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TS Fuzzy Logic-Based Rotor Resistance Tuning in case of Induction Machine Vector Control

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Original scientific paper

In this paper, we focus on the estimation of the rotor resistance to online tune the controllers in case of the Indirect Rotor Field Orientation Control (IRFOC) of Induction Machine (IM). The proposed method is based on the development of an adaptive Takagi-Sugeno (TS) fuzzy flux observer, described in a d-q synchronous rotating frame, to concurrently estimate the IM states and the rotor resistance variation. An investigation of the local pole placement is carried out in order to guarantee both the stability and specified observer dynamic performances. The observer's gains design is based on the resolution of sufficient conditions driven into LMIs terms (Linear Matrix Inequalities). Simulation and experimentation are carried out to show the effectiveness of the proposed results.

Key words: Rotor resistance estimation, Fuzzy logic, Luenberger observer, D-stability analysis, IM Vector Control

Ugađanje otpora rotora vektorski upravljanog indukcijskog motora korištenjem TS neizrazite logike. U ovom radu fokusiramo se na estimaciju otpora rotora za ugađanje parametera kontrolera tijekom rada indukcijskog motora (IM) upravljanog metodom indirektne kontrole orijentacije polja rotora (IRFOC). Predložena metoda je bazirana na razvoju adaptivnog Takagi-Sugeno (TS) neizrazitog obzervera toka, opisanog u d-q sinkronom rotacijskom okviru, kako bi se istovremeno estimirala stanja i varijacije otpora rotora IM-a. Provedeno je istraživanje lokalnog postavljanja polova kako bi se osigurala stabilnost i zadane dinamičke performanse obzervera. Dizajn pojačanja estimatora baziran je na rješenju dovoljnog broja uvjeta izraženih pomoću LMN izraza (linearne matrične nejednakosti). Simulacija i eksperimenti su provedeni kako bi se pokazala ispravnost predloženih rezultata.

Ključne riječi: estimacija otpora rotora, neizrazita logika, Luenbergov estimator, analiza D-stabilnosti, vektorsko upravljanje indukcijskog motora

1 INTRODUCTION

The induction motor has a major interest in relation to other types of motor due to its qualities of robustness, low cost of manufacturing and maintenance. Within the development and implementation of field oriented control, the IMs were able to compete with DC machines in high performance applications [1, 2]. This method, based on the control of machine states and magnetic torque, is now the most used one in the industry, whether in the areas of railway traction, machine tool or robotics. However, it is worse to note that the performances of this control approach are very sensitive to parameters variation and depend especially, on rotor resistance (R_r) variation which affect principally the speed regulation as well as the decoupling performance. This problem stimulates a lot of works that focus on online R_r adaptation using several methods such as Kalman filtering [3, 4], neural network [5, 6], recursive algorithm [7], MRAS adaptive observers [8–10], sliding mode observer [11, 12] or Luenberger adaptive observer [13–15].

Recently, significant research efforts have been devoted to the nonlinear system. In this context, nonlinear systems described by TS fuzzy models has been the subject of many research works and studies according to their simplicity and their capacity to describe a large class of nonlinear systems [16–18]. Moreover, many studies focus on the development of this approach to improve its robustness and its dynamics' performances. Among developed methods, we note that the $D-$stability based on LMI approach [18, 19] has been an interesting research field due to its capability to improve the system dynamic performances [20, 21].

In this paper, we present an online scheme to tune the rotor resistance based on TS adaptive flux observer in the synchronous reference frame in case of IRFOC. The main advantage to use such reference frame is to dealt with continuous signal in steady states, so why it is considered as the most accurate and versatile [22–24]. In addition, we take in account to guarantee some dynamic performances for the observer, which is a necessary step to ensure the stability and the real implementation of the algorithm due to technical limits of experimental setup. To satisfy this previously conditions we present a D-stability analysis based on intersection of LMIs regions.

As a whole, this paper is organised as follows: in section 2 and 3, the problem is formulated and the goal of the paper is stated. Section 4 presents the main results of this paper and includes results on stability and D-stability of the proposed adaptive fuzzy observer. In section 5, the validity of proposed results is carried out through simulation and experimentation.

2 DESCRIPTION OF INDUCTION MOTOR

The induction machine can be presented in synchronous d-q reference frame by the following state space model:

$$\begin{cases} \dot{x}(t) = A(x(t))x(t) + Bu(t) \\ y(t) = C(x(t))x(t) \end{cases} \tag{1}$$

such that:

$$\begin{cases} x(t) = \begin{bmatrix} i_{sd} & i_{sq} & \Psi_{rd} & \Psi_{rq} \end{bmatrix}^T \\ y(t) = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^T \end{cases} \tag{2}$$

$$A(x(t)) = \begin{bmatrix} -\gamma & \omega_s & \frac{K_s}{\tau_r} & K_s n_p \omega_m \\ -\omega_s & -\gamma & -K_s n_p \omega_m & \frac{K_s}{\tau_r} \\ \frac{M}{\tau_r} & 0 & -\frac{1}{\tau_r} & \omega_{sl} \\ 0 & \frac{M}{\tau_r} & -\omega_{sl} & -\frac{1}{\tau_r} \end{bmatrix} \tag{3}$$

$$B(x(t)) = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^T \tag{4}$$

$$C(x(t)) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{5}$$

$$v(t) = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^T \tag{6}$$

$\omega_{sl} = \omega_s - n_p\omega_m, \gamma = \frac{1}{\sigma\tau_s} + \frac{1-\sigma}{\sigma\tau_r}, \sigma = 1 - \frac{M^2}{L_s L_r}, K_s = \frac{M}{\sigma L_s L_r}, \tau_S = \frac{L_s}{R_s}, \tau_r = \frac{L_r}{R_r}$.

Where $\begin{pmatrix} i_{sd} & i_{sq} \end{pmatrix}$ are stator currents, $\begin{pmatrix} \Psi_{rd} & \Psi_{rq} \end{pmatrix}$ are rotor flux, $\begin{pmatrix} v_{sd} & v_{sq} \end{pmatrix}$ are stator voltages, R_s is the stator resistance, R_r is the rotor resistance, L_s is the stator inductance, L_r is the rotor inductance, M is the mutual inductance, σ is the leakage coefficient, ω_m is the motor angular velocity, ω_s is the synchronous angular velocity, f is the friction constant, J is the moment of inertia and n_p is the number of poles pairs.

3 TS FUZZY MODEL OF INDUCTION MACHINE

Using the TS approach [16, 17], the nonlinear model of the IM in a synchronous reference frame can be described by the fuzzy $if - Then$ rules and will be employed here to deal with the IM.

Based on (1), we consider the nonlinearity terms $z_i(t) \in \begin{bmatrix} z_{imin} & z_{imax} \end{bmatrix}$ of the matrix $A(x(t))$ such that:

$$\begin{cases} z_1(t) = \omega_m \\ z_2(t) = \omega_s \end{cases}$$

then we can transform nonlinear terms as follow:

$$z_i(t) = F_{i1}\left(z_i(t)\right) z_{imax} + F_{i2}\left(z_i(t)\right) z_{imin} \tag{7}$$

where:

$$\begin{cases} F_{i1}\left(z_i(t)\right) = \frac{z_i(t) - z_{imin}}{z_{imax} - z_{imin}} \\ F_{i2}\left(z_i(t)\right) = \frac{z_{imax} - z_i(t)}{z_{imax} - z_{imin}} \end{cases} \tag{8}$$

The rules of the fuzzy model for the nonlinear TS system are of the following form:

$$if\ z_1(t)\ is\ F_{1i}\ and\ z_2(t)\ is\ F_{2i}$$

$$then\ \dot{x}(t) = A_i x(t) + Bu(t),\ i = \begin{matrix} 1 & \dots & n \end{matrix} \tag{9}$$

The global fuzzy model is inferred as follows:

$$\dot{x}(t) = \sum_{i=1}^{n} h_i(z(t)) \left(A_i x(t) + Bu(t)\right) \tag{10}$$

were:

$$\mu_i(z(t)) = \prod_{k=1}^{2} F_{ik}(z(t)) \tag{11}$$

and

$$h_i(z(t)) = \frac{\mu_i(z(t))}{\sum_{i=1}^{n} \mu_i(z(t))} \tag{12}$$

for all t, $h_i(z(t)) > 0$ and $\sum_{i=1}^{n} h_i(z(t)) = 1$

4 R_R ESTIMATION ALGORITHM

In the following, we will focus on the development of full Luenberger states observer in a synchronous reference frame. In addition, an adaptive algorithm will be designed to the online estimation of R_r to improve the control performances face to R_r variation, which is mentioned as one of the major limits of IRFOC.

4.1 *Fuzzy adaptive observer*

We assume that the real value of the rotor resistance is composed by a nominal value (noted in the following by (R_r), and a variable value $\left(\tilde{R}_r\right)$. Then the matrix of local state A_i becomes uncertain. Thereafter, we can rewrite the fuzzy model of the IM as follows:

$$\dot{x}(t) = \sum_{i=1}^{n} h_i(z(t)) \left((A_i + \Delta A_i) x(t) + Bu(t) \right) \quad (13)$$

such that:

$$\Delta A_i = H_i \tilde{R}_r = H \tilde{R}_r \quad (14)$$

and

$$H = \begin{bmatrix} \rho & 0 & Ks/Lr & 0 \\ 0 & \rho & 0 & Ks/Lr \\ Msr/Lr & 0 & -1/Lr & 0 \\ 0 & Msr/Lr & 0 & -1/Lr \end{bmatrix} \quad (15)$$

such that $\rho = -(1-\sigma)/(\sigma Lr)$.

To ensure the estimation of stator currents, rotor flux and the online tuning of the rotor resistance R_r, we propose the following adaptive fuzzy full observer:

$$\dot{\hat{x}}(t) = \sum_{i=1}^{n} h_i(z(t)) \left(\left(A_i + \widehat{\Delta A_i} \right) \hat{x}(t) + Bu(t) + L_i \left(y(t) - \hat{y}(t) \right) \right) \quad (16)$$

such that the uncertain term can be presented as follow:

$$\widehat{\Delta A_i} = H \widehat{\tilde{R}_r} \quad (17)$$

$\widehat{\tilde{R}_r}$ is the estimated variable rotor resistance, $\hat{x}(t)$ is the observer state vector $\hat{y}(t)$ is the observer output vector and L_i is the observer gain matrix.

4.2 *Stability analysis of TS adaptive observer*

Theorem 1 *The adaptive flux fuzzy observer (16) is stable if there exists a matrices $X > 0$ and W_i such that the following LMIs are satisfied:*

$$A_i^T X + X A_i - C^T W_i^T - W_i C < 0, \quad for\ i = 1 \ldots\ldots n \quad (18)$$

The observer matrix gain will be determined such that:

$$L_i = W_i^T X^{-1} \quad (19)$$

and the estimated variable rotor resistance $\widehat{\tilde{R}_r}$ is identified by the following adaptive scheme.

$$\widehat{\tilde{R}_r} = \frac{1}{\lambda} \int \hat{x}(t)^T H^T X e_n(t) + e_n(t)^T X H \hat{x}(t) \quad (20)$$

where the parameter λ is an arbitrary positive gain updated only in a powering operation and $e_n(t)^T = \begin{bmatrix} \left(i_{sd} - \hat{i}_{sd}\right) & \left(i_{sq} - \hat{i}_{sq}\right) & 0 & 0 \end{bmatrix}$.

Proof: We define, in the first step, the error vector as follows:

$$e(t) = x(t) - \hat{x}(t) \quad (21)$$

By differencing (21) we obtain the error dynamics :

$$\dot{e}(t) = \sum_{i=1}^{n} h_i(z(t)) \left((A_i - L_i C) e(t) + \Delta A_i x(t) - \widehat{\Delta A_i} \hat{x}(t) \right) \quad (22)$$

Considering the Lyapunov function V candidate that:

$$V = \frac{1}{2} e^T X e + \frac{\lambda}{2} \tilde{e}_r^2 \quad (23)$$

where $\tilde{e}_r = \tilde{R}_r - \widehat{\tilde{R}_r}$, $X > 0$ and $\lambda > 0$.

According to Lyapunov approach, the proposed fuzzy adaptive observer is stable if the following system is satisfied.

$$\begin{cases} V > 0 \\ \dot{V} < 0 \end{cases} \quad (24)$$

The first condition of the system $V > 0$ is automatically satisfied by the choose of matrix $X > 0$.

The second condition $\dot{V} < 0$ will be treated as to obtain the gain matrix as well as the adaptive scheme of rotor resistance estimation.

Using (23) the derivate of Lyapunov function is presented by the following equation:

$$\dot{V} = \dot{e}^T X e + e^T X \dot{e} + \lambda \tilde{e}_r \dot{\tilde{e}}_r \quad (25)$$

then, by using (22) we can rewrite (25) as follow:

$$\begin{aligned}\dot{V} = \sum_{i=1}^{n} h_i(z(t)) \Big[& e(t)^T \left(A_i - L_iC\right)^T Xe(t) + \\ & e(t)^T X \left(A_i - L_iC\right) e(t) + \\ & x(t)^T \Delta A_i^T Xe(t) - \hat{x}(t)^T \widehat{\Delta A_i}^T Xe(t) + \\ & e(t)^T X \Delta A_i x(t) - e(t)^T X \widehat{\Delta A_i} \hat{x}(t) \Big] + \lambda \tilde{e}_r \dot{\tilde{e}}_r\end{aligned} \tag{26}$$

To simplify, we divide the derivate of Lyapunov function into two functions $\dot{V_1}$ and $\dot{V_2}$ such that:

$$\dot{V} = \dot{V_1} + \dot{V_2} \tag{27}$$

where:

$$\begin{aligned}\dot{V_1} = \sum_{i=1}^{n} & h_i(z(t)) e(t)^T \left(A_i - L_iC\right)^T Xe(t) + \\ & e(t)^T X \left(A_i - L_iC\right) e(t)\end{aligned} \tag{28}$$

and

$$\begin{aligned}\dot{V_2} = \sum_{i=1}^{n} & h_i(z(t)) x(t)^T \Delta A_i^T Xe(t) - \\ & \hat{x}(t)^T \widehat{\Delta A_i}^T Xe(t) + e(t)^T X \Delta A_i x(t) - \\ & e(t)^T X \widehat{\Delta A_i} \hat{x}(t) + \lambda \tilde{e}_r \dot{\tilde{e}}_r\end{aligned} \tag{29}$$

By considering, in the first step, the sub-Lyapunov function V_1, we can affirm that $\dot{V_1} < 0$ if there exist a matrices $X > 0$ and W_i such that the described LMIs in (18) are satisfied. Then the observer matrix gain can be synthesized as (19).

In the second step, and while considering $\dot{V_2} = 0$, we propose and adaptive scheme to the online adaptation of rotor resistance.

On the basis of the analysis of the first sub-Lyapunov function, we can confirm that the matrix $\sum_{i=1}^{n} h_i(z(t)) \left(A - L_iC\right)$ is negative definite, then we can affirm that there exit $t1 > 0$ such that $\forall t > t1$, $x(t) \rightarrow \hat{x}(t)$. In addition, using the state space model we can conclude that:

$$\left(\Delta A_i - \widehat{\Delta A_i}\right) = H \tilde{e}_r \tag{30}$$

Then (29) could be presented as follow:

$$\begin{aligned}\dot{V_2} = \sum_{i=1}^{n} & h_i(z(t)) \hat{x}(t)^T H^T \Delta \tilde{R}_r Xe(t) + \\ & e(t)^T X H \Delta \tilde{R}_r \hat{x}(t) + \lambda \tilde{e}_r \dot{\tilde{e}}_r\end{aligned} \tag{31}$$

By considering $\dot{V_2} = 0$ and

$$e(t)^T = e_n(t)^T = \begin{bmatrix} \left(i_{sd} - \hat{i}_{sd}\right) & \left(i_{sq} - \hat{i}_{sq}\right) & 0 & 0 \end{bmatrix},$$

the adaptive scheme for $\tilde{R}_r$ online estimation is given by:

$$\widehat{\tilde{R}_r} = \frac{1}{\lambda} \int \hat{x}(t)^T H^T X e_n(t) + e_n(t)^T X H \hat{x}(t) \tag{32}$$

■

We note that the presented results still inadequate to the real implementation since the observer performances are not fixed yet. Indeed, the observer is stable but not faster than the system. Moreover, the oscillatory dynamics of the observer is not fixed yet (this problem may cause a lot of oscillation in the output of the observer. Then it will damage the control). In addition, we should not forget that we are limited by a maximum sampling time defined by the used hardware for implementation. To overcome these problems, we propose in the following work a D-stability analysis to guarantee a TS poles placement in a specified region.

4.3 D-stability analysis of TS adaptive observer

To set certain system performance, we must sometimes to limit the range of stability. These are known as D-stability (Appendix).

In the following works, we will focus on the $D^\sharp-$ stability analysis described by the clustering of vertical stripe D_1 such that $(a_2 < reel(z) < a_1)$ and a horizontal one D_2 such that $|Im(z)| < b$. We use the concept of LMI regions for formulate investment objectives of LMI terms.

Theorem 2 *The adaptive TS flux observer (16) is stable with a guaranteed $D^\sharp-$ Stability if there exists a matrices $X > 0$ and W_i such that the following LMIs are satisfied:*

$$\left\{\begin{array}{c} X > 0 \\ \begin{bmatrix} \Theta_i & 0 \\ 0 & \Lambda_i \end{bmatrix} < 0 \\ \begin{bmatrix} -2bX & \Xi_i \\ -\Xi_i & -2bX \end{bmatrix} < 0 \\ i = 1 \ldots\ldots n \end{array}\right. \tag{33}$$

where:

$$\left\{\begin{array}{c} \Theta = XA_i - W_iC + A_i^T X - C^T W_i^T - 2a_1 X \\ \Lambda = -XA_i + W_iC - A_i^T X + C^T W_i^T + 2a_2 X \\ \Xi = XA_i - W_iC - A_i^T X + C^T W_i^T \end{array}\right.$$

The observer matrix gain will be determined such that:

$$L_i = W_i^T X^{-1} \tag{34}$$

and the estimated variable rotor resistance $\widehat{\tilde{R}_r}$ is identified by the following adaptive scheme.

$$\widehat{\tilde{R}_r} = \frac{1}{\lambda}\int \hat{x}(t)^T H^T X e_n(t) + e_n(t)^T X H \hat{x}(t) \quad (35)$$

where the parameter λ is an arbitrary positive gain updated only in a powering operation.

Proof: Based on Lemma 1 (appendix), we can conclude that the matrix $\sum_{i=1}^{n} h_i(z(t))\,(A_i - L_i C)$ is D_j-stable if and only if there exists a symmetric positive definite matrix X such that:

$$M_{Dj}\left(\sum_{i=1}^{n} h_i(z(t))\,(A_i - L_iC)\,, X\right) =$$
$$\alpha_j \otimes X + \beta_j \otimes \sum_{i=1}^{n} h_i(z(t))\,(A_i - L_iC)\,X +$$
$$\beta_j^T \otimes X \sum_{i=1}^{n} h_i(z(t))\,(A_i - L_iC)^T < 0$$

Then using the Lemma 2 (appendix), we can conclude that the adaptive TS flux fuzzy observer (16) is $D^\sharp$-stable if there exists a matrices $X > 0$ and W_i such that the following inequalities are satisfied.

$$\begin{gathered}\alpha_j \otimes X + \beta_j \otimes \sum_{i=1}^{n} h_i(z(t))\,(A_i - L_iC)\,X + \\ \beta_j^T \otimes X \sum_{i=1}^{n} h_i(z(t))\,(A_i - L_iC)^T < 0 \\ j = 1\ldots 2\end{gathered} \quad (36)$$

While considering $L_i = W_i^T X^{-1}$, the equation system (36) is equivalent the following LMIs one:

$$\begin{cases} \begin{bmatrix} \Theta_i & 0 \\ 0 & \Lambda_i \end{bmatrix} < 0 \\ \begin{bmatrix} -2bX & \Xi_i \\ -\Xi_i & -2bX \end{bmatrix} < 0 \\ i = 1\ldots\ldots n \end{cases}$$

where:

$$\begin{cases} \Theta = XA_i - W_iC + A_i^TX - C^TW_i^T - 2a_1X \\ \Lambda = -XA_i + W_iC - A_i^TX + C^TW_i^T + 2a_2X \\ \Xi = XA_i - W_iC - A_i^TX + C^TW_i^T \end{cases}$$

The estimated variable rotor resistance $\widehat{\tilde{R}_r}$ is identified using the same demarche employed in the proof of the Theorem 1. ■

5 SIMULATION & EXPERIMENTAL RESULTS

In this section, simulation and experimental results are presented to evaluate the effectiveness of the proposed control scheme for IM.

In the following, we will consider an IRFOC scheme derived from the Direct Rotor Field Orientation Control (DRFOC) developed in [25]. We conserve the main scheme and the main controller gains. However we consider a reference flux value instead of the estimated one.

Figure 1 shows the block diagram of the proposed IRFOC with rotor resistance tuning of IM drive system. The bloc diagram consists of an IM, a PWM voltage source inverter, an IRFOC controller, coordinate translators, and a TS adaptive observer.

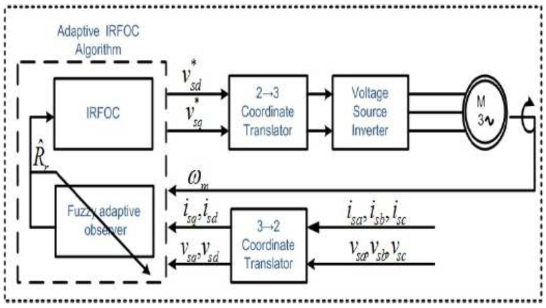

Fig. 1: Block diagram of IRFOC with rotor resistance tuning of induction motor drive system.

The characteristics of the IM 1.5 KW parameters are listed in the Table 1.

$R_s = 5.72\Omega$	$R_r = 4.2\Omega$
$L_s = 0.462H$	$L_r = 0.462H,$
$M = 0.4402H,$	$J = 0.0049Kg.m^2$
$f = 0.003N.m.s.rd^{-1}$	$n = 2$

Table 1

The main aim of the present study is to test performances of the proposed algorithm to track uncertainties in the rotor resistance due to temperature changes or modeling uncertainties. Hence, we will consider, in the following, that the rotor resistance is assumed to be $R_r = 3\Omega$ (-40% of the nominal value). Then, the initial value of controllers and observer gains will be calculated based on this effective value to test the convergence of the estimated rotor resistance to the real one. In an other hand, we suppose that the IM operates in a range of 250 rps in the both forward and reverse direction then, the minimal and maximal value of the non linearities $z_i(t)$ are defined as follow:

$\omega_{m_{min}}$	$-250rps$
$\omega_{m_{max}}$	$250rps$
$\omega_{s_{min}}$	$-600rps$
$\omega_{s_{max}}$	$600rps$

While considering the Theorem 2 and solving the LMIs (33) such that $a_1 = -6000$, $a_2 = 0$, $b = 1800$, the figure 2 illustrates the position of the local poles of the TS IM model and the TS observer. We remake that the D-stability of the observer is well guaranteed. Indeed, it is at least two times faster than the machine with a limited oscillation dynamics and a guaranteed of a minimum of a reel pole value to ensure the implementation of the observer algorithm in a microprocessor. We note that the choice of $a_2 = 0$ was made to decease conservativeness while resolving the LMI's terms. However, we verify in the same time observer local poles placement relatively to the IM ones. As a matter of fact, a further future work will have to consider the possibility to present less conservative conditions to resolve automatically this problem.

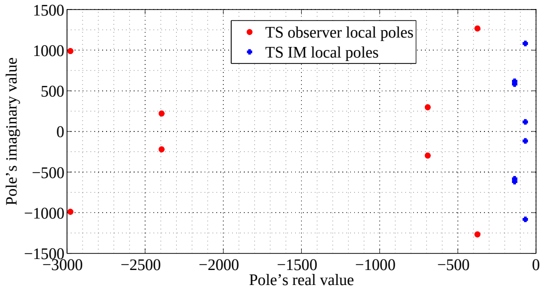

Fig. 2: Local poles position of both TS observer and IM TS model.

The gain matrices and the matrix X can obtained as:

$$L_1 = 10^3 \begin{bmatrix} 2.8823 & -0.6228 \\ 0.6228 & 2.8823 \\ -0.0177 & 0.1523 \\ -0.1523 & -0.0177 \end{bmatrix},$$

$$L_2 = 10^3 \begin{bmatrix} 3.1475 & -1.4220 \\ 1.4220 & 3.1475 \\ -0.0197 & -0.1292 \\ 0.1292 & -0.0197 \end{bmatrix},$$

$$L_3 = 10^3 \begin{bmatrix} 3.1475 & 1.4220 \\ -1.4220 & 3.1475 \\ -0.0197 & 0.1292 \\ -0.1292 & -0.0197 \end{bmatrix},$$

$$L_4 = 10^3 \begin{bmatrix} 2.8823 & 0.6228 \\ -0.6228 & 2.8823 \\ -0.0177 & -0.1523 \\ 0.1523 & -0.0177 \end{bmatrix},$$

$$X = 10^{-3} \begin{bmatrix} 0.0406 & 0 & 0.0210 & 0 \\ * & 0.0406 & 0 & 0.0210 \\ * & * & 2.8844 & 0 \\ * & * & * & 2.8844 \end{bmatrix}.$$

The operational conditions of simulations and experimental tests are fixed such that:

-The reference rotor flux is kept constant at the nominal value 1 Wb.

-The speed references is kept equal to zero from $t = [0s\ 1.5s]$, then it removes to reach the value of 60 rps at $t = 3.5s$, then it changes from $t = 11.5s$ to reach the same speed in the reverse direction at $t = 13.5s$.

-The value of applied is kept equal to $0N.m$ between $t = [0s\ 1.5s]$ and equal to $3N.m$ between t=[1.5s 20s].

5.1 Simulation results

In this part of this manuscript, we present two simulation studies. During the first one, an open loop system control is considered. Hence, the adaptive observer is disconnected from the IRFOC control bloc. The value of the rotor resistance used to design the IRFOC bloc controller is fixed to 3 ohm. However in the closed loop system, we use the estimated rotor resistance to design the IRFOC bloc controller.

5.1.1 Open loop system control results

Figures 3, 4, 5, present the main results of this test. Indeed, figure 3(a) presents the evolution of the rotor speed relatively to the reference one. The tracking error is described in figure 3(b). In figures 4 and 5, the evolution of the d-q axis components of the rotor flux relatively to the references signals are given. In addition, the tracking errors are described. Through the analysis of the obtained results we can point the finger on the gaps between the d-q component of the rotor flux and its references signals. This problem influence on the machine dynamics and its efficiency.

5.1.2 Closed loop system results

To overcome the problems mentioned during the first test, and in order to ensure a decoupled control of the rotor flux and torque, we consider in the actual test a closed loop system control within the IRFOC bloc controllers are tuned depending upon to the estimated rotor resistance.

Figures 6, 7,8, 9, 10 and 11 present the main results of the second simulation test. In figure 6, we describe the evolution of the rotor speed relatively to the reference signal

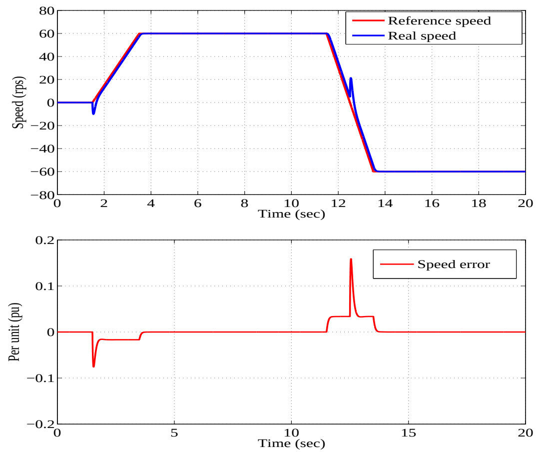

Fig. 3: Reference& real rotor speed.

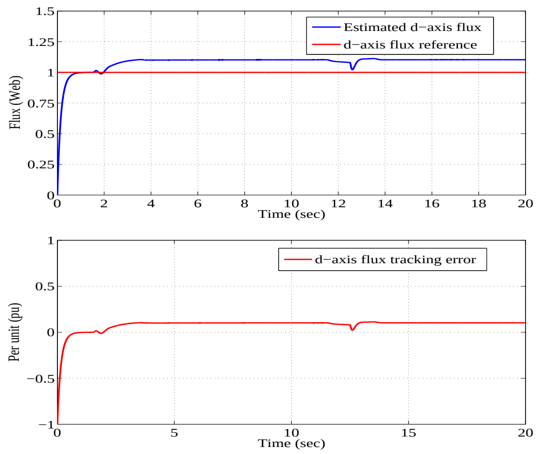

Fig. 4: Estimated d-axis flux components.

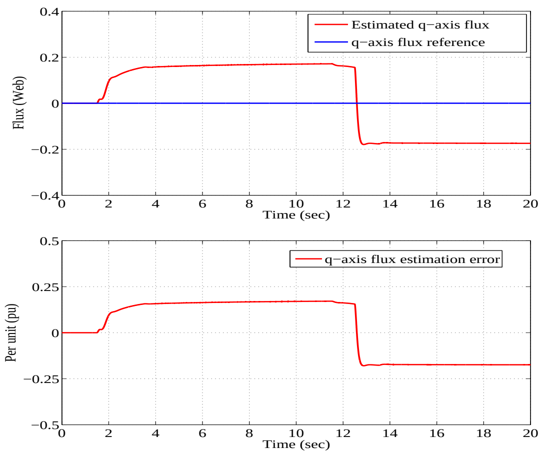

Fig. 5: Estimated d-axis flux components.

as well as the tracking error waveform. We note that the obtained results are similar to the previous ones of the first test. Furthermore, we notice an error in the transient state and especially when the machine changes the rotating direction meanwhile it is subjected to an applied load torque. In Figure 7, we present the estimated rotor resistance and the estimation error signal relatively to the nominal value. On the basis of the estimated rotor resistance, an online tune of the IRFOC block controllers is ensured. The results and the performances of a such closed loop control system are clear while analyzing the figures 8 and 9. Indeed the latest figures show the evolution of the d-q components of the rotor flux relatively to the reference signal as well as the tracking errors. We notice that the decoupling performance is well maintained which was not the case in the first test. This provides better dynamic performances for the machine as well as a better energy efficiency while ensuring that the machine is under its nominal magnetization. To check the performance of the proposed observer, we describe in figures 10 and 11 the real components and the estimated stator currents and their estimated waveforms. In addition the error signal is given for each signal. The analysis of the obtained results shows a good estimation behavior despite any changes in the rotor resistance or the rotor speed.

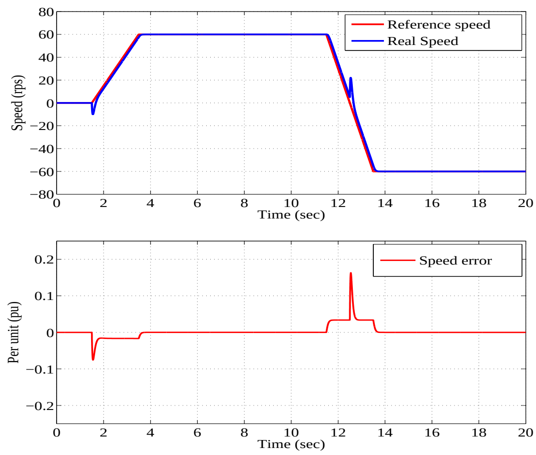

Fig. 6: Reference& real rotor speed.

5.1.3 Experimental results

A prototype implementation of the proposed algorithm was carried out (Figure 12). The experimental setup is composed by a squirrel-cage IM, an insulated gate bipolar transistor (IGBT) source voltage inverter, a real time controller board (DSP1104) controller card, an incremental encoder with 5000 pulses per revolution, two voltage sensors and three hall-effect current sensors for the mea-

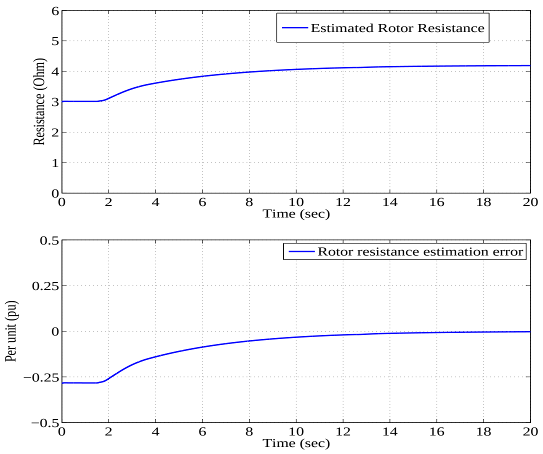

Fig. 7: Estimated rotor resistance.

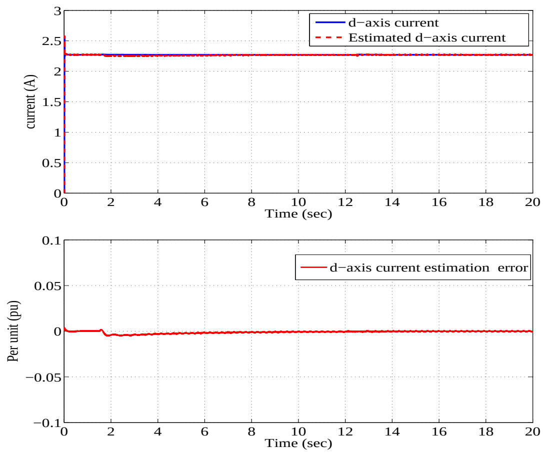

Fig. 10: Estimated & real d-axis currents.

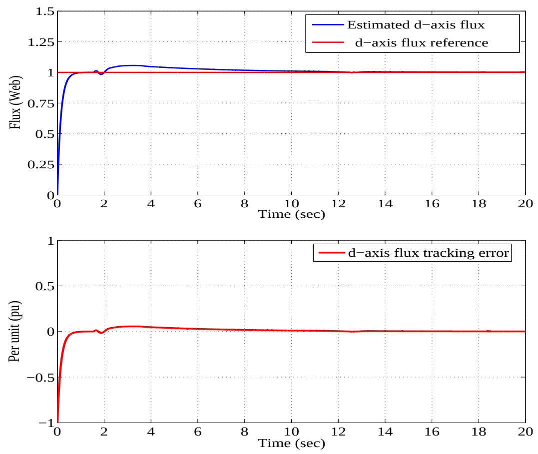

Fig. 8: Estimated d-axis flux components.

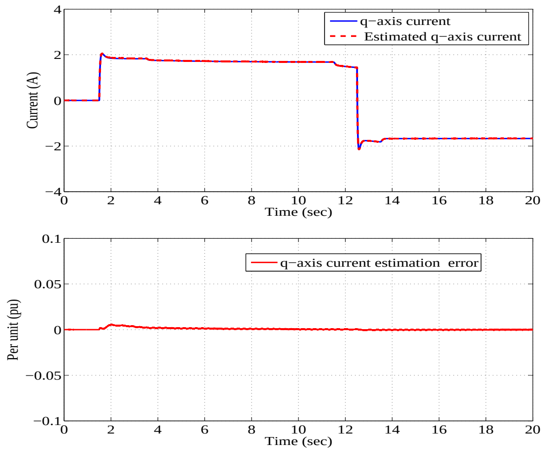

Fig. 11: Estimated & real d-axis currents.

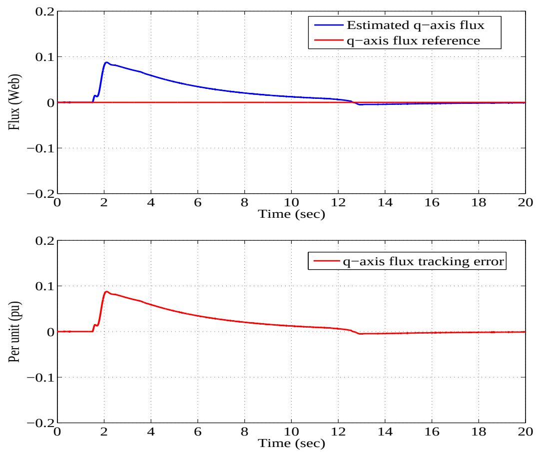

Fig. 9: Estimated d-axis flux components.

surement of stator currents. A load torque is generated through the control of a magnetic power brake.

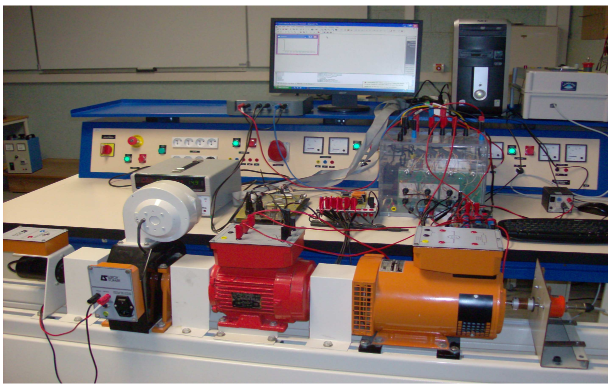

Fig. 12: Experimental setup

Figures 13, 14, 15, 16, 17 and 18 show the experimental results. Comparing the described results in Figure 13 (which shows the evolution of the rotor speed relative to the reference signal and the tracking error waveform) with those obtained in simulation (Figure 6), we can remark a great similarity even in transient state. Regarding the estimation of the rotor resistance, the obtained results (Figure 14) show a good estimation quality despite a small static error which is of the order of 0.02 Pu. The analysis of figures 15 and 16 (that show the evolution of the d-q components of the rotor flux relatively to the reference signal as well as the tracking errors) shows that the quality of reference signals' tracking is good and the decoupling phenomenon is well insured. A minor tracking error is remarkable for the q-axis flux component that may be caused by a rotor resistance estimation error or uncertainties of other parameters of the machine. The analysis of Figures 17 and 18 (which show the real components and the estimated components of the stator currents as well as the estimated error waveforms) shows a good similarity of the obtained results by simulation and confirms the convergence of the proposed observer despite the change of the resistance or rotor speed.

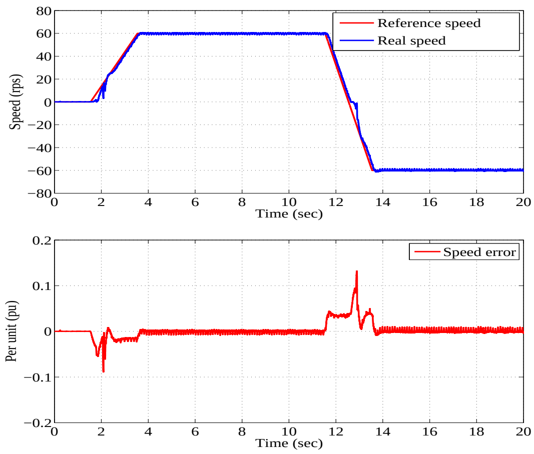

Fig. 13: Reference& real rotor speed.

6 CONCLUSIONS

In this paper, we have dealt with the problem of rotor resistance tune in a IRFOC control through the design of $D-$stable TS fuzzy adaptive observer based on the Park model in the synchronous reference frame. The design conditions are driven in strict LMI terms. Thanks to the proposed approach we ensure good performances of IRFOC control in case of rotor resistance variation. A method of poles placement of the full states observer is studied. The control and the check operations were simplified grace to the ability to dealt with dc quantities (currents, flux).The validity of the developed results of the IM drive was proven

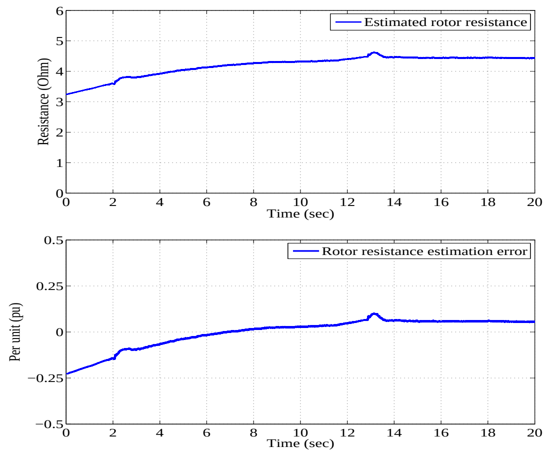

Fig. 14: Estimated rotor resistance.

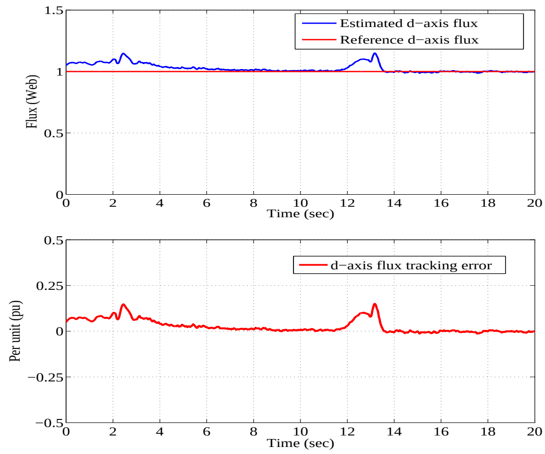

Fig. 15: Estimated d-axis flux components.

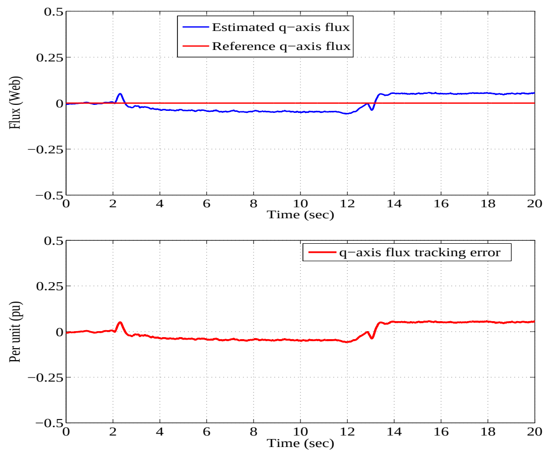

Fig. 16: Estimated d-axis flux components.

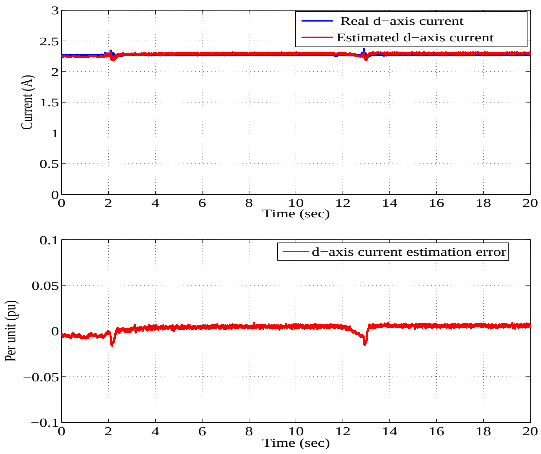

Fig. 17: Estimated & real d-axis currents.

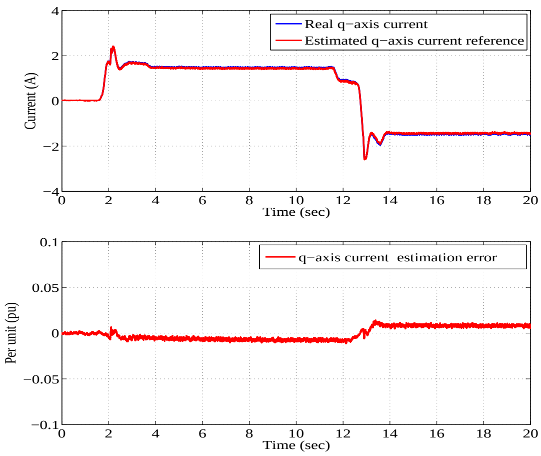

Fig. 18: Estimated & real d-axis currents.

by simulation and experimentation.

Appendix

IM characteristics:

	Value
Base current	$3.5\sqrt{2}$A
Base voltage	$220\sqrt{2}$ v
Base speed	149.7492 rps
Base flux	1 Web

Definition 1 *[26]: A subset D of the complex plane is a LMI region if there exists a symmetric matrix $\alpha \in \Re^{m*m}$ and a matrix $\beta \in \Re^{m*m}$such that:*

$$D = \left\{ z \in \mathbb{C} : f_D(z) = \alpha + \beta z + \beta^T \bar{z} \right\}$$

Lemma 1 *[26]: The matrix A is D-stable if and only if there exists a symmetric positive definite matrix $X > 0$ such that:*

$$M_D\left(A, X\right) = \alpha \otimes X + \beta \otimes AX + \beta^T \otimes XA^T < 0$$

where $\otimes$ is the Kronecker product.

Lemma 2 *[27]*: Let $D^\sharp = \bigcap_{i=1}^{r} D_i$ such that D_i is a subset described as follow:

$$M_D\left(A, X\right) = \alpha_i \otimes X + \beta_i \otimes AX + \beta_i^T \otimes XA^T < 0$$

The matrix A is $D^\sharp$ -stable if and only if there exists a symmetric positive definite matrix $X > 0$ such that:

$$M_{D^\sharp}\left(A, X\right) = \alpha_i \otimes X + \beta_i \otimes AX + \beta_i^T \otimes XA^T < 0$$
$$i = 1 \ldots\ldots r$$

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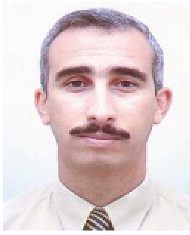

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