HIGH GAIN FLUX OBSERVER FOR FIELD-ORIENTED CONTROL OF AN INDUCTION MOTOR

A. BECHOUCHE H. SEDIKI B. BOUKAIS S. HADDAD
Department of Electrical Engineering, Mouloud MAMMERI University of Tizi-Ouzou
BP 17 RP, 15000 Tizi-Ouzou, Algeria
e-mail: ali_bechouche@yahoo.fr

Abstract: *This paper deals with the observation and the field oriented control (FOC) of an induction motor (IM). A high gain flux observer is associated in order to estimate the rotor flux assuming the mechanical and stator currents are measured. A robustness tests are carried out by parametric variation in the proposed observer. To valid the observer, an experiment has been set up, dSPACE card based on a Numeric-intensive Texas Instrument TMS320C31 floating point DSP is used. With an aim to establish a comparison between the theoretical and experimental results, the numerical simulation conditions are taken the same as those of the experiment. Simulation and experimental curves are presented to show the performance of a high gain flux observer in IM drive system.*

Key words: *High gain observer, induction motor (IM), field-oriented control (FOC), real-time control.*

Nomenclature

L_s , R_s	Stator inductance and resistance.
T_r	Rotor time constant.
J	Moment of inertia.
f_v	Viscous damping coefficient.
T_l	Load torque.
n_p	Number of pole pairs.
I_{rm}	Rotor magnetizing current.
ω	Mechanical speed.
σ	Leakage factor.
s, r	Stator and rotor index.
$\hat{x}$	Estimate of x.

1. Introduction

It is well known that the induction motor (IM) is used as an electromechanical actuator and is highly appreciated in industry. Nevertheless, it is much more difficult to achieve high performance with IM than with the other types of electrical machines, this can be seeing by comparing, between them, the produced torques. However, for the IM the recent advances in the field of nonlinear control combined with the evolution of the microprocessors technology and the power devices, allow the implementation of powerful nonlinear control laws [1], [2]. In the literature, the problem of IMs control assumes that all the variables state are available from measurement and all parameters are known in order to implement the control laws [3], [4].

The field-oriented control (FOC) has now become a popular method of IM control. This is mainly because the advantages it offers outweigh the advantages offered by all other methods of IM control. In FOC, within the normal operation range, the rotor flux is kept constant and theoretically, for a given rotor flux, the torque-slide characteristic of the system is linear within the limitation of the power converter circuit. In other methods of control there is always a pull-out torque irrespective of the power supply [5]. For direct field-oriented control (DFOC) of IMs, accurate knowledge of the rotor flux vector magnitude and position is necessary. In a squirrel-cage motor, the rotor currents are not measurable [6]. To overcome these disadvantages, estimate or observation techniques developed in automatic and used in many application fields are used. The estimators, which operate in open loop, are less robust in case of a system parametric variation. To obtain an improvement operation, it is necessary to use the state observers having a feedback which acts on the input according to an error caused by parametric variations or a bad initialization of the process [7], [8]. The main contribution of this paper is to present a design methodology of a high gain flux observer for an IM drive system and the experimental validation on a test bench.

This paper is organized as follows: in section 2, the model of IM is reminded. In the third section we synthesized a high gain flux observer. The FOC is discussed in section 4. Section 5 gives the simulation results. Section 6 deals the experimental results. Some conclusions are drawn finally.

2. The induction motor model

In this section, we remind the two-phase equivalent machine representation of the IM. Assuming that we have three-phase balanced a.c voltage and the stator windings are uniformly distributed. The IM can be described by five nonlinear differential equation with four electrical variables [stator currents ($I_{s\alpha}$, $I_{s\beta}$) and rotor currents magnetizing ($I_{rm\alpha}$, $I_{rm\beta}$)], one mechanical variable [rotor speed (ω)], and two control variables [stator voltages ($V_{s\alpha}$, $V_{s\beta}$)]. In a stator-fixed frame (α,β), the electrical subsystem is represented by

$$\begin{aligned}
\dot{I}_{s\alpha} &= -a_1 I_{s\alpha} + a_3 I_{rm\alpha} + a_4 \omega I_{rm\beta} + b_1 V_{s\alpha} \\
\dot{I}_{s\beta} &= -a_1 I_{s\beta} - a_4 \omega I_{rm\alpha} + a_3 I_{rm\beta} + b_1 V_{s\beta} \\
\dot{I}_{rm\alpha} &= a_2 I_{s\alpha} - a_2 I_{rm\alpha} - \omega I_{rm\beta} \\
\dot{I}_{rm\beta} &= a_2 I_{s\beta} + \omega I_{rm\alpha} - a_2 I_{rm\beta}
\end{aligned} \qquad (1)$$

and the mechanical subsystem is given by

$$\dot{\omega} = a_5 I_{s\beta} I_{rm\alpha} - a_5 I_{rm\beta} I_{s\alpha} - a_6 \omega - b_2 T_l \qquad (2)$$

with

$$a_1 = \frac{1}{\sigma}\left(\frac{1}{T_s} + \frac{1-\sigma}{T_r}\right), a_2 = \frac{1}{T_r}, a_3 = a_2\left(\frac{1-\sigma}{\sigma}\right), a_4 = \frac{a_3}{a_2},$$

$$a_5 = \frac{n_p^2}{J}\left(1-\sigma\right) L_s, a_6 = \frac{f}{J}, b_1 = \frac{1}{\sigma L_s}, b_2 = \frac{n_p}{J}.$$

3. High gain flux observer for induction motor

This section is devoted to the synthesis of a high gain observer adapted to the observable nonlinear systems [9]. The IM model with velocity measurement belongs to this type of systems [10].

Let us consider the IM electric subsystem given in the following form:

$$\begin{cases} \dot{x} = f\left(x\right) + g\left(x\right) u \\ y = h\left(x\right) \end{cases} \qquad (3)$$

Such as:

$$x = \begin{pmatrix} I_{s\alpha} & I_{s\beta} & I_{rm\alpha} & I_{rm\beta} \end{pmatrix}^t, \quad u = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \end{bmatrix}^t$$

And

$$f\left(x\right) = \begin{bmatrix} -a_1 I_{s\alpha} + a_3 I_{rm\alpha} + a_4 \omega I_{rm\beta} \\ -a_1 I_{s\beta} - a_4 \omega I_{rm\alpha} + a_3 I_{rm\beta} \\ a_2 I_{s\alpha} - a_2 I_{rm\alpha} - \omega I_{rm\beta} \\ a_2 I_{s\beta} + \omega I_{rm\alpha} - a_2 I_{rm\beta} \end{bmatrix},$$

$$g\left(x\right) = \begin{bmatrix} b_1 & 0 & 0 & 0 \\ 0 & b_1 & 0 & 0 \end{bmatrix}^t, \quad h\left(x\right) = \begin{bmatrix} h_1 & h_2 \end{bmatrix}^t = \begin{bmatrix} I_{s\alpha} & I_{s\beta} \end{bmatrix}^t.$$

The proposed high gain observer is based on the search for a transformation $z=\Phi(x)$ such as the system (3) will be written in the following form [11]:

$$\begin{cases} \dot{z} = Az + \varphi\left(u, z\right) \\ y = Cz \end{cases} \qquad (4)$$

This is possible if on the one hand the system is observable and on the other hand if, locally there exists p integers such as:

$$\dim\left(z\right) = \dim\left(h_1, L_f h_1, ..., L_f^{\eta_1} h_1, ..., h_p, ..., L_f^{\eta_p} h_p\right) = n \qquad (5)$$

Then we obtain:

$$A = \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_p \end{bmatrix}; \quad A_k = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ \vdots & 0 & \ddots & 1 \\ 0 & \cdots & \cdots & 0 \end{bmatrix} \qquad (6)$$

$$C = \begin{bmatrix} C_1 & & \\ & \ddots & \\ & & C_p \end{bmatrix}; \quad C_k = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix} \qquad (7)$$

The high gain observer is defined by:

$$\begin{cases} \dot{\hat{z}} = A\hat{z} + \varphi\left(u, \hat{z}\right) + \Delta^{-1} K \left(y - \hat{y}\right) \\ \hat{y} = C\hat{z} \end{cases} \qquad (8)$$

Let μ be defined by: μ_1=1 and $\mu_{k+1}=\mu_k+\eta_{k+1}$ for k=1,…,p.

Now, we will make the following assumptions:

1. The function φ is globally Lipschitzian with respect to x, uniformly with respect to u.

   Let $K = \begin{bmatrix} K_1 & & \\ & \ddots & \\ & & K_p \end{bmatrix}$, be a matrix of adequate dimension such that, for each block K_i, the matrix (A_i-$K_i C_i$) has all its eigenvalues with strictly negative real part.

Assume that one can find two set of integers $\sigma=\{\sigma_1,\ldots,\sigma_n\}$ and $\delta=\{\delta_1,\ldots, \delta_p\}$ with $\delta_i>0$; i=1,…,p, such that:

2. $\sigma_{\mu k+1}=\sigma_{\mu k+m-1}+\delta_k$; k=1,…,p; m=1,…,η_k-1.
3. $\frac{\partial \varphi_i}{\partial x_i} \not\equiv 0 \Rightarrow \sigma_i \geq \sigma_j$; i=1,…,n; j=1,…,n; $j\neq\mu_k$; k=1,…,p.

Then the system (3) is observable for T small enough, [10], and we obtain:

$$\Delta = \begin{bmatrix} \Delta_1 & & \\ & \ddots & \\ & & \Delta_p \end{bmatrix}; \quad \Delta_k = \begin{bmatrix} T^{\delta_k} & & & 0 \\ & T^{2\delta_k} & & \\ & & \ddots & \\ 0 & & & T^{\eta_k \delta_k} \end{bmatrix} \qquad (9)$$

Thus the matrix K will have the following form:

$$K = \begin{bmatrix} k_1 & k_2 & 0 & 0 \\ 0 & 0 & k_3 & k_4 \end{bmatrix}^t \qquad (10)$$

By calculation of the coefficients σ_i and δ_i, we deduce the matrix Δ, which is given explicitly by:

$$\Delta = \begin{bmatrix} T & 0 & 0 & 0 \\ 0 & T^2 & 0 & 0 \\ 0 & 0 & T & 0 \\ 0 & 0 & 0 & T^2 \end{bmatrix} \qquad (11)$$

The estimate $\hat{x}$ of the state x can be obtained by $\hat{x} = \Phi^{-1}\left(\hat{z}\right)$. Sometimes, the function Φ^{-1} cannot be expressed in z; another means to ovoid this difficulty consists in writing the observer equation of the in function of x [12]. Thus, by taking account of the following equation:

$$\dot{z} = \left[\frac{\partial \Phi(x)}{\partial x} \right] \dot{x} \quad (12)$$

And if we pose vector z as follows:

$$z = \begin{pmatrix} z_1 & z_2 & z_3 & z_4 \end{pmatrix}^t = \begin{pmatrix} h_1 & L_f h_1 & h_2 & L_f h_2 \end{pmatrix}^t \quad (13)$$

We obtain the following transformation:

$$\begin{cases} z_1 = I_{s\alpha} \\ z_2 = -a_1 I_{s\alpha} + a_3 I_{rm\alpha} + a_4 \omega I_{rm\beta} \\ z_3 = I_{rm\beta} \\ z_4 = -a_1 I_{s\beta} - a_4 \omega I_{rm\alpha} + a_3 I_{rm\beta} \end{cases} \quad (14)$$

From (14), by calculating the jacobien of z, we find:

$$\left[\frac{\partial \Phi(x)}{\partial x} \right] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -a_1 & 0 & a_3 & a_4\omega \\ 0 & 0 & 0 & 1 \\ 0 & -a_1 & -a_4\omega & a_3 \end{bmatrix} \quad (15)$$

Thus, the high gain flux observer in the original coordinates will be written as follows:

$$\dot{\hat{x}} = f(\hat{x}) + g(\hat{x})u + \left[\frac{\partial \Phi(\hat{x})}{\partial \hat{x}} \right]^{-1} \Delta^{-1} K (y - \hat{y}) \quad (16)$$

It is easy to see that, this observer is an original copy of the model i.e. the system (3), $\dot{\hat{x}} = f(\hat{x}) + g(\hat{x})u$, plus a corrective term which is explicitly given, $\left(\frac{\partial \Phi(\hat{x})}{\partial \hat{x}} \right)^{-1} \Delta^{-1} K (y - \hat{y})$.

The matrix K is selected to ensure the stability of matrix A-KC, i.e., the eigenvalues with negative real part. This condition makes possible the error exponential convergence [9].

4. Field-oriented control

The principle of the FOC is to carry the IM driving characteristics to that of DC motor. This method is based on the electric variables transformation towards a reference frame which turns with the rotor flux vector. In this new reference mark, the rotor flux dynamics is maintained constant, the speed dynamics becomes linear and uncoupled. In general, two types of FOC are possible: on the one hand, the DFOC where the rotor flux amplitude and position are estimated and on the other hand, the indirect field-oriented control (IFOC) where only the rotor flux position is estimated [7], [8], [13]. In the Fig.1 we present the DFOC scheme of IM i.e. the rotor magnetizing current I_{rm} is controlled to an I_{rmref}. States nonmeasurable, such as the rotor magnetizing current, are reconstituted by the proposed observer.

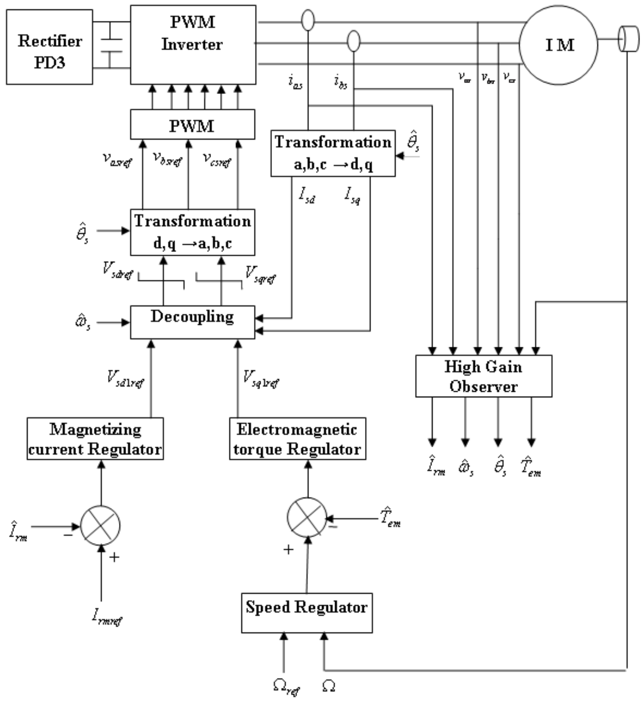


Fig. 1. DFOC scheme of IM using a high gain observer.

5. Simulation results

In this part, we present the simulation results of the system describes previously. This simulation was carried out by using software Matlab/Simulink.

a) Speed response test: The Fig.7 shows the results obtained in speed response with load torque. In this case, the IM is coupled with DC generator which feeds a resistive load. The load torque applied to the IM is proportional to the speed and admits for following expression: $T_l=0.013\Omega$. In Fig.7.a, we note that the IM speed follows perfectly its reference value in steady state, but a weak error of 15% is recorded in the transition state. The rotor magnetizing current observed I_{rm} and its reference are shown in Fig.7.b, we note that the rotor magnetizing current observed is equal to its reference. This proves that the observer converges quickly. In Fig.7.c,d,e,f a zoom on the stator currents and rotor magnetizing currents, corresponding at the inversion time of the rotor speed direction given in a stator-fixed frame (α, β), show a perfect agreement between actual values and their values given by the high gain observer.

b) Speed regulation test: The simulation results in case of speed regulation test are presented in Fig.8. When the load torque is applied with a value about 8N.m at *t=3s*, the decrease of the speed is lower than 8% (see Fig.8.a.). In Fig.8.b, the rotor magnetizing current I_{rm} is maintained equal to its reference value in spite of the load torque disturbance. The observer remains very powerful when the load torque is applied, the IM real states and the observed states are superimposed (see Fig.8.c,d,e,f).

c) Robustness test: To test the observer robustness with respect to the parametric variation, it was simulated a test in speed responses with load torque disturbance by assigning to T_r a variation about -10% in the observer. The obtained simulation results are given in Fig.9. One note that the speed response, given in Fig.9.a., does not undergo any sensitive alteration even to the rotor rotation inversion. On the other hand, the rotor magnetizing current I_{rm} deviates slightly from the reference in the speed transition state (see Fig.9.b). In Fig.9.c,d,e,f the reconstitution of the stator currents and rotor magnetizing currents by the observer remains very satisfactory. The observed currents and actual currents are identical. This confirms the robustness of the observer.

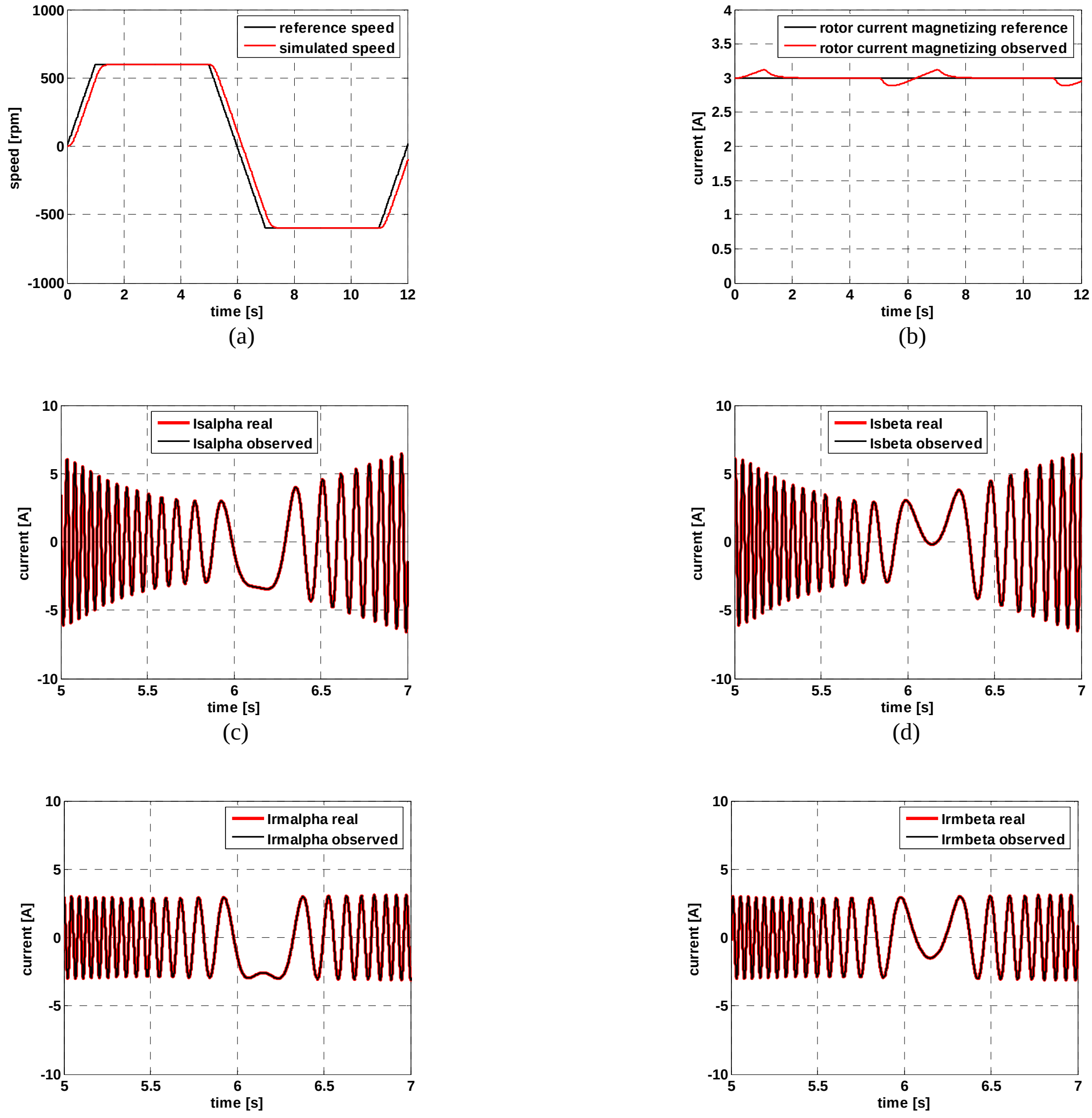
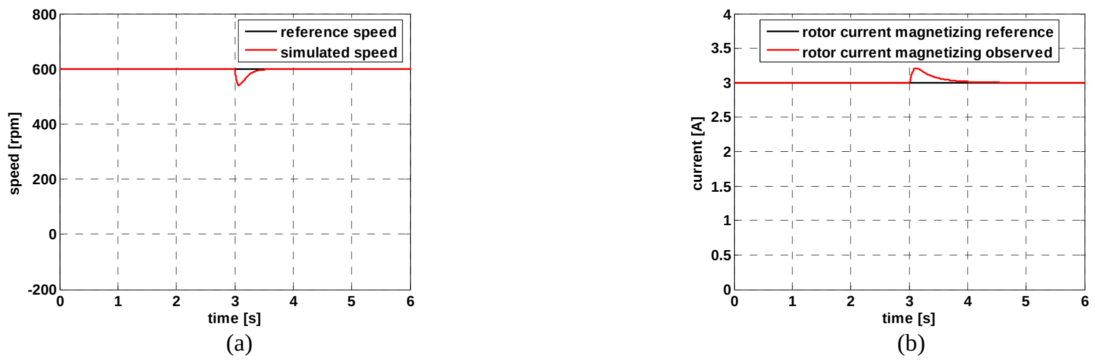


Fig. 7. Speed response test.



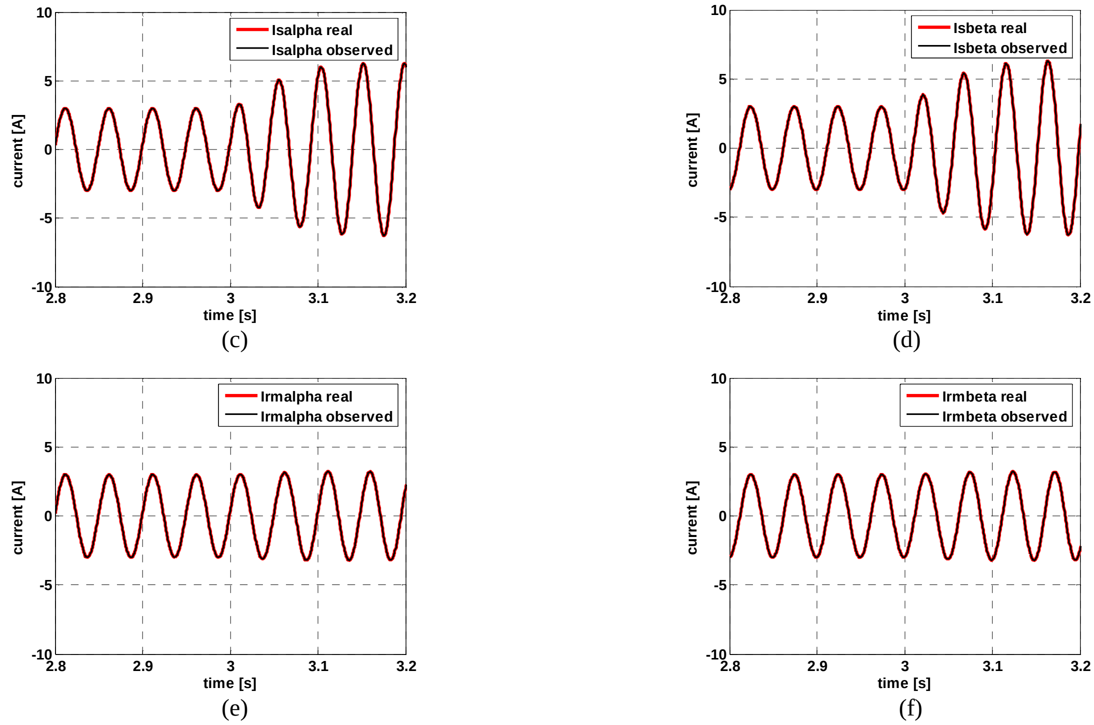


Fig. 8. Speed regulation test.

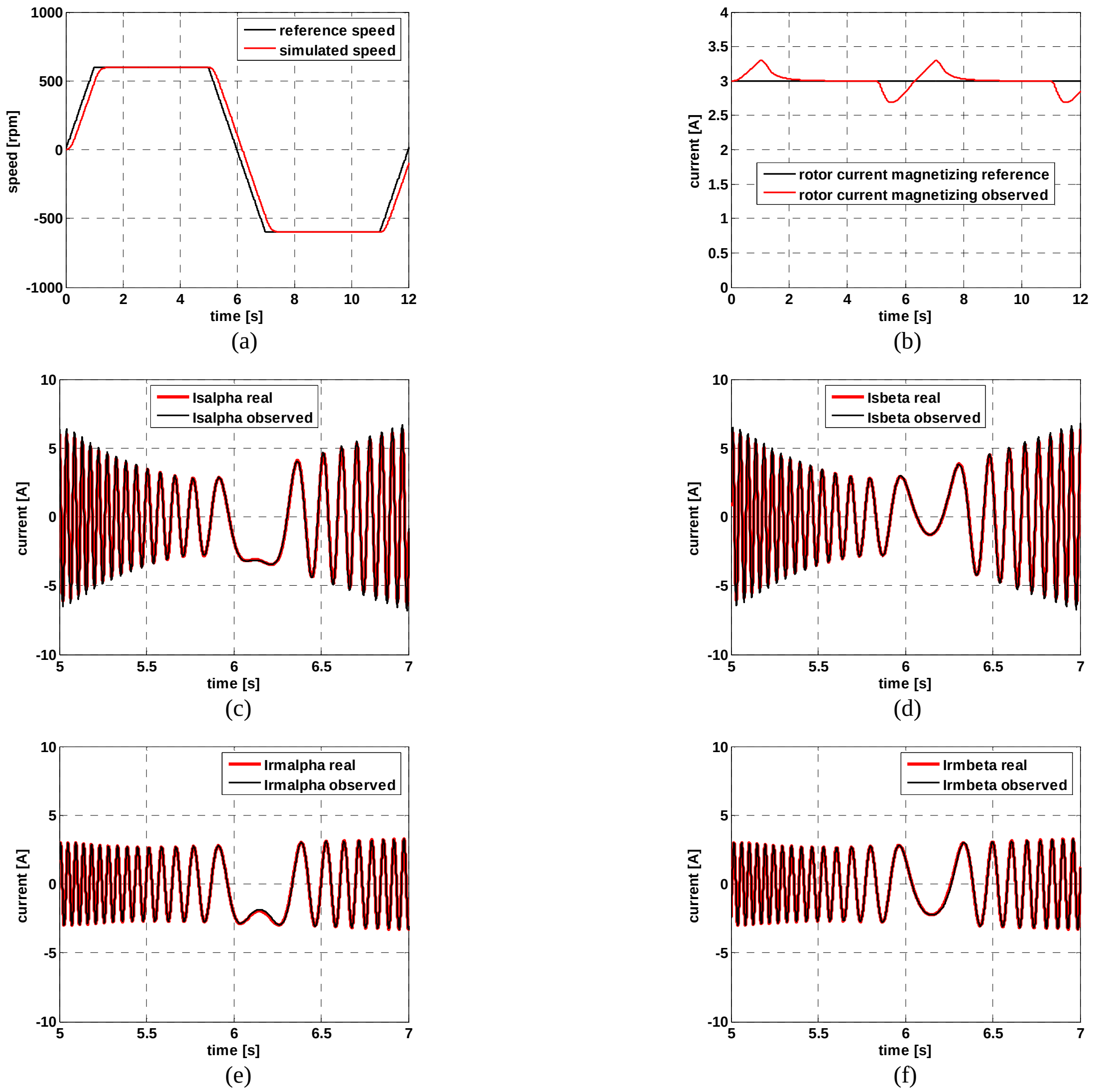


Fig. 9. Robustness test (-10% on T_r).

6. Experimental results

To valid the proposed high gain observer, an experiment has been set up. DSPACE card based on a Numeric-intensive Texas Instrument TMS320C31 floating point DSP is used. The control and observer's algorithms are transcribed in MATLAB/Simulink. The real time interface (RTI) is used to build real time code, and to download and execute this code on dSPACE hardware [14]. For the power unit, a voltage-source insulated-gate-bipolar-transistor-based inverter has been used to feed the induction motor. The current are measured by Hall Effect voltage transducers provided with forth order Butterworth low-pass filter to monitor only the fundamental signal. The filter cut-off frequency is regulated at f_c=500Hz.

The system used for the experimental checking, conceived to validate the control strategies of electric machines, is shown at Fig.10 [15].

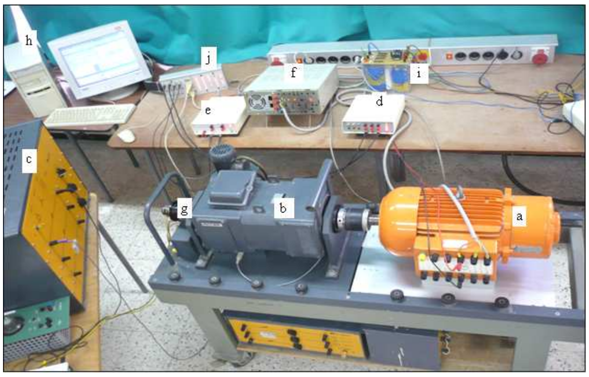


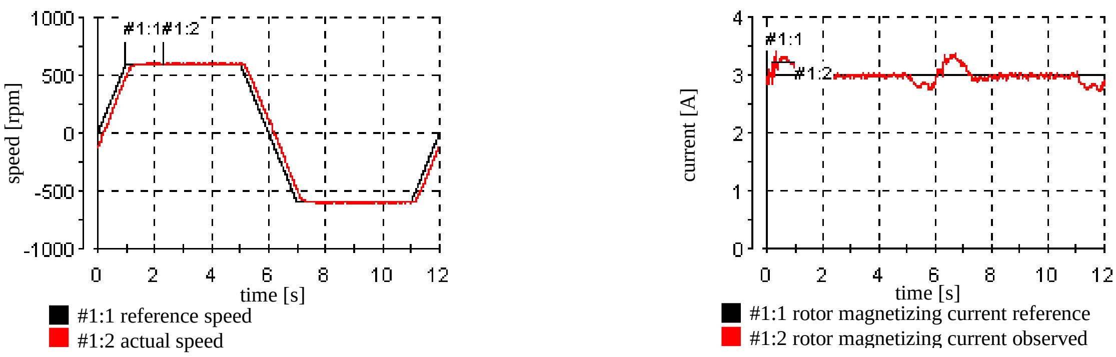
Fig. 10. Photo of the experimental system: (a: induction motor, (b,c) : system of load, (d,e): current and voltage transducers, f : IGBT based-inverter, g : incremental coder, h : PC including dSPACE, i: three-phase rectifier and capacitive filter, j: dSPACE external panel).

The presented experimental results were obtained under the same conditions as simulation. Thus, a comparison between the practical and theoretical results is possible. It is noted that some variable states are not given because they still inaccessible to measurement.

a) Speed response test: The Fig.11 shows the experimental results of speed response with application of load torque using DC generator feeding a resistive load. The obtained results are acceptable and identical with those obtained in simulation. The speed error is weak in the transition state, but becomes null in the steady state (see Fig.11.a,b). In Fig.11.c,d we note a superposition between the stator currents $I_{s\alpha}$ and $I_{s\beta}$ estimated by the observer and those given by the Hall effect current transducer, corresponding at the inversion time of the rotor speed direction, this shows that the observer gives correct and satisfactory results.

b) Speed regulation test: The Fig.12 presents the experimental results obtained in case of the speed regulation test. When the load torque is applied at *t=3s*, we note a weak speed drop. Then, it returns to its reference value after 100ms (see Fig.12.a). In Fig.12.b, the rotor magnetizing current observed I_{rm} undergoes a light increase when the load torque is applied but remains unimportant. In fig.12c.d, we note that, against application of the load torque, the stator currents $I_{s\alpha}$ and $I_{s\beta}$ are well reconstructed by the observer.

c) Robustness test: Fig.13 shows the experimental results of the speed response when the rotor time constant is varied about -10% in the observer. As it can see, the performances of the implemented algorithm remain the same one compared to the case without parametric variation. This confirms the robustness of proposed observer. Nevertheless, the verification of the observation error on the rotor magnetizing current I_{rm} is not possible since this last is not accessible to measurement.



(a) (b)

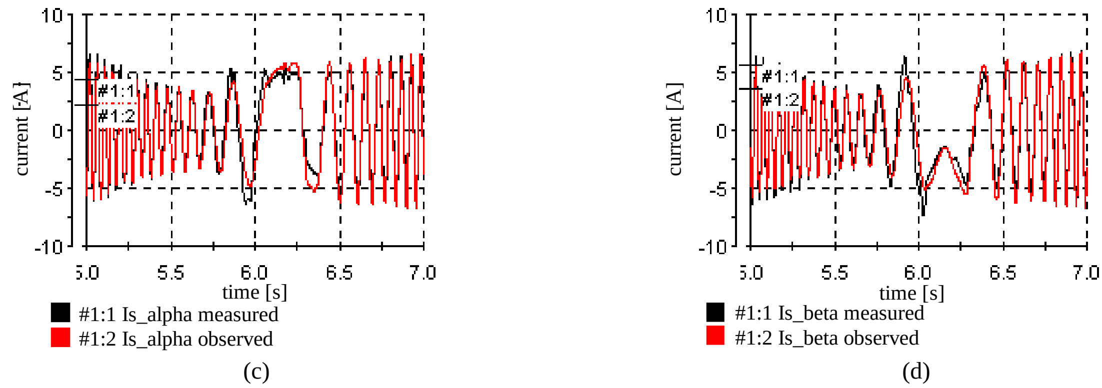


Fig. 11. Speed response test.

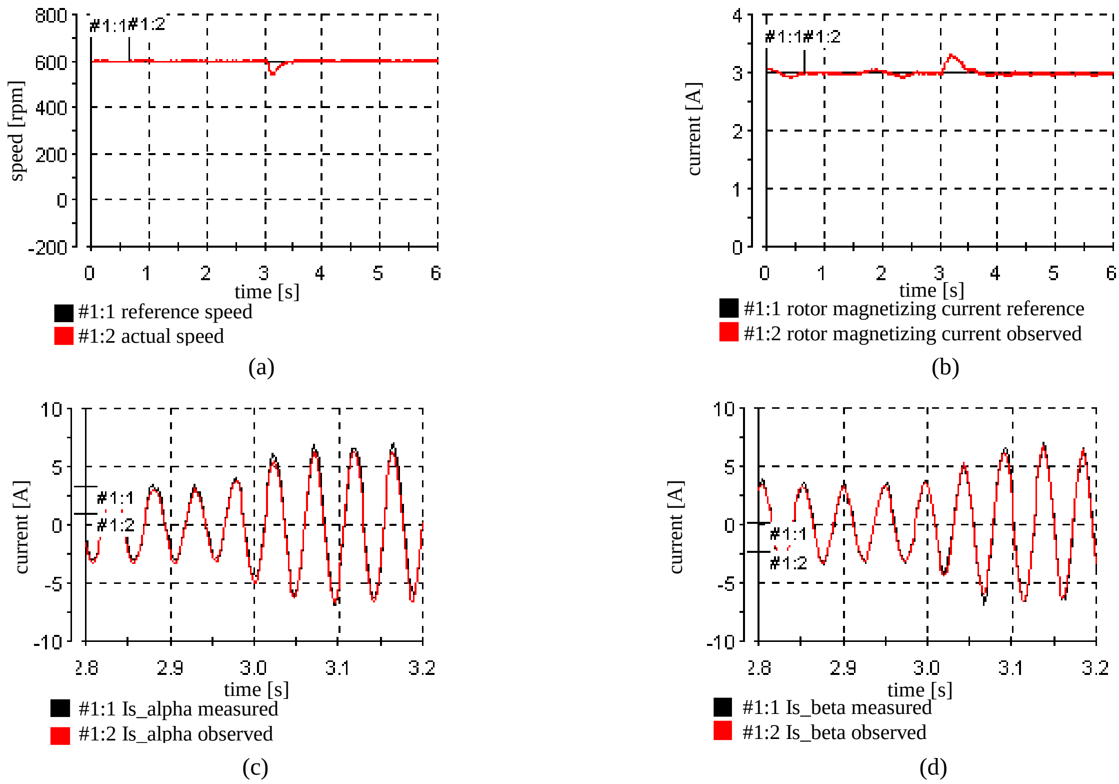
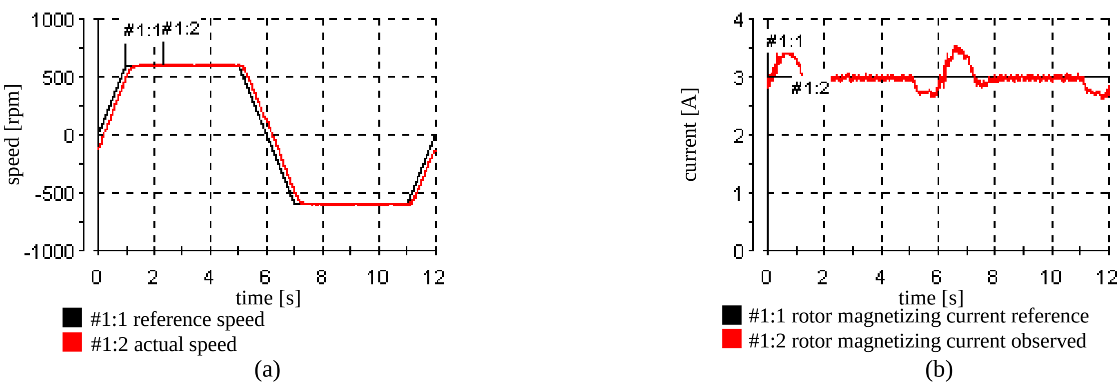
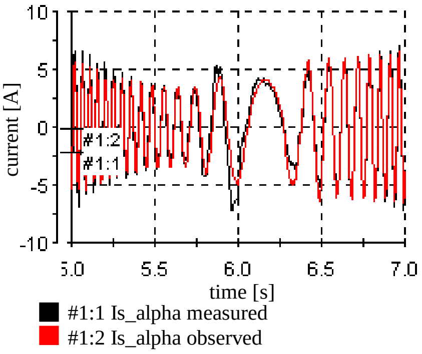
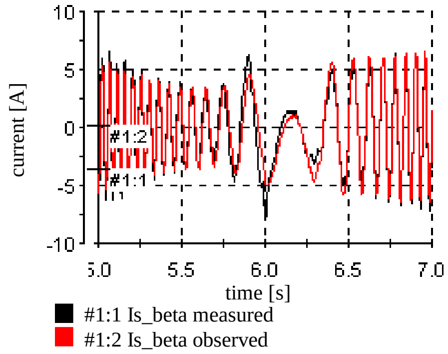


Fig. 12. Speed regulation test.





(c)



(d)

Fig. 13. Robustness test (-10% on T_r).

7. Conclusion

This work has been devoted to the real-time control of an IM where a high gain flux observer has been proposed and associated with the FOC. In order to establish a comparison between the theoretical and experiment, the conditions of the numerical simulations were taken the same as the used in the experiment. The obtained results demonstrate the convergence of the proposed observer to reconstitute the IM states and a good performance was obtained in presence of variations in the rotor time-constant.

The proposed observer has been implemented using dSPACE board jointed with floating point DSP, TMS320C31. The obtained experimental results are very satisfactory and validate those obtained by simulation.

Appendix

Induction motor parameters: Normal rated power: 3*KW*; Nominal speed: 1415*rpm*; Nominal voltage: 220*V*; Nominal intensity: 6.3*A*; p=2; R_s=1.46*Ohm*; L_s=0.28*H*; T_r=0.11*s*; σ=0.0747; J=0.043$Nm/rad/s^2$; f_v=0.0034*Nm/rad/s*; C_s=1*N.m*.

The regulators parameters used are:

- Electromagnetic torque regulator (PI): $K_{Cem}=140.88$, $\tau_{Cem}=0.014$.
- Magnetizing current regulator (PI): $K_{rm}=171.667$, $\tau_{rm}=0.296$.
- Speed regulator (IP): $K_{i\Omega}=5.957$, $K_{p\Omega}=1.017$.

The optimized values used of the observer gain are: $k_1=k_3=2$, $k_2=k_4=1$, T=0.1

References

1. Bodson M., Chiasson J., and Novotnak R.: *High Performance Induction Motor Control Via Input-Output Linearization*. In: IEEE Control Systems Magazine, 1994, Vol. 14, No. 4, p. 25-33.

2. Raumer T., Dion J., Dugard L.: *Applied Nonlinear control of an induction motor using Digital Signal Processing*. In: IEEE Transaction on Control Systems Technology, Vol. 2, No. 4, 1994, p. 327-335.

3. Chiasson, J.: *Nonlinear controllers for induction motors*. In: IFAC Conference System Structure and Control, Nantes, France 1995, p. 572-583.

4. Verghese, G. C., Sanders, S. R.: *Observers for flux estimation in induction machines*. In: IEEE Transaction on Industrial Electronics, Vol. 35, No. 1, 1988, p. 85-93.

5. Ho, E. Y. Y., Sen, P. C.: *Decoupling control of induction motor drives*. In: IEEE Transaction on Industry Application, Vol. 35, No. 2, 1988. p. 253-262.

6. Leonhard, W.: *Control of AC machines with the help of micro-electronics*. In: Third IFAC Symposium on Control in Power Electronics and Electrical Drives, Lausanne, 1983, p. 35-57.

7. Leonard. W.: *Control of Electrical Drives*. Springer Verlag, 2nd edition, 1996.

8. Canudas de Wit. C. : *Commande des moteurs asynchrones. (Control of asynchronous motors)* Volume 1 and 2. Hermes Edition, France, 2000.

9. Bornard, G., Hammouri, H.: *A high Gain Observer for a Class of Uniformly Observable Systems*. In: IEEE Proceeding of the 30th Conference on Decision and Control Brighton, England, December 1991, p. 1494-1496.

10. Ghanes, M.: *Observation et commande de la machine asynchrone sans capteur mécanique. (Observation and control of the asynchronous machine without mechanical sensor)* In : Ph.D. Thesis, University of Nantes, France, November 2005.

11. Gauthier, J. P., Hammouri, H., Othman, S.: *A Simple Observer for Nonlinear Systems Applications to Bioreactors*. In: IEEE Transaction on Automatic Control, Vol. 37, June 1992, p. 876-880.

12. Liu. F. : *Synthèse d'observateurs à entrées inconnues pour les systèmes non linéaires. (Synthesis of observers with unknown inputs for the nonlinear systems)* In: Ph.D. Thesis, University of Caen - Basse Normandie, France, December 2007.

13. Caron, J. P., Hautier, J.P. : *Modélisation et commande de la machine asynchrone. (Modeling and control of the asynchronous machine)* Technip Edition, France, 1995.

14. dSPACE documentation: *DS 1102 RTI and Implementation Guide*. January 2001.

15. Sediki, H., Djennoune, S., Boukais, B.: *On-line compensation of nonlinearity in PWM inverter feeding induction motor*. In: Journal of Electrical Engineering, Vol. 09, N° 01, 2009, p. 109-116.