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Discrete-time command filtered adaptive fuzzy fault-tolerant control for induction motors with unknown load disturbances

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Abstract

In this paper, a command filtered fault-tolerant control (CFFTC) approach is investigated for induction motors (IMs) discrete-time system in the presence of actuator faults and unknown load disturbances. Firstly, the IMs system discrete-time model is obtained by Euler method. Then, the fuzzy logic systems (FLSs) is utilized to compensate for unknown actuator faults. Besides, introducing the error compensation mechanism into discrete-time systems via command filters, "complexity of computation" and noncausal problem can be conquered, and the filtering error is avoided concurrently. Finally, simulation results demonstrate the validity of the presented fault-tolerant method for IMs system.

1. Introduction

During the past decade, the comprehensive performance of induction motors had been notably improved with the rapid development of power electronics [1]. Due to its reliable characteristics, simple structure and convenient maintenance, induction motor is extensively applied in industrial and agricultural production [2]. Nevertheless, resulting from power grid

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disturbances and power transistors failure, actuator faults deteriorate control performance and even generate disastrous accidents in the operation of motors [3,4]. In addition, the driver systems of IMs possess complex characteristics such as multivariable, strong couplings, severe nonlinearity, unknown load disturbances and uncertain parameters [5]. Therefore, the research of fault-tolerant control technologies for IMs is be of essentiality, which ensures the position tracking performance by compensating for the actuator faults.

During the past years, numerous fault-tolerant control schemes [6–9] were proposed with the adaptive control method [10–13] and universal approximators of neural networks [14–16] or fuzzy logic systems [17–21]. Among these works, an observer-based fault detection and isolation (FDI) approach was presented in [9] which using various observers to estimate the states of nonlinear state-feedback system in the presence of the actuator faults. In [19], an actuator failure compensation control method where the actuator failures were compensated by using fuzzy approximation was exploited for uncertain stochastic nonlinear systems. To overcome actuator faults that occur during the actual operation of motors, Chen used observer technology for constructing fault detection mechanism, combined with adaptive technology to estimate the actuators fault factors and ensure the tracking performance by adjusting or reconstructing the control law [22]. Compared with [22], the control parameters can be adjusted by the adaptive laws to compensate actuators fault in [23] and [24], which simplify the structure of control system. Consequently, it is of crucial practical significance to extend the obtained works to a discrete-time case, which is easier to settle practical problems [25].

In another research field, backstepping [27,28] become one of the most effective control methods for dynamic nonlinear systems. Nevertheless, the noncausal problem [29] arises during constructing the controllers via backstepping for discrete-time system, since the virtual controller contains future state information. To solve this problem, the expression of time $k+1$ was obtained by the recursion formula to represent the future information in [27], which may make the design of controller more complicated. As an alternative, by dynamic surface control (DSC) approach [31,32], the expression of time $k+1$ can be approximated by dynamic surface filters, which settles "complexity of computation" problem. However, the filtering errors that may degrade the accuracy of the control system arise from the filtering process, which has not been considered in the DSC method. Therefore, the command filtered control (CFC) method was developed in [33–35], where the compensating signals were introduced to restrain the filtering errors and the "complexity of computation" problem was concurrently conquered. Until now, the combination of the fault-tolerant method and CFC approach is not fully investigated in the IMs discrete-time system.

Motivated by the aforementioned works, a CFFTC approach is raised for IMs system in the presence of actuator faults and unknown load disturbances. Comparing with the existing literature, the main contributions of the designed method are as follows:

(1) In face of actuator faults in IMs, this paper proposes a command filtered fault-tolerant control approach, which updates the control parameters directly by the adaptive laws to compensate actuators fault and makes it more applicable to implement in engineering.
(2) Compared with [36] and [37], the proposed method introduces the error compensation mechanism into discrete-time systems via command filters, which not only conquers "complexity of computation" and noncausal problem but also avoids the filtering error and achieves higher accuracy.

Table 1
The physical meaning of notations.

Notation	Physical meaning	Unit
Δ_t	the sampling period	s
θ	the rotor position	rad
ω	the rotor angular velocity	rad/s
ψ_d	the rotor flux linkage	Wb
J	the rotor inertia	$\mathrm{Kg}\cdot\mathrm{m}^2$
T_L	the load torque	$\mathrm{N}\cdot\mathrm{m}$
n_p	the pole number	/
i_q and i_d	the q and d axis currents	A
L_s and L_r	the inductances of stator and rotor	H
L_m	mutual inductance	H
R_s and R_r	the resistances of stator and rotor	Ω

2. Mathematical model and preliminaries

2.1. Discrete-time model of IMs

Assumption 1. The saturation and iron losses in the motor are not considered [26,27].

In the $(d-q)$ axis, the IMs system discrete-time model oriented by rotor flux is described as [25,27]:

$$\begin{aligned}
\theta(k+1) &= \theta(k)+\Delta_t\omega(k),\\
\omega(k+1) &= \omega(k)+\Delta_t\frac{n_pL_m}{L_rJ}\psi_d(k)i_q(k)-\Delta_t\frac{T_L}{J},\\
i_q(k+1) &= i_q(k)-\Delta_t\frac{L_m^2R_r+L_r^2R_s}{\sigma L_sL_r^2}i_q(k)-\Delta_t\frac{L_mn_p}{\sigma L_sL_r}\omega(k)\psi_d(k)-\Delta_tn_p\omega(k)i_d(k)\\
&\quad-\Delta_t\frac{L_mR_r}{L_r}\frac{i_q(k)i_d(k)}{\psi_d(k)}+\Delta_t\frac{1}{\sigma L_s}u_q^f(k),\\
\psi_d(k+1) &= \psi_d(k)-\Delta_t\frac{R_r}{L_r}\psi_d(k)+\Delta_t\frac{L_mR_r}{L_r}i_d(k),\\
i_d(k+1) &= i_d(k)-\Delta_t\frac{L_m^2R_r+L_r^2R_s}{\sigma L_sL_r^2}i_d(k)+\Delta_t\frac{L_mR_r}{\sigma L_sL_r^2}\psi_d(k)+\Delta_tn_p\omega(k)i_q(k)\\
&\quad+\Delta_t\frac{L_mR_r}{L_r}\frac{i_q^2(k)}{\psi_d(k)}+\Delta_t\frac{1}{\sigma L_s}u_d^f(k).
\end{aligned}\tag{1}$$

where $\sigma=1-(L_m^2/L_sL_r)$, $u_q^f(k)$ and $u_d^f(k)$ are the input signals; and other notations are defined in Table 1.

2.2. Actuator faults model for IMs

During the motor operation, the actuator may not function properly under various factors. Define $u(k)$ is the actual controller. In this paper, two faults are considered. The first one is the loss of effectiveness and it is modelled by:

$$u^f(k)=(1-\rho)u(k)\tag{2}$$

where $0 \leq \rho < 1$ denotes the loss rate of actuator effectiveness. The second one is bias and described by:

$$u^f(k) = u(k) + p(k) \tag{3}$$

where $p(k)$ denotes the bounded bias function. Combining the two models, the actuator faults can be described as:

$$u^f(k) = (1 - \rho)u(k) + p(k). \tag{4}$$

2.3. The IMs system discrete-time model with actuator faults

To simplify the above discrete-time model, define the following variables:

$$\begin{aligned}
&\varphi_1(k) = \theta(k),\ \ \varphi_2(k) = \omega(k),\ \ \varphi_3(k) = i_q(k), \varphi_4(k) = \psi_d(k),\ \ \varphi_5(k) = i_d(k),\\
&a_1 = \frac{n_p L_m}{L_r J},\ \ a_2 = -\frac{1}{J},\ \ b_1 = -\frac{L_m^2 R_r + L_r^2 R_s}{\sigma L_s L_r^2},\ \ b_2 = -\frac{L_m n_p}{\sigma L_s L_r}, b_3 = n_p,\\
&b_4 = \frac{L_m R_r}{L_r},\ \ b_5 = \frac{1}{\sigma L_s},\ \ c_1 = -\frac{R_r}{L_r},\ \ c_2 = \frac{L_m R_r}{\sigma L_s L_r^2}.
\end{aligned} \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (1), the IMs system discrete-time model with possible actuator faults can be described as:

$$\begin{aligned}
\varphi_1(k+1) &= \varphi_1(k) + \Delta_t \varphi_2(k),\\
\varphi_2(k+1) &= \varphi_2(k) + a_1 \Delta_t \varphi_3(k)\varphi_4(k) + a_2 \Delta_t T_L,\\
\varphi_3(k+1) &= (1 + b_1\Delta_t)\varphi_3(k) + b_2\Delta_t\varphi_2(k)\varphi_4(k) - b_3\Delta_t\varphi_2(k)\varphi_5(k) - b_4\Delta_t\frac{\varphi_3(k)\varphi_5(k)}{\varphi_4(k)}\\
&\quad + b_5\Delta_t[(1-\rho_q)u_q(k) + p_q(k)],\\
\varphi_4(k+1) &= (1 + c_1\Delta_t)\varphi_4(k) + b_4\Delta_t\varphi_5(k),\\
\varphi_5(k+1) &= (1 + b_1\Delta_t)\varphi_5(k) + c_2\Delta_t\varphi_4(k) + b_4\Delta_t\frac{\varphi_3^2(k)}{\varphi_4(k)} + b_3\Delta_t\varphi_2(k)\varphi_3(k)\\
&\quad + b_5\Delta_t[(1-\rho_d)u_d(k) + p_d(k)].
\end{aligned} \tag{6}$$

where ρ_q and ρ_d denote the loss rates of actuators effectiveness, $p_q(k)$ and $p_d(k)$ denote the actuators bias functions in input signals $u_q^f(k)$ and $u_d^f(k)$ respectively; $u_q(k)$ and $u_d(k)$ denote the actual controllers.

Assumption 2. The desired signals $\varphi_{1d}(k)$ and $\varphi_{4d}(k)$ are known, smooth and bounded [30].

Lemma 1 [12]. *There exists a FLS $g(k) = W^T P(x(k)) + \tau$ for any $\tau > 0$, where $g(k)$ defined on a compact set Ω_x is an unknown smooth function, τ is the approximation error satisfying for $|\tau| \leq \varepsilon$ and ε is a small positive constant. $W \in R^N$ denotes ideal constant weight vector. $P(x(k)) = \left[P^1(x(k)),\ P^2(x(k)), \ldots P^N(x(k))\right]^T$ is a fuzzy basis function vector, which has the following property $\lambda_{\max}[P(x(k))^T P(x(k))] < l$. And $x(k) = [x_1(k),\ x_2(k), \ldots x_n(k)] \in \Omega_x$ is bounded.*

Lemma 2 [36]. *The discrete-time command filter is defined as:*

$$\begin{aligned}
z_{i,1}(k+1) &= z_{i,1}(k) + \Delta_t \omega_n z_{i,2}(k),\\
z_{i,2}(k+1) &= z_{i,2}(k) + \Delta_t[-2\zeta\omega_n z_2(k) - \omega_n(z_{i,1}(k) - \alpha_i(k))], i = 1, 2, 3.
\end{aligned} \tag{7}$$

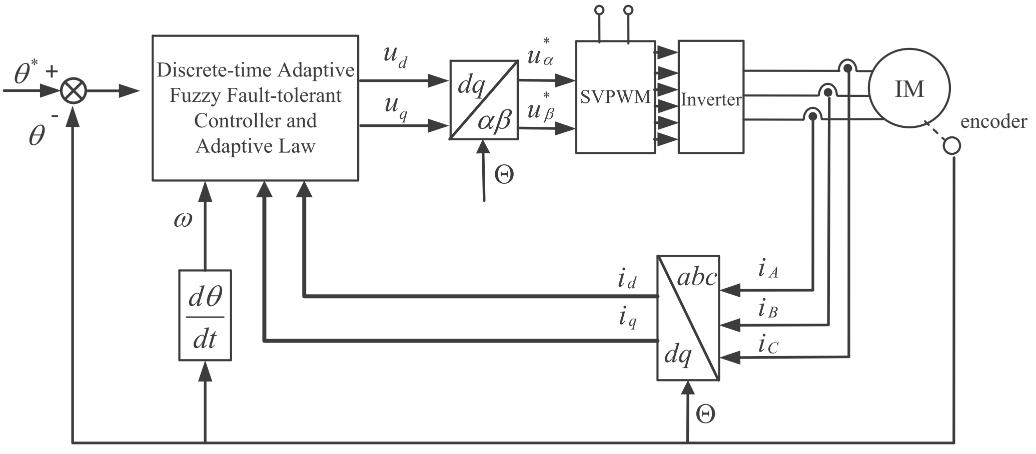


Fig. 1. Block diagram of the discrete-time CFFTC system for IMs.

where $z_{i,1}(k+1)$ are the output signals of discrete-time command filter. If input signals $\alpha_i(k)$ satisfy $|\alpha_i(k+1)-\alpha_i(k)| \le \varpi_1$ and $|\alpha_i(k+2)-2\alpha_i(k+1)+\alpha_i(k)| \le \varpi_2$ for any $k \ge 1$, where ϖ_1 and ϖ_2 are positive constants and $z_{i,1}(0)=\alpha_i(0)$, $z_{i,2}(0)=0$. Then for any $\varrho > 0$, there exists $0 < \zeta \le 1$ and $\omega_n > 0$, which ensure that $|z_{i,1}(k)-\alpha_i(k)| \le \varrho$, $\Delta z_{i,1}(k) = |z_{i,1}(k+1)-z_{i,1}(k)|$ are bounded.

3. Design for command filtered adaptive fuzzy fault-tolerant controller

In this section, an adaptive fuzzy command filtered fault-tolerant controller for IMs discrete-time system with unknown load disturbances will be designed. The block diagram of the discrete-time CFFTC system system is exhibited in Fig. 1.

For the desired state signals $\varphi_{1d}(k)$ and $\varphi_{4d}(k)$, the tracking error variables are defined as:

$$\begin{cases} e_1(k) = \varphi_1(k) - \varphi_{1d}(k), \\ e_2(k) = \varphi_2(k) - \varphi_{1c}(k), \\ e_3(k) = \varphi_3(k) - \varphi_{2c}(k), \\ e_4(k) = \varphi_4(k) - \varphi_{4d}(k), \\ e_5(k) = \varphi_5(k) - \varphi_{3c}(k). \end{cases} \tag{8}$$

where $\varphi_{1c}(k) = z_{1,1}(k)$, $\varphi_{2c}(k) = z_{2,1}(k)$ and $\varphi_{3c}(k) = z_{3,1}(k)$. Construct the compensated error signals as $\nu_{i_1}(k) = e_{i_1}(k) - \xi_{i_1}(k)$, $(i_1 = 1,2,3,4,5)$, where $\xi_{i_1}(k)$ are the compensating signals.

Step 1: The Lyapunov candidate is designed as $V_1(k) = \frac{1}{2}\nu_1^2(k)$. The first-order difference of $V_1(k)$ is procured as:

$$\Delta V_1(k) = \frac{1}{2}[\varphi_1(k) + \Delta_t\varphi_2(k) - \varphi_{1d}(k+1) - \xi_1(k+1)]^2 - \frac{1}{2}\nu_1^2(k). \tag{9}$$

Construct the virtual control law $\alpha_1(k)$ and the compensating signal $\xi_1(k)$ as

$$\alpha_1(k) = \frac{1}{\Delta_t}[\varphi_{1d}(k+1) - \varphi_1(k)] + t_1\xi_1(k), \tag{10}$$

$$\xi_1(k+1) = \Delta_t[\xi_2(k) + \varphi_{1c}(k) - \alpha_1(k) + t_1\xi_1(k)], \ \ |t_1| < 1. \tag{11}$$

Bringing Eqs. (10) and (11) into Eq. (9) attains:

$$\Delta V_1(k) = \frac{1}{2}[\Delta_t(\varphi_2(k) - \alpha_1(k)) - \xi_1(k+1)]^2 - \frac{1}{2}{\nu_1}^2(k) = \frac{1}{2}\Delta_t^2\nu_2^2(k) - \frac{1}{2}\nu_1^2(k) \tag{12}$$

Step 2: The Lyapunov candidate is designed as $V_2(k) = V_1(k) + \frac{1}{2}\nu_2^2(k)$. The first-order difference of $V_2(k)$ is procured as:

$$\Delta V_2(k) = \frac{1}{2}[\varphi_2(k) + a_1\Delta_t\varphi_3(k)\varphi_4(k) + a_2\Delta_t T_L - \varphi_{1c}(k+1) - \xi_2(k+1)]^2 + \Delta V_1(k) - \frac{1}{2}\nu_2^2(k). \tag{13}$$

Construct the virtual control law $\alpha_2(k)$ and the compensating signal $\xi_2(k)$ as:

$$\alpha_2(k) = \frac{1}{a_1\Delta_t\varphi_4(k)}[\varphi_{1c}(k+1) - \varphi_2(k)] + t_2\xi_2(k), \tag{14}$$

$$\xi_2(k+1) = a_1\Delta_t\varphi_4(k)[\xi_3(k) + \varphi_{2c}(k) - \alpha_2(k) + t_2\xi_2(k)], \ \ |t_2| < 1. \tag{15}$$

Remark 1. When the virtual control law is obtained via backstepping method without CFC method, then $\alpha_2(k)$ will be given as:

$$\alpha_2(k) = \frac{\alpha_1(k+1) - \varphi_2(k)}{a_1\Delta_t\varphi_4(k)} \tag{16}$$

where $\alpha_2(k)$ contains variable $\alpha_1(k+1) = \frac{\varphi_{1d}(k+2) - \varphi_1(k+1)}{\Delta_t}$ which covers future information $\varphi_1(k+1)$. In [27], the expression of variable $\alpha_1(k+1)$ was obtained by the recursion formula, then $\alpha_1(k+1) = \frac{\varphi_{1d}(k+2) - \varphi_1(k) - \Delta_t\varphi_2(k)}{\Delta_t}$. However, the "complexity of computation" problem arises as the order of the system gets higher because the actual controller contains more future information, such as variable $\alpha_1(k+n-1) = \frac{\varphi_{1d}(k+n) - \varphi_1(k+n-1)}{\Delta_t}$ at **Step n**, which makes the controller more complicated. In this paper, $\varphi_{1c}(k+1)$ can be obtained by the command filters and the filtering error can be conquered, which alleviates the calculational burden. Thus, the noncausal problem can be solved.

For the practice IMs system, T_L is unknown, fluctuant and bounded, then we assume that $|T_L| \le d$ and $d \ge 0$. Substituting Eqs. (14) and (15) into Eq. (13) gets:

$$\begin{aligned}\Delta V_2(k) &\le \frac{1}{2}\left\{a_1^2\Delta_t^2\varphi_4^2(k)[(\nu_3(k) + \xi_3(k) + \varphi_{2c}(k) - \alpha_2(k) + t_2\xi_2(k) - \xi_2(k+1)] + a_2\Delta_t T_L\right\}^2 \\ &\quad + \Delta V_1(k) - \frac{1}{2}\nu_2^2(k) \\ &\le a_1^2\Delta_t^2\varphi_4^2(k)\nu_3^2(k) + \Delta V_1(k) - \frac{1}{2}\nu_2^2(k) + a_2^2\Delta_t^2 d^2.\end{aligned} \tag{17}$$

Step 3: The Lyapunov candidate is designed as $V_3(k) = V_2(k) + \frac{1}{2}\nu_3^2(k)$. The first-order difference of $V_3(k)$ is procured as:

$$\Delta V_3(k) = \frac{1}{2}[b_5\Delta_t((1-\rho_q)u_q(k) + p_q(k)) + f_3(k)]^2 + \Delta V_2(k) - \frac{1}{2}\nu_3^2(k). \tag{18}$$

where $f_3(k) = (1 + b_1\Delta_t)\varphi_3(k) + b_2\Delta_t\varphi_2(k)\varphi_4(k) - b_3\Delta_t\varphi_2(k)\varphi_5(k) - b_4\Delta_t\frac{\varphi_3(k)\varphi_5(k)}{\varphi_4(k)} - \varphi_{2c}(k+1) - \xi_3(k+1)$.

According to **Lemma 2**, for any $\varepsilon_3 > 0$, there exists a FLS $W_3^T P_3(z_3(k))$ such that

$$g_3(k) = \frac{f_3(k) + b_5\Delta_t p_q(k)}{1-\rho_q} = W_3^T P_3(z_3(k)) + \tau_3 \tag{19}$$

where $x_3(k) = [\varphi_1(k), \varphi_2(k), \varphi_3(k), \varphi_4(k), \varphi_5(k)]^T$, τ_3 is the approximation error, and $|\tau_3| \le \varepsilon_3$.

With $\xi_3(k) = 0$, the controller $u_q(k)$ and the adaptive law $\hat{\phi}_3(k)$ are given as:

$$u_q(k) = -\frac{1}{b_5\Delta_t}\hat{\phi}_3(k)\|P_3(z_3(k))\|, \tag{20}$$

$$\hat{\phi}_3(k+1) = \hat{\phi}_3(k) + \gamma_3\|P_3(z_3(k))\|\nu_3(k+1) - \delta_3\hat{\phi}_3(k), \tag{21}$$

where γ_3 and δ_3 are positive parameters.

Define $\|W_3^T\| = \phi_3$, where ϕ_3 is an unknown positive constant. Then, $\tilde{\phi}_3 = \phi_3 - \hat{\phi}_3$ denotes the estimate error, where $\hat{\phi}_3$ is the estimation of ϕ_3. Substituting Eqs. (19) and (20) into Eq. (18) gets:

$$\begin{aligned}\Delta V_3(k) &= \frac{1}{2}\Big[\big(1-\rho_q\big)\tilde{\phi}_3(k)\|P_3(z_3(k))\| + \big(1-\rho_q\big)\tau_3\Big]^2 + \Delta V_2(k) - \frac{1}{2}\nu_3^2(k)\\ &\le (1-\rho_q)^2\tilde{\phi}_3^2(k)\|P_3(z_3(k))\|^2 + (1-\rho_q)^2\varepsilon_3^2 + \Delta V_2(k) - \frac{1}{2}\nu_3^2(k).\end{aligned} \tag{22}$$

Step 4: The Lyapunov candidate is designed as $V_4(k) = V_3(k) + \frac{1}{2}\nu_4^2(k)$. The first-order difference of $V_4(k)$ is procured as:

$$\Delta V_4(k) = \frac{1}{2}[(1+c_1\Delta_t)\varphi_4(k) + b_4\Delta_t\varphi_5(k) - \varphi_{4d}(k+1) - \xi_4(k+1)]^2 + \Delta V_3(k) - \frac{1}{2}\nu_4^2(k). \tag{23}$$

Construct the virtual control law $\alpha_3(k)$ and the compensating signal $\xi_4(k)$ as:

$$\alpha_3(k) = \frac{1}{b_4\Delta_t}[\varphi_{4d}(k+1) - (1+c_1\Delta_t)\varphi_4(k)] + t_4\xi_4(k), \tag{24}$$

$$\xi_4(k+1) = b_4\Delta_t[\xi_5(k) + \varphi_{3c}(k) - \alpha_3(k) + t_4\xi_4(k)],\ \ |t_4| < 1. \tag{25}$$

Bringing Eqs. (24) and (25) into Eq. (23) attains:

$$\Delta V_4(k) = \frac{1}{2}b_4^2\Delta_t^2\nu_5^2(k) + \Delta V_3(k) - \frac{1}{2}\nu_4^2(k). \tag{26}$$

Step 5: The Lyapunov candidate is designed as $V_5(k) = V_4(k) + \frac{M}{2}\nu_5^2(k)$. The first-order difference of $V_5(k)$ is procured as:

$$\Delta V_5(k) = \frac{M}{2}[b_5\Delta_t((1-\rho_d)u_d(k) + p_d(k)) + f_5(k)]^2 + \Delta V_4(k) - \frac{M}{2}e_3^2(k), \tag{27}$$

where $f_5(k) = (1+b_1\Delta_t)\varphi_5(k) + c_2\Delta_t\varphi_4(k) + b_4\Delta_t\frac{\varphi_3^2(k)}{\varphi_4(k)} + b_3\Delta_t\varphi_2(k)\varphi_3(k) - \varphi_{3c}(k+1) - \xi_5(k+1)$.

According to **Lemma 2**, for any $\varepsilon_5 > 0$, there exists a FLS $W_5^T P_5(z_5(k))$ such that

$$g_5(k) = \frac{f_5(k) + b_5\Delta_t p_d(k)}{1-\rho_d} = W_5^T P_5(z_5(k)) + \tau_5, \tag{28}$$

where $x_5(k) = [\varphi_1(k), \varphi_2(k), \varphi_3(k), \varphi_4(k), \varphi_5(k)]^T$, τ_5 is the approximation error, and $|\tau_5| \le \varepsilon_5$.

With $\xi_5(k) = 0$, the controller $u_d(k)$ and the adaptive law $\hat{\phi}_5(k)$ are given as:

$$u_d(k) = -\frac{1}{b_5\Delta_t}\hat{\phi}_5(k)\|P_5(z_5(k))\|, \tag{29}$$

$$\hat{\phi}_5(k+1) = \hat{\phi}_5(k) + \gamma_5\|P_5(z_5(k))\|\nu_5(k+1) - \delta_5\hat{\phi}_5(k). \tag{30}$$

where γ_5 and δ_5 are positive parameters.

Define $\|W_5^T\| = \phi_5$, where ϕ_5 is an unknown positive constant. Then, $\tilde{\phi}_5 = \phi_5 - \hat{\phi}_5$ denotes the estimate error, where $\hat{\phi}_5$ is the estimation of ϕ_5. Substituting Eqs. (28) and (29) into Eq. (27) gets:

$$\begin{aligned}\Delta V_5(k) &= \frac{M}{2}\Big[(1-\rho_d)\tilde{\phi}_5(k)\|P_5(z_5(k))\| + (1-\rho_d)\tau_5\Big]^2 + \Delta V_4(k) - \frac{M}{2}e_5^2(k)\\ &\le -\frac{M}{2}\nu_5^2(k) - \frac{1}{2}\nu_4^2(k) - \frac{1}{2}\nu_3^2(k) - \frac{1}{2}\nu_2^2(k) - \frac{1}{2}\nu_1^2(k) + M(1-\rho_d)^2\tilde{\phi}_5^2(k)\|P_5(z_5(k))\|^2\\ &\quad + M(1-\rho_d)^2\varepsilon_5^2 + (1-\rho_q)^2\tilde{\phi}_3^2(k)\|P_3(z_3(k))\|^2 + (1-\rho_q)^2\varepsilon_3^2 + \frac{1}{2}b_4^2\Delta_t^2\nu_5^2(k)\\ &\quad + a_1^2\Delta_t^2\varphi_4^2(k)\nu_3(k) + \frac{1}{2}\Delta_t^2\nu_2^2(k) + a_2^2\Delta_t^2 d^2. \end{aligned} \tag{31}$$

Theorem 1. *Consider the IMs discrete-time system (6) with Assumptions 1-2, the desired signals $\varphi_{1d}(k)$ and $\varphi_{4d}(k)$. If the virtual control laws are given as (10), (14) and (24), the adaptive laws are constructed as (21) and (30), then we design the fault-tolerant controllers (20) and (29) such that all closed-loop signals are semi-globally uniformly ultimately bounded (SGUUB) and the tracking error $e_1(k)$ converges to a small neighborhood of the origin.*

4. Stability analysis

Proof. The Lyapunov function is chosen as:

$$V(k) = V_5(k) + \frac{1}{2\gamma_3}\tilde{\phi}_3^2(k) + \frac{M}{2\gamma_5}\tilde{\phi}_5^2(k). \tag{32}$$

The first-order difference of $V(k)$ is procured as:

$$\Delta V(k) = \Delta V_5(k) + \frac{1}{2\gamma_3}[\tilde{\phi}_3^2(k+1) - \tilde{\phi}_3^2(k)] + \frac{M}{2\gamma_5}[\tilde{\phi}_5^2(k+1) - \tilde{\phi}_5^2(k)]. \tag{33}$$

According to $\tilde{\phi}_{i_2}(k+1) = \hat{\phi}_{i_2} - \phi_{i_2}(k+1)$, $(i_2 = 3, 5)$ attains:

$$\begin{aligned}\tilde{\phi}_{i_2}^2(k+1) - \tilde{\phi}_{i_2}^2(k) &= \phi_{i_2}^2 - \tilde{\phi}_{i_2}^2(k) + (1-\delta_{i_2})^2\hat{\phi}_{i_2}^2(k) - 2(1-\delta_{i_2})\phi_{i_2}\hat{\phi}_{i_2}(k)\\ &\quad + 2(1-\delta_{i_2})\gamma_{i_2}\|P_{i_2}(z_{i_2}(k))\|\nu_{i_2}(k+1)\hat{\phi}_{i_2}(k)\\ &\quad - 2\gamma_{i_2}\|P_{i_2}(z_{i_2}(k))\|\nu_{i_2}(k+1)\phi_{i_2}\\ &\quad + \gamma_{i_2}^2\|P_{i_2}(z_{i_2}(k))\|^2\nu_{i_2}^2(k+1). \end{aligned} \tag{34}$$

Using $\|P_{i_2}(z_{i_2}(k))\| \leq l_{i_2}$, $(i_2 = 3, 5)$ and invoking Young's inequality, we have:

$$\begin{aligned}
&2\gamma_{i_2}\|P_{i_2}(z_{i_2}(k))\|\nu_{i_2}(k+1)\hat{\phi}_{i_2}(k) \leq \gamma_{i_2}^2\nu_{i_2}^2(k+1)l_{i_2} + \hat{\phi}_{i_2}^2(k),\\
&-2\gamma_{i_2}\|P_{i_2}(z_{i_2}(k))\|\nu_{i_2}(k+1)\phi_{i_2} \leq \nu_{i_2}^2(k+1)l_{i_2} + \phi_{i_2}^2,\\
&\gamma_{i_2}^2\|P_{i_2}(z_{i_2}(k))\|^2\nu_{i_2}^2(k+1) \leq \gamma_{i_2}^2\nu_{i_2}^2(k+1)l_{i_2},\\
&-2\phi_{i_2}\hat{\phi}_{i_2}(k) \leq \hat{\phi}_{i_2}^2(k) + \phi_{i_2}^2.
\end{aligned} \tag{35}$$

Substituting Eq. (35) into $\tilde{\phi}_{i_2}^2(k+1) - \tilde{\phi}_{i_2}^2(k)$, $(i_2 = 3, 5)$ attains:

$$\begin{aligned}
\tilde{\phi}_3^2(k+1) - \tilde{\phi}_3^2(k) \leq{}& (1-\rho_q)^2\big(4\gamma_3^2 l_3 - 2\gamma_3^2\delta_3 l_3 + 2\gamma_3 l_3\big)\varepsilon_3^2 + (\gamma_3 - \delta_3 + 2)\phi_3^2\\
&+ (1-\rho_q)^2\big(4\gamma_3^2 l_3^2 - 2\gamma_3^2\delta_3 l_3^2 + 2\gamma_3 l_3^2 - 1\big)\tilde{\phi}_3^2(k) + \big(\delta_3^2 - 4\delta_3 + 3\big)\hat{\phi}_3^2(k),
\end{aligned} \tag{36}$$

$$\begin{aligned}
\tilde{\phi}_5^2(k+1) - \tilde{\phi}_5^2(k) \leq{}& (1-\rho_d)^2\big(4\gamma_5^2 l_5 - 2\gamma_5^2\delta_5 l_5 + 2\gamma_5 l_5\big)\varepsilon_5^2 + (\gamma_5 - \delta_5 + 2)\phi_5^2\\
&+ (1-\rho_d)^2\big(4\gamma_5^2 l_5^2 - 2\gamma_5^2\delta_5 l_5^2 + 2\gamma_5 l_5^2 - 1\big)\tilde{\phi}_5^2(k) + \big(\delta_5^2 - 4\delta_5 + 3\big)\hat{\phi}_5^2(k).
\end{aligned} \tag{37}$$

Define $\varphi_4^2(k) \leq A$, where $A > 0$ is a constant. Substituting Eqs. (36) and (37) into Eq. (33), we can obtain:

$$\begin{aligned}
\Delta V \leq{}& \left(\frac{1}{2}b_4^2\Delta_t^2 - \frac{M}{2}\right)\nu_5^2(k) - \frac{1}{2}\nu_4^2(k) + \left(a_1^2\Delta_t^2 A - \frac{1}{2}\right)\nu_3^2(k) + \left(\frac{1}{2}\Delta_t^2 - \frac{1}{2}\right)\nu_2^2(k) - \frac{1}{2}\nu_1^2(k)\\
&+ \frac{1}{2\gamma_3}[(\delta_3^2 - 4\delta_3 + 3)\hat{\phi}_3^2(k) + \beta_3 + (1-\rho_q)^2(4\gamma_3^2 l_3^2 - 2\gamma_3^2\delta_3 l_3^2 + 2\gamma_3 l_3^2\\
&+ 2\gamma_3 l_3 - 1)\tilde{\phi}_3^2(k)]\\
&+ \frac{M}{2\gamma_5}[(\delta_5^2 - 4\delta_5 + 3)\hat{\phi}_5^2(k) + \beta_5 + (1-\rho_d)^2(4\gamma_5^2 l_5^2 - 2\gamma_5^2\delta_5 l_5^2\\
&+ 2\gamma_5 l_5^2 + 2\gamma_5 l_5 - 1)\tilde{\phi}_5^2(k)],
\end{aligned} \tag{38}$$

where

$$\begin{aligned}
\beta_3 &= (\gamma_3 - \delta_3 + 2)\phi_3^2 + \gamma_3 a_2^2\Delta_t^2 d^2 + (1-\rho_q)^2(4\gamma_3^2 l_3 - 2\gamma_3^2\delta_3 l_3 + 2\gamma_3 l_3 + 2\gamma_3)\varepsilon_3^2,\\
\beta_5 &= (\gamma_5 - \delta_5 + 2)\phi_5^2 + \frac{\gamma_5}{M}a_2^2\Delta_t^2 d^2 + (1-\rho_d)^2(4\gamma_5^2 l_5 - 2\gamma_5^2\delta_5 l_5 + 2\gamma_5 l_5 + 2\gamma_5)\varepsilon_5^2.
\end{aligned} \tag{39}$$

Selecting design parameters Δ_t, M, ζ, ω_n, γ_3, γ_5, δ_3 and δ_5, the following inequalities are satisfied: $\Delta_t^2 - \frac{1}{2} < 0$, $\frac{1}{2}b_4^2\Delta_t^2 - \frac{M}{2} < 0$, $a_1^2\Delta_t^2 A - \frac{1}{2} < 0$, $\delta_j^2 - 4\delta_j + 3 < 0$ and $4\gamma_j^2 l_j^2 - 2\gamma_j^2\delta_j l_j^2 + 2\gamma_j l_j^2 + 2\gamma_j l_j - 1 < 0$, $(j = 3, 5)$. Once the error $|\nu_3(k)| > \sqrt{\frac{\beta_3}{\gamma_3 - 2\gamma_3 a_1^2\Delta_t^2 A}}$ and $|\nu_5(k)| > \sqrt{\frac{M\beta_5}{M\gamma_5 - \gamma_5 b_4^2\Delta_t^2}}$, it can be attained that $\Delta V(k) \leq 0$. Then $\lim_{k\to\infty}\|\nu_1(k)\| \leq \sigma$ is obtained, where $\sigma < 0$ is a sufficiently small constant. We assume that $\varphi_{i_3c}(k) - \alpha_{i_3}(k)$, $(i_3 = 1, 2, 3)$ are bounded, thus the compensating signals $\xi_{i_1}(k)$, $(i_1 = 1, 2, 3, 4, 5)$ and the tracking error $e_1(k)$ are bounded [38]. Finally, the SGUUB of the closed-loop system is guaranteed. □

Table 2
The parameters of IMs.

$J = 0.0586$ Kg · m^2	$R_s = 0.1$ Ω	$R_r = 0.15$ Ω
$L_m = 0.068$ H	$L_s = 0.0699$ H	$L_r = 0.0699$ H

5. Simulation results

In this section, four cases are carried out to verifying the effectiveness of the CFFTC method proposed in this paper. The motor and load parameters in the IMs model considering actuator faults and load disturbances are expressed in Table 2:

Select the sampling period as $\Delta_t = 0.0025$s. The initial values for system (6) are defined as $\varphi_1(0) = \varphi_2(0) = \varphi_3(0) = \varphi_5(0) = 0$ and $\varphi_4(0) = 1$. The reference signals are chosen as $\varphi_{1d}(k) = \sin(\Delta_t k\pi/2)$ and $\varphi_{4d}(k) = 1$. The actuator faults are given as:

$$\rho_q = \begin{cases} 0, & 0 \le k < 4000 \\ 0.6, & k \ge 4000 \end{cases}, \rho_d = \begin{cases} 0, & 0 \le k < 4000 \\ 0.3, & k \ge 4000 \end{cases},$$

$$p_q(k) = \begin{cases} 0, & 0 \le k < 4000 \\ \sin(\frac{\Delta_t k\pi}{2}), & k \ge 4000 \end{cases}, p_d(k) = \begin{cases} 0, & 0 \le k < 4000 \\ 0.25\cos(\frac{\Delta_t k\pi}{2}), & k \ge 4000 \end{cases}.$$

The following four cases are implemented to illustrate the performance of the proposed controller.

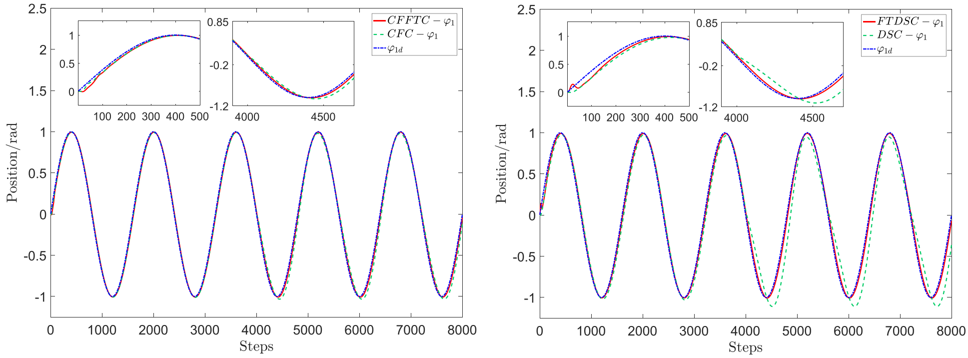
Case(a): First, the proposed CFFTC method is applied to IMs, and we give the design parameters as $\zeta = 0.25, \omega_n = 230, \gamma_3 = 0.0175, \gamma_5 = 0.25, \delta_3 = 1.25, \delta_5 = 1.25, t_1 = t_2 = t_4 = 0.9$. The load parameter is selected as: $T_L = \begin{cases} 1.0 \text{ N} \cdot \text{m}, & 0 \le k < 2000, \\ 1.5 \text{ N} \cdot \text{m}, & k \ge 2000. \end{cases}$. The fuzzy membership functions are choosen as follows: $\mu_{F_n^m} = \exp\left[\frac{-(\varphi_n + h)^2}{2}\right], (n = 1, 2, 3, 4, 5)$, where integer $m \in [1, 11]$ and integer $h \in [-5, 5]$.

Case(b): Next, for comparison with Case(a), the discrete-time command filtered control (CFC) method without FTC is also applied to IMs, and the same design parameters as Case(a) are chosen.

Case(c): Then, to further illustrates the superiority of the proposed method, the adaptive fuzzy fault-tolerant dynamic surface control (FTDSC) method in [37] is applied to IMs for another comparison. The design parameters are selected as $\zeta_1 = 0.0012, \zeta_2 = 0.00074, \zeta_3 = 0.0012, \gamma_3 = 0.023, \gamma_5 = 0.25, \delta_3 = 1.25, \delta_5 = 1.75$, where ζ_1, ζ_2 and ζ_3 are the time constants of dynamic surface filter. And other parameters are chosen the same as Part (a).

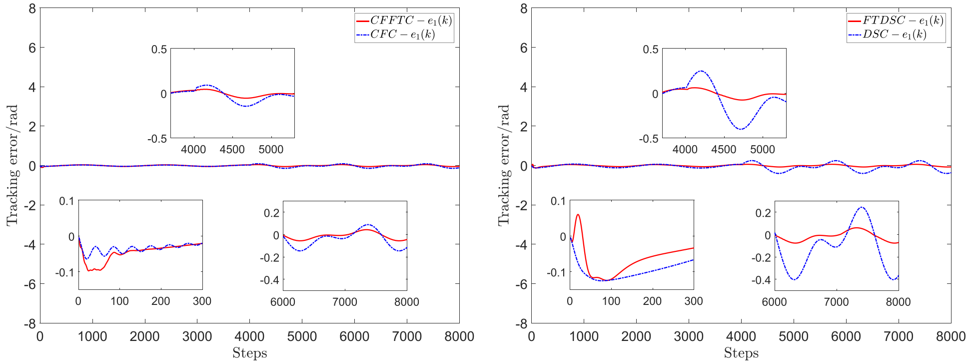
Case(d): Finally, for comparison with Case(c), the discrete-time dynamic surface control (DSC) method without FTC is also applied to IMs, and the same design parameters Case(c) are chosen.

The simulation comparison results of the above four cases are illustrate in Figs. 2–8. Figs. 2(a)-8(a) reflect the results of the control scheme with CFC in the Case(a) and Case(b), while Figs. 2(b)–8(b) show the results with DSC in the Case(c) and Case(d). Fig. 2(a) and Fig. 2(b) show the tracking trajectories of $\varphi_1(k)$ and the desired trajectory $\varphi_{1d}(k)$. Fig. 3 denotes the tracking error $e_1(k)$. Figs. 5–8 show the trajectories of $u_q(k)$, $u_d(k)$, $i_q(k)$ and $i_d(k)$, which illustrate the effectiveness of the CFFTC method proposed in this paper.



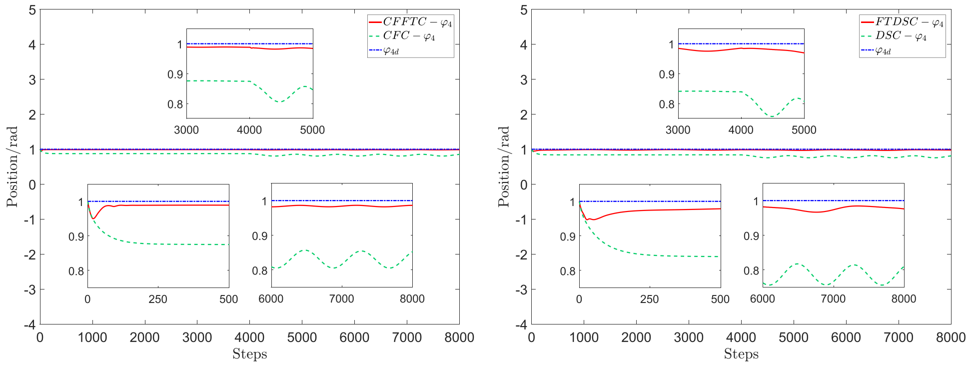
(a) Trajectory of the φ_1 with CFC. (b) Trajectory of the φ_1 with DSC.

Fig. 2. (a) Trajectory of the φ_1 with CFC. (b) Trajectory of the φ_1 with DSC.



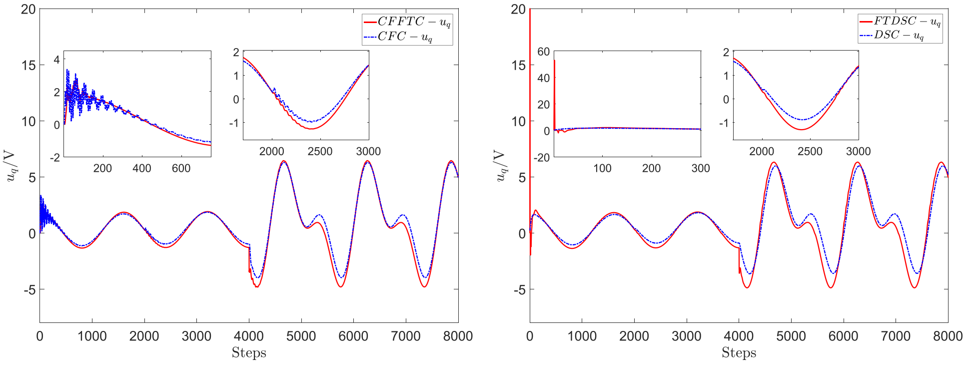
(a) Tracking error e_1 with CFC. (b) Tracking error e_1 with DSC.

Fig. 3. (a) Tracking error e_1 with CFC. (b) Tracking error e_1 with DSC.



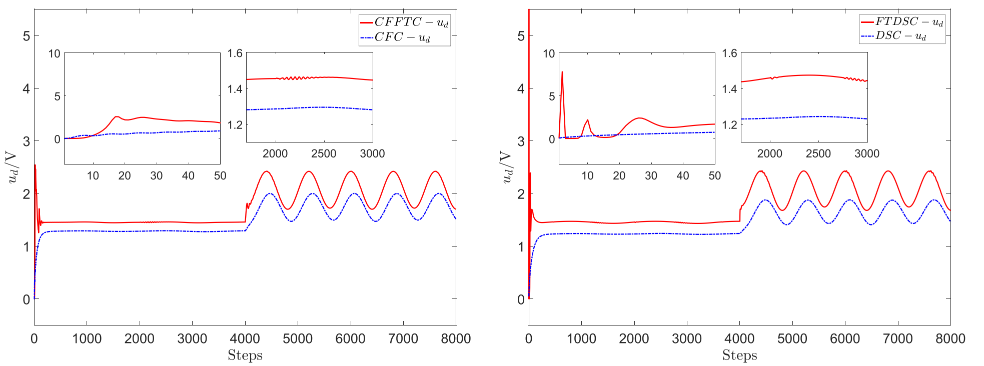
(a) Trajectory of the φ_4 with CFC. (b) Trajectory of the φ_4 with DSC.

Fig. 4. (a) Trajectory of the φ_4 with CFC. (b) Trajectory of the φ_4 with DSC.



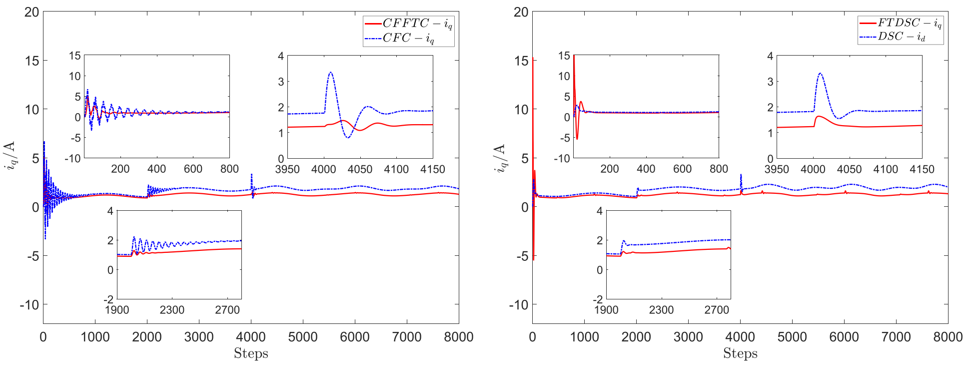
(a) u_q with CFC. (b) u_q with DSC.

Fig. 5. (a) u_q with CFC. (b) u_q with DSC.



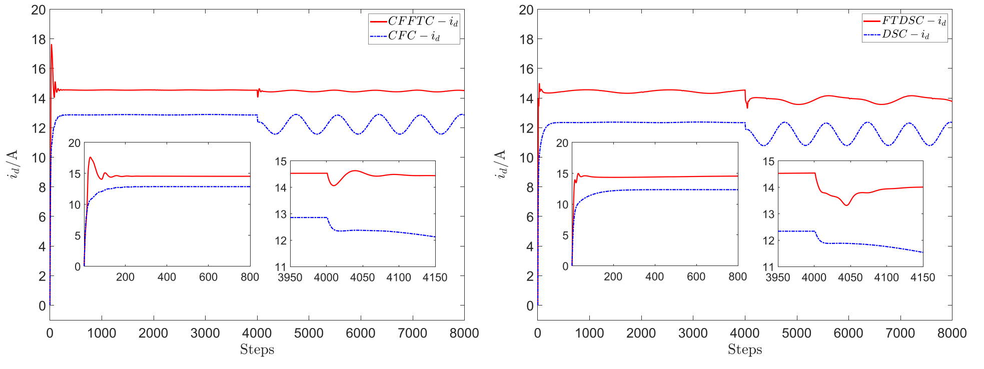
(a) u_d with CFC. (b) u_d with DSC.

Fig. 6. (a) u_d with CFC. (b) u_d with DSC.



(a) i_q with CFC. (b) i_q with DSC.

Fig. 7. (a) i_q with CFC. (b) i_q with DSC.



(a) i_d with CFC. (b) i_d with DSC.

Fig. 8. (a) i_d with CFC. (b) i_d with DSC.

Remark 2. In the simulation, a load torque disturbance appearing when $k = 2000$, T_L changes from 1.0 to 1.5. When $k \geq 4000$ steps, two types of actuator faults are taken into account to express the availability of the proposed scheme. Simulation confirms that the FTC method proposed in Case(a) and Case(c) achieves the good tracking performance in the presence of actuator faults, compared with non-FTC method in Case(b) and Case(d).

Remark 3. From the simulation results of Case(a) and Case(c), it can be seen that both FTC methods can satisfy control effects. However, Figs. 2–4 show that the CFFTC method constructed in Case(a) can make the rotor position $\varphi_1(k)$ and flux linkage $\varphi_4(k)$ track the reference signals $\varphi_{1d}(k)$ and $\varphi_{4d}(k)$ with less adjustment time and smaller tracking error than those in Case (c).

Remark 4. Note that the proposed discrete-time CFFTC method achieves a good tracking performance since the saturation and iron losses in the motor are not considered and some required inequalities are satisfied. For all that, this work just obtains some preliminary results, and we will consider how to reduce the aforementioned restrictions. Besides, the switching control method provided an efficacious tool to deal with load torque mutation in the IMs driver system. Consequently, it is of crucial practical significance to extend the obtained works to the discrete-time case. In future research activities, we will take account of the influence of iron losses and the effective combination of switching control technique [39–43] and FTC method.

6. Conclusion

In this paper, a CFFTC method for IMs in the presence of possible actuator faults and unknown load disturbances is proposed. The actuator faults considered in this paper include loss of effectiveness and bias. Combining CFC technology and error compensation mechanism, noncausal problem and complexity of computation can be resolved. It is proved that all signals in the closed-loop system are SGUUB. The simulation results demonstrate the validity of the proposed fault-tolerant method for IMs system. Future works will be committed to take account of the influence of iron losses and the effective combination of switching control technique and FTC method.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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