Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 57(3), 703–713(2016)

Habib ben Zina, Moez Allouche, Mansour Souissi, Mohamed Chaabane, Larbi Chrifi-Alaoui and Maha Bouattour

Descriptor Observer Based Fault Tolerant Tracking Control for Induction Motor Drive

DOI 10.7305/automatika.2017.02.1650
UDK 681.516.7.09.037.26-048.63:621.313.333.044

Original scientific paper

This paper presents an active Fault Tolerant Control (FTC) strategy for induction motor (IM) that ensures Field Oriented Control (FOC) and offset the effect of the sensor faults despite of the load torque disturbance. The proposed approach uses a fuzzy descriptor approach to estimate simultaneously the system state and the sensor fault. The physical model of IM is approximated by the Takagi-Sugeno (T-S) fuzzy technique in the synchronous d-q rotating frame with field-oriented control strategy. The stability conditions are analyzed using Lyapunov theory. The controller and observers gains are calculated by solving a set of Linear Matrix Inequalities (LMIs). Finally, the effectiveness of the proposed strategy have been illustrated in simulation and experimental results.

Key words: Fault tolerant control, T-S model, Induction motor, Field Oriented Control, sensor fault, LMIs

Upravljanje otporno na kvarove asinkronog motora zasnovano na deskriptorskom observeru. U ovom radu je predstavljena strategija upravljanja otpornog na kvarove za asinkroni motor koja omogućuje vektorsko upravljanje bez pogreške uslijed kvara senzora i postojećeg poremećaja momenta tereta. Predloženi pristup koristi neizraziti deskriptor za estimaciju stanja sustava i kvara senzora. Fizikalni model asinkronog motora s vektorskim upravljanjem aproksimiran je korištenjem Takagi-Sugeno modela u rotirajućem d-q koordinatnom sustavu. Uvjeti stabilnosti analizirani us korištenjem Ljapunovljeve teorije. Konstante pojačanja regulatora i observera su izračunati rješavanjem skupa linearnih matričnih nejednadžbi. Učinkovitost predložene strategije je ilustrirana simulacijskim i eksperimentalnim rezultatima.

Ključne riječi: upravljanje otporno na kvarove, Takagi-Sugeno model, asinkroni motor, vektorsko upravljanje, kvar senzora, linearne matrične nejednadžbe

NOMENCLATURE

i_{sd}, i_{sq} : The (d, q) stator currents.

ψ_{rd}, ψ_{rq} : The (d, q) rotor flux.

ω_m : The rotor speed.

ω_s : The electrical stator speed.

L_s, L_r : The stator and rotor inductances.

M : The mutual inductance.

R_s, R_r : The stator and rotor resistances.

n_p : The pole pairs number.

f : The friction coefficient.

1 INTRODUCTION

Today, Induction Motors (IM) become very used in a wide range of industrial applications especially in electric drive traction. This is due to their reliability, robustness and low cost. However, the control of IM is known to be difficult, since the dynamic system is nonlinear, some electrical variables are not measurable such as flux and its parameters are often imprecisely known or variable.

It is known that if a fault occurs the control performance may be deteriorated and in some cases can lead to system instability. To overcome this drawbacks, the strategy for fault detection and isolation (FDI) and for Fault tolerant control (FTC) are introduced to offset the fault effect and maintain system stability [1-6]. In literature, we find two approaches for the design of fault tolerant control: Passive Fault Tolerant Control (PFTC) and Active Fault Tolerant Control (AFTC). The first approach requires priori information about the fault which may affect the system. These fault is considered as uncertainty or disturbance which are taken into account in the design of the control law [7]. In the second approach, according to the information provided by the FDI block the control law compensate the fault on-line [8,9,10]. However, the success of previous methods depends on the system model complexity. Takagi-Sugeno (T-S) technique is considered as an efficient way to represent nonlinear system. It consist to decompose the model of the nonlinear system into a series of linear models involving nonlinear weighting functions. The equivalent fuzzy model describes the dynamic of behavior of the system [11]. This approach has been successfully integrated in nonlinear system modeling and control. The problem of tracking control for T-S and faulty models has been studied by a few numbers of works [12,13].

Because of several stress, IM can be affected by various faults [14]. In addition, the overall performance of induction motor drives with a feedback structure depends not only on the health of the motor itself but also on the performance of the driving circuits and sensors: the encoder, voltage sensors and current sensors. FTC problem for IM becomes an important topic of research in the last years [15,16,17,18,23]. The papers [15,16], present a robust fault tolerant control using the combination of the backstepping control and the sliding mode observer. In [17], the problem of the FTC of IM drives is presented where two control techniques are used: the indirect field-oriented control (IFOC) in the fault free case and speed control with slip regulation (SCSR) in the case of current sensor fault. In [18], the author presents a comparative studies between several fault tolerant control schemes of IM. The paper [19], presents a FTC strategy in inverter fault case. To counteract, the mechanical fault and guarantee the IM control performances, the author in [20] proposes an implicit fault control. Recently, FTC of IM based electrical vehicles has been introduced in order to maintain the system stability despite on the presence of sensor and actuator faults [21,22].

In our work, we exploit the performances of the FTC for state feedback control for IM to guarantee the stability and the operating in safe despite the speed sensor fault. A fuzzy descriptor observer is designed to give simultaneous estimation of system state and sensor fault. This estimation will be exploited in an observer based FTC to guarantee the control performances of the IM with respect to load torque disturbance.

This paper is organized as follows: Section 2 introduces the physical model of the IM and an open-loop control strategy is designed. A fuzzy observer-based fault tolerant tracking control is considered in section 3. In section 4, simulation and experimental results are provided to demonstrate the design effectiveness. Section 5 concludes this paper.

Notation : The symbol (*) denotes the transpose elements in the symmetric positions.

2 OPEN LOOP CONTROL

2.1 Physical model of induction motor

Under the assumptions of the linearity of the magnetic circuit, the model of the IM in the synchronous d-q reference frame can be described as

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t) + w(t) \tag{1}$$

where

$$f(x(t)) = \begin{bmatrix} -\alpha i_{sd} + \omega_s i_{sq} + \frac{K_s}{T_r}\psi_{rd} + K_s n_p \omega_m \psi_{rq} \\ -\omega_s i_{sd} - \alpha i_{sq} - K_s n_p \omega_m \psi_{rd} + \frac{K_s}{T_r}\psi_{rq} \\ \frac{M}{Tr} i_{sd} - \frac{1}{T_r}\psi_{rd} + (\omega_s - n_p\omega_m)\psi_{rq} \\ \frac{M}{Tr} i_{sq} - (\omega_s - n_p\omega_m)\psi_{rd} - \frac{1}{T_r}\psi_{rq} \\ \frac{n_p M}{J L_r}(\psi_{rd} i_{sq} - \psi_{rq} i_{sd}) - \frac{f}{J}\omega_m \end{bmatrix},$$

$$w(t) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{C_r}{J} \end{bmatrix}, g(x(t)) = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$u(t) = \begin{bmatrix} u_{sq} \\ u_{sd} \end{bmatrix}, \alpha = \left(\frac{1}{\sigma \tau_s} + \frac{1-\sigma}{\sigma \tau_r}\right),$$

$$\sigma = 1 - \frac{M^2}{L_s L_r}, \tau_s = \frac{L_s}{R_s}, \tau_r = \frac{L_r}{R_r}, K_s = \frac{M}{\sigma L_s L_r}.$$

$$x(t) = \begin{bmatrix} i_{sd} & i_{sq} & \Psi_{rd} & \Psi_{rq} & \omega_m \end{bmatrix}^T$$

2.2 open loop control

This section is dedicated to present the open loop control strategy. If we replace the state variables of the IM $x(t) = \begin{bmatrix} i_{sd} & i_{sq} & \Psi_{rd} & \Psi_{rq} & \omega_m \end{bmatrix}^T$ by the corresponding reference $\begin{bmatrix} i_{sdc} & i_{sqc} & \psi_{rdc} & 0 & \omega_{mc} \end{bmatrix}^T$ in (1), we obtain

$$\begin{cases} \frac{d}{dt} i_{sdc} = -\alpha i_{sdc} + \omega_s i_{sqc} + \frac{K_s}{\tau_r}\psi_{rdc} + \frac{1}{\sigma L_s} u_{sdc} \\ \frac{d}{dt} i_{sqc} = -\omega_s i_{sdc} - \alpha i_{sqc} - K_s n_p \omega_{mc}\psi_{rdc} + \frac{1}{\sigma L_s} u_{sqc} \\ 0 = -(\omega_s - n_p w_{mc})\psi_{rdc} - \frac{M}{\tau r} i_{sqc} \\ \frac{d}{dt}\psi_{rdc} = \frac{M}{\tau r} i_{sqc} - \frac{1}{\tau_r}\psi_{rdc} \\ \frac{d}{dt}\omega_{mc} = \frac{n_p M}{J L_r}(\psi_{rdc} i_{sqc}) - \frac{f}{J}\omega_{mc} - \frac{1}{J} C_r \end{cases} \tag{2}$$

To guarantee the field oriented control performances, the open-loop reference stator current, the electrical speed and the open loop control can be written as follows:

$$\begin{cases} i_{sdc} = \frac{\psi_{rdc}}{M} + \frac{\tau_r}{M}\frac{d}{dt}\psi_{rdc} \\ i_{sqc} = \frac{J L_r}{n_p M \psi_{rdc}}\left(\frac{C_r}{J} + \frac{f}{J}\omega_{mc} + \frac{d}{dt}\omega_{mc}\right) \end{cases} \tag{3}$$

$$\omega_{sc} = n_p \omega_{mc} + \frac{M}{\tau_r \psi_{rdc}} i_{sqc} \tag{4}$$

$$\begin{cases} u_{sdc} = \sigma L_s \left(\frac{d}{dt} i_{sdc} + \alpha i_{sdc} - \omega_{sc} i_{sqc} - \frac{K_s}{\tau_r}\psi_{rdc}\right) \\ u_{sqc} = \sigma L_s \begin{pmatrix} \frac{d}{dt} i_{sqc} + \alpha i_{sqc} + \omega_{sc} i_{sdc} + \\ K_s n_p \omega_{mc} \psi_{rdc} \end{pmatrix} \end{cases} \tag{5}$$

2.3 Takagi-Sugeno Fuzzy Induction motor model

When the field-oriented control strategy is considered, the IM becomes similar to the separately excited DC motor. In this condition, the rotor flux vector(ψ_{rd}, ψ_{rq}) is aligned to the d-axis, and we obtain

$$\begin{cases} \psi_{rd} = \psi_{rdc} \\ \psi_{rq} = 0 \end{cases} \tag{6}$$

To guarantee the field-oriented control performance, the electrical speed of the stator in the rotating synchronous d-q frame can be expressed as

$$\omega_s = n_p \omega_m + \frac{M}{\tau_r \psi_{rd}} i_{sq} \tag{7}$$

If we replace the electrical speed (7) in the physical model (1), the nonlinear model of the IM can be written as

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + w(t) \\ y(t) = Cx(t) \end{cases} \tag{8}$$

where

$$A = \begin{bmatrix} -\alpha & \omega_s & \frac{K_s}{\tau_r} & K_s n_p \omega_m & 0 \\ -\omega_s & -\alpha & -K_s n_p \omega_m & \frac{K_s}{\tau_r} & 0 \\ \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} & \frac{M}{\tau_r \psi_{rdc}} i_{sq} & 0 \\ 0 & \frac{M}{\tau_r} & -\frac{M}{\tau_r \psi_{rdc}} i_{sq} & -\frac{1}{\tau_r} & 0 \\ 0 & 0 & -\frac{n_p M}{J L_r} i_{sq} & -\frac{n_p M}{J L_r} i_{sd} & -\frac{f}{J} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 & 0 \end{bmatrix}^T, C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The system (8) contains the following three nonlinearities:

$$\begin{cases} z_1(t) = i_{sd}(t) \\ z_2(t) = i_{sq}(t) \\ z_3(t) = \omega_m(t) \end{cases} \tag{9}$$

By using the well known sector nonlinearity technique. The local weighting functions are defined by

$$\begin{cases} F_{1j}(t) = \frac{z_j(t) - z_{j\min}}{z_{j\max} - z_{j\min}} \\ F_{2j}(t) = \frac{z_{j\max} - z_j(t)}{z_{j\max} - z_{j\min}} \end{cases} \tag{10}$$

Thus we can transform the non linear terms under the following shape:

$$z_j(t) = F_{1j}(t) z_{j\max} + F_{2j}(t) z_{j\min}; j = \{1, 2, 3\} \tag{11}$$

Consequently, the global fuzzy model of the IM can be written in the following form:

$$\dot{x}(t) = \sum_{i=1}^{8} h_i(z(t))(A_i x(t)) + Bu(t) + w(t) \tag{12}$$

where

$$\begin{cases} h_i(z(t)) = \frac{\mu_i(z(t))}{\sum_{i=1}^{8} \mu_i(z(t))}, \mu_i(z(t)) = \prod_{k=1}^{3} F_{ik}(z_k(t)) \\ h_i(z(t)) > 0, \sum_{i=1}^{8} h_i(z(t)) = 1 \end{cases}$$

3 OBSERVER BASED FAULT TOLERANT TRACKING CONTROL

3.1 Reference model

As in [24], to specify the desired trajectory, the reference model is chosen as follows

$$\dot{x}_r(t) = A_r x_r(t) + r(t) \tag{13}$$

where $x_r(t) = \begin{bmatrix} i_{sdr} & i_{sqr} & \psi_{rdr} & \psi_{rqr} & \omega_{mr} \end{bmatrix}^T$ is the reference state.

$$A_r = \begin{bmatrix} -\zeta_1 & \omega_{sr} & \zeta_2 & K_s n_p \omega_{mr} & 0 \\ -\omega_{sr} & -\zeta_1 & -K_s n_p \omega_m & \frac{K_s}{\tau_r} & 0 \\ \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} & \frac{M}{\tau_r \psi_{rdr}} i_{sqr} & 0 \\ 0 & \frac{M}{\tau_r} & -\frac{M}{\tau_r \psi_{rdr}} i_{sqr} & -\frac{1}{\tau_r} & 0 \\ 0 & 0 & -\frac{n_p M}{J L_r} i_{sqr} & -\frac{n_p M}{J L_r} i_{sdr} & -\frac{f}{J} \end{bmatrix}$$

$\zeta_1 = (\alpha + K_\Psi)$, $\zeta_2 = (\frac{K_s}{\tau_r} + \frac{M K_f}{L_s \tau_r})$ and $\omega_{sr} = n_p \omega_{mr} + \frac{M}{\tau_r \psi_{rdc}} i_{sqr}$

where K_Ψ and K_f are positive constants introduced to improve the dynamic of the IM. $r(t)$ is a bounded reference input given as

$$r(t) = \begin{bmatrix} B & I \end{bmatrix} \begin{bmatrix} U_r(t) \\ w(t) \end{bmatrix} \tag{14}$$

where

$$U_r(t) = \begin{bmatrix} U_{sdr} \\ U_{sqr} \end{bmatrix}$$

$$U_{sdr} = \sigma L_s \begin{bmatrix} \frac{d}{dt} i_{sdc} + (\alpha + K_i) i_{sdc} - \omega_{sc} i_{sqc} \\ + \left(\frac{M K_\psi - L_s K_s}{\tau_R L_s} \right) \Psi_{rdc} \end{bmatrix}$$

$$U_{sqr} = \sigma L_s \begin{bmatrix} \frac{d}{dt} i_{sqc} + (\alpha + K_f) i_{sqc} + \omega_{sc} i_{sdc} \\ + K_s n_p \omega_{mc} \Psi_{rdc} \end{bmatrix}$$

The reference model (13) can be described via T-S fuzzy model where the global fuzzy reference model is inferred as

$$\dot{x}_r(t) = \sum_{j=1}^{8} h_j(z_r(t))(A_{rj} x_r(t)) + r(t) \tag{15}$$

To attenuate the external disturbances, we consider the H_∞ performances related to the tracking error $x_r(t) - x(t)$ as follows

$$\int_0^{t_f} \left([x_r(t) - x(t)]^T Q [x_r(t) - x(t)] \right) \leq \gamma^2 \int_0^{t_f} \left(r(t)^T r(t) + w(t)^T w(t) dt \right) \quad (16)$$

3.2 Fault tolerant Tracking control strategy

In order to point up the proposed approach, the fault is injected to the T-S model (12) that represents the model of the IM. The faulty system can be written in the following structure:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{8} h_i(z(t))(A_i x(t) + Bu(t) + w(t)) \\ y(t) = Cx(t) + Df(t) \end{cases} \quad (17)$$

where $f(t) \in \Re^l$ denote the sensor fault. D is of appropriate dimension and assumed to be of full column rank. Construct the augmented descriptor system consisting of the system (17) and the sensor fault as follows:

$$\begin{cases} \bar{E}\dot{\bar{x}}(t) = \sum_{i=1}^{8} h_i(z(t)) \begin{pmatrix} \bar{A}_i \bar{x}(t) + \bar{B}u(t) + \\ \bar{H}w(t) + \bar{D}x_s(t) \end{pmatrix} \\ y(t) = \bar{C}\bar{x}(t) = C_0 \bar{x}(t) + x_s(t) \end{cases} \quad (18)$$

where

$$x_s(t) = Df(t), \bar{x}(t) = \begin{bmatrix} x(t) \\ x_s(t) \end{bmatrix}, \bar{E} = \begin{bmatrix} I_n & 0 \\ 0 & 0 \end{bmatrix},$$
$$\bar{A}_i = \begin{bmatrix} A_i & 0 \\ 0 & -I_p \end{bmatrix}, \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}, \bar{D} = \begin{bmatrix} 0 \\ I_p \end{bmatrix},$$
$$C_0 = \begin{bmatrix} C & 0 \end{bmatrix}, \bar{C} = \begin{bmatrix} C & I_p \end{bmatrix}, \bar{H} = \begin{bmatrix} I \\ 0 \end{bmatrix}$$

and the vector $x_s(t)$ is considered as an auxiliary state of the augmented system (18).

The following fuzzy observer is constructed to estimate simultaneously system state and the sensor fault

$$\begin{cases} E\dot{z}(t) = \sum_{i=1}^{8} h_i(z(t)) \left(N_i z(t) + \bar{B}u \right) \\ \hat{\bar{x}}(t) = z(t) + Ly(t) \end{cases} \quad (19)$$

where $z(t) \in \Re^{n+p}$ is the auxiliary state vector and $\hat{\bar{x}}(t) \in \Re^{n+p}$ is the state estimation vector. $E, N_i \in \Re^{(n+p)*(n+p)}$, $L \in \Re^{(n+p)*p}$ are the gain matrices of the observer. Let us define the observer error as follows:

$$\bar{e}(t) = \bar{x}(t) - \hat{\bar{x}}(t) = \begin{bmatrix} e_0^T(t) & e_s^T(t) \end{bmatrix}^T \quad (20)$$

From (18) and (19) we obtain

$$\left(\bar{E} + EL\bar{C} \right) \bar{x}(t) - E\hat{\bar{x}}(t) = \sum_{i=1}^{8} h_i(z(t)) \left((\bar{A}_i + +N_i LC_0)\bar{x}(t) - N_i \hat{\bar{x}}(t) + (\bar{D} + N_i L)x_s(t) + \bar{H}w(t) \right) \quad (21)$$

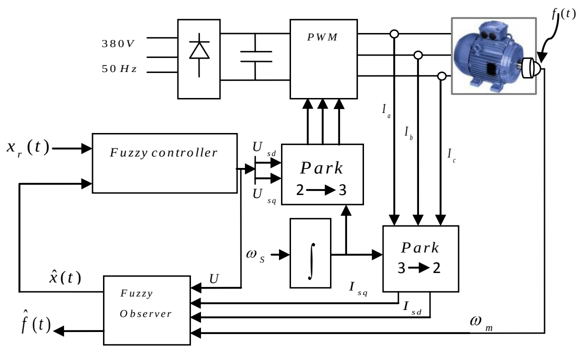

Fig. 1. Fault tolerant control strategy

if we choose

$$\begin{array}{l} N_i = \bar{A}_i + N_i LC_0 \\ E = \bar{E} + EL\bar{C} \\ \bar{D} = -N_i L \end{array} \quad (22)$$

the dynamic error can be written in the following form

$$E\dot{\bar{e}}(t) = \sum_{i=1}^{8} h_i(z(t)) \left(N_i \bar{e}(t) + \bar{H}w(t) \right) \quad (23)$$

In order to guarantee the constraints (22), the observer parameters E, N_i, L are chosen as follows

$$N_i = \begin{bmatrix} A_i & 0 \\ -C & -I_p \end{bmatrix}, L = \begin{bmatrix} 0 \\ I_p \end{bmatrix}, E = \begin{bmatrix} I_n & 0 \\ RC & R \end{bmatrix} \quad (24)$$

with $R \in \Re^{p*p}$ is non singular matrix. Then the dynamic error can be written in the following form:

$$\dot{\bar{e}}(t) = \sum_{i=1}^{8} h_i(z(t)) \left(S_i \bar{e}(t) + \tilde{H}w(t) \right) \quad (25)$$

where

$$S_i = E^{-1} N_i = \begin{bmatrix} A_i & 0 \\ -CA_i - R^{-1}C & R^{-1} \end{bmatrix},$$
$$\tilde{H} = E^{-1}\bar{H} = \begin{bmatrix} I_n \\ -C \end{bmatrix}$$

The following fuzzy controller is employed to deal with the above control system design.

$$u(t) = \sum_{i=1}^{8} h_i(z(t)) K_i \left(\hat{x}(t) - x_r(t) \right) \quad (26)$$

The FT controller design methodology is illustrated by the scheme illustrated in figure 1.
The tracking error is defined as follows

$$e_t = x(t) - x_r(t) \quad (27)$$

Then from (15,17) and (26), the tracking error dynamic is:

$$\begin{aligned}\dot{e}_t(t) = \sum_{i=1}^{8}\sum_{j=1}^{8} h_j(z(t))h_i(z(t))\,((A_i + BK_j)e_r(t) \\ BK_j e(t) + (A_i - A_{rj})x_r(t) + w(t) - r(t))\end{aligned} \tag{28}$$

We construct an augmented system containing the tracking error and the estimation error:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{8}\sum_{j=1}^{8} h_j(z(t))h_i(z(t))\left(\tilde{A}_i\tilde{x}(t) + \tilde{F}_{ij}\Phi(t)\right) \tag{29}$$

where

$$\tilde{x}(t) = \begin{bmatrix} e_t \\ e_0 \\ e_s \end{bmatrix}, \Phi(t) = \begin{bmatrix} w(t) \\ r(t) \\ x_r(t) \end{bmatrix},$$

$$\tilde{A}_{ij} = \begin{bmatrix} A_i + BK_j & -BK_j & 0 \\ 0 & A_i & 0 \\ 0 & -CA_i - R^{-1}C & -R^{-1} \end{bmatrix},$$

$$\tilde{F}_{ij} = \begin{bmatrix} I & -I & A_i - A_{rj} \\ I & 0 & 0 \\ -C & 0 & 0 \end{bmatrix}$$

The H_∞ performances (16) related to the tracking error can be modified as follows:

$$\int_0^{t_f} \tilde{x}^T \tilde{Q}\tilde{x}dt \le \gamma^2 \int_0^{t_f} \Phi(t)dt \tag{30}$$

where $\tilde{Q} = \begin{bmatrix} Q & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

Now the goal is to design a fuzzy controller able to force the output of the IM to tracks the reference signal in both the faulty and fault-free cases.

Theorem 1. For a given positive scalar μ, the closed loop fuzzy system in (29) is asymptotically stable and the H_∞ performance is guaranteed with an attenuation level γ, if there exists some matrices $X_1 = X_1^T > 0, P_2 = P_2^T > 0, P_3 = P_3^T > 0,\ Y_j,\ \Omega$ and the scalar γ satisfy the following LMI:

$$\begin{bmatrix}
\Xi_{11} & -BY_i & 0 & I & -I & A_i - A_{rj} & 0 & 0 & 0 & 0 & 0 & X_1 \\
* & -2\mu X & 0 & 0 & 0 & 0 & \mu I & 0 & 0 & 0 & 0 & 0 \\
* & * & -2\mu I & 0 & 0 & 0 & 0 & \mu I & 0 & 0 & 0 & 0 \\
* & * & * & -2\mu I & 0 & 0 & 0 & 0 & \mu I & 0 & 0 & 0 \\
* & * & * & * & -2\mu I & 0 & 0 & 0 & 0 & \mu I & 0 & 0 \\
* & * & * & * & * & -2\mu I & 0 & 0 & 0 & 0 & \mu I & 0 \\
* & * & * & * & * & * & \Xi_{77} & \Xi_{78} & P_2 & 0 & 0 & 0 \\
* & * & * & * & * & * & * & \Xi_{88} & -P_3C & 0 & 0 & 0 \\
* & * & * & * & * & * & * & * & -\gamma^2 I & 0 & 0 & 0 \\
* & * & * & * & * & * & * & * & * & -\gamma^2 I & 0 & 0 \\
* & * & * & * & * & * & * & * & * & * & -\gamma^2 I & 0 \\
* & * & * & * & * & * & * & * & * & * & * & -Q^{-1}
\end{bmatrix} < 0 \tag{31}$$

where

$$\begin{aligned}
\Xi_{11} &= A_iX_1 + X_1A_i^T + BY_i + (BY_i)^T \\
\Xi_{77} &= P_2A_i + A_i^TP_2 \\
\Xi_{78} &= A_i^TC^TP_3 - C^T\Omega^T \\
\Xi_{88} &= -\Omega^T - \Omega \\
K_i &= Y_iX_1^{-1} \\
R &= (\Omega^{-1}P_3)^{-1}
\end{aligned}$$

then the tracking control performance is guaranteed and the sensor fault can be easily estimated by:

$$\hat{f}(t) = (D^TD)^{-1}D^T \begin{bmatrix} 0 & I_n \end{bmatrix} \hat{\tilde{x}}(t) \tag{32}$$

Remark. Theorem 1 derives a condition that guarantee the stability of the closed loop system and the trajectory tracking performances. The result is expressed in the form of linear matrix inequalities (LMI) which can be easily solved by using standard Matlab LMI Tolbox [25].

Proof: See Appendix

4 SIMULATIONS RESULTS

In this section numerical simulations have been performed to validate the developed control scheme. The IM is characterized by the following parameters:

The reference rotor speed started at $t = 2s$ and increase to the desired value 90rad/s at $t = 3.5s$. The load torque of value $C_r = 5Nm$ is applied at $t = 5s$. The reference flux Ψ_{rdr} starts at the beginning of time with value of $1Wb$. A speed sensor fault is chosen as bias which appears and disappears during a short time. This fault and can be modeled as follow:

$$f(t) = \begin{cases} 0\ if\ t\ \in [0,8] \\ 50\ if\ t\ \in [8,12] \\ 0\ if\ t\ \in [12,20] \end{cases}$$

The simulation results illustrated in fig. 2-6 show the trajectories of IM state together with the reference

Table 1. Induction motor parameters

Pole pairs numbers	2
Stator resistance	10.5 Ω
Rotor resistance	4.3047 Ω
Stator inductance	0.4718 mH
Rotor inductance	0.4718 mH
Mutual inductance	0.447 mH
Motor inertia	0.0293 $k_g.m^2$
Friction coefficient	$0.001 N.m.rad^{-1}$
Motor rated power	$1.1 Kw$
Motor rated speed	$1500 tr/min$

states. In absence of FTC, the system state diverge from their desired trajectory. In the other hand, fig. 7 clearly demonstrates that the accurate estimate of the sensor fault signal is achieved using the descriptor observer. It has been shown that through descriptor technique, the proposed scheme is able to estimate the sensor fault and to compensate the unknown input disturbance. The simulations results demonstrate the effectiveness of the proposed control approach. It's clear that the proposed fuzzy FTC law forces the state variables to track the reference trajectory even in presence of sensors faults to ensure the decoupling control characteristic of IM.

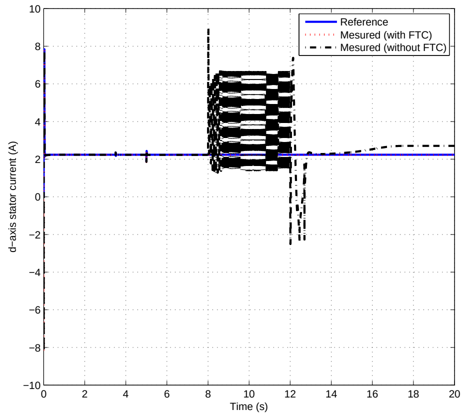

Fig. 3. d-axis stator current

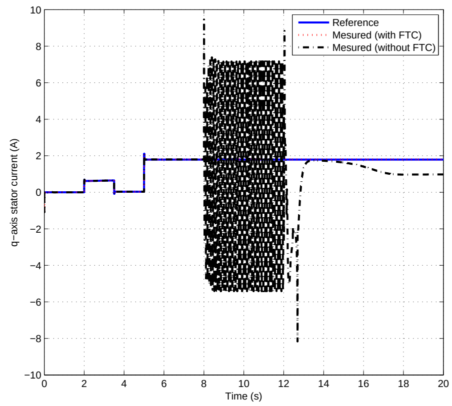

Fig. 4. q-axis stator current

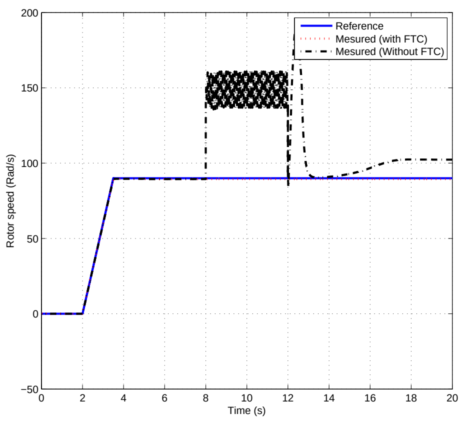

Fig. 2. rotor speed

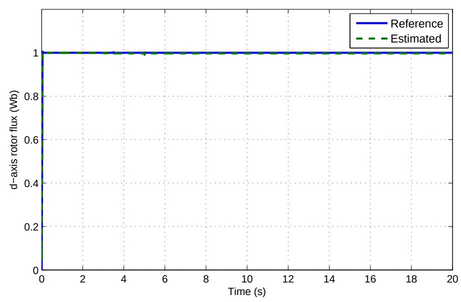

Fig. 5. d-axis rotor flux

5 EXPERIMENTAL RESULTS

In order to verify the performances of the proposed method, the experimental tests were carried out using the test benchmark, of Laboratory of Innovative Technology (LTI), University of Picardie Jules Verne at Cuffies France, presented in fig.9. The IM stator is fed by a SEMIKRON converter (4 kW, IGBT modules) controlled by the dsp 1104 board. The dspace board receives the measured current and the actual position thought the current transducer board LA-55NP and a 5000 points incremental encoder. The interface is used to provide galvanic isolation to all

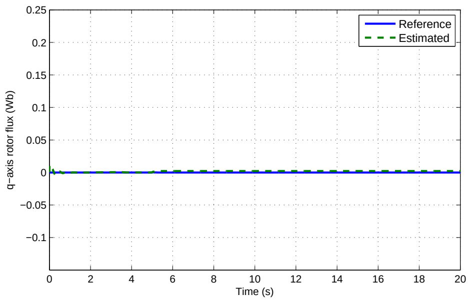

Fig. 6. q-axis rotor flux

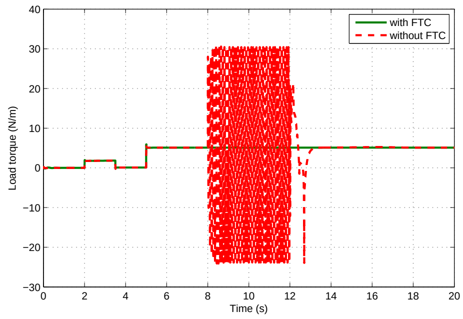

Fig. 7. Load torque

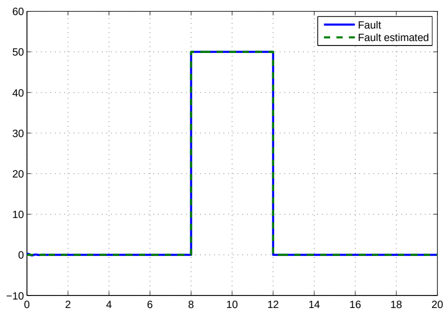

Fig. 8. Fault

signals connected to the dspace controller.

To show the validity and the effectiveness of the proposed control approach, the same control objectives as the simulation are adopted. The controller and observer gains used here are the same as those used in our system simulation. The same speed sensor fault are chosen as the similar case of the simulation results.

The fig.10-14 illustrate the experimental results. We can see that using the fuzzy fault tolerant controller, the system state undergo a fluctuation and remain close to the desired reference value with small tracking error. The disagreement seen between the experimental and corresponding simulation results can be explained by inaccuracies that exist in our data acquisition system, the dead times of the

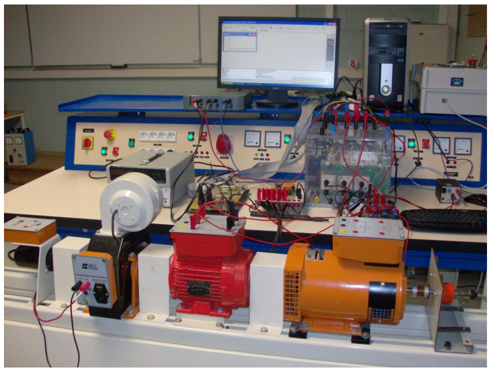

Fig. 9. The test benchmark

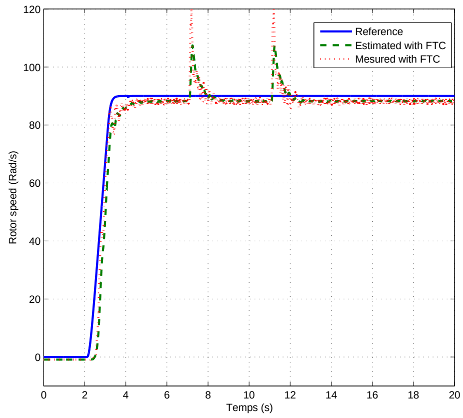

Fig. 10. rotor speed

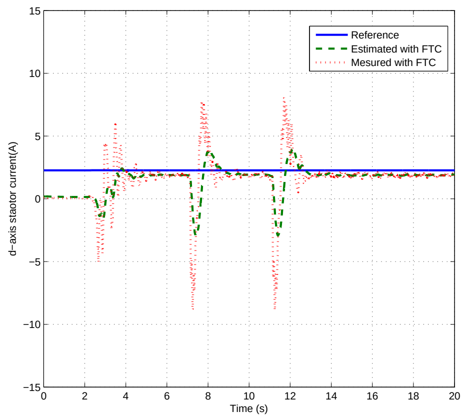

Fig. 11. d-axis stator current

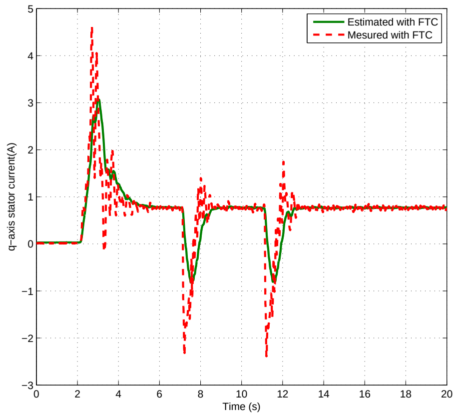

Fig. 12. q-axis stator current

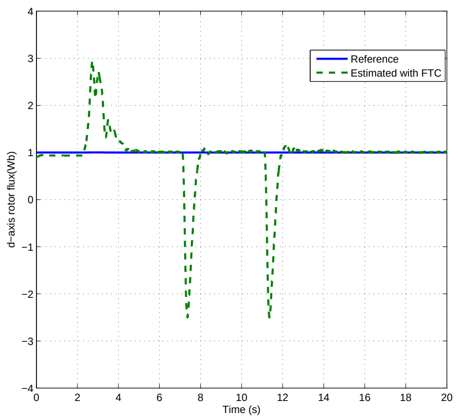

Fig. 13. d-axis rotor flux

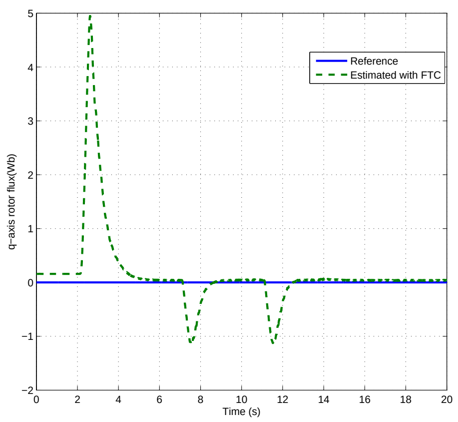

Fig. 14. q-axis rotor flux

inverter power switching signals as well as due to magnetic saturation and motor iron loss that are not taken into account in our system modeling. This confirms that the performances of the FTC scheme are satisfactory and allowing acceptable functioning of the IM even in the occurrence of the sensor fault.

6 CONCLUSION

In this work, a fuzzy fault tolerant tracking control has been designed for the field oriented IM drive affected by external disturbance and sensor fault. The T-S fuzzy model is used to represent the induction motor in the synchronous d-q frame rotating. In order to guarantee the tracking performances, a fuzzy observer is used to estimate simultaneously the system state and the sensor fault. The stability condition has been proposed in terms of LMIs. Finally, simulation and experimental results are given to illustrate the effectiveness of the proposed fuzzy controller. Its noted that this results will be extended by considering the parametric uncertainties to take into account the variation of the resistance value that can be affect the decoupling control.

REFERENCES

[1] J. Lunze and J. Schroder, "Sensor and actuator fault diagnosis of systems with discrete inputs and outpus, IEEE Transaction System, vol. 34, no. 2, pp. 1096-1107, 2004.

[2] X. S. Li., et al., "Analysis and Simplification of Three-Dimensional Space Vector PWM for Three-Phase Four-Leg Inverters, IEEE Transactions on Industrial Electronics, vol. 58, pp. 450-464, 2011.

[3] D. Ichalal, B. Marx, D. Maquin and J. Ragot, New fault tolerant control strategy for nonlinear systems with multiple model approach, Conference on Control and Fault-Tolerant Systems, pp. 606-611, France 2010.

[4] H. Noura, D. Sauter, F. Hamelin and D. Theilliol, Fault-tolerant Control in dynamics systems: Application to a winding machine, IEEE control systems Magazine, vol. 20, no. 1, pp. 33-49, 2000.

[5] J. J. Gertler, Analytical Redundancy Methods in Fault Detection and Isolation - A Survey and Synthesis. , Proceedings of IFAC Safeprocess Conference, vol. 1, pp. 9-22. Baden-Baden, Germany, 1991.

[6] J. Chen, R. J. Patton, H. Zhang, Design of unknown input observers and robust fault detection fillters. International Journal of Control, vol. 63, no. 1, pp. 85-105, 1996.

[7] S. Sun, S. Wang, B. Wu, Design of Luenberger robust fault detection observer, Journal of Zhejiang University (Engineering Science), vol. 38, no. 6, pp. 708-711, 2004.

[8] R. J. Veillette, J. V. Medanic, and W. R. Perkins, Design of reliable control systems. IEEE Transaction on Automatic Control, vol. 37, pp. 290-304, 1992.

[9] G. H. Yang, J. L. Wang and Y. C. Soh, Realable H_∞ controller design for linear system. Automatica, vol. 37, no. 5, pp. 717-725, 2001.

[10] Z. Gao and P. J. Antsaklis, Stability of the pseduo-inverse method for recongurable control systems. Int. J. Control, vol. 53, pp. 717-729, 1991.

[11] J. Jiang, Design of reconfigurable control system using eigenstructure assignment. Int. J. Control, vol. 59, pp. 395-410, 1994.

[12] T. Tanaka and M. Sugeno, Fuzzy identification of systems and its applications to modelling and control. IEEE Transaction. Sys. Man. Cyber., vol. 15, no. 1, pp. 116-132, 1985.

[13] M. Chadli, S. Aouaouda, H. R. Karimi, P. Shi, Robust fault tolerant tracking controller design for a VTOL aircraft. Journal of the Franklin Institute, vol. 350, no. 9, pp. 2627-2645, 2012.

[14] S. Aouaouda, M. Chadli, M. Tarek Khadir, T. Bouarar, Robust fault tolerant tracking controller design for unknown inputs T-S models with unmesurable premise variables. Journal of process control, vol. 1, no. 22, pp. 861-872, 2012.

[15] D. U. Campos-Delgado, D. R. Espinoza-Trejo and E. Palacios, Fault tolerant control in variable speed drives: a survey. IET Electric Power Applications, vol. 2, no. 2, pp. 121-134, 2008.

[16] N. Djeghali, M. Ghanes, S. Djennoune, J. P. Parbot and M. Tajdine, Fault Tolerant Control For Induction Motors Using Sliding Mode Observers. International Workshop on variable structure systems, Mexico city Mexico, pp. 190-196, 2010.

[17] N. Djeghali, M. Ghanes, S. Djennoune and J. P. Parbot, Sensor Fault Tolerant Control For Induction Motors. International Journal of Control, Automation and Systems vol.11 no.3, pp. 563-576, 2013.

[18] B. Tabbache, N. Rizoug, M. Benbouzid and Abdelaziz Kheloui, A Control Regonfuguration Strategy for Post-Sensor FTC in Induction Motor-Based EVs. IEEE transactions on vehicular technology, vol. 62, no. 3, pp. 965 - 971, 2013.

[19] A. M. S. Mendes, A. J. Marques Cardoso, Fault-Tolerant Control operating strategies Applied to three-Phase Induction-Motors Drives. IEEE Transaction Industrial Electronics, vol.53, no.6, pp. 1807 - 1817, 2006.

[20] A. M. S. Mendes, A. J. Marques Cardoso, Fault-Tolerant Control operating strategies Applied to three-Phase Induction-Motors Drives. IEEE Transaction Industrial Electronics, vol.53, no.6, pp. 1807 - 1817 2006.

[21] C. Boniventoa, A. Isidoria, L. Marconia, A. Paolia, Implicit fault-tolerant control: application to induction motors. Automatica, vol.40, no. 3, pp. 355-371, 2004.

[22] M. E. Benzoubid, D. Diallo and M. Zeraoulia, Advenced Fault Tolerant Control of Induction Motor Drive for EV/HEV Tracion Application: From Conventional to Modern and Intelligent Control Techniques. IEEE Transaction Vehicular Technology, vol.56 , no.2, pp. 519-528, 2007.

[23] B. Tabbache, M. Benzoubid, A. Kheloui, J-M Bourgeot and A. Mamoune, An improved fault-tolernat control scheme for PWM inverter-fed induction motor-based EVs, ISA Transactions vol. 52, pp. 862-869, 2013.

[24] C. Chandan and V. Vimlesh, Speed and current sensor fault detection and isolation technique for induction motor drive using axes transformation. IEEE transactions on industrial electronics, vol. 62, no. 3, pp. 1943-1954, 2015.

[25] M. Allouche, M. Chaabane, M. Souissi, D. Mehdi and F. Tadeo, State Feedback Tracking Control for Indirect Fieled-oriented Induction Motor Using Fuzzy Approach. International Journal of Automation and Computing, vol. 10, pp. 99-110, 2013.

[26] S. Boyd, L. ElGhaoui, E. Feron,V. Balakrishnan, Linear Matrix Inequalities in System and Control, Theory (SIAM, Philadelphia, 1994).

Habib ben Zina received the master degree in automatic control from the University of Tunis 2012. Also, he obtained the Ph. D. degree in electrical engineering from the National Engineering School of Sfax, Tunisia in 2016. His research interests include robust observer and fault tolerant control for Takagi-Sugeno models.

Moez Allouche received the M. Sc degree from National Engineering School of Sfax, Tunisia in 2006. Also, he obtained the Ph. D. degree in electrical engineering from the National Engineering School of Sfax, Tunisia in 2010. Currently, he is an assistant professor in High Institute of Industrial Systems of Gabes. His research interests include robust control, renewable energies (solar energies). Nonlinear Control, Fault Tolerant Control, Fault Detection and Isolation, Takagi-Sugeno (TS) Modeling, Nonlinear Observer Design, Model-based Fuzzy Control, descriptor system.

Mansour Souissi received his Ph. D. degree in physical sciences from the University of Tunis, Tunisia in 2002. He is a professor in automatic control at Preparatory Institute of Engineers of Sfax, Tunisia. Since 2003, he is holding a research position at Automatic Control Unit, National School of Engineers of Sfax, Tunisia. He is a member of the organization committees of several national and international conferences (STA, CASA). His research interests include robust control, optimal control, fuzzy logic, linear matrix inequalities, and applications of these techniques to agriculture systems.

Mohamed Chaabane received the Ph.D degree in electrical engineering from the University of Nancy, French in 1991. He was associate professor at the University of Nancy, and is a researcher at Center of Automatic Control of Nancy (CRAN) from 1988 to 1992. He is currently a professor in National School of Engineers of Sfax, and he is editor-in-chief of the International Journal on Sciences and Techniques of Automatic Control and Computer Engineering (IJSTA). Since 1997, he is holding a research position at Automatic Control Unit, National School of Engineers of Sfax. His research interests include robust control, delay systems, and descriptor systems.

Larbi Chrifi-Alaoui received the Ph.D. in Automatic Control from the Ecole Centrale de Lyon. Since 1999 he has a teaching position in automatic control in Aisne University Institute of Technology, UPJV, Cuffies-Soissons, France. From 2004 to 2010 he was the Head of the Department of Electrical Engineering and industrial informatics. His research interests are mainly related to linear and non-linear control theory including sliding mode control, adaptive control, robust control, with applications to electric drive and mecatronics systems.

Maha Bouattour was born in Sfax, Tunisia. She received the Master degrees in Electrical Engineering from the University of Sfax, Tunisia, in 2005, and the Ph.D. degree in Electrical Engineering from the University of Picardie Jules Verne, France, and the from the University of Sfax, in 2010. She is an Associate professor with the Laboratory of Sciences and Techniques of Automatic & computer engineering Lab-STA, National Engineering School of Sfax ENIS, University of Sfax. Her current research interests include fuzzy control and fault tolerant control.

AUTHORS' ADDRESSES

Habib ben Zina, Ph.D.
Asst. Prof. Moez Allouche, Ph.D.
Prof. Mansour Souissi, Ph.D.
Prof. Mohamed Chaabane, Ph.D.
Assoc. Prof. Maha Bouattour, Ph.D.
Laboratory of Sciences and Techniques of Automatic Control and Computer Engineering,
National Engineering School of Sfax,
University of Sfax,
Soukra Street, Sfax, 3072, Tunisia
email: {habibbenzina, moez_allouche, maha_bouattour}@yahoo.fr, mansour.souissi@ipeis.rnu.tn, chaabane.ucpi@gmail.com
Asst. Prof. Larbi Chrifi-Alaoui, Ph.D.
Laboratoire des Technologies Innovantes,
University of Picardie Jules Verne,
13 Avenue F. Mitterrand, 02880, Cuffies, France
email: larbi.alaoui@u-picardie.fr

Received: 2016-01-14
Accepted: 2016-11-05

APPENDIX

Proof of theorem 1

Consider the following candidate Lyapunov function for the augmented system (29)

$$V(\tilde{x}^T(t)) = \tilde{x}^T(t)\tilde{P}\tilde{x}(t) \quad (33)$$

The time derivative of the candidate Lyapunov function is:

$$\dot{V}(\tilde{x}(t)) = \sum_{i=1}^{8}\sum_{j=1}^{8} h_i(z(t)h_j(z_r(t)\left[\tilde{x}^T(t)\left(\tilde{A}_{ij}^T\tilde{P} + \tilde{P}\tilde{A}_{ij}\right)\tilde{x}(t) + \Phi^T(t)\tilde{F}_{ij}^T\tilde{P}\tilde{x}(t) + \tilde{x}^T(t)\tilde{P}\tilde{F}_{ij}\Phi(t)\right] \quad (34)$$

To achieve the performance required by (30) and the closed loop stability of (29) the following inequality must hold

$$\dot{V}(\tilde{x}^T(t)) + \tilde{x}^T(t)\tilde{Q}\tilde{x}(t) - \gamma^2\Phi^T(t)\Phi(t) \leq 0 \quad (35)$$

The inequality (35) after substituting $\dot{V}(\bar{e})$ from equation (34) becomes:

$$\sum_{i=1}^{8}\sum_{j=1}^{8} h_i(z(t))h_j(z_r(t))\begin{bmatrix}\tilde{x}(t)\\ \Phi(t)\end{bmatrix}^T J \begin{bmatrix}\tilde{x}(t)\\ \Phi(t)\end{bmatrix} \leq 0 \quad (36)$$

$$J = \begin{bmatrix}\tilde{A}_{ij}^T\tilde{P} + \tilde{P}\tilde{A}_{ij} + \tilde{Q} & \tilde{P}\tilde{F}_{ij}\\ \tilde{F}_{ij}^T\tilde{P} & -\gamma^2 I\end{bmatrix}$$

(36) is satisfied if the following condition holds

$$\begin{bmatrix}\tilde{A}_{ij}^T\tilde{P} + \tilde{P}\tilde{A}_{ij} + \tilde{Q} & \tilde{P}\tilde{F}_{ij}\\ \tilde{F}_{ij}^T\tilde{P} & -\gamma^2 I\end{bmatrix} \leq 0 \quad (37)$$

$\tilde{P}$ is structured as : $\tilde{P} = diag\begin{bmatrix} P_1 & P_2 & P_3\end{bmatrix}$.
Then by using $\Omega = P_3(R^{-1})$ the inequality (37) can be written as follows:

$$\begin{bmatrix}\Theta_{11} & -P_1BK_j & 0 & P_1 & -P_1 & P_1(A_i - A_{rj})\\ * & \Theta_{22} & \Theta_{23} & P_2 & 0 & 0\\ * & * & \Theta_{33} & -P_3C & 0 & 0\\ * & * & * & -\gamma^2 I & 0 & 0\\ * & * & * & * & -\gamma^2 I & 0\\ * & * & * & * & * & -\gamma^2 I\end{bmatrix} < 0 \quad (38)$$

where

$$\Theta_{11} = P_1(A_i + BK_j) + (A_i + BK_j)^T P_1 + Q$$
$$\Theta_{22} = P_2A_i + A_i^T P_2$$
$$\Theta_{23} = -(CA_i)^T + C^T\Omega^T$$
$$\Theta_{33} = -\Omega^T - \Omega$$

The condition (38) contains nonlinear terms. Now, the goals is to formulate as an LMI problem.
Hence after partitioning the inequality (38), we obtain

$$\pi_{ij} = \begin{bmatrix}\pi_{11} & \pi_{12}\\ \pi_{21} & \pi_{22}\end{bmatrix} \quad (39)$$

where $\pi_{11} = \Theta_{11}$, $\pi_{12} = [-P_1BK_j \quad 0 \quad P_1 \ldots \ldots -P_1 \quad P_1(A_i - A_{rj})]$ and π_{22} is the lower right block of (39).
To effect the necessary change of variable the congruence lemma is required. Pre and post multiplying (38) by Z defining in the following form

$$Z = diag(P_1^{-1}\ X), X = diag\begin{pmatrix} P_1^{-1} & I & I & I & I\end{pmatrix}$$

then it follows that

$$\begin{bmatrix}P_1^{-1}\pi_{11}P_1^{-1} & P_1^{-1}\pi_{12}X\\ X\pi_{21} & X\pi_{22}X\end{bmatrix} \leq 0 \quad (40)$$

(40) implied that $X\pi_{22}X$ is negative then using Lemma 4 [19], we obtain

$$X\pi_{22}X \leq -2\mu X - \mu^2\pi_{22}^{-1} \quad (41)$$

$$\begin{bmatrix}P_1^{-1}\pi_{11}P_1^{-1} & P_1^{-1}\pi_{12}X & 0\\ X\pi_{21}P_1^{-1} & -2\mu X & \mu I\\ 0 & \mu I & \pi_{22}\end{bmatrix} < 0 \quad (42)$$

After subsisting $\pi_{11}, \pi_{12}, \pi_{22}$ in (42), the LMI condition presented in theorem 1 hold.