}} &= \begin{bmatrix} 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}
\end{aligned}
$$

$z1$, $z2$, $z3$, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ need to meet the orthogonal to each other

$$
\begin{aligned}
&\boldsymbol{\alpha}^{\mathrm{T}} \cdot \boldsymbol{\beta} = 0 \\
&\boldsymbol{\alpha}^{\mathrm{T}} \cdot z1 = \boldsymbol{\beta}^{\mathrm{T}} \cdot z1 = 0 \\
&\boldsymbol{\alpha}^{\mathrm{T}} \cdot z2 = \boldsymbol{\beta}^{\mathrm{T}} \cdot z2 = z1^{\mathrm{T}} \cdot z2 = 0 \\
&\boldsymbol{\alpha}^{\mathrm{T}} \cdot z3 = \boldsymbol{\beta}^{\mathrm{T}} \cdot z3 = z1^{\mathrm{T}} \cdot \boldsymbol{z3} = z2^{\mathrm{T}} \cdot z3 = 0
\end{aligned} \tag{4}
$$

The matrix that satisfies (4) is not unique. For the isolated neutrals, all zero-sequence current components can be avoided, so $z2$ and $z3$ can be written as

$$
\begin{aligned}
z2 &= [1 \quad 1 \quad 1 \quad 0 \quad 0]^{\mathrm{T}} \\
z3 &= [0 \quad 0 \quad 0 \quad 1 \quad 1]^{\mathrm{T}}
\end{aligned}
$$

It is noticed that $\boldsymbol{\beta}$ is not orthogonal to $z3$, according to the restraint condition $i_{\mathrm{D}}+i_{\mathrm{E}}=0$, $\boldsymbol{\beta}$ can be modified as

$$
\boldsymbol{\beta}^{\mathrm{T}} = \begin{bmatrix} 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 & 0 \end{bmatrix}
$$

It will not affect the electromechanical energy conversion result of the α–β subspace. $z1$ can be deduced according to (4), and the static decoupling transformation matrix can be written as

$$
\boldsymbol{T}_{5\mathrm{s}} = \frac{1}{3}\begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 & 0 \\
1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\
1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 1
\end{bmatrix} \tag{5}
$$

It is only necessary to transform α–β components into the general synchronous reference frame d–q components. The rotating transformation matrix is

$$
\boldsymbol{P}_5 = \begin{bmatrix}
\cos\theta & \sin\theta & \boldsymbol{0} \\
-\sin\theta & \cos\theta & \boldsymbol{0} \\
\boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I}_3
\end{bmatrix} \tag{6}
$$

where $\boldsymbol{I}_3$ is a three-dimensional unit matrix. The final transformation matrix is

$$
\boldsymbol{T}_5 = P_5\boldsymbol{T}_{5\mathrm{s}} \tag{7}
$$

2.3 Modelling based on vector space decomposition

Similar to the modelling process of the healthy motor, by multiplying $\boldsymbol{T}_5$ to (1) and (2), the mathematical model under open-phase fault in the synchronous reference frame can be expressed as

$$
\begin{aligned}
\boldsymbol{T}_5\boldsymbol{U}_\mathrm{s} &= \boldsymbol{T}_5\boldsymbol{R}_\mathrm{s}\boldsymbol{I}_\mathrm{s} + \boldsymbol{T}_5\frac{\mathrm{d}\boldsymbol{\psi}_\mathrm{s}}{\mathrm{d}t} \\
&= (\boldsymbol{T}_5\boldsymbol{R}_\mathrm{s}\boldsymbol{T}_5^{-1})(\boldsymbol{T}_5\boldsymbol{I}_\mathrm{s}) + \frac{\mathrm{d}(\boldsymbol{T}_5\boldsymbol{\psi}_\mathrm{s})}{\mathrm{d}t} - \left(\frac{\mathrm{d}\boldsymbol{T}_5}{\mathrm{d}t}\boldsymbol{T}_5^{-1}\right)(\boldsymbol{T}_5\boldsymbol{\psi}_\mathrm{s}) \quad (8) \\
&= \boldsymbol{R}_{dq}\boldsymbol{I}_{dq} + \frac{\mathrm{d}\boldsymbol{\psi}_{dq}}{\mathrm{d}t} - \boldsymbol{\Omega}\boldsymbol{\psi}_{dq}
\end{aligned}
$$

$$
\begin{aligned}
\boldsymbol{T}_5\boldsymbol{\psi}_\mathrm{s} &= \boldsymbol{T}_5\boldsymbol{L}_\mathrm{s}\boldsymbol{I}_\mathrm{s} + \boldsymbol{T}_5\boldsymbol{\psi}_\mathrm{m} \\
&= (\boldsymbol{T}_5\boldsymbol{L}_\mathrm{s}\boldsymbol{T}_5^{-1})(\boldsymbol{T}_5\boldsymbol{I}_\mathrm{s}) + (\boldsymbol{T}_5\boldsymbol{\gamma}_\mathrm{s})\psi_m \qquad (9) \\
&= \boldsymbol{L}_{dq}\boldsymbol{I}_{dq} + \boldsymbol{\psi}_{dqm}
\end{aligned}
$$

only the d–q subspace is considered, where

$$
\begin{aligned}
\boldsymbol{U}_{dq} &= \boldsymbol{T}_5\boldsymbol{U}_\mathrm{s} = \begin{bmatrix} u_d & u_q \end{bmatrix}^\mathrm{T} \\
\boldsymbol{R}_{dq} &= \boldsymbol{T}_5\boldsymbol{R}_\mathrm{s}T_5^{-1} = R_\mathrm{s}\boldsymbol{I}_2 \\
\boldsymbol{I}_{dq} &= \boldsymbol{T}_5\boldsymbol{I}_\mathrm{s} = \begin{bmatrix} i_d & i_q \end{bmatrix}^\mathrm{T} \\
\boldsymbol{\psi}_{dq} &= \boldsymbol{T}_5\boldsymbol{\psi}_\mathrm{s} = \begin{bmatrix} \psi_d & \psi_q \end{bmatrix}^\mathrm{T}
\end{aligned}
$$

The velocity matrix can be written as

$$\boldsymbol{\Omega} = \frac{\mathrm{d}\boldsymbol{T}_5}{\mathrm{d}t}\boldsymbol{T}_5^{-1} = \omega\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \qquad (10)$$

The inductance matrix is

$$\boldsymbol{L}_{dq} = \boldsymbol{T}_5\boldsymbol{L}_\mathrm{s}\boldsymbol{T}_5^{-1} = L_\mathrm{aal}\boldsymbol{I}_2 + 3L_0A(\theta) \qquad (11)$$

where

$$A(\theta) = \begin{bmatrix} 0.75 + 0.25\cos2\theta & -0.25\sin2\theta \\ -0.25\sin2\theta & 0.75 - 0.25\cos2\theta \end{bmatrix}.$$

The permanent magnet flux linkage is

$$\psi_{dqm} = \boldsymbol{T}_5\psi_m = \psi_\mathrm{fd}\begin{bmatrix} 0.75 + 0.25\cos2\theta \\ -0.25\sin2\theta \end{bmatrix} \qquad (12)$$

The stator voltage in the d–q frame can be written as

$$
\begin{aligned}
\boldsymbol{U}_{dq} &= \boldsymbol{R}_{dq}\boldsymbol{I}_{dq} + \boldsymbol{L}_{dq}\frac{\mathrm{d}\boldsymbol{I}_{dq}}{\mathrm{d}t} + \left(\frac{\mathrm{d}\boldsymbol{L}_{dq}}{\mathrm{d}t} - \boldsymbol{\Omega}\boldsymbol{L}_{dq}\right)\boldsymbol{I}_{dq} \\
&\quad + \omega\psi_{\mathrm{f}d}B(\theta) \qquad (13)
\end{aligned}
$$

where

$$B(\theta) = \begin{bmatrix} -0.25\sin2\theta \\ 0.75 - 0.25\cos2\theta \end{bmatrix}.$$

The $z1$-axis voltage can be expressed as

$$u_{z1} = Ri_{z1} + L_\mathrm{aal}\frac{\mathrm{d}i_{z1}}{\mathrm{d}t} \qquad (14)$$

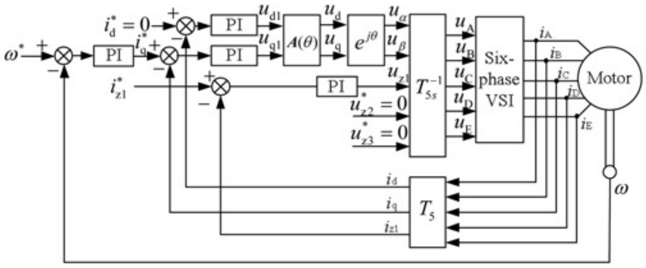

Fig. 3 *Fault-tolerant control strategy of DT-PMSM based on the reduced order mathematical model*

The $z2$-axis and $z3$-axis zero-sequence current components are zero due to the isolated neutrals, so corresponding current controllers are disabled, i.e. u_{z2}^*andu_{z3}^* are set to zero.

3 Vector control of the DT-PMSM with one open phase

There is no coupling between the $z1$-axis and the d–q subspace, so the z1-axis current controller can be designed independently. However, there is a strong coupling between d-axis and q-axis according to (13), the coupling can be reduced by multiplying the inverse matrix $\boldsymbol{A}^{-1}(\theta)$ to (13). The new voltage vector is defined as $\boldsymbol{U}_{d1q1} = \boldsymbol{A}^{-1}(\theta)\boldsymbol{U}_{dq} = \begin{bmatrix} u_{d1} & u_{q1} \end{bmatrix}^\mathrm{T}$. The control system for DT-PMSM with one open phase is shown in Fig. 3. Two different modes of operation are considered, i.e. minimum stator loss and maximum torque output [12]. The vector control for minimum stator loss could be realised by setting the current references in the $z1$-axis to zero, i.e. $i_{z1}^* = 0$.According to the inverse transformation of the static decoupling transformation matrix $\boldsymbol{T}_5$s, the desired currents for the remaining five healthy phases in the minimum stator loss mode can be obtained

$$
\begin{cases}
i_\mathrm{A} = I_\mathrm{m}\cos\theta \\
i_\mathrm{B} = 1.803I_\mathrm{m}\cos(\theta - 106.1°) \\
i_\mathrm{C} = 1.803I_\mathrm{m}\cos(\theta + 106.1°) \\
i_\mathrm{D} = 0.866I_\mathrm{m}\cos\theta \\
i_\mathrm{E} = 0.866I_\mathrm{m}\cos(\theta - 180°)
\end{cases} \qquad (15)
$$

where Im is the current amplitude of the DT-PMSM on the healthy operation. It is difficult to directly calculate the current reference of the harmonic subspace in the maximum torque output mode, but it can be obtained by the indirect method. According to the MMF balance principle [7], the desired currents for the remaining five healthy phases in maximum torque output mode are

$$
\begin{cases}
i_\mathrm{A} = 0 \\
i_\mathrm{B} = 1.732I_\mathrm{m}\cos(\theta - 90°) \\
i_\mathrm{C} = 1.732I_\mathrm{m}\cos(\theta + 90°) \\
i_\mathrm{D} = 1.732I_\mathrm{m}\cos\theta \\
i_\mathrm{E} = 1.732I_\mathrm{m}\cos(\theta - 180°)
\end{cases} \qquad (16)
$$

Multiplying the static decoupling transformation matrix $\boldsymbol{T}_5$s to (15), the current reference in the $z1$-axis is $-i_\alpha^*$, i.e. $i_{z1}^* = -i_\alpha^*$.

The stator losses and the maximum amplitude of stator currents in different control modes are listed in Table 1. The three-phase operation mode is to disable the whole three-phase winding containing the faulty phase.

4 Experiment result

To verify the feasibility of the proposed control strategy, we conducted experiments on a surface mounted DT-PMSM. The parameters of the DT-PMSM are listed in Table 2.

Table 1 Stator losses and the maximum amplitude of stator currents in different control modes

Mode	Mean stator losses, I_m^2R	Maximum amplitude of stator currents, I_m
six-phase operation	3	1
three-phase operation	6	2
min stator loss	4.5	1.803
max torque output	6	1.732

Table 2 Parameters of the DT-PMSM in experiment

pole number	3
induction *LD*	2.04 mH
induction *LQ*	2.04 mH
phase resistance	1.4 Ω/phase
permanent magnet flux	0.28 Wb

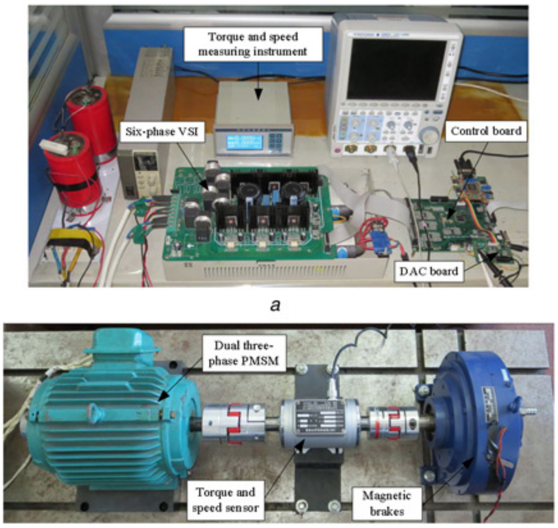

Fig. 4 *Experiment system rig*
a Drive control rig
b Motor test rig

The prototype of the experimental system rig is shown in Fig. 4. The core controller is a 16-bit MCU XE164 which is manufactured by Infineon Company. The DC bus voltage is 250 V, the switching frequency is 10 kHz with dead time 1.5 µs, the SPWM strategy is used, the motor speed is constant at 200 r/min, and the load is constant at 5 Nm in the experiments.

Fig. 5 presents the experimental results in normal condition, the speed with lower ripples that can be neglected. Experimental results with F phase open-circuit fault without fault-tolerant control are shown in Fig. 6. The currents appear obvious distortions, and the speed has an obvious secondary pulsation. The current vector locus in the α–β subspace is no longer a circle.

Fig. 7 shows the experimental results of minimum stator loss control with one open phase. The secondary pulsation of the speed is suppressed significantly. From the current waveform, it can be seen that the amplitudes and phases of each phase current have changed. Fig. 8 shows the experimental results of maximum

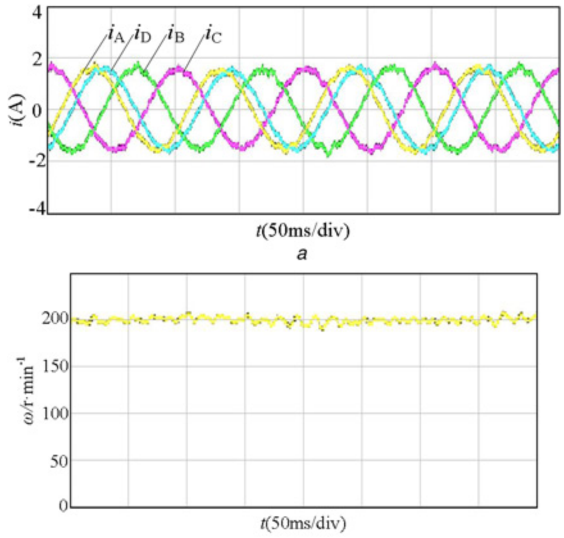

Fig. 5 *Experimental results in normal mode*
a Phase current
b Speed

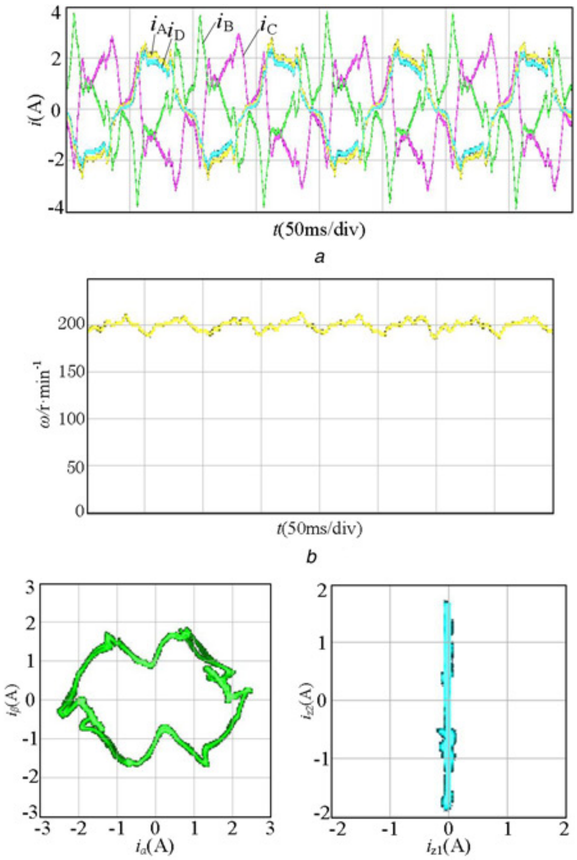

Fig. 6 *Experimental results with one open phase without fault-tolerant control*
a Phase current
b Speed
c α–β subspace currents
d *z*1–*z*2 subspace currents

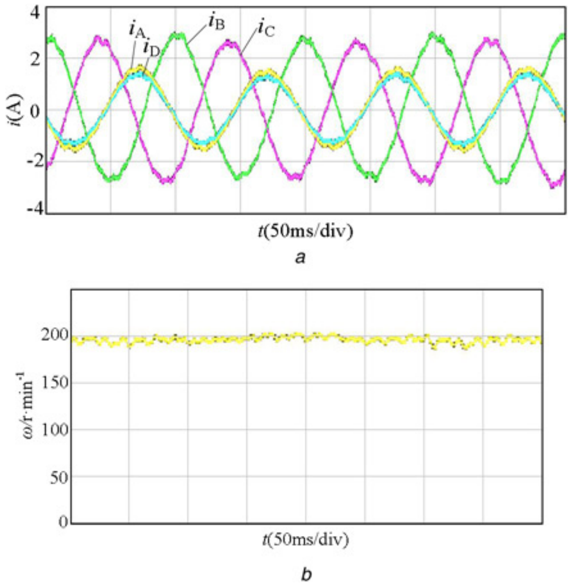

Fig. 7 *Experimental results of minimum stator loss control with one open phase*
a Phase current
b Speed

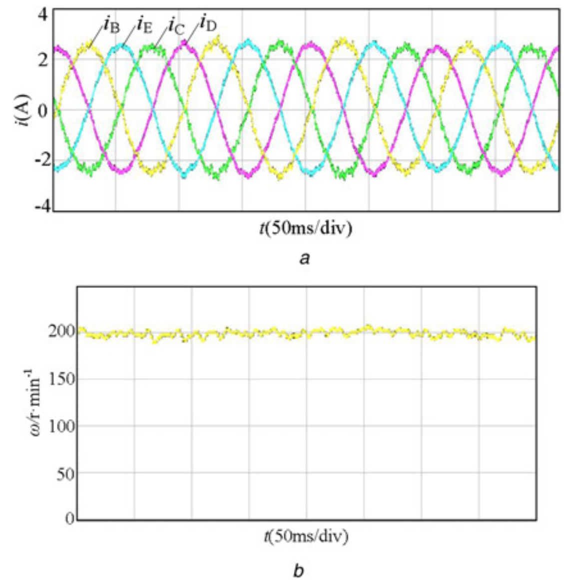

Fig. 8 *Experimental results of maximum torque output control with one open phase*
a Phase current
b Speed

torque output control with one open phase. It can be seen that the maximum amplitude of the stator currents is significantly reduced, and the amplitudes of each phase are basically equal.

Fig. 9 shows the motor startup waveforms. It can be seen that there is no significant difference between fault-tolerant control and normal operation of the motor. It shows that the fault-tolerant control strategy adopted in this paper has good dynamic response capability.

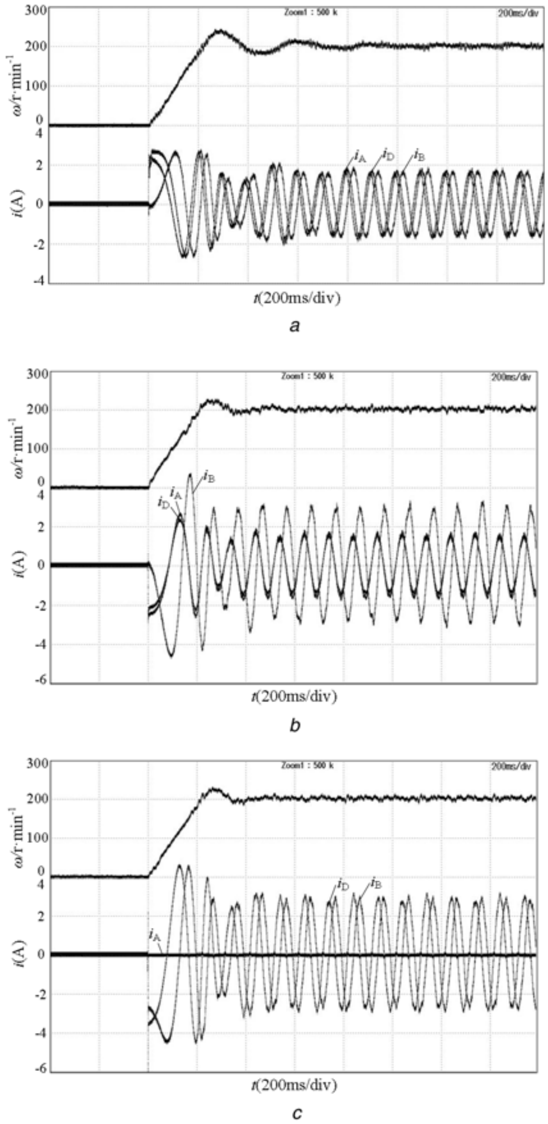

Fig. 9 *Motor startup waveforms*
a Normal mode
b Minimum stator loss control
c Maximum torque output control

5 Conclusion

With the DT-PMSM as the research object, the fault-tolerant control strategy with one open phase is researched. The transformation matrix is determined based on vector space decomposition modelling method and the mathematic model is set up. The experimental results demonstrate the effectiveness and feasibility of the proposed fault-tolerant control strategy. The proposed fault-tolerant control strategy can suppress the torque ripple effectively and improve the reliability of the drive system.

6 Acknowledgments

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