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Indirect Adaptive Fuzzy Sliding Mode Observer for Sensorless Induction Machine Drive

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Abstract - **In this paper a full state sliding mode observer for the sensorless speed control of a field oriented Induction Motor (IM), is presented. The observer switching gains are fine-tuned using fuzzy logic controllers in such manner to minimize the error between actual and estimated stator current components expressed in the stationary reference frame (α,β). It is proposed to adapt off-line these switching gains using fuzzy regulators. Then the mean values of the two tuned switching gains are used as new constant gains to perform the observer dynamics and accuracy. In fact, based on the current model of the machine, the fuzzy adapted sliding mode full-state observer is used to estimate the machine rotor flux components and speed, in particular.**

Simulation results are presented and discussed to show the validity and the performance of the proposed observer, in the case of two power different motors.

Key words: **induction motor, sliding mode, switching gains, fuzzy logic, adaptive observer, sensorless control.**

I. INTRODUCTION

The indirect vector control with rotor flux orientation is widely used in the control of the induction machine drives. It presents good performances, but requires additional sensors on the machine. The presence of these sensors increases the cost, the complexity of the drive and reduces the robustness of the overall system. In fact, in the electrical machines control, it is not possible to measure all the necessary variables in the control implementation. So, the search for observers to obtain state variables which can be used in the algorithm control is actively continued by researchers.

Sensorless speed control of electrical drives, in particular, is becoming more attractive. Reliability and maintenance low level are the advantages of these drives. The speed information must be reconstituted from the terminal quantities (voltage and current components) of the machine using flux observers which are based on the induction machine model. One of the main problems involved in these observers is the integration process relating to the induction machine dynamics.

The application of a pure integrator for the flux estimation has dc drift and initial value problems [1],[2]. These problems are solved by the use of a low pass filter [3]. To estimate more accurately the machine flux in a wide speed range, the filter should have a very low cutting frequency [3],[4]. In the case of the model reference adaptive system (MRAS) methods, a comparison between the outputs of two estimates are made. Then, the output errors are used to derive a suitable adaptation mechanism that generates the estimated speed [5]. The Kalman filter approaches are known to be able to get accurate speed information, but have some inherent disadvantages, such as the influence of noise and large computational burden [6]. In [7] the approach, based on the singular perturbation theory, decomposes the original system of the observer dynamic errors into separate slow and fast subsystems of lower dimensions and permits a simple design and determination of the observer gains. The rotor flux observer accuracy is guaranteed through the stator currents observer. Then the rotor time constant is estimated using the stator currents estimation error and the observed rotor flux, based on the Lyapunov stability theory. Also, adaptive sliding mode observers for sensorless field-oriented control of induction motors were proposed in several works such as [8]. In this kind of observers, the rotor flux and the stator current are estimated using the sliding mode concept. The speed adaptation algorithm was derived based on the current estimation error and the estimated rotor flux components. The switching gains have to be set large enough to overcome the system uncertainty and the parameter variations. But very large switching gains can affect seriously the global stability of the drive.

In this paper, a fuzzy adapted sliding mode observer is designed to estimate the stator current and rotor flux components of the induction machine. Then the rotor speed and rotor time-constant are estimated using the previously estimated current and flux. To overcome the drive global stability problems, it is proposed to adapt the observer switching gains by using fuzzy logic regulator whose inference rules are based on the minimization of the estimation errors of the stator current components. Then the mean values of these fuzzy adapted gains are used as designed constant switching gains of the proposed sliding mode observer. Simulation results will show that this proposed fuzzy designed sliding mode observer could give good dynamic performance and accuracy and ensure the global stability of the drive, in the case of different power range machines.

II. Sliding Mode Observer

Sliding mode control theory, due to its order reduction, disturbance rejection, strong robustness and simple implementation, is recognized as one of the prospective control methodologies for electrical machines. The basic concepts and principles of electric drives sliding mode control were demonstrated in [9].

A- Induction motor modeling

Equations describing the induction machine dynamic model in the stationary frame (α,β) and the associated mechanical equation are expressed as follows:

$$\begin{aligned}
\frac{di_{\alpha s}}{dt} &= -\gamma i_{\alpha s} + \frac{k}{T_r}\psi_{\alpha r} + k\omega_r\psi_{\beta r} + \frac{1}{\sigma L_s}V_{\alpha s} \\
\frac{di_{\beta s}}{dt} &= -\gamma i_{\beta s} + \frac{k}{T_r}\psi_{\beta r} - k\omega_r\psi_{\alpha r} + \frac{1}{\sigma L_s}V_{\beta s} \\
\frac{d\psi_{\alpha r}}{dt} &= \frac{L_m}{T_r}i_{\alpha s} - \frac{1}{T_r}\psi_{\alpha r} - \omega_r\psi_{\beta r} \\
\frac{d\psi_{\beta r}}{dt} &= \frac{L_m}{T_r}i_{\beta s} - \frac{1}{T_r}\psi_{\beta r} + \omega_r\psi_{\alpha r} \\
\frac{d\omega_r}{dt} &= G(i_{\beta s}\psi_{\alpha r} - i_{\alpha s}\psi_{\beta r}) - \frac{T_l}{J} - \frac{f_r\omega_r}{J}
\end{aligned} \tag{1}$$

With:

$\gamma = \frac{R_s}{\sigma L_s} + \frac{R_r L_m^2}{\sigma L_r^2 L_s}$, $G = \frac{3}{2}\frac{pL_m}{JL_r}$, $T_r = \frac{L_r}{R_r}$, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ and $k = \frac{L_m}{\sigma L_s L_r}$.

Let us rewrite the first four equations of the IM model (1) in the following form:

$$\begin{aligned}
\dot{I} &= kD\psi_r - \gamma I + \frac{1}{\sigma L_s}V_s \\
\dot{\psi}_r &= -D\psi_r + \frac{L_m}{T_r}I
\end{aligned} \tag{2}$$

Where: $I = \begin{bmatrix} i_{\alpha s} & i_{\beta s} \end{bmatrix}^T$ $\quad \dot{I} = \begin{bmatrix} \frac{di_{\alpha s}}{dt} & \frac{di_{\beta s}}{dt} \end{bmatrix}^T$ $\quad V_s = \begin{bmatrix} V_{\alpha s} & V_{\beta s} \end{bmatrix}^T$ $\quad \psi_r = \begin{bmatrix} \psi_{\alpha r} & \psi_{\beta r} \end{bmatrix}^T$

$$\dot{\psi}_r = \begin{bmatrix} \frac{d\psi_{\alpha r}}{dt} & \frac{d\psi_{\beta r}}{dt} \end{bmatrix}^T \quad \text{and} \quad D = \begin{bmatrix} \frac{1}{T_r} & \omega_r \\ -\omega_r & \frac{1}{T_r} \end{bmatrix}$$

Note that the term $D\psi_r$ in (2) is common in both current and flux equations. Hence the structure of the current observer can be expressed by [10]:

$$\dot{\hat{I}} = k\phi - \gamma\hat{I} + \frac{1}{\sigma L_s}V_s \tag{3}$$

Where: $\hat{I} = \begin{bmatrix} \hat{i}_{\alpha s} & \hat{i}_{\beta s} \end{bmatrix}^T$, $\dot{\hat{I}} = \begin{bmatrix} \frac{d\hat{i}_{\alpha s}}{dt} & \frac{d\hat{i}_{\beta s}}{dt} \end{bmatrix}^T$ and $\phi = \begin{bmatrix} \phi_{\alpha r} & \phi_{\beta r} \end{bmatrix}^T$

$\hat{i}_{\alpha s}$ and $\hat{i}_{\beta s}$ are the estimated stator current components in the reference frame (α,β). They are used to generate the following sliding mode non linear control:

$$\begin{aligned}
\phi_{\alpha r} &= -\lambda_1 sign(s_1) \\
\phi_{\beta r} &= -\lambda_2 sign(s_2)
\end{aligned} \tag{4}$$

Where:

$$s_1 = \hat{i}_{\alpha s} - i_{\alpha s}$$
$$s_2 = \hat{i}_{\beta s} - i_{\beta s} \tag{5}$$

With s_1 and s_2 are sliding mode surfaces, λ_1 and λ_2 are the switching gains which represent control magnitudes and are determined from the sliding mode condition existence: $s\dot{s} < 0$, where $s = \begin{bmatrix} s_1 & s_2 \end{bmatrix}^T$. One can obtain:

$$\lambda_1 > \left| \frac{\gamma}{k} s_1 + \frac{\psi_{\alpha r}}{T_r} + \omega_r \psi_{\beta r} \right|$$
$$\lambda_2 > \left| \frac{\gamma}{k} s_2 + \frac{\psi_{\beta r}}{T_r} - \omega_r \psi_{\alpha r} \right| \tag{6}$$

By choosing λ_1 and λ_2 large enough, the sliding mode occurs and (s=0). Let us rewrite currents equations of (2) and (3) as follows:

$$\dot{I} = kD\psi_r - \gamma I + \frac{1}{\sigma L_s} V_s = f_1$$
$$\dot{\hat{I}} = k\phi - \gamma \hat{I} + \frac{1}{\sigma L_s} V_s = f_2 \tag{7}$$

The estimated stator currents components converge to their actual values when the system trajectories reach the sliding mode surfaces. Then, flux components $\psi_{\alpha r}$ and $\psi_{\beta r}$ will be obtained by using the sliding mode function. Finally, the estimated rotor flux components are used to determine rotor speed and time-constant. According to the relationship (7), one can write the following expression:

$$f = k\phi - \gamma(\hat{I} - I) - kD\psi_r$$

Where: $f = f_2 - f_1$

This can be rewritten as follows:

$$D\psi_r = \phi - \frac{\gamma}{k} e - \frac{f}{k} \tag{8}$$

Such as: $e = \hat{I} - I$, $\hat{I} = \begin{bmatrix} \hat{i}_{\alpha s} & \hat{i}_{\beta s} \end{bmatrix}^T$ and $I = \begin{bmatrix} i_{\alpha s} & i_{\beta s} \end{bmatrix}^T$.

From this latter relationship (8), $D\psi_r$ can be determined and flux components, rotor speed and time-constant can be expressed.

a) Rotor f*lux estimation*

Let us rewrite the equation (8) as follows:

$$D\psi_r = \phi - \frac{\gamma}{k} e - \frac{f}{k} = c \tag{9}$$

Where: $c = \begin{bmatrix} c_1 & c_2 \end{bmatrix}^T$

If we substitute the equation (9) in the flux equation of the system (2), the rotor flux components according to axis α and β are determined by:

$$\psi_r = \int \left(-c + \frac{L_m}{T_r} I \right) dt \tag{10}$$

b)- Rotor speed and time-constant estimation

Once the rotor flux components are estimated, the speed and the rotor time-constant could be also estimated. Let us write the equation (9) as:

$$D\psi_r = \begin{bmatrix} \frac{1}{T_r} & \omega_r \\ -\omega_r & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \psi_{\alpha r} \\ \psi_{\beta r} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \tag{11}$$

This equation can be formulated as follows:

$$\begin{bmatrix} \psi_{\alpha r} & \psi_{\beta r} \\ \psi_{\beta r} & -\psi_{\alpha r} \end{bmatrix} \begin{bmatrix} \frac{1}{T_r} \\ \omega_r \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

And finally, one can obtain:

$$\begin{bmatrix} \frac{1}{T_r} \\ \omega_r \end{bmatrix} = \frac{1}{\psi_{\alpha r}^2 + \psi_{\beta r}^2} \begin{bmatrix} \psi_{\alpha r} & \psi_{\beta r} \\ \psi_{\beta r} & -\psi_{\alpha r} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$$

This means that:

$$\omega_r = \frac{1}{\psi_{\alpha r}^2 + \psi_{\beta r}^2} \left(c_1 \psi_{\beta r} - c_2 \psi_{\alpha r} \right) \text{ and } T_r = \frac{\psi_{\alpha r}^2 + \psi_{\beta r}^2}{c_1 \psi_{\alpha r} + c_2 \psi_{\beta r}}. \tag{12}$$

III. FUZZY LOGIC ADAPTIVE CONTROLLER

a)- Fuzzy logic adaptive controller, principle and design

To design a fuzzy sliding mode adapted observer, it is proposed to fine-tune its switching gains in order to ensure the drive global stability and minimize the error between the estimated and actual stator currents $\hat{I}$ and I respectively. For this purpose, a fuzzy logic controller whose inference rules is based on a certain expertise carried out on the two observer switching gains, is used. This expertise is a qualitative knowledge about the effect of varying the switching gains on the stator current estimation errors. Also, two empirical limitations (upper and lower bounds) are imposed on the switching gains in order to ensure the stability of the observer and the whole drive.

The structure of the two controllers contains three main parts, fuzzification, inference and defuzzification. The inputs of the fuzzy logic controller are the normalized estimation error e_r and its normalized variation de_r such as:

$$e_r = G_{e_r} e = G_{e_r} \left(\hat{I} - I \right)$$

$$de_r = G_{de_r} \left(e_r (t + \Delta t) - e_r (t) \right)$$

Where:

$e_r = \begin{bmatrix} e_{r1} & e_{r2} \end{bmatrix}^T$, $de_r = \begin{bmatrix} de_{r1} & de_{r2} \end{bmatrix}^T$, $G_{e_r} = \begin{bmatrix} G_{e_{r1}} & G_{e_{r2}} \end{bmatrix}^T$ and $G_{de_r} = \begin{bmatrix} G_{de_{r1}} & G_{de_{r2}} \end{bmatrix}^T$.

G_{e_r} and G_{de_r} are the inputs scaling factors of the fuzzy regulator. They are adjusted in order to obtain desired dynamic performance and good accuracy of the estimated variables. And, the outputs of the regulator are the normalized increments of the two switching gains noted: $\Delta\lambda = \begin{bmatrix} \Delta\lambda_1 & \Delta\lambda_2 \end{bmatrix}^T$.

b)- Fuzzy sets

Inputs e_r and de_r as well as the output variable $\Delta\lambda$ of the fuzzy controller are normalized in the interval [-1 1] using the scaling factors G_{e_r}, G_{de_r} and G_λ where $G_\lambda = [G_{\lambda 1} \quad G_{\lambda 2}]^T$. e_r, de_r and $\Delta\lambda$ are fuzzified by five fuzzy sets, for which trapezoidal and triangular membership functions (see figure (1)) are used and named as: NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small), PL (Positive Large). Also, the inference rules matrix is illustrated by table 1. To get the controllers output increment $\Delta\lambda$, the sum-product function is used as an inference method and the gravity center method as a deffuzzification strategy. So, the following expression of $\Delta\lambda$ is established [11-13]:

$$\Delta\lambda = \frac{\sum_{i=1}^{n} \mu_i X_{Gi} S_i}{\sum_{i=1}^{n} \mu_i S_i} \tag{13}$$

Where:

$\mu_i = [\mu_{1i} \quad \mu_{2i}]^T$,

n is the number of the inference rules,

μ_i is the fulfillment degree of the i_{th} rule,

S_i and X_{Gi} are the surface and the gravity center of the output fuzzy membership set corresponding to the i_{th} rule.

The controller output at the $(k+1)^{\text{th}}$ sample given at $(t+\Delta t)$, is expressed by the following equation:

$$\lambda(k+1) = \lambda(k) + G_\lambda \Delta\lambda(k+1) \tag{14}$$

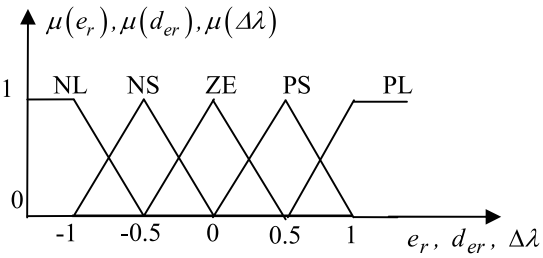


Fig. 1. Inputs and output membership functions

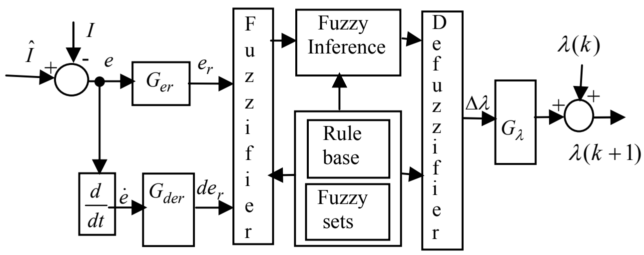


Fig. 2. Block diagram of the fuzzy logic controllers

Table I Fuzzy controller rule base

de_r \ e_r	NL	NS	ZE	PS	PL
PL	ZE	PS	PL	PL	PL
PS	NS	ZE	PS	PL	PL
ZE	NL	NS	ZE	PS	PL
NS	NL	NL	NS	ZE	PS
NL	NL	NL	NL	NS	ZE

The fuzzy regulator provides two adaptive switching gains. We can use these fuzzy regulators to adapt the sliding mode observer. But we can also, as it is noted, take the mean value of this adaptive gains to implement a sliding mode observer with constant switching gains. Good dynamic performance and accuracy of the estimated variables were noted in this latter case. In fact, this was checked and validated for different power induction motors (in this paper the simulation results of two different power induction motors are presented and discussed in the following section).

c) *Determination of the sliding mode observer switching gains*

The fuzzy regulator adjusts the two switching gains of the observer, as it is established in (14). The initial values of these two gains are determined from the sliding mode existence condition expressed by the inequality (6). Also, based on these values, empirical lower and upper bounds of the two tuned gains are proposed in this paper on the same two gains (based on a multitude simulation tests applied to several motors, it is concluded that two and five times of minor values of the inequality (6) gives good results). Finally, the mean values of the sliding mode observer fuzzy self-tuned switching gains are used as constant switching gains of the observer (i.e. the fuzzy controllers are used as a design process of the sliding mode observer switching gains).

IV. SIMULATION RESULTS

The estimated speed is used as a feedback for speed regulation by a PI controller (see figure (3)). It is assumed that this PI speed controller is designed to give good dynamic performance of the overall drive. The induction motor is supplied by a current PWM voltage source inverter (see block diagram of figure 3). The machine dynamic model is used to calculate actual values of currents, fluxes and speed, whereas, the observer model is used to estimate current, flux components and speed. The sliding mode observer switching gains are firstly adjusted by fuzzy logic controllers. Then, the mean values are taken to implement the final sliding mode observer with constant switching gains. Let us discuss now the designed fuzzy-sliding mode observer dynamic and static performances, in the case of square and trapezoidal speed references for two different motors (see appendix). The robustness test control is also carried out, by the introduction and the suppression of the rated load torque.

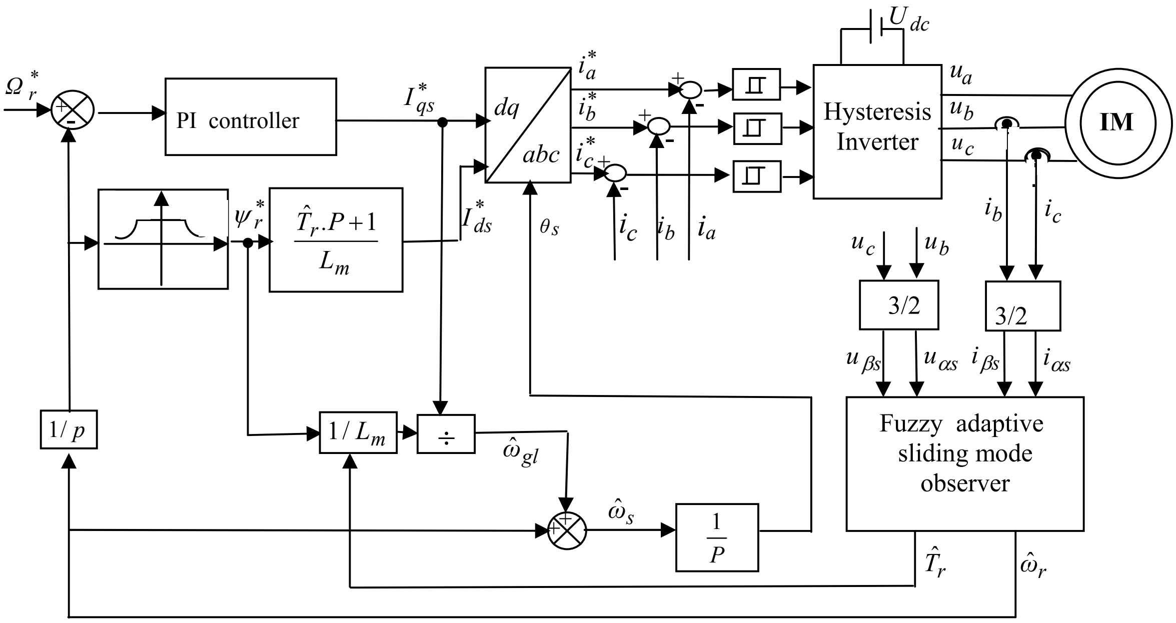


Fig. 3. Block diagram of the indirect field oriented speed control with adaptive fuzzy sliding mode observer

a) Case of the machine A

a.1)- Trapezoidal reference speed: Figure (5) presents simulation results of a trapezoidal reference speed. This manner of speed reference variation allows us to check the performances of the sliding mode observer for various operating conditions (motor and generator operating, in direct and inverse rotation, variable and constant speed). The switching gains are given the mean values of the fuzzy adapted gains obtained by the fuzzy logic controller (see figure 4). It can be noticed according to these results that the estimated current components track their actual values. The same remark could be concluded for rotor flux components and speed. In fact, the rotor flux and the speed estimation errors haven't exceeded 0.8% and 0.3 % respectively in transient operation, 1.1% and 0.8 % respectively in the steady state operation. This shows the satisfactory dynamic performance and accuracy of the fuzzy adapted sliding mode observer.

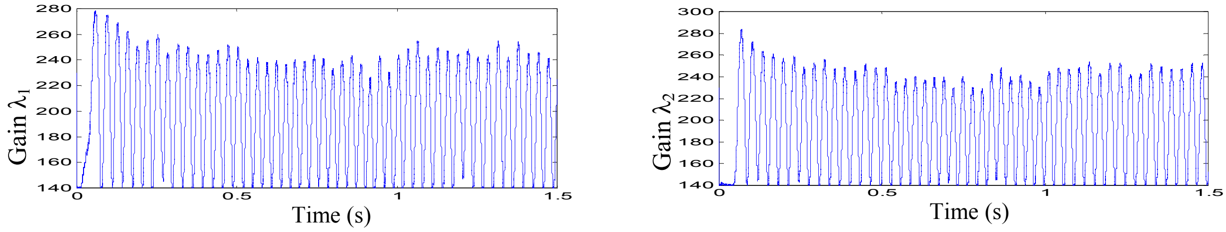


Fig.4. Fuzzy adapted switching gains

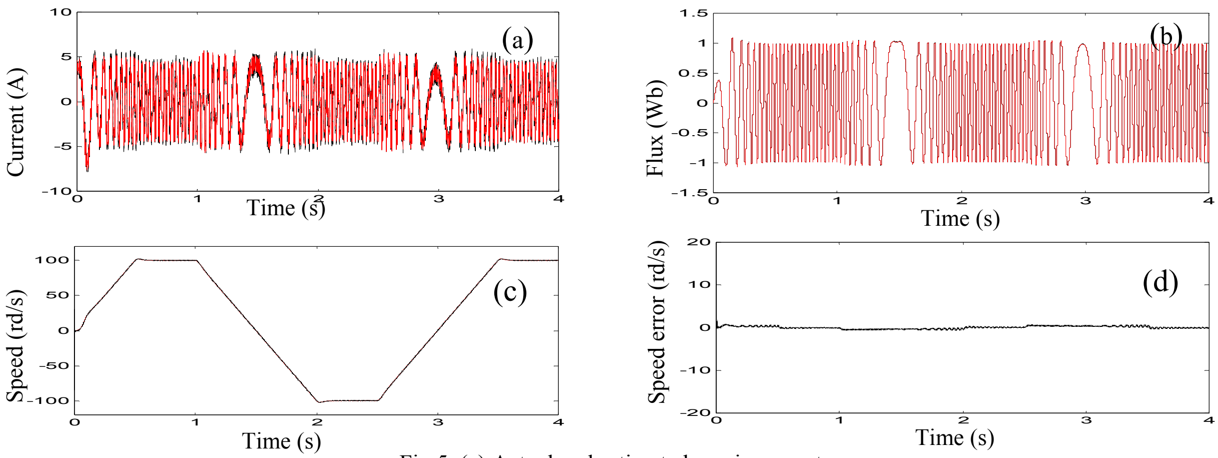


Fig.5. (a) Actual and estimated α axis currents,
(b) Actual and estimated α axis flux
(c) Actual and estimated speed
(d) Speed estimation error

a.2)- Square reference speed: In figure (6), a square reference speed of (± 100 rad/s) is applied as control input to test the speed observer performances. One can note that the estimated current and rotor flux components track very well their actual values. The estimated speed converges also perfectly to its actual value. In fact, the rotor flux and the speed estimation errors haven't exceeded 3.5% and 0.4 % respectively in transient operation, 1.2% and 0.8% respectively in the steady state operation. This shows the satisfactory dynamic performance and accuracy of the fuzzy adapted sliding mode observer, and proves once more that the observer dynamic performance and accuracy are quite satisfactory.

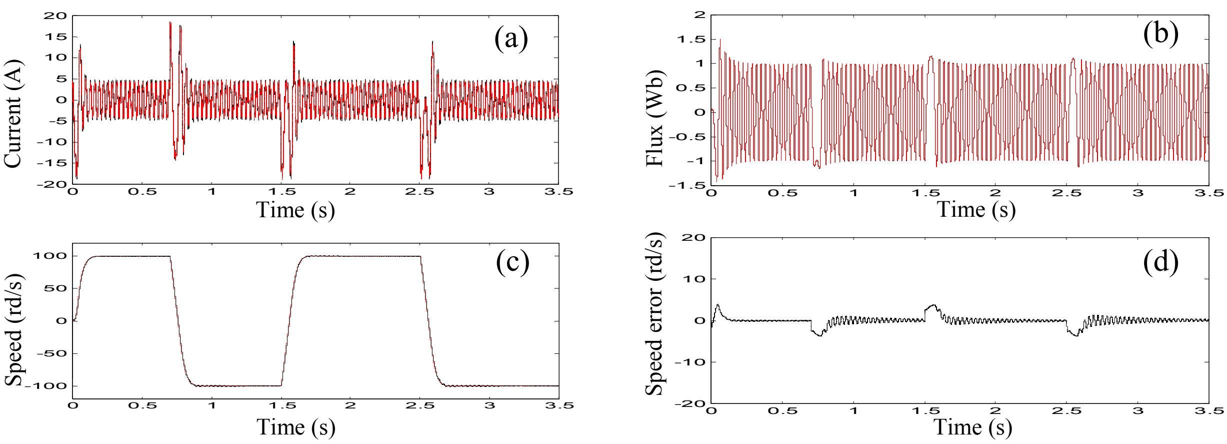


Fig.6. (a) Actual and estimated α axis current,
(b) Actual and estimated α axis flux,
(c) Actual and estimated speed,
(d) Speed estimation error

a.3)- Load effect on the observer performance

The machine is started without load, then a rated load torque T_l = 10 Nm is introduced at t=0.5s, and cancelled at t=1 s. Simulation results are shown in figure (8). One can notice once more the good convergence of the estimated current and rotor flux components towards their actual values. The speed tracks also its reference rapidly after a light deviation at the moment of the application and the suppression of the load torque. The estimated speed is practically confused with its actual value. In fact, the rotor speed estimation errors haven't exceeded 3.8% in transient operation and 0.5% in the steady state operation. This proves the robustness of the speed estimation algorithm against the introduction and the cancellation of the load torque.

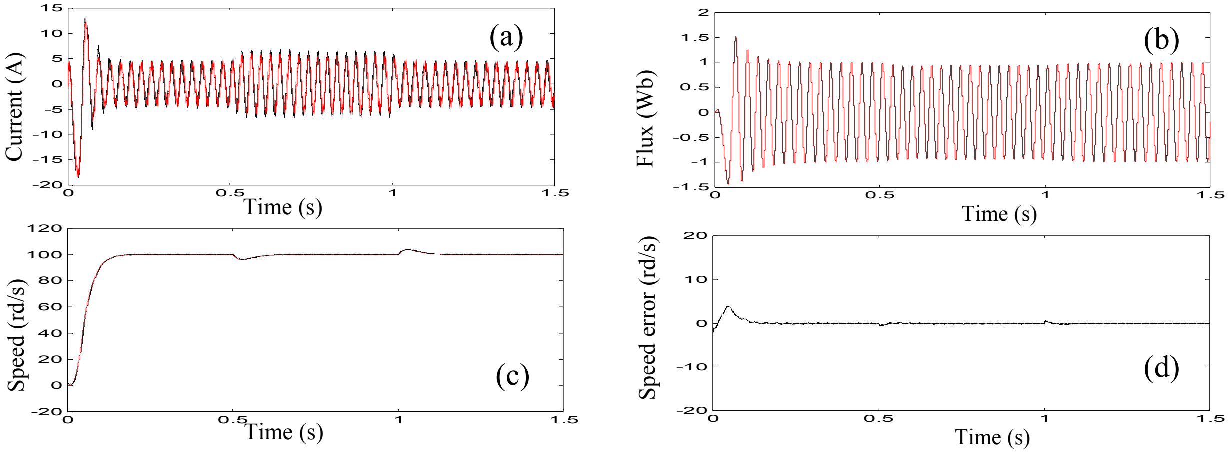


Fig. 7. (a) Actual and estimated α axis current,
(b) Actual and estimated α axis flux,
(c) Actual and estimated speed,
(d) Speed estimation error.

b)- Case of the machine B

In the same way, after the determination of the suitable sliding mode observer switching gains, using the previously described fuzzy method, the observer is tested in the same manner as for machine A. In this case, a load torque T_l = 70 Nm is introduced at t=0.8s, and suppressed at t=1.6s. Simulation results are illustrated in figures 9, 10 and 11. It is noted in this case also that the proposed fuzzy designed observer gives good dynamic performance and satisfactory accuracy.

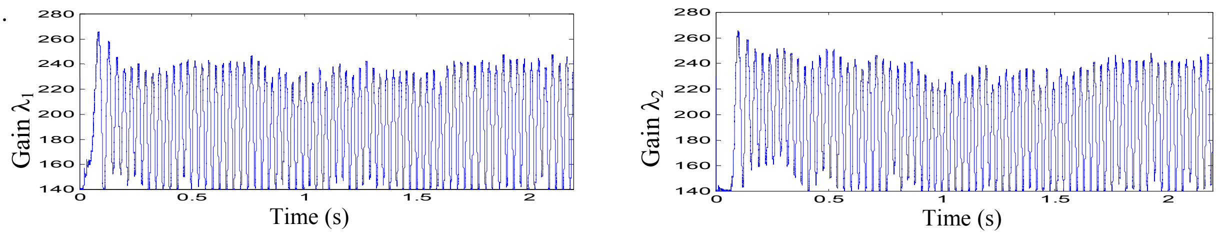
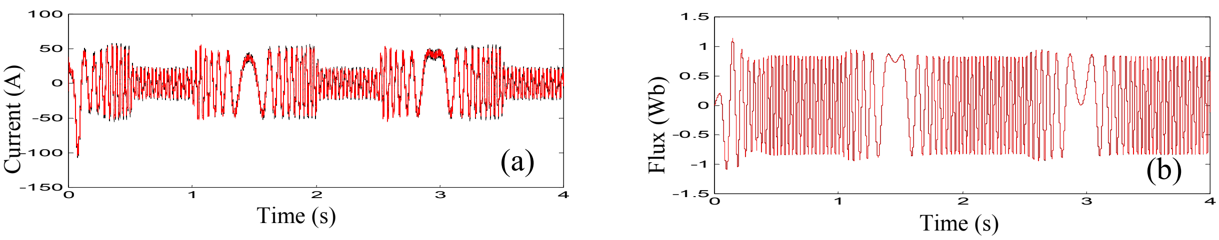


Fig. 8. Fuzzy adapted switching gains

b.1)- Trapezoidal reference speed



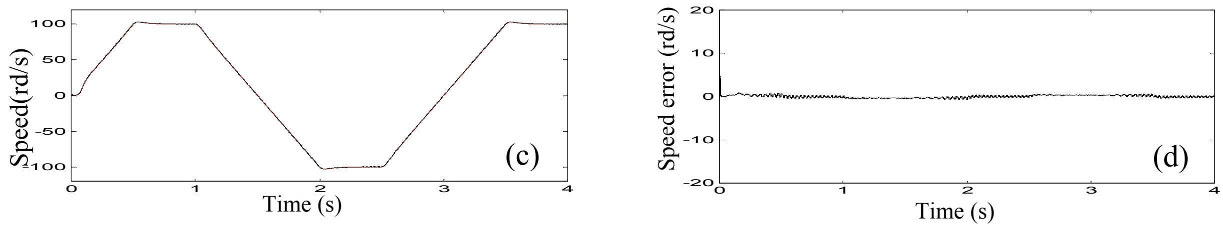


Fig.9. (a) Actual and estimated α axis current
(b) Actual and estimated α axis flux
(c) Actual and estimated speed
(d) Speed estimation error

b.2)- Square reference speed

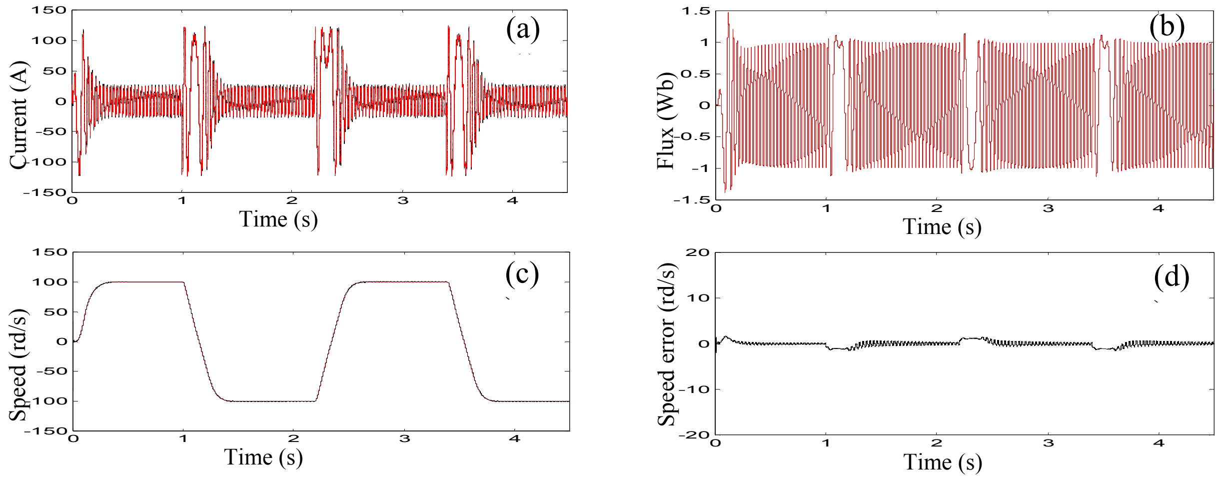


Fig. 10. (a) Actual and estimated α axis current,
(b) Actual and estimated α axis flux,
(c) Actual and estimated speed,
(d) Speed estimation error

b.3)- Load effect on the observer

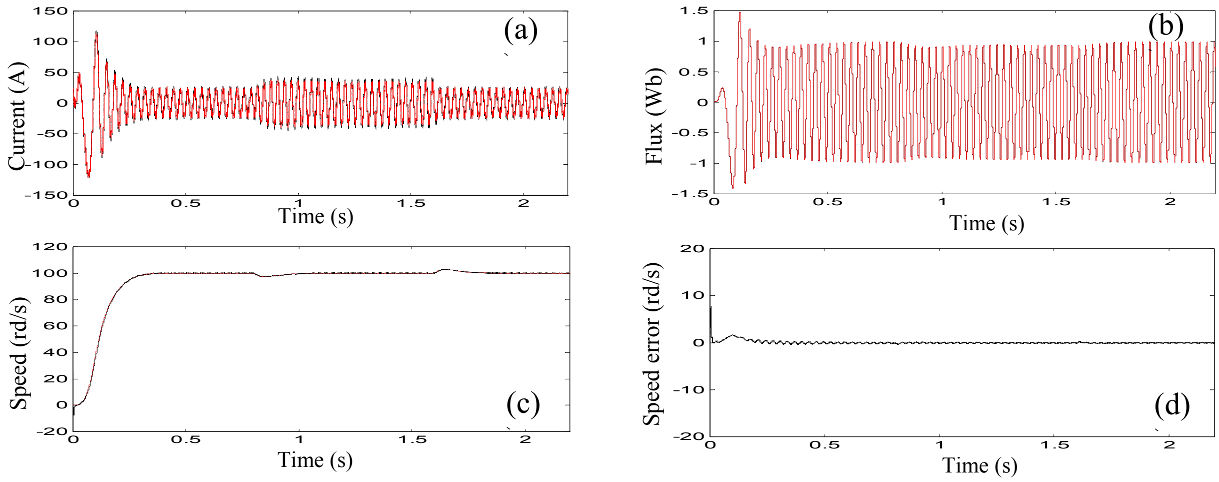


Fig.11. (a) Actual and estimated α axis current,
(b) Actual and estimated α axis flux,
(b) Actual and estimated speed,
(d) Speed estimation error.

V. Conclusion

In this paper, rotor flux components and speed of a field oriented induction motor are estimated using a full state fuzzy adapted sliding mode observer. It is noted that stator current and rotor flux components as well as rotor speed track their actual values rapidly and accurately for different operating conditions. This fast, accurate and robust tracking is ensured by a sliding mode observer for which the switching gains are provided by a proposed fuzzy logic adaptive mechanism. In fact, the proposed fuzzy adapted switching gains make it possible to acquire good dynamic and static performances for the observer and the whole drive. The suggested method has been checked by simulation on two different induction machines and given good results.

VI. Appendix (Machines Parameters)

Parameters	Machine A	Machine B
Pole pairs, p	2	2
Rated power, P_n(kW)	1.5	15
R_s (Ω)	4.85	0.29
R_r(Ω)	3.80	0.38
L_s(H)	0.274	0.05
L_r(H)	0.274	0.05
L_m(H)	0.258	0.0473
$J(kg.m^2)$	0.031	0.5
f_r(Nm.s/rad)	0.001136	0.0

VII. List of Symbols

L_s , L_r : stator and rotor inductances,

R_s , R_r : stator and rotor resistances,

L_m : mutual inductance,

J : inertia moment,

f_r : coefficient of viscous friction

σ : leakage factor

T_l : load torque

T_r : rotor time constant

p , P : poles pair number, Laplace operator

ω_s , $\hat{\omega}_{sl}$: synchronous frequency, estimated slip frequency.

ω_r , Ω_r^* : electrical rotor speed, mechanical rotor reference speed

I_{ds} , I_{dr} : stator currents components in the synchronous rotating reference frame,

$\psi_{\alpha r}$, $\psi_{\beta r}$: rotor flux components (actual values) in the reference stationary frame (α, β)

$\hat{\psi}_{\alpha r}$, $\hat{\psi}_{\beta r}$: rotor flux components (estimated values) in the reference stationary frame (α, β)

$i_{\alpha s}$, $i_{\beta s}$: stator current components (actual values) in the reference stationary frame (α, β)

$\hat{i}_{\alpha s}$, $\hat{i}_{\beta s}$: stator current components (estimated values) in the reference stationary frame (α, β)

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