Hindawi Publishing Corporation
Advances in Electrical Engineering
Volume 2014, Article ID 915072, 7 pages
http://dx.doi.org/10.1155/2014/915072

Research Article

Robust Adaptive Fault-Tolerant Tracking Control of Three-Phase Induction Motor

Hossein Tohidi and Koksal Erenturk

Department of Electrical and Electronic Engineering, Ataturk University, 25240 Erzurum, Turkey

Correspondence should be addressed to Hossein Tohidi; huseyn.tohidi@gmail.com

Received 17 June 2014; Revised 23 August 2014; Accepted 23 August 2014; Published 4 September 2014

Academic Editor: Mamun B. Ibne Reaz

This paper deals with the problem of induction motor tracking control against actuator faults and external disturbances using the linear matrix inequalities (LMIs) method and the adaptive method. A direct adaptive fault-tolerant tracking controller design method is developed based on Lyapunov stability theory and a constructive algorithm based on linear matrix inequalities for online tuning of adaptive and state feedback gains to stabilize the closed-loop system in order to reduce the fault effect with disturbance attenuation. Simulation results reveal the merits of proposed robust adaptive fault-tolerant tracking control scheme on an induction motor subjected to actuator faults.

1. Introduction

With technology advances and modern control systems complexity increasing, rotating electrical machines play important roles in many fields especially in industrial processes because of their rigid, rugged, low price, reliable relative simplicity, and easy to maintain behaviors [1, 2]. However, the reliable electric drives are essential in all safety critical applications such as aerospace, transportation, medical, and military applications. In these applications, the reliability of electric drive systems must be ensured, and any failure in motor drives may result in loss of property and human life. Therefore, it is absolutely necessary for the motor drives (utilized in safety critical applications) in order to have a fault-tolerant capability and an ability to produce a satisfactory output torque even in the presence of faults [3–5]. That is why designing reliable drives has received great attention in the recent years.

When a fault occurs in system components including sensors, actuators, and plant, it can cause performance reduction and the closed-loop system instability. Therefore, there is a crucial need to design a class of controllers to compensate the faults effects and guarantee system stability with acceptable performance. FTC design approaches develop controllers in order to guarantee system stability in the presence of faults and disturbances. They are classified as two main classes: passive FTC and active FTC [6–11]. In the passive FTC approach, robust control techniques are utilized to design a fixed controller for maintaining the acceptable system stability and performances throughout normal or faulty cases [11]. The passive FTC approach considers fault as a special kind of uncertainties, and consequently controllers are fixed and designed to be robust against a class of presumed faults. Then designing proper controllers becomes more conservative, and attainable control performance may not be satisfactory. On the other hand, the FTC based on active technique can compensate faults either by selecting a precomputed control law or by synthesizing a new online control strategy [3, 10–12]. Since the active FTC approach provides flexibility to choose various controllers, different suitable controllers can be selected to reach a better performance. The active FTC design approach is based on fault detection and isolation (FDI). The controller reconfiguration is a special case of active FTC systems based on the fault diagnostic information, which is provided by an FDI mechanism [9, 13–15]. Figure 1 shows a closed-loop system with an active FTC strategy including the FDI block.

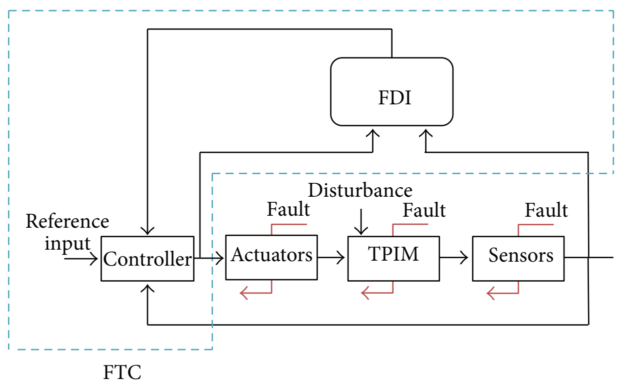


Figure 1: The closed-loop system with FTC and FDI.

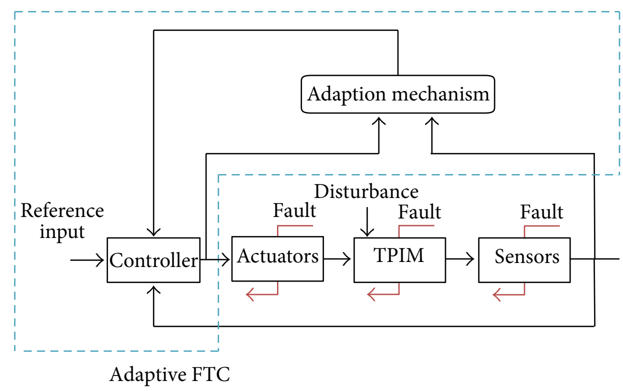


Figure 2: The closed-loop system with adaptive FTC.

Another typical approach for fault compensation is based on adaptive tuning. The developments of adaptive fault-tolerant compensation controller have been reported based on model reference adaptive control, where the outputs of the closed-loop system could track the commanded reference outputs [16–20]. The idea adaptive FTC is that of designing a control unit able to automatically offset the effect of the faults, without the need of an explicit FDI process and consequent explicit reconfiguration. Figure 2 shows a closed-loop system with an adaptation mechanism for online tuning of controller parameters.

In the most of mentioned works such as [21, 22], unmatched external disturbance term has not been considered in the control process or it is hard to guarantee the asymptotical stability in the presence of disturbance term. However, the unmatched external disturbance plays an important role and it is able to decline closed-loop system performance. Therefore, studying the FTC design in the presence of unmatched external disturbance seems necessary and challenging.

In this paper, motivated by the development of fault-tolerant tracking control for TPIM, the problem of fault-tolerant tracking control of TPIM with actuator faults in the presence of bounded disturbances is presented in comparison with [11, 16]; a direct adaptive method is proposed for a fixed state feedback fault-tolerant tracking control that guarantees the closed-loop system stability in the presence of actuator faults and unmatched external disturbances. Based on the Lyapunov stability theorem, a novel constructive algorithm based on linear matrix inequalities (LMIs) is developed. For this purpose, we first proposed an adaptation mechanism for online tuning of the controller parameters. Then, a robust fixed state feedback controller is constructed for the closed-loop system.

This paper is organized as follows: in Section 2, the induction motor mathematical model is presented. The fault-tolerant tracking control problem formulation is described in Section 3. Section 4 presents the design method of the direct robust adaptive fault-tolerant tracking controller. In Section 5, the merits of the proposed approach are verified by the simulations on TPIM subjected to the actuator faults and disturbances. Finally, conclusions are given in Section 6.

2. Dynamic Model of an Induction Motor

In this section, the dynamic model of TPIM is presented in a synchronously reference frame by the following equations [23]:

$$\begin{aligned}
\frac{d}{dt} i_{ds} &= \sigma R_s i_{ds} + \omega_s i_{qs} + \mu L_m \omega_r i_{qs} \\
&\quad + \mu R_r i_{dr} + \mu L_r \omega_r i_{qr} + \sigma V_{ds}, \\
\frac{d}{dt} i_{qs} &= -\omega_s i_{ds} - \mu L_m \omega_r i_{ds} - \sigma R_s i_{qs} \\
&\quad - \sigma L_m \omega_r i_{dr} + \mu R_r i_{qr} + \sigma V_{qs}, \\
\frac{d}{dt} i_{dr} &= \mu R_s i_{ds} - \delta L_m \omega_r i_{qs} - \delta R_r i_{dr} \\
&\quad + \omega_s i_{qr} - \sigma L_s \omega_r i_{qr} - \mu V_{ds}, \\
\frac{d}{dt} i_{qr} &= \mu L_s \omega_r i_{ds} + \mu R_s i_{qs} - \omega_s i_{dr} \\
&\quad + \sigma L_s \omega_r i_{dr} - \delta R_r i_{qr} - \mu V_{qs}, \\
\frac{d}{dt} \omega_r &= \frac{3}{2} \frac{n_p^2}{J} L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) - \frac{n_p}{J} T_L,
\end{aligned} \tag{1}$$

where i_{ds}, i_{qs} are the components of the stator current, i_{dr}, i_{qr} are the components of the rotor current, ω_r is the rotor speed vector, V_{ds}, V_{qs} are stator voltage, ω_s is synchronous speed, T_L is an unknown load torque, n_p is the number of pair poles, J is the moment of inertia coefficient, and α_r, μ, δ, and σ are constants which are defined as

$$\alpha_r = L_s L_r - L_m^2, \quad \mu = \frac{L_m}{\alpha_r}, \quad \delta = \frac{L_s}{\alpha_r}, \quad \sigma = \frac{L_r}{\alpha_r}, \tag{2}$$

where R_s and R_r are stator and rotor resistances, L_s and L_r are stator and rotor inductances, and L_m is the mutual inductance.

Equation (1) can be given by the following state-space form:

$$\dot{x}(t) = Ax(t) + Bu(t) + B_1 w(t), \tag{3}$$

where $x(t) = [x_1 \;\; x_2 \;\; x_3 \;\; x_4 \;\; x_5]^T = [i_{ds} \;\; i_{qs} \;\; i_{dr} \;\; i_{qr} \;\; \omega_r]^T$ is the state vector of the induction motor, $u(t) = (V_{ds}, V_{qs})^T$ is a control vector, $w(t) = T_L$ represents the unknown disturbance function, and A, B, and B_1 are known real constant matrixes with appropriate dimensions.

3. Preliminaries and Problem Formulation

In this section, some useful notations and lemma are expressed. The notations in this paper are fairly standard.

In this context R stands for the set of real numbers. For a given matrix A, A^T denotes its transpose. I denotes a unity matrix with appropriate dimension. For given matrices M_k, $k = 1, \ldots, n$, the notation $\operatorname{diag}_{k=1}^{n}\{M_k\}$ denotes the block-diagonal matrix with M_k along the diagonal denoted for brevity. Moreover, the following lemma is used in this paper.

Lemma 1 (see [24] (Rayleigh inequality)). *Consider a non-singular symmetric matrix $Q \in R^{n\times n}$ and the minimum and maximum eigenvalues of Q as $\lambda_{\min}$ and $\lambda_{\max}$, respectively. Using these notations, for any $x \in R^n$, one can define $\lambda_{\min}(Q)\|x\|^2 \le x^T Q x \le \lambda_{\max}(Q)\|x\|^2$.*

Now, consider the following continuous-time linear system:

$$\dot{x}(t) = Ax(t) + Bu^F(t) + B_1 w(t), \tag{4}$$

where $x(t) \in R^n$ is the state vector, $u^F \in R^m$ is the faulty control input vector, and $w(t) \in R^q$ is a continuous vector function which represents the bounded external disturbances. A, B, and B_1 are known real constant matrixes with appropriate dimensions.

Assume $u_i^F(t)$ is the output signal of ith actuator that is faulty and $u_i(t)$ is the input signal of ith actuator. Then, we denote a general actuator fault model by

$$u_i^F(t) = \rho_i u_i(t), \quad i = 1, 2, \ldots m, \tag{5}$$

where ρ_i is the unknown time-varying actuator efficiency factor and $\underline{\rho_i}$ and $\overline{\rho_i}$ are the known lower and upper bounds of ρ_i, respectively. Table 1 illustrates the actuator fault modes.

From (5), *one can obtain*

$$u^F(t) = \rho u(t), \tag{6}$$

where $\rho = diag_i\{\rho_i\}$, $i = 1, 2, \ldots .m$ Then, the set of operators with the above structure can be denoted by

$$\Delta_\rho = \left\{\rho : \rho = diag_i\{\rho_i\}, \rho_i \in \left[\underline{\rho_i}, \overline{\rho_i}\right]\right\}. \tag{7}$$

Hence, the dynamic of system (4) *with actuator faults* (6) *can be described as follows:*

$$\dot{x}(t) = Ax(t) + B\rho u(t) + B_1 w(t). \tag{8}$$

To ensure the achievement of fault-tolerant objectives, the following assumptions in the FTC design are also assumed to be valid.

Assumption 1. All pairs $(A, B\rho)$ are uniformly completely controllable for any actuator fault mode under consideration.

Table 1: Fault Modes.

Fault mode	$\underline{\rho_i}$	$\overline{\rho_i}$
Normal	1	1
Loss of effectiveness	>0	<1

Assumption 2. The unmatched external disturbance $w(t)$ is bounded.

Assumption 3. The reference signal $x_{\text{ref}}(t)$ is smooth and bounded.

If we defined the tracking error as

$$e(t) = x(t) - x_{\text{ref}}(t), \tag{9}$$

according to the previous assumptions and according to (8) and (9), the error dynamics will be as follows:

$$\dot{e}(t) = Ae(t) + B\rho u(t) + Ax_{\text{ref}}(t) + B_1 w(t). \tag{10}$$

The system (10) can be rewritten as

$$\dot{e}(t) = Ae(t) + B\rho u(t) + \overline{B}_1 \overline{w}(t), \tag{11}$$

where

$$\overline{B}_1 = [B_1 \;\; A], \qquad \overline{w}(t) = [w(t) \;\; x_{\text{ref}}(t)]^T. \tag{12}$$

Assumption 4. The known positive constant $\overline{D}$ is assumed to satisfy the following inequality:

$$\|\overline{w}\| \le \overline{D}. \tag{13}$$

4. Direct Robust Adaptive Fault-Tolerant Tracking Controller Design

In this section, designing a direct adaptive fault-tolerant controller to guarantee closed-loop system stability via adaptive state feedback is developed. In this context, we designed an adaptive law to update the controller parameter when the mode of occurred fault is unknown.

Consider the following FTC law for the system (11):

$$u(t) = k_1 e(t) + k_2(t), \tag{14}$$

where $k_1 \in R^{m\times n}$ and $k_2(t) \in R^m$ are, respectively, the fixed and time-varying matrix gains that will be designed later.

From (11) and (14), the closed-loop system can be presented by

$$\dot{e}(t) = (A + B\rho k_1) e(t) + B\rho k_2(t) + \overline{B}_1 \overline{w}(t), \tag{15}$$

where $k_2(t) = [k_{2,1}(t), \ldots, k_{2,m}(t)]^T \in R^m$. The following adaptive law is suggested to design the adaptive FTC:

$$k_2(t) = \frac{-(e^T PB)^T \beta \hat{k}_3(t)}{\|e^T PB\| \alpha}, \tag{16}$$

where α and β are suitable positive constants which satisfy the following equation:

$$\frac{\alpha}{\beta} \leq \left\| \sqrt{\rho} \right\|^2, \tag{17}$$

and $\widehat{k}_3$ is updated by

$$\frac{d\widehat{k}_3}{dt} = \frac{\gamma \left(\left\| e^T PB \right\| \widehat{k}_3 - \left\| e^T P\overline{B}_1 \right\| k_3 \right)}{\widehat{k}_3 - k_3}, \tag{18}$$

where k_3 is a fixed parameter that will be selected by users for achieving better time response and, to compensate fault effects sooner, γ is any positive constant. In order to ensure the achievements of FTC objectives such as closed-loop stability and disturbance attenuation, the following theorem is considered.

Theorem 2. *Under Assumptions 1–4, the control law* (14) *for any positive matrix Q guarantees the closed-loop system* (15) *asymptotic stability if there exist a positive symmetric matrix R and constant matrix Z for any $\rho \in \Delta\rho$ such that*

$$\begin{bmatrix} \mu & R \\ R & -Q^{-1} \end{bmatrix} < 0, \quad \mu = RA^T + AR + Z^T \rho^T B^T + B\rho Z. \tag{19}$$

Furthermore with a feasible solution for LMI (R, Z)

$$R = P^{-1}, \qquad k_1 = ZP. \tag{20}$$

Remark 3. Parametric LMI in Theorem 2 is dependent on ρ but, for feasibly solving it, there is no need to know about ρ for any given time of simulation, because we only solve the parametric LMI for lower and upper boundaries of the ρ matrix components. For example, if the system has m actuators LMI must be solved for 2^m repetition and at last the answer of LMI for simulation will be the convex combination of the answers [9, 12].

Proof. For the closed-loop system described by (15), consider the following Lyapunov candidate:

$$V\left(e, \widetilde{k}_3\right) = e^T Pe + \gamma^{-1} \widetilde{k}_3^2, \tag{21}$$

where $\widetilde{k}_3$ is the parametric error and its dynamics can be written as

$$\widetilde{k}_3(t) = \widehat{k}_3(t) - k_3, \tag{22}$$

where k_3 is constant.

According to (15) the time derivative of the Lyapunov function becomes

$$\begin{aligned} \frac{dV\left(e, \widetilde{k}_3\right)}{dt} &= e^T \left[\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \right] e \\ &\quad + 2e^T PB\rho k_2 + 2e^T P\overline{B}_1 \overline{w} + 2\gamma^{-1} \widetilde{k}_3 \dot{\widetilde{k}}_3. \end{aligned} \tag{23}$$

By multiplying $\|e^T PB\|$ by the numerator and denominator of (16) and substituting it in (23), (23) can be rewritten as follows:

$$\begin{aligned} \frac{dV\left(e, \widetilde{k}_3\right)}{dt} &= e^T \left[\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \right] e \\ &\quad - 2e^T PB\rho \frac{\left(e^T PB\right)^T \beta \left\| e^T PB \right\| \widehat{k}_3}{\left\| e^T PB \right\|^2 \alpha} \\ &\quad + 2e^T P\overline{B}_1 \overline{w} + 2\gamma^{-1} \widetilde{k}_3 \dot{\widetilde{k}}_3. \end{aligned} \tag{24}$$

Considering (17) it will be easy to show that

$$\begin{aligned} \frac{dV\left(e, \widetilde{k}_3\right)}{dt} &\leq e^T \left[\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \right] e \\ &\quad - 2\left\| e^T PB \right\| \widehat{k}_3 + 2e^T P\overline{B}_1 \overline{w} + 2\gamma^{-1} \widetilde{k}_3 \dot{\widetilde{k}}_3. \end{aligned} \tag{25}$$

Since $x^T P\overline{B}_1 \overline{w}$ is scalar and by applying Assumption 4 and Lemma 1, one can get

$$2e^T P\overline{B}_1 \overline{w} \leq 2\left\| e^T P\overline{B}_1 \right\| \|\overline{w}\| \leq 2\left\| e^T PB_1 \right\| \overline{D}. \tag{26}$$

Then, inequality (27) can be derived from (25) and (26) as follows:

$$\begin{aligned} \frac{dV\left(e, \widetilde{k}_3\right)}{dt} &\leq e^T \left[\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \right] e \\ &\quad - 2\left\| e^T PB \right\| \widehat{k}_3 + 2\left\| e^T PB_1 \right\| \overline{D} + 2\gamma^{-1} \widetilde{k}_3 \dot{\widetilde{k}}_3, \end{aligned} \tag{27}$$

where the constant k_3 is assumed to satisfy the following inequality:

$$k_3 \geq \overline{D}. \tag{28}$$

Considering (27) and (28) and using of error dynamic of controller parameter, the adaptation law (18) can be derived as

$$\begin{gathered} -2\left\| e^T PB \right\| \widehat{k}_3 + 2\left\| e^T P\overline{B}_1 \right\| k_3 + 2\gamma^{-1} \widetilde{k}_3 \dot{\widetilde{k}}_3 = 0, \\ k_3 = cte \Longrightarrow \dot{\widetilde{k}}_3 = \dot{\widehat{k}}_3, \\ \gamma^{-1} \widetilde{k}_3 \dot{\widehat{k}}_3 = \left\| e^T PB \right\| \widehat{k}_3 - \left\| e^T P\overline{B}_1 \right\| k_3, \\ \frac{d\widehat{k}_3}{dt} = \frac{\gamma \left(\left\| e^T PB \right\| \widehat{k}_3 - \left\| e^T P\overline{B}_1 \right\| k_3 \right)}{\widehat{k}_3 - k_3}. \end{gathered} \tag{29}$$

Hence the derivative of Lyapunov function will be as

$$\frac{dV\left(e, \widetilde{k}_3\right)}{dt} \leq e^T \left[\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \right] e. \tag{30}$$

By defining the positive matrix Q in a way that

$$\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) \leq -Q \tag{31}$$

we can get

$$\left(A + B\rho k_1\right)^T P + P\left(A + B\rho k_1\right) + Q \leq 0. \quad (32)$$

Taking into account $R = P^{-1}$ and $k_1 = ZP$ leads to

$$RA^T + AR + Z^T \rho^T B^T + B\rho Z + RQR < 0. \quad (33)$$

Then by using Schur's Lemma, the LMI form of (33) will be in the following form:

$$\begin{bmatrix} \mu & R \\ R & -Q^{-1} \end{bmatrix} < 0, \quad \mu = RA^T + AR + Z^T \rho^T B^T + B\rho Z,$$
$$R = P^{-1}, \quad k_1 = ZP. \quad (34)$$

Finally from (30), we can get

$$\frac{dV\left(e, \tilde{k}_3\right)}{dt} \leq -e^T Q e < 0. \quad (35)$$

Then, the global adaptive fault-tolerant compensation control problem with disturbance rejection is solvable. Moreover, the closed-loop system with FTC is asymptotically stable and the states tracking error $e(t)$ will converge to zero for every initial state $x(0)$ of the TPIM. □

The following algorithm summarizes the suggested FTC implementation method.

Step 1. Check Assumptions 1–4 to be satisfied in all conditions.

Step 2. Solve LMI and compute the matrix P and k_1 using (34) assuming $Q^T = Q > 0$.

Step 3. Compute the gains $k_2(t)$ using (16) and (18).

Step 4. Compute robust adaptive control law with (14).

5. Simulation Results

In this section, some numerical simulations have been performed to validate the proposed FTC scheme. The induction motor parameters are given in the appendix.

The system (3) is linearized about an operating point using MATLAB, where

$$A = \begin{pmatrix} -69 & 5359 & 51 & 5145 & -38 \\ -5359 & -69 & -5146 & 51 & 12 \\ 67 & -5170 & -53 & -4963 & 39 \\ 5170 & 67 & 4963 & -53 & -13 \\ -270 & -828 & -438 & -803 & 0 \end{pmatrix},$$
$$B_2 = \begin{bmatrix} 38.96 & 0 \\ 0 & 38.96 \\ -37.72 & 0 \\ 0 & -37.72 \\ 0 & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -80 \end{bmatrix}. \quad (36)$$

The following test consists of 5 Nm load torque which is applied to the motor at 0.2 sec; also the actuator fault occurred in the following modes.

Mode 1. Actuators 1 and 2 are in normal mode; that is,

$$\rho_1^1 = \rho_2^1 = 1, \qquad 0 \leq t \leq 0.4, \qquad t \geq 0.44. \quad (37)$$

Mode 2. Actuators 1 and 2 are all in loss of effectiveness mode; for example,

$$\rho_1^2 = 0.7, \qquad \rho_2^2 = 0.7, \qquad 0.4 \leq t \leq 0.42. \quad (38)$$

Mode 3. Actuators 1 and 2 are all in loss of effectiveness mode; that is, in this mode the effectiveness of the actuators was decreased more than Mode 2:

$$\rho_1^3 = 0.5, \qquad \rho_2^3 = 0.2, \qquad 0.42 \leq t \leq 0.44. \quad (39)$$

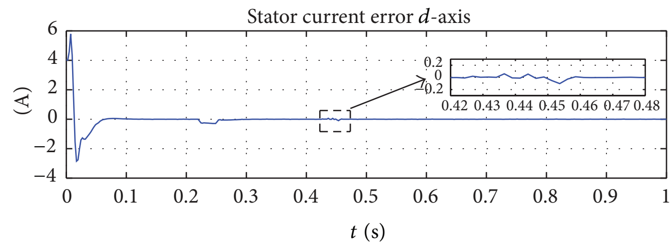
The following constants and initial conditions are taken for simulation:

$$\gamma = 1, \quad \alpha = 1, \quad \beta = 20, \quad x(0) = [4, 4, 1, 1, 10]^T,$$
$$\hat{k}_3(0) = 0, \quad Q = I_5. \quad (40)$$

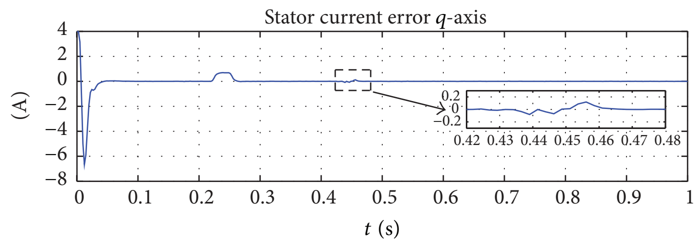
By solving LMI inequality (34) using LMI optimization algorithm with MATLAB, k_1 and P can be obtained as follows:

$$k_1 = \begin{bmatrix} 31.3198 & 54.2543 & 36.3926 & 37.4848 & -7.4969 \\ 156.8406 & 105.1832 & 177.2575 & 100.9172 & -2.3716 \end{bmatrix},$$
$$P = \begin{bmatrix} 3.9102 & 5.0484 & 4.3809 & 4.6873 & 0.0950 \\ 5.0484 & 36.2473 & 7.3945 & 34.3687 & -1.8239 \\ 4.3809 & 7.3945 & 5.3520 & 6.9827 & 0.0419 \\ 4.6873 & 34.3687 & 6.9827 & 32.7983 & -1.7876 \\ 0.0950 & -1.8239 & 0.0419 & -1.7876 & 0.2753 \end{bmatrix}. \quad (41)$$

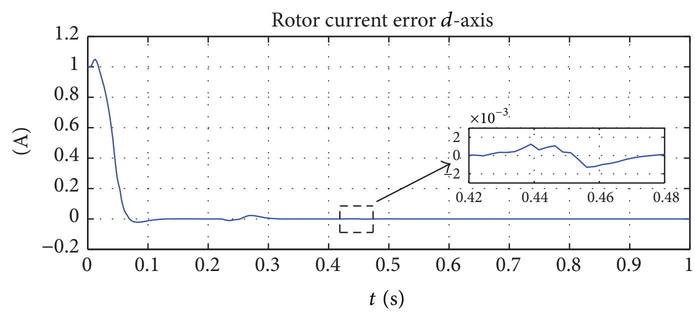
The closed-loop simulation results are reported in Figures 3(a)–3(e) in the presence of faults and disturbances. Figures 3(a) and 3(b) present the steady state stator currents, Figures 3(c) and 3(d) show the rotor currents, and Figure 3(e) illustrates the speed tracking errors. The simulation results illustrate the performances of the developed approach in terms of states tracking error $e(t)$ and converged to zero in a short time for any initial condition of the motor. These figures responses are remarkable when a constant load torque of 5 N·m value is applied at $t = 0.2$ s and the actuator faults occurred at $t = 0.4$ s. Indeed, Figures 3(a)–3(d) show that the stator and rotor currents tracking errors are asymptotically decaying to zero despite the actuator occurring fault. In addition, a less tracking error for speed is reported in Figure 3(e) under both healthy and faulty conditions, and this demonstrates that the disturbance and fault rejection are guaranteed truly. In other words, simulation results demonstrate that the proposed



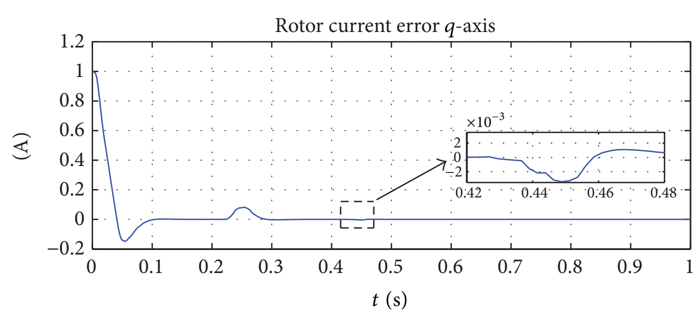
(a)



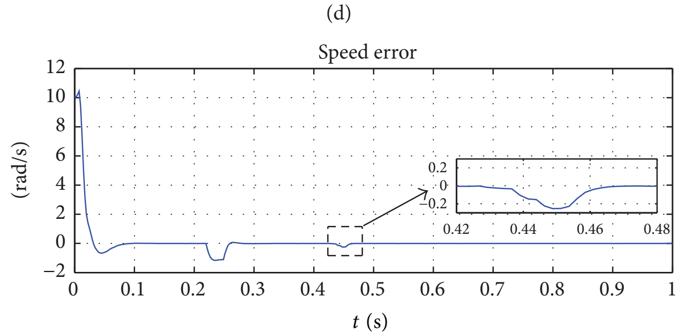
(b)



(c)



(d)



(e)

FIGURE 3: (a)–(e) Responses of the TPIM states under the fixed state feedback FTC (load torque is applied at $t = 0.2$ s and the actuator faults occurred at $t = 0.4$ s).

systems adaptively reorganize themselves in the event of actuator faults and in the presence of bounded disturbances to sustain the best control performance. However, the fixed state feedback has a simpler structure in comparison with the adaptive state feedback, and then it can be used in practical implementations extensively.

6. Conclusion

In this paper, the fault-tolerant tracking problem for three-phase induction motor against actuator faults and bounded disturbances is studied. A direct adaptive fault-tolerant tracking controller design method is developed based on the online tuning of adaptive FTC law to reduce the tracking error and to guarantee maximum performance in the event of faults and disturbances. It has been also shown that one of the adaptive state feedback gains can be fixed which is more suitable from a practical point of view. The effectiveness of the proposed method is revealed using numerical simulation on the induction motor in the presence of actuator faults and disturbances.

Appendix

The induction motor parameters are selected as 3 HP/2.4 KW, $U = 460\,\mathrm{V}(L-L,\mathrm{RMS})$, 60 Hz, $I_n = 4\,\mathrm{A}$, and $n_r = 1750\,\mathrm{RPM}$. The parameters are $J = 0.025\,\mathrm{Kg{\cdot}m^2}$, $R_s = 1.77\,\Omega$, $R_r = 1.34\,\Omega$, $X_{ls} = 5.25\,\Omega$, $X_{lr} = 4.57\,\Omega$, $X_m = 139\,\Omega$, and $n_p = 2$.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] F. Jadot, F. Malrait, J. Moreno-Valenzuela, and R. Sepulchre, "Adaptive regulation of vector-controlled induction motors," *IEEE Transactions on Control Systems Technology*, vol. 17, no. 3, pp. 646–657, 2009.

[2] A. M. S. Mendes and A. J. M. Cardoso, "Fault-tolerant operating strategies applied to three-phase induction-motor drives," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 6, pp. 1807–1817, 2006.

[3] B. Tabbache, N. Rizoug, M. E. H. Benbouzid, and A. Kheloui, "A control reconfiguration strategy for post-sensor FTC in induction motor-based EVs," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 3, pp. 965–971, 2013.

[4] K. S. Gaeid, H. W. Ping, M. Khalid, and A. Masaoud, "Sensor and sensorless fault tolerant control for induction motors using a wavelet index," *Sensors*, vol. 12, no. 4, pp. 4031–4050, 2012.

[5] T. A. Najafabadi, F. R. Salmasi, and P. Jabehdar-Maralani, "Detection and isolation of speed-, DC-link voltage-, and current-sensor faults based on an adaptive observer in induction-motor drives," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 5, pp. 1662–1672, 2011.

[6] F. Zidani, D. Diallo, M. Benbouzid, and R. Naït-Saïd, "A fuzzy-based approach for the diagnosis of fault modes in a voltage-fed PWM inverter induction motor drive," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 2, pp. 586–593, 2008.

[7] Y. Zhang and J. Jiang, "Bibliographical review on reconfigurable fault-tolerant control systems," *Annual Reviews in Control*, vol. 32, no. 2, pp. 229–252, 2008.

[8] M. E. H. Benbouzid, D. Diallo, and M. Zeraoulia, "Advanced fault-tolerant control of induction-motor drives for EV/HEV traction applications: From conventional to modern and intelligent control techniques," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 519–528, 2007.

[9] P. Apkarian, P. Gahinet, and G. Becker, "Self-scheduled H_∞ control of linear parameter-varying systems: a design example," *Automatica*, vol. 31, no. 9, pp. 1251–1261, 1995.

[10] M. Benosman, "A survey of some recent results on nonlinear fault tolerant control," *Mathematical Problems in Engineering*, vol. 2010, Article ID 586169, 25 pages, 2010.

[11] X. Z. Jin, "Robust adaptive switching fault-tolerant control of a class of uncertain systems against actuator faults," *Mathematical Problems in Engineering*, vol. 2013, Article ID 852502, 9 pages, 2013.

[12] I. Hwang, S. Kim, Y. Kim, and C. E. Seah, "A survey of fault detection, isolation, and reconfiguration methods," *IEEE Transactions on Control Systems Technology*, vol. 18, no. 3, pp. 636–653, 2010.

[13] A. Mihankhah, F. R. Salmasi, and K. Salahshoor, "Partial and total actuator faults accommodation for input-affine nonlinear process plants," *ISA Transactions*, vol. 52, no. 3, pp. 351–357, 2013.

[14] T. J. J. Lombaerts, G. H. N. Looye, Q. P. Chu, and J. A. Mulder, "Design and simulation of fault tolerant flight control based on a physical approach," *Aerospace Science and Technology*, vol. 23, no. 1, pp. 151–171, 2012.

[15] C. Bonivento, A. Isidori, L. Marconi, and A. Paoli, "Implicit fault-tolerant control: application to induction motors," *Automatica*, vol. 40, no. 3, pp. 355–371, 2004.

[16] D. Ye and G.-H. Yang, "Adaptive fault-tolerant tracking control against actuator faults with application to flight control," *IEEE Transactions on Control Systems Technology*, vol. 14, no. 6, pp. 1088–1096, 2006.

[17] X. Zhang, M. M. Polycarpou, and T. Parisini, "Fault diagnosis of a class of nonlinear uncertain systems with Lipschitz nonlinearities using adaptive estimation," *Automatica*, vol. 46, no. 2, pp. 290–299, 2010.

[18] A. Astolfi, D. Karagiannis, and R. Ortega, *Nonlinear and Adaptive Control with Applications*, Springer, 2008.

[19] G. C. Goodwin and K. S. Sin, *Adaptive Filtering Prediction and Control*, Dover, New York, NY, USA, 2009.

[20] X. Zhang, T. Parisini, and M. M. Polycarpou, "Adaptive fault-tolerant control of nonlinear uncertain systems: an information-based diagnostic approach," *IEEE Transactions on Automatic Control*, vol. 49, no. 8, pp. 1259–1274, 2004.

[21] H. Tohidi and H. Azmi, "Nonlinear state feedback fault tolerant controller design applied to three phase induction motor," in *Proceedings of the ICEEE Conference*, pp. 2258–2265, 2013.

[22] M. J. Corless and G. Leitmann, "Continuous state feedback guaranteeing uniform ultimate boundedness for uncertain dynamic systems," *IEEE Transactions on Automatic Control*, vol. 26, no. 5, pp. 1139–1144, 1981.

[23] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electric Machinery and Drive Systems*, IEEE Press, 2002.

[24] H. J. Marquez, *Nonlinear Control Systems: Analysis and Design*, Wiley-Interscience, Hoboken, NJ, USA, 2003.