Sensorless Vector Control for Induction Motor Drive Based on an Adaptive Speed Observer using the Fuzzy-Logic Approach

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Abstract :This paper proposes a sensorless speed observer method of an induction motor using fuzzy logic approach in rotor field-oriented control system. Speed and rotor flux are estimated from only measurable variables, the stator voltages and currents. The proposed estimation algorithm uses a deterministic state observer combined with an intelligent adaptive mechanism based on fuzzy logic. The introducing of fuzzy logic is applied to achieve high-performance, a low sensibility to parameter variations and external influences. In order to verify its performances test the behavior of the control algorithm, numerical simulations are achieved. The simulation results have shown a good estimate speed and flux and an excellent tracking performance and have demonstrated convincingly the usefulness of adaptive observer based on fuzzy logic in variable speed drives with high performance.

Index Terms-- Induction motor, field oriented control, fuzzy-logic, adaptive flux and speed observer.

1. NOMENCLATURE

n	subscript for nominal value
r , s	subscripts stand for rotor and stator
$(.)_d$, $(.)_q$	in (d-q) reference frame
$(.)_\alpha$, $(.)_\beta$	in (α-β) reference frame
$(\hat{.})$	estimate of (.)
L_s, L_r, L_m	stator, rotor and mutual inductances
R_s, R_r	stator and rotor resistances
T_s, T_r	stator and rotor time constants
σ	total leakage coefficient
J, B	inertia and coefficient of friction
p	number of poles pair
T_e, T_l	electromagnetic and load torque
θ_s	spatial position of rotor flux
ω_r	electrical angular rotor speed
ω_s	synchronously rotating angular speed
$\omega_{sl} = \omega_s - \omega_r$	slip frequency
$\Omega_r = p \,.\, \omega_r$	mechanical angular speed of the rotor
$\varepsilon(k)$, $d\varepsilon(k)$	error and variation of the error

2. INTRODUCTION

The variable speed electric drives using induction motors have been extensively developed in recent years due to advances in power electronics and new programmable components (DSP or microcontrollers). These techniques are now mature and can design systems for high performance. However, the majority of these control strategies requires a perfect knowledge of the motor speed or position of its shaft, hence the use of sensor dedicated to the measure these variables.

Therefore, many studies and intensive works have focused on research techniques avoiding the utilization of speed sensor, while maintaining a high level of performance [1]. Indeed these techniques, called sensorless, are a challenge both technically and economically because they provide many advantages the most important being a lower cost, more compact drive system, less maintenance, reducing measurement noise… In recent literature, many approaches have been suggested for the design of sensorless control systems; a large part of the proposed methods is based on estimators or state observers dependent mathematical model of induction motor [2].

The techniques most used exploit model of the motor and are principally based on the use of deterministic Luenberger observer [3] or on Model Reference Systems (MRAS) [4]-[5], another method based on the Extended Kalman Filter algorithm (EKF) is used by Lee and Chen [6]-[7]. Generally, the determination of the speed requires information of the flux, but in the low or zero frequency the induction phenomena is strongly reduced or canceled and thus the speed information disappears [1,2]. Therefore, the observability of the state of the induction machine is problematic at low and zero speed and so can deteriorate dynamic performances of the system and even lead to instability, this can be accentuated by the problems of parametric drift.

To overcome the difficulties associated to the modeling of the motor, and avoid problems of parametric variations, several studies based on estimating the saliences position of the machine have been proposed [8].Their principal advantage is the insensitivity to drifts of the parameters, but these techniques also fail at low and zero speed.

Estimation is often improved by the injection of high-frequency signals in order to locate the position of the rotor and so obtain the speed value [9]. These techniques promise to give better results in low speed, but they require signal processing methods very efficient but expensive volume calculation.

In the context of the approaches without model, techniques using artificial intelligence, particularly Fuzzy Logic [10], can raise the challenge of estimating low speed for their efficiency in solving problems related to modeling errors and parametric uncertainties. This work deals a sensorless vector control with direct orientation of rotor flux for induction motor drives, and in particular the improvement of performances of the flux and speed adaptive observer developed by H. Kubota and al [11]. This observer includes a mechanism of adaptation based on a conventional PI controller. And although the speed estimation gives good results in general, its performances proved limited, particularly at low speed with high sensibility to parameter variations. The idea is to replace the mechanism generating the adaptation law by an organ of control based on fuzzy logic. This flux and speed adaptive observer, based on a fuzzy adaptive mechanism, combined with a startup procedure can advantageously replace the speed sensor. Fuzzy Logic approach provides an effective mean for describing systems with too complex or too uncertainties defined to admit a precise mathematical model [12]-[13]. The proposed sensorless vector control scheme showed a good behavior in the transient and steady states, with an excellent disturbance rejection of the load torque. Numerical simulations demonstrate the effectiveness of proposed control over different operating conditions, a precise estimation in low and zero speed.

3. ADAPTIVE FLUX AND SPEED FUZZY OBSERVER

The objective of this observer is reconstruction the rotor flux and speed without using expensive and bulky sensors, and thus achieves a variable speed drive of high performances. Flux components and the value of the speed are not measured, they are considered as the unknown parameters in the system of equations based on the model of the motor.

A. Dynamic Model of IM in (α-β) Reference Frame

The model of induction motor in the stationary reference (*α-β*) can be described by the following state representation [2]-[3]:

$$\begin{cases} \dot{X} = A(\omega_R).X + BU \\ Y = C.X \end{cases} \qquad (1)$$

with

$$X = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \psi_{r\alpha} & \psi_{r\beta} \end{bmatrix}^T$$

$$Y = i_s = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \end{bmatrix}^T \qquad U = v_s = \begin{bmatrix} v_{s\alpha} & v_{s\beta} \end{bmatrix}^T$$

$$A(\omega_r) = \begin{bmatrix} \begin{bmatrix} a_1 & 0 \\ 0 & a_1 \end{bmatrix} & \begin{bmatrix} a_2 & a_3.\omega_r \\ a_3.\omega_r & a_2 \end{bmatrix} \\ \begin{bmatrix} a_4 & 0 \\ 0 & a_4 \end{bmatrix} & \begin{bmatrix} a_5 & -\omega_r \\ \omega_r & a_5 \end{bmatrix} \end{bmatrix}$$

$$B = \begin{bmatrix} a_6 & 0 & 0 & 0 \\ 0 & a_6 & 0 & 0 \end{bmatrix}^T \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T$$

$$a_1 = -\left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r}\right) \qquad a_2 = \frac{1}{T_r.L_m}.\frac{(1-\sigma)}{\sigma}$$

$$a_3 = \frac{1}{L_m}.\frac{(1-\sigma)}{\sigma} \qquad a_4 = \frac{L_m}{T_r}$$

$$a_5 = -\frac{1}{T_r} \qquad a_6 = \frac{1}{\sigma.L_s}$$

B. Adaptive Speed and Flux Observer

Let's consider the speed like a constant and unknown parameter, it is about to determine a law of adaptation for estimating its value. The observer can be described by the following state equation [11]:

$$\dot{\hat{X}} = A(\hat{\omega}_R).\hat{X} + BU + K.(i_s - \hat{i}_s)$$

(2)

The matrix K represents the gain of the observation matrix; it governs the dynamics and the observer's robustness and is defined as follows:

$$K = \begin{bmatrix} K_1 & K_2 & K_3 & K_4 \\ K_2 & K_1 & -K_4 & K_3 \end{bmatrix}$$

(3)

The coefficients K_1, K_2, K_3 and K_4 are calculated by:

$$K_1 = (1-k_1).\left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r} + \frac{1}{T_r}\right)$$

$$K_2 = (k_1-1).\hat{\omega}_r$$

$$K_3 = \frac{\left(1-k_1^2\right)}{a_3}.\left(\frac{1}{\sigma.L_s} + \frac{(1-\sigma)}{\sigma.T_r} + \frac{a_3}{T_r}\right) + \frac{(k_1-1)}{a_3}.\left(\frac{1}{\sigma.T_s} + \frac{(1-\sigma)}{\sigma.T_r} + \frac{1}{T_r}\right)$$

$$K_4 = \frac{(k_1-1)}{a_3}.\hat{\omega}_r \qquad k_1 \succ 1$$

The coefficient k_1 is chosen for impose an observer dynamic faster than the system. The difference between the observer and the model of the motor represents the estimation error of stator current and rotor, it is given by:

$$\dot{e} = (A - K.C).e + (\Delta A).\hat{X}$$

(4)

$$\Delta A = A(\omega_r) - A(\hat{\omega}_r)$$

where

$$A(\hat{\omega}_r) = \begin{bmatrix} 0 & 0 & 0 & a_3.\Delta\hat{\omega}_r \\ 0 & 0 & -a_3.\Delta\hat{\omega}_r & 0 \\ 0 & 0 & 0 & -\Delta\hat{\omega}_r \\ 0 & 0 & \Delta\hat{\omega}_r & 0 \end{bmatrix} \quad \Delta\omega_r = \omega_r - \hat{\omega}_r$$

The speed is generated by the adaptive mechanism and Lyapunov theory [11] allows deducing the adaptation law.

$$e = X - \hat{X} = \begin{bmatrix} e_{isa} & e_{isb} & e_{\psi ra} & e_{\psi rb} \end{bmatrix}^T$$

with

$$e_{isa} = i_{sa} - \hat{i}_{sa} \qquad e_{isb} = i_{sb} - \hat{i}_{sb}$$

$$e_{\psi ra} = \psi_{ra} - \hat{\psi}_{ra} \qquad e_{\psi rb} = \psi_{rb} - \hat{\psi}_{rb}$$

By choosing an adequate candidate function, the following adaptation law is gotten by:

$$\hat{\omega}_e = \left(K_p + \frac{K_i}{s}\right)\left(e_{isa}.\hat{\psi}_{rb} - e_{isb}.\hat{\psi}_{ra}\right)$$

(5)

K_p and K_i are positive constants.

The speed is estimated by a simple PI controller, its role is to minimize the error and deliver speed adaptation law:

$$e = \left(e_{isa}.\hat{\psi}_{rb} - e_{isb}.\hat{\psi}_{ra}\right)$$

(6)

The adaptive observer is stable, so the induction motor and its control system will be stable over a wide range.

The norm of rotor flux and its spatial position are obtained from following equations:

$$\hat{\psi}_r = \sqrt{\hat{\psi}_{ra}^2 + \hat{\psi}_{rb}^2}$$

(7)

$$\hat{\theta}_s = atan\left(\frac{\hat{\psi}_{rb}}{\hat{\psi}_{ra}}\right)$$

(8)

Figure 1 represents the structure of the flux and speed observer proposed.

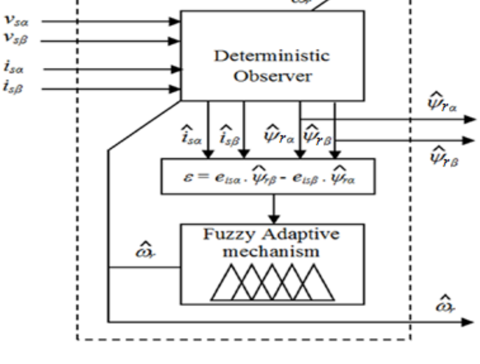


Fig. 1. Structure of the flux and speed observer proposed.

C. Fuzzy Adaptation Mechanism

With the aim of improve the observer's behavior and to introduce human expertise in its treatment, the adaptive mechanism is replaced by a PI fuzzy controller. The design of a control mechanism based on fuzzy logic is justified by non-linearities of the system, the imprecision of the mathematical model explained above, and its relative ease of implementation [10-12]. Approach of fuzzy logic is different from that of the classic automatic, in the sense that it does not treat mathematical relations well defined, but it exploits the knowledge of an expert [13].

These are expressed by means of conduct rules based on a symbolic vocabulary and with the manipulation of inferences with several rules using the fuzzy operators AND, OR, THEN, applied to linguistic variables. For example, a typical rule reads as follows:

IF error is Positive Small (**PS**), **AND** error variation is negative small (**NS**) **THEN** output of fuzzy controller is Zero (**Z**)

The bloc diagram of the fuzzy adaptation mechanism is represented in figure 2.

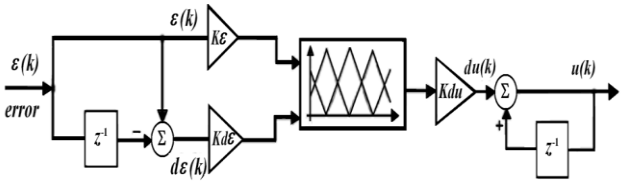


Fig. 2. Block diagram of the fuzzy adaptation mechanism.

The Inputs and the output are deterministic values, the inputs signals for the fuzzy control system are the error $\varepsilon(k)$ and variation of error $d\varepsilon(k)$:

$$e(k) = e_{isa}(k).\hat{y}_{rb}(k) - e_{isb}(k).\hat{y}_{ra}(k) \quad (9)$$

$$de(k) = e(k) - e(k-1) \quad (10)$$

Inputs and output are pondered by normalization gains K_ε, $K_{d\varepsilon}$, K_{du}, which can act on the sensitivity of the mechanism and thus largely contribute to improving the response. $du(k)$ represents the increment of the drive signal, and output of the fuzzy controller $u(k)$ is the value of the estimated speed defined by:

$$u(k) = \hat{w}_r(k) = \hat{w}_r(k-1) + d\hat{w}_r(k)$$

(11)

The universe of discourse is partitioned into the five linguistic variables NB, NS, ZE, PS and PB; these labels denote 'Negative Big', 'Negative Small', 'Zero Equal', 'Positive Small' and 'Positive Big' respectively. The shape of membership functions defined is illustrated in Figure 3.

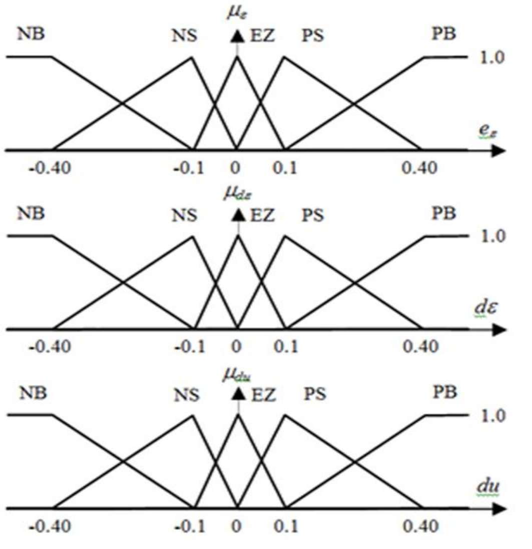


Fig. 3. Membership functions in the universe of discourse.

The fuzzy rules representing human expertise and generates control actions are presented in Table 1.

TABLE I

Rules of Expert Fuzzy System Inference

		$d\varepsilon$				
		NB	**NS**	**ZE**	**PS**	**PB**
ε	**NB**	*NB*	*NB*	*NS*	*PB*	*PS*
	NS	*ZE*	*NS*	*ZE*	*PS*	*ZE*
	ZE	*PB*	*PB*	*ZE*	*PS*	*NB*
	PS	*ZE*	*PS*	*PB*	*NS*	*NB*
	PB	*PB*	*PS*	*NS*	*NS*	*NB*

For the digital treatment of the inferences, we opted for choices requiring volumes and reduced time of calculations, respectively:

- mini and max methods for the logic AND and OR,
- mini and max methods for implication and aggregation.

4. DYNAMIC MODEL OF IM AND VECTOR CONTROL

A. Dynamic Model of IM in (d-q) Reference Frame

The mathematical model of induction motor drive can be described by the following nonlinear equations, in a synchronously rotating (*d-q*) reference frame as [14]:

$$\begin{cases} \dfrac{di_{sd}}{dt}=-\left(\dfrac{R_s}{s.L_s}+\dfrac{1-s}{s.T_r}\right)i_{sd}+w_e.i_{sq}+\dfrac{L_m}{s.L_s.L_r.T_r}.y_{rd} \\ \qquad +\dfrac{L_m.w_r}{s.L_s.L_r}.y_{rq}+\dfrac{1}{s.L_s}.v_{sd} \\ \dfrac{di_{sq}}{dt}=-w_e.i_{sd}-\left(\dfrac{R_s}{s.L_s}+\dfrac{1-s}{s.T_r}\right)i_{sq}-\dfrac{L_m.w_r}{s.L_s.L_r}.y_{rd} \\ \qquad +\dfrac{L_m}{s.L_s.L_r.T_r}.y_{rq}+\dfrac{1}{s.L_s}.v_{sq} \end{cases}$$

(12)

$$\begin{cases} \dfrac{dy_{rd}}{dt}=\dfrac{L_m}{T_r}.i_{sd}-\dfrac{1}{T_r}.y_{rd}+w_{sl}.y_{rq} \\ \dfrac{dy_{rq}}{dt}=\dfrac{L_m}{T_r}.i_{sq}-w_{sl}.y_{rd}-\dfrac{1}{T_r}.y_{rq} \end{cases}$$

(13)

with $s=1-\dfrac{L_m^2}{L_s.L_r}$

The motor load system can be described by:

$$J.\frac{dw_r}{dt}=p.(T_e-T_l)-B.w_r$$

(14)

$$T_e=\frac{3}{2}.\frac{p.L_m}{L_r}.\left(y_{rd}.i_{sq}-y_{rq}.i_{sd}\right)$$

(15)

B. Rotor Field-Oriented Vector Control

The main objective of the Field Oriented Control strategy for induction motors is the independently control to the torque and the flux as in DC machines. This is done by using a (*d-q*) rotating reference frame synchronously with the rotor flux space vector [3]-[14].

The *d*-axis is aligned with the rotor flux space vector and the rotor flux orientation is then expressed by the following condition:

$$y_{rq}=0 \quad \text{and} \quad y_r=y_{rd}=L_m.i_{sd}=\text{constant}$$

(16)

So the rotor flux can be adjusted from the direct component of stator current, while the torque can be controlled from the quadrate component of stator current when the rotor flux is kept constant. The electromagnetic torque is then given by:

$$T_e=\frac{3}{2}.\frac{p.L_m}{L_r}.\left(y_{rd}.i_{sq}\right)$$

(17)

In the case of sensorless vector control proposed, amplitude and spatial position of rotor flux are determined by the adaptive flux and speed observer.

The general equations to rotor flux oriented control are given by [4]-[14]:

$$i_{sd}^* = \frac{1}{L_m}.\psi_r^*$$

(18)

$$i_{sq}^* = \frac{2}{3}.\frac{L_r}{p.L_m}.\frac{T_e}{y_r^*}$$

(19)

$$w_s^* = p.\Omega_r + w_{sl}^* = p.\Omega_r + \frac{L_m}{T_r}.\frac{i_{sq}^*}{y_r^*}$$

(20)

Figure 4 shows the bloc diagram of the sensorless vector control proposed for induction motor drive.

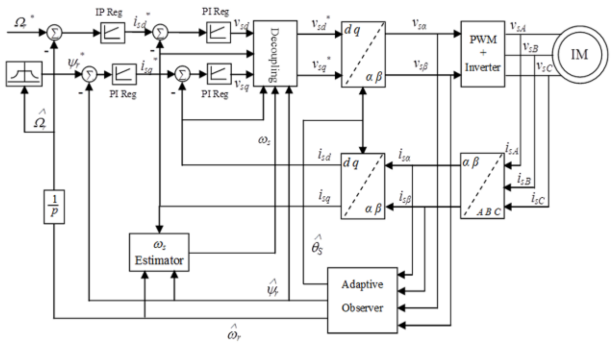


Fig. 4. Membership functions in the universe of discourse.

To stabilize the speed loop and to improve the dynamics of the system during the transient state, the IP controller (Proportional-Integral) was preferred to the conventional PI regulator. The regulation of the stator currents i_{sd}^*, i_{sq}^* is assigned to two identical PI controllers. Another PI controller regulates the rotor flux and minimizes the error between its reference value, obtained by field weakening block and its estimated value delivered by the observer. In addition, a decoupling block is introduced to separate the mutual actions of the two orthogonal axes. The reference value of rotor flux is given by a weakening block

The reference voltages v_{sd}^*, v_{sq}^*, impose the flux and electromagnetic torque desired after reference change by an inverse transformation via the voltage inverter.

5. RESULT AND DISCUSSION

The proposed control structure was implemented in the environment software MATLAB/SIMULINK, and tested with various operating conditions, to illustrate the performance of the fuzzy adaptive observer. The parameters of the induction motor used are given in appendix.

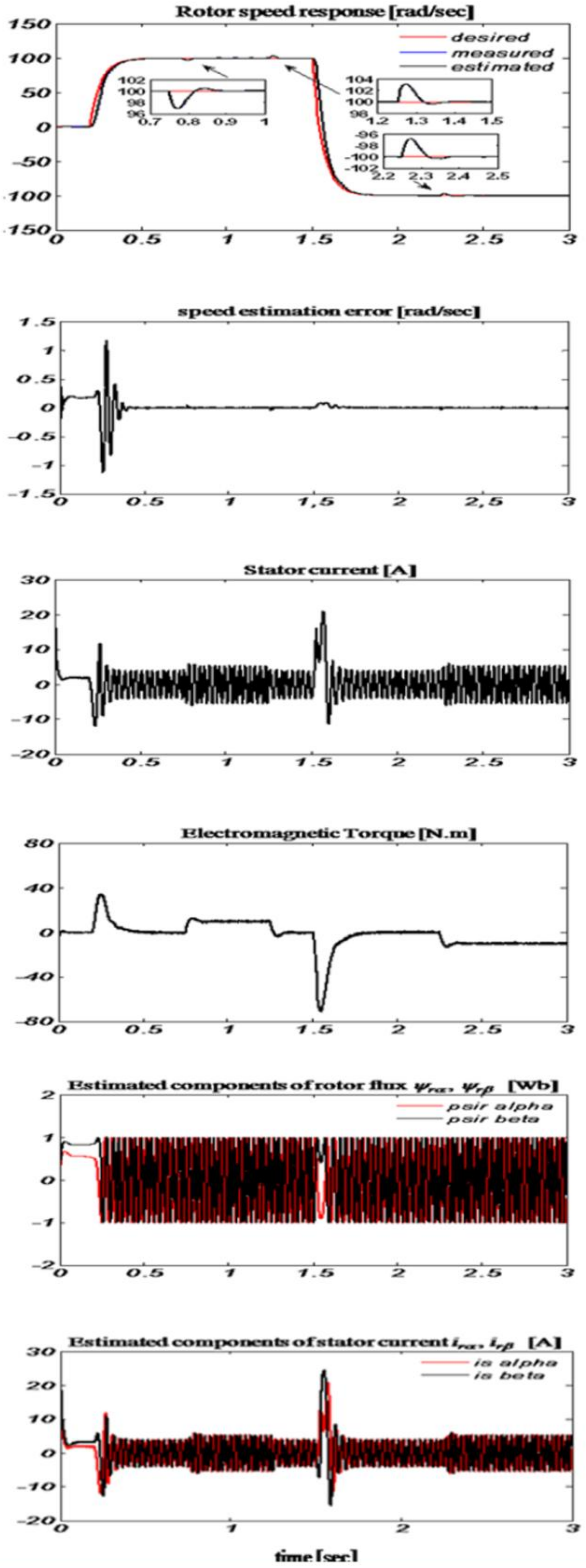
Figure 5 shows the response of the proposed speed sensorless for a step reference since 0 rad/s for 100 rad/sec, and a reverse speed to -100 rad/sec. Disturbances are introduced by applying and removing a load torque equal to 10 Nm at 0.75 s and 1.25 s, then reapplying the same load torque at 2.25 s. The obtained dynamics presents a reaction time very low in transient state. The speed and flux observed show a very low sensitivity to disturbances, good accuracy around and at zero speed, and the control system rejects those load disturbances with a time of rejection extremely small.

Figures 6 displays the responses of the structure control proposed for a variable speed reference, with no load torque. These results show clearly very satisfactory performances in tracking, the measured or actual motor speed perfectly follows the reference trajectory, with a minimal tracking error. The observer's response illustrates an excellent precision of the estimated speed and fluxes, for high and low speeds, but also at zero speed operating.

6. CONCLUDING REMARKS

This paper has presented a sensorless direct field-oriented control of induction motor drive associated with an adaptive speed observer using a fuzzy logic approach. The system was designed and analyzed, and the effectiveness of the proposed scheme is checked extensively by simulation. The observer estimate the rotor flux and the rotor speed simultaneously, with good transients and steady states performances under different operating conditions. The algorithm developed offers excellent behavior at nominal and low speeds, at zero speed, and a big robustness to load torque variation. All results confirm the good dynamic performances of the drive system equipped with the developed observer, and demonstrate the validity of the described method. Another interesting feature is the simplicity and ease of implementation of this approach. Consequently this method may find practical use in many applications to drive systems for variable speed without mechanical sensor for AC motor.

The obtained results were very successful and confirm the validity of the adaptive fuzzy observer proposed. This study shows that it is possible to achieve an adaptive observer for sensorless control of induction motor based approaches to artificial intelligence with high performances.



Rotor speed response [rad/sec]

speed estimation error [rad/sec]

Stator current [A]

Electromagnetic Torque [N.m]

Estimated components of rotor flux $\psi_{r\alpha}, \psi_{r\beta}$ [Wb]

Estimated components of stator current $i_{r\alpha}, i_{r\beta}$ [A]

Fig. 5. Performances of speed control using the fuzzy adaptive observer proposed with a step and reverse speed under load change.

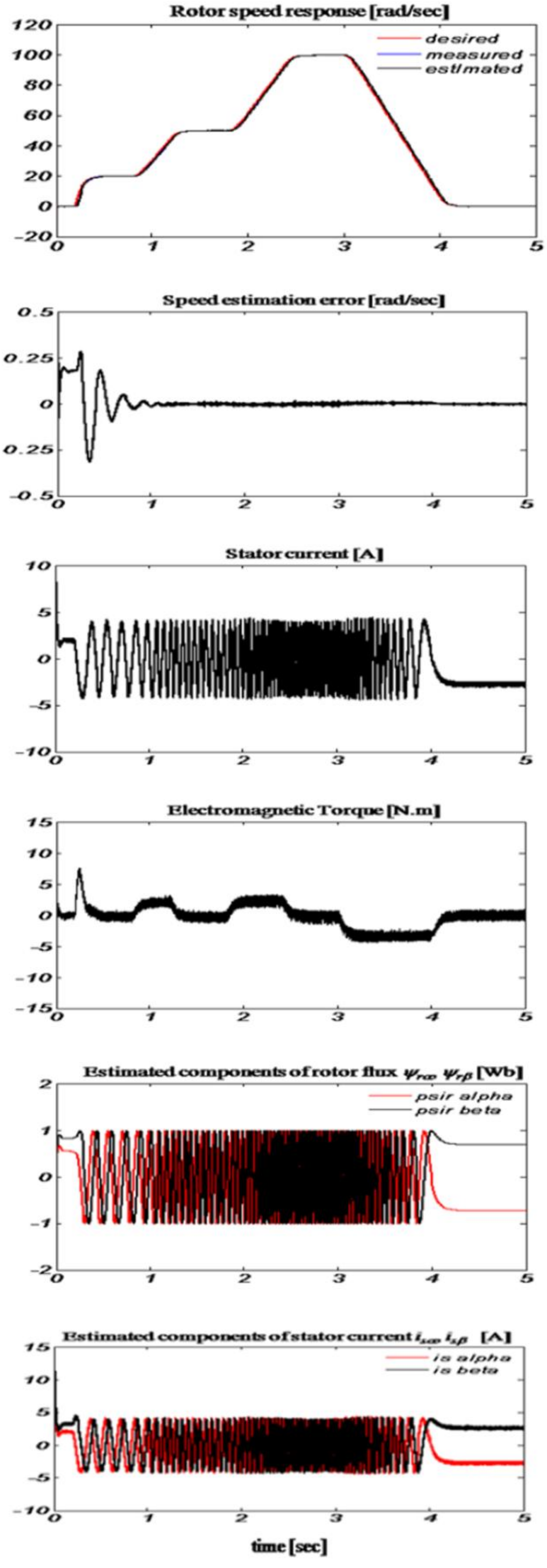


Fig. 6. Performances of speed control using the fuzzy adaptive observer proposed with a variable speed reference and no-load change.

APPENDIX

MOTOR PARAMETERS

Rated values
1.5 kW, 3 phase, 220/380 V, 11.25/6.5 A, Y connected,
50 Hz, 4 poles, 1420 rpm,
Rated parameters
R_s = 4.85Ω, R_r = 3.805 Ω, L_s = 0.274 H, L_r = 0.274 H,
L_m = 0.258 H, J = 0.031 kg.m^2, B = 0.00334 kg.m.s^{-1}.

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