ROBUST ADAPTIVE FAULT TOLERANT CONTROL OF THREE PHASE INDUCTION MOTOR

HosseinTohidi [*1], KoksalErenturk [2]

*[1 *]Department of Electrical Engineering, College of Engineering, Malekan Branch, Islamic Azad University, Malekan, Iran.Corresponding Author Email: Tohidi.iau@gmail.com*

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

ABSTRACT: *This paper investigates a robust adaptive feedback control scheme to solve a fault-tolerant control (FTC) problem for a three phase induction motor (TPIM) with actuator faults and external disturbances. A constructive algorithm based on linear matrix inequality (LMI) is developed for online tuning the output-feedback gains. The stability of closed-loop system is guaranteed by compensating the actuator faults with disturbance attenuation. The merits of proposed controller have been verified by the simulation on a Three Phase Induction motor.*

KEYWORDS: Actuator Faults, Fault Tolerant Control (FTC), Linear Matrix Inequality (LMI), Output Feedback Controller, Three Phase Induction Motor (TPIM).

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 maintenance 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 ability to produce a satisfactory output torque even in the presence of faults [3-5]. That's why that designing reliable drives has received great attention in 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 in two main classes: Passive FTC and Active FTC [6-9]. 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 [10]. 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 pre-computed control law or by synthesizing a new online control strategy [3,10-12]. Since the active FTC approach provides flexibility to choose various controllers, then 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 [9,1315]. Fig. 1 shows a closed-loop system with an active FTC strategy including the FDI block.

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]. This approach does not need FDI block. Fig. 2 shows a closed-loop system with an adaptation mechanism for on-line 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, a novel adaptive output feedback strategy is developed to solve the problem of FTC with more general loss of actuators effectiveness than the published works for TPIM. This technique is progressed by applying the LMI technique. Also, the close-loop system asymptotic stability is proved under mentioned faults and unmatched external disturbances. In comparison with the previous works like [1,16], the controller design algorithm is simplified and the number of online parameter tuning assumptions is reduced. Moreover, another goal is to design a fixed output feedback controller which do not requires flux measurements.

This paper is organized as follows: In Section 2, the induction motor mathematical model is presented. The FTC Problem formulation is described in Section 3. In Section 4, a direct adaptive robust output feedback controller is developed and a constructive algorithm based on LMI is presented for controller design. In Section 5, the merits of the proposed FTC are verified by the simulations on TPIM subjected to the actuator faults and disturbances. Finally, conclusions are given in Section 6.

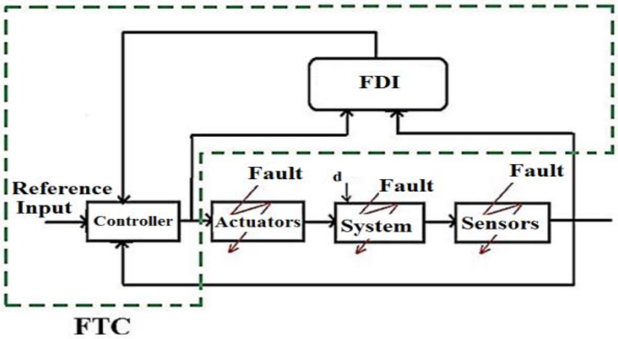


Figure 1. The closed-loop system with FTC and FDI

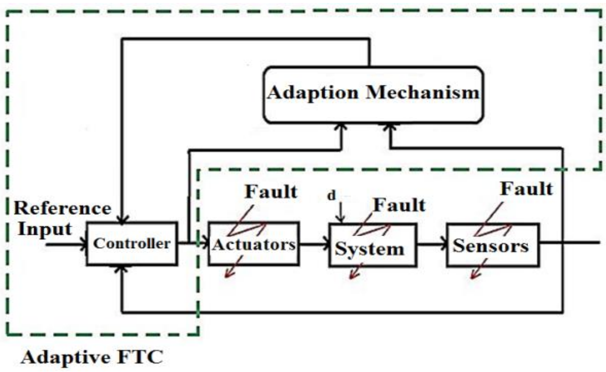


Figure 2. The closed-loop system with adaptive FTC

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]:

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

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, α_r, μ, δ and σ are constants which are defined as:

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

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.

To express the model of the induction motor with the measurable parameters (currents and rotor speed) as decision variables, the equations (1) can be given by the following state-space form:

$$\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu(t) + B_1 w(t) \\
y(t) &= Cx(t)
\end{aligned} \tag{2}$$

Where

$$x(t) = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{bmatrix}^T = \begin{bmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr} & \omega_r \end{bmatrix}^T$$

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, $y(t) = (i_{ds}, i_{qs}, \omega_r)$ is the vector of measurable variables, A, B, B_1 and C are known real constant matrixes with appropriate dimensions.

I. 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 denote its transpose. I Denotes a unity matrix with appropriate dimension. For given matrices M_k, $k = 1, \ldots, n$, the notation $diag_{k=1}^{n}\{M_k\}$ denotes the block-diagonal matrix with M_k along the diagonal and denoted for brevity. Moreover, the following Lemma is used in this paper.

Lemma1 [24]**:** (Rayleigh Inequality) Consider a nonsingular 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

$$\begin{aligned}
\dot{x}(t) &= Ax(t) + Bu^F(t) + B_1 w(t) \\
y(t) &= Cx(t)
\end{aligned} \tag{3}$$

Where $x(t) \in R^n$ is the state vector, $u^F \in R^m$ is the faulty control input vector, $w(t) \in R^q$ is a continuous vector function which represents the bounded external disturbances and $y(t) \in R^p$ is the measured output vector.

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

$$u_i^F(t) = \rho_i u_i(t), \qquad i = 1, 2, \ldots m \tag{4}$$

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

Table I. Fault Modes

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

From (4), one can obtain

$$u^F(t) = \rho u(t) \tag{5}$$

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

$$\Delta_\rho = \{\rho : \rho = diag_i\{\rho_i\}, \rho_i \in [\underline{\rho_i}, \overline{\rho_i}]\} \tag{6}$$

Hence, the dynamic of system (3) with actuator faults (5) can be described as follows:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B\rho u(t) + B_1 w(t) \\ y(t) &= Cx(t) \end{aligned} \tag{7}$$

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

Assumption1. All pairs $(A, B\rho)$ are uniformly completely controllable for any actuator fault mode under consideration.

Assumption2. The unmatched external disturbance w is a piecewise continuous bounded function, that is, there exist known positive constant $\overline{w}$ such that

$$\|w\| \le \overline{w}, \tag{8}$$

Assumption3. The stator current and rotor speed are measurable.

Remark1. Assumption 1 is standard and denotes the internal stability of each normal and fault isolated system to satisfying this assumption. Assumption 2 is quite natural and is common in the robust fault-tolerant control literature.

3- Direct Robust Adaptive Output Feedback FTC

In this section, we develop the adaptive laws to update the controller parameters when the loss of actuator effectiveness is unknown. Then, a method for designing direct adaptive fault-tolerant controllers to guarantee closed-loop system stability via adaptive output feedback is presented in Theorem1. Consider the following FTC Law for the system (7):

$$u(t) = k_1 y(t) + k_2(t) \tag{9}$$

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 design later.

From (7) and (9), the closed-loop system can be presented by

$$\dot{x}(t) = (A + B\rho(t)k_1 C)x(t) + B\rho(t)k_2(t) + B_1 w(t) \tag{10}$$

The following adaptive law is suggested to design the adaptive FTC.

$$k_2(t) = \frac{-\left(y^T PCB\right)^T \beta \hat{k}_3(t)}{\left\|y^T PCB\right\| \alpha} \tag{11}$$

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

$$\frac{\alpha}{\beta} \le \left\|\sqrt{\underline{\rho}}\right\|^2, \tag{12}$$

For $\underline{\rho} = diag_i\{\underline{\rho_i}\} \in \Delta_\rho,\ \ i = 1,2,\ldots m,$ and $\hat{k}_3(t) \in R$ is updated by the following adaptive law:

$$\frac{d\hat{k}_3}{dt} = \frac{\gamma(\left\|x^T C^T PCB\right\|\hat{k}_3 - \left\|x^T C^T PCB_1\right\|k_3)}{\hat{k}_3 - k_3} \tag{13}$$

Where γ is any positive constant and $\hat{k}_3(t_0)$ is finite. From (13) we can see $\hat{k}_3(t) \ge 0$ if $\hat{k}_3(t_0) \ge 0$ .In order to ensure the achievements of FTC objectives such as closed-loop stability and disturbance attenuation, the following theorem is considered.

Theorem1. Under assumptions 1,2 and 3, the control law (9) for any positive matrix Q guarantees the closed-loop system (10) asymptotic stable if there exists a positive symmetric matrix R and constant matrix Z for any $\rho \in \Delta\rho$ such that :

$$\begin{bmatrix} \mu & R \\ R & -Q^{-1} \end{bmatrix} \langle 0, \quad \mu = RA^T + AR + Z^T \rho^T B^T + B\rho Z \tag{14}$$

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

$$P = ((CC^T)^{-1}C)R^{-1}(C^T(CC^T)^{-1}), \ \ k_1 = ZR^{-1}(C^T(CC^T)^{-1})$$

Remark2. Parametric LMI in the Theorem 1 is dependent on ρ but for feasibly solving of 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 so 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 adaptive closed-loop system described by (10), consider the following Lyapunov candidate:

$$V(y, \tilde{k}_3) = y^T Py + \gamma^{-1}\tilde{k}_3^2 \tag{15}$$

According to the (7) Lyapunov functional will be as

$$V(x, \tilde{k}_3) = x^T C^T PCx + \gamma^{-1}\tilde{k}_3^2 \tag{16}$$

Where $\tilde{k}_3(t)$ is the parametric error and its dynamics can be written as

$$\tilde{k}_3(t) = \hat{k}_3(t) - k_3 \tag{17}$$

Where k_3 is constant.

According to (10) the time derivative of the Lyapanov function becomes

$$\begin{aligned} \frac{dV(x, \tilde{k}_3)}{dt} &= x^T\left[(A + B\rho k_1)^T P + P(A + B\rho k_1)\right]x \\ &+ 2x^T PB\rho k_2 + 2x^T PB_1 w + 2\gamma^{-1}\tilde{k}_3\dot{\tilde{k}}_3 \end{aligned} \tag{18}$$

By multiplying $\left\|x^T C^T PCB\right\|$ to the numerator and denominator of (11) and substituting it in (18), the equation (18) can be rewritten as follows:

$$\begin{aligned} \frac{dV(x, \tilde{k}_3)}{dt} &= x^T\left[(A + B\rho k_1 C)^T C^T PC + C^T PC(A + B\rho k_1 C)\right]x \\ &- 2x^T C^T PCB\rho \frac{\left(x^T C^T PCB\right)^T \beta \left\|x^T C^T PCB\right\| \hat{k}_3(t)}{\left\|x^T C^T PCB\right\|^2 \alpha} \\ &+ 2x^T C^T PCB_1 w + 2\gamma^{-1}\tilde{k}_3\dot{\tilde{k}}_3 \end{aligned} \tag{19}$$

Considering (12) it will be easy to show that:

$$\begin{aligned} \frac{dV(x, \tilde{k}_3)}{dt} &\le x^T\left[(A + B\rho k_1 C)^T C^T PC + C^T PC(A + B\rho k_1 C)\right]x \\ &- 2\left\|x^T C^T PCB\right\|\hat{k}_3 + 2x^T C^T PCB_1 w + 2\gamma^{-1}\tilde{k}_3\dot{\tilde{k}}_3 \end{aligned} \tag{20}$$

Since $x^T C^T PB_1 w$ is scalar, and by applying assumption 2 and Lemma 1, one can get:

$$2x^T C^T PCB_1 w \le 2\|x^T C^T PCB_1\|\|w\| \le 2\|x^T C^T PCB_1\|\overline{w} \quad (21)$$

Then, inequality (22) can be derived from Equations (20) and (21) as follows.

$$\frac{dV(x,\tilde{k}_3)}{dt} \le x^T\left[(A+B\rho k_1 C)^T C^T PC + C^T PC(A+B\rho k_1 C)\right]x \quad (22)$$
$$-2\|x^T C^T PCB\|\hat{k}_3 + 2\|x^T C^T PCB_1\|\overline{w} + 2\gamma^{-1}\tilde{k}_3\dot{\tilde{k}}_3$$

Where the constant k_3 is assumed to satisfy the following inequality

$$k_3 \ge \overline{w} \quad (23)$$

Considering (22) and (23) and using of error dynamic of controller parameter, the adaptation law (13) can be derived as

$$-2\|x^T C^T PCB\|\hat{k}_3 + 2\|x^T C^T PCB_1\|\overline{w} + 2\gamma^{-1}\tilde{k}_3\dot{\tilde{k}}_3 = 0$$

$$k_3 = cte \Rightarrow \dot{\tilde{k}}_3 = \dot{\hat{k}}_3$$

$$\gamma^{-1}\tilde{k}_3\dot{\hat{k}}_3 = \|x^T C^T PCB\|\hat{k}_3 - \|x^T C^T PCB_1\|k_3$$

$$\frac{d\hat{k}_3}{dt} = \frac{\gamma(\|x^T C^T PCB\|\hat{k}_3 - \|x^T C^T PCB_1\|k_3)}{\hat{k}_3 - k_3}$$

Hence the derivative of Lyapanov function will be as

$$\frac{dV(x,\tilde{k}_3)}{dt} \le x^T\left[(A+B\rho k_1 C)^T C^T PC + C^T PC(A+B\rho k_1 C)\right]x \quad (24)$$

By defining the Positive matrix Q in a way that:

$$(A+B\rho k_1 C)^T C^T PC + C^T PC(A+B\rho k_1 C) \le -Q \quad (25)$$

we can get:

$$(A+B\rho k_1 C)^T C^T PC + C^T PC(A+B\rho k_1 C) + Q \le 0 \quad (26)$$

Multiply both sides of (26) in $(C^T PC)^{-1}$

$$(C^T PC)^{-1}\{(A+B\rho k_1 C)^T C^T PC + C^T PC(A+B\rho k_1 C) + Q\}(C^T PC)^{-1} \le 0 \quad (27)$$

Taking into account $R = (C^T PC)^{-1}$ and $Z = k_1 CR$, leads to

$$RA^T + AR + Z^T \rho^T B^T + B\rho Z + RQR \langle 0 \quad (28)$$

Then by using the Schur's Lemma, the LMI form of (28) will be in the following form:

$$\begin{bmatrix} \mu & R \\ R & -Q^{-1} \end{bmatrix} \langle 0, \quad \mu = RA^T + AR + Z^T \rho^T B^T + B\rho Z \quad (29)$$

$$P = \left[\left(CC^T\right)^{-1} C\right] R^{-1} \left[C^T \left(CC^T\right)^{-1}\right],$$

$$k_1 = ZR^{-1}\left(C^T\left(CC^T\right)^{-1}\right)$$

Finally from (24), we can get

$$\frac{dV(x,\tilde{k}_3)}{dt} \le -x^T Q x \langle 0 \quad (30)$$

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 system states $x(t)$ will converge to zero.

The following algorithm summarizes the suggested FTC implementation method:

Step 1) Check Assumptions $1 \sim 3$ to be satisfied in all conditions.

Step 2) Solve LMI and Compute the matrix P and k_1 using (29) with assuming $Q^T = Q > 0$.

Step 3) Compute the gains $k_2(t)$ using (11) and (13).

Step 4) Compute robust adaptive control Law with (9).

4- SIMULATION RESULTS

Numerical simulations have been performed to validate the proposed FTC scheme. The induction motor parameters are given in the appendix. The system (1) is linearized about an operating point using MATLAB, and the equation (1) can be given by the state-space form (2), where

$$A = \begin{pmatrix} -69 & 5359 & 51 & 5145 & -38 \\ -5359 & -69 & -5146 & 51 & 12 \\ 67 & -5170 & -53 & -4963 & 39 \\ 5170 & 67 & 4963 & -53 & -13 \\ -270 & -828 & -438 & -803 & 0 \end{pmatrix}$$

$$B = \begin{bmatrix} 38.96 & 0 \\ 0 & 38.96 \\ -37.72 & 0 \\ 0 & -37.72 \\ 0 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -80 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

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

Mode 1) Actuators 1, 2 are in normal mode, i.e.

$$\rho_1^1 = \rho_2^1 = 1, \qquad 0 \le t \le 0.4, \qquad t \ge 0.44$$

Mode 2) Actuators 1, 2 are all in loss of effectiveness mode, i.e.

$$\rho_1^2 = 0.8, \rho_2^2 = 0.8, \qquad 0.4 \le t \le 0.42$$

Mode 3) Actuators 1, 2 are all in loss of effectiveness mode, i.e. in this mode the effectiveness of the actuators were decreased more than mode 2.

$$\rho_1^3 = 0.6, \rho_2^3 = 0.5, \qquad 0.42 \le t \le 0.44$$

The following constants and initial conditions are taken for simulation.

$$\gamma = 1, \quad \alpha = 1, \quad \beta = 20, \quad x(0) = [3,3,1,1,5]^T, \hat{k}_3(0) = 0, \quad Q = I_5$$

BySolving LMI (29) by LMI optimization algorithm, k_1 and P can be obtained as:

$$k_1 = \begin{bmatrix} -72 & -1283 & 877 \\ -11798 & -205 & -168 \end{bmatrix}, \qquad P = \begin{bmatrix} 2.8787 & 0.1519 & 0 \\ 0.1519 & 4.4159 & 0 \\ 0 & 0 & 2.8707 \end{bmatrix}$$

The computer simulation results are shown in Fig. 3. It shows that the system states $x(t)$ are converged to zero in a short time for any initial conditions.

Fig. 4 (a-e) is the response of the TPIM states with fixed output feedback FTC in the above mentioned faulty case. This figure responses are remarkable when the load torque is applied at t=0.2s andthe actuator faults is occurred at t=0.4s. In the other word, simulation results demonstrate that the proposed fault compensation scheme has a considerable influence on the performance of the induction motor. Moreover, the adaptive output feedback has a simple structure in comparison with the adaptive state feedback, and then it can be used in practical implementations extensively. Also, there is no need for flux measuring in the output feedback control scheme.

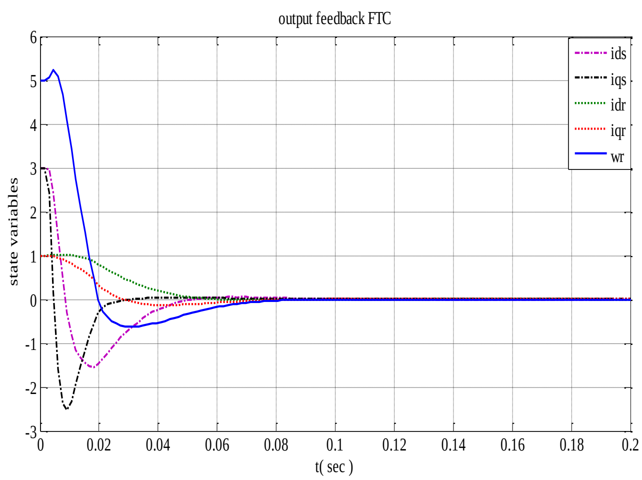
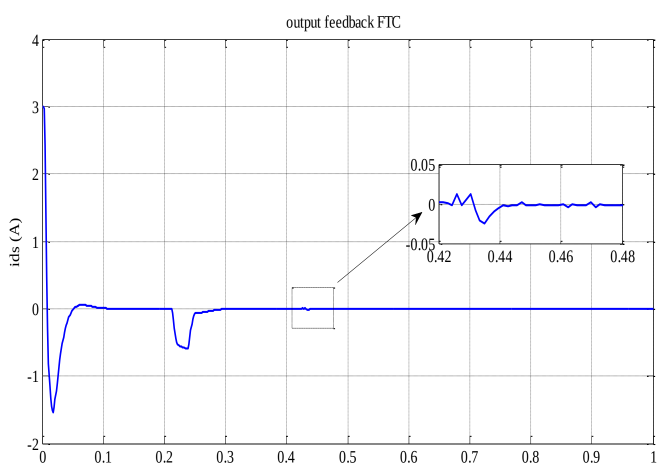
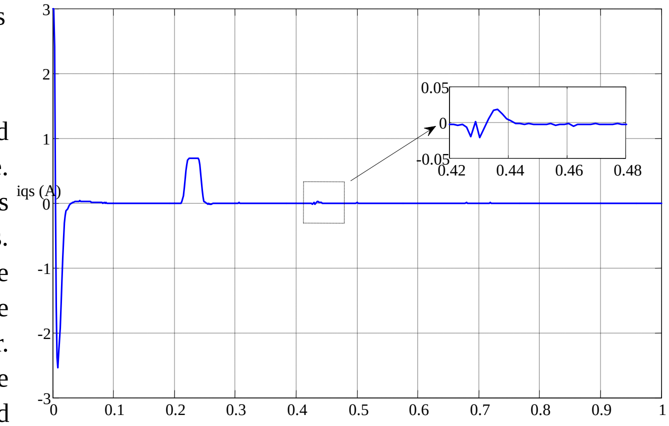


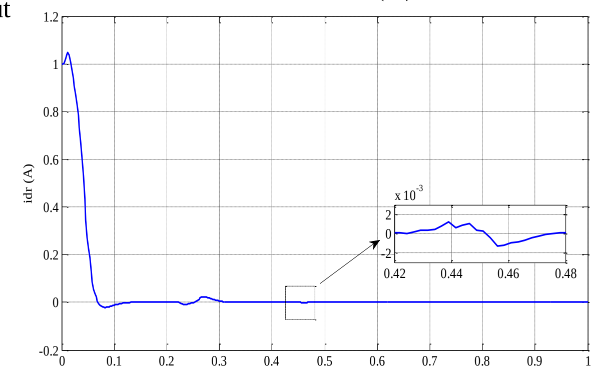
Figure 3.Responses of TPIM under the fixed output feedback FTC for normal mode.



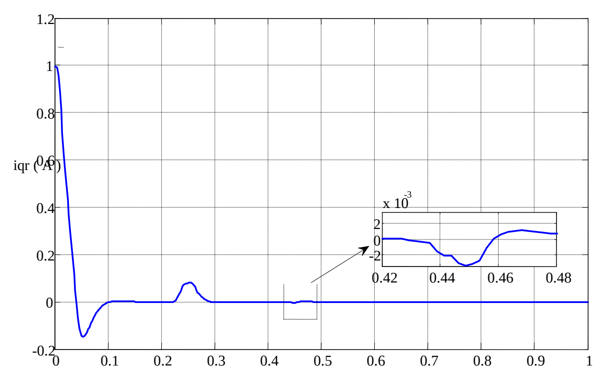
(a)



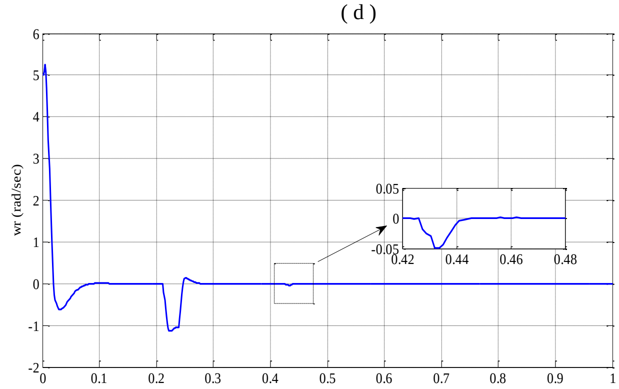
(b)



(c)



(d)



(e)

Figure 4(a-e). Responses of TPIM under the fixed output feedback FTC (load torque is applied at t=0.2s andthe actuator faults is occurred at t=0.4s).

5- CONCLUSION

In this paper, the robust Adaptive output feedback fault-tolerant controllers were developed for TPIM with actuator faults and bounded disturbances. Using the Lyapunov stability theory, a constructive algorithm based on LMIs was developed for on-line tuning of adaptive FTC laws to stabilize the closed-loop system. Numerical simulations on Three Phase Induction Motor demonstrate the effectiveness of the proposed FTC method.

6- APPENDIX

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

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