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Full Length Research Paper

Implementation of a reduced-order Estimator for an Asynchronous Machine drive system

Implémentation d'un Estimateur d'ordre reduit pour le control d'une Machine Asynchrone

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Abstract:
A reduced-order discrete-time Extended Sliding Mode Observer (ESMO) is introduced, in this paper, for on-line estimation of rotor fluxes and rotor time constant. The satisfying simulations results on Matlab-Simulink© environment and experimental results carried out on a 1,8 kW induction machine demonstrate the excellent performance and high robustness of the proposed ESMO against parameter variations, modeling uncertainty and measurement noise. It is concluded that the implementation in real-time of this reduced-order ESMO in the industrial applications, compared with the full-order ESMO, permit on the one hand to overcome the heavy computational effort, complexity and hard tuning of the estimation algorithm and, on the other hand, to reduce the execution time of the observation with a good accuracy and considerable rapidity.

Keywords: Induction motors; Reduced-order extended sliding mode observers; Parameter estimation; Test bench.

Résumé :
Des algorithmes d'observation par modes glissants étendus d'ordre réduit ont introduits dans ce document, pour l'estimation en flux et constante de temps rotorique. De résultats de simulations réalisées sur Matlab-Simulink© et les résultats expérimentaux issus de tests sur une machine à induction de 1,8 kW, montrent l'excellente performance et une grande robustesse de l'ESMO d'ordre réduit proposé. Il est conclu que la mise en œuvre en temps réel de cet ordre réduit ESMO dans les applications industrielles, par rapport à l'ESMO d'ordre complet, ce qui permet d'une part de surmonter l'effort de calcul lourd, la complexité et le réglage dur de l'algorithme d'estimation et, d'autre part, de réduire le temps d'exécution de l'observation avec une bonne précision et une rapidité considérable.

Mots-clés : Moteur à induction; ESMO d'ordre réduit; Paramètre d'estimation; Banc de test.

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1. Introduction
The induction machine (IM) is widely used in industrial applications due to its reasonable cost, robust qualities and simple maintenance. However, the control of IM

drives is proved very difficult since the dynamic systems are nonlinear, the electric rotor variables (such as flux, torque) are not measurable and the physical parameters are often imprecisely known or variable. For instance, the rotor resistance drifts with the temperature of the rotor current frequency. One of the most significant developments in this area has been the Field-Oriented Control (FOC) [1-2] which allows an efficient control of the torque dynamics of an IM. However, a variation of the rotor resistance can induce a lack of field orientation. In order to achieve better dynamic performance, an on-line estimation of rotor fluxes and rotor resistance is necessary. In [3-4], a full-order Sliding Mode Observer (SMO) has been used with success for rotor fluxes estimation. This full-order SMO, built from the dynamic model of the IM by adding corrector gains with switching terms [5-7], is used to provide not only the un-measurable state variable estimation (rotor fluxes) but also the estimation of the measurable parameters (stator currents). However the determination of the measurable parameters estimation imposes some estimation algorithms very long and usually sophisticated with an increase of the computational volume. Therefore, in order to reduce the computation rate of the estimation algorithms, the currents estimation is not necessary since they are measured. So after a brief review of the IM model and the conventional sliding mode observer, the main aim of this study is to present the experimental results carried out on a 1.8 kW IM drive system [8] in order to show the effectiveness of the proposed Reduced-order Discrete-time Extended Sliding Mode Observer (RDESMO) method which permits to solve only the problem of the rotor fluxes and rotor time constant estimations.

2. Induction Motor Model and Full-Order Sliding Mode Observer

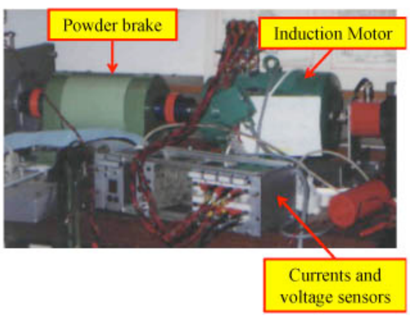

Figure 1. A global view of the test bench

This study, conducted in the Laboratory of applied Electronic (ESATIC Abidjan, Côte d'Ivoire) by a theoretical work, has been implemented and validated in real-time on a test bench (**Figure 1**); which is constructed and assembled in the research Centre of Electrical Engineering, National Institute of Applied Sciences (INSA) in Lyon-France. Globally the test bench is composed of an induction motor; a powder brake completed by current and voltage sensors. An engine bench description is basically detailed in the results section. By assuming that the saturation of the magnetic parts and the hysteresis phenomenon are neglected, the classical dynamic model of the induction motor in a (d, q) synchronous reference frame can be described by De Fornel and Louis [9]:

$$\begin{cases} V_{ds} = R_s.I_{ds} + \dfrac{d\Phi_{ds}}{dt} - \omega_s.\Phi_{qs} \\ V_{qs} = R_s.I_{qs} + \dfrac{d\Phi_{qs}}{dt} + \omega_s.\Phi_{ds} \end{cases} \qquad (1.a')$$

$$\begin{cases} \Phi_{ds} = \dfrac{L_m}{L_r}\Phi_{dr} + \sigma.L_s.I_{ds} \\ \Phi_{qs} = \dfrac{L_m}{L_r}\Phi_{qr} + \sigma.L_s.I_{qs} \end{cases} \qquad (1.a'')$$

$$\begin{bmatrix} \Phi_{ds} \\ \Phi_{dr} \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{dr} \end{bmatrix} \qquad (1.b')$$

and

$$\begin{bmatrix} \Phi_{qs} \\ \Phi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{qr} \end{bmatrix} \qquad (1.b'')$$

From Equations 1.a and 1.b, using as state variables the rotor fluxes (Φ_{dr}, Φ_{qr}) and the stator currents (I_{ds}, I_{qs}), the electrical dynamic model of the IM, completed with the output equation, can be represented as a time-varying fourth-order system given by:

$$\dot{x} = f(x) + g.u \quad ; y = [y_1 \quad y_2]^T = [I_{ds} \quad I_{qs}]^T$$

with $x = [\Phi_{dr}\ \Phi_{qr}\ I_{ds}\ I_{qs}]^T$, $u = [\ V_{ds}\ V_{qs}\ ]^T$

$$f(x) = \begin{bmatrix} -\sigma_r.\Phi_{dr} + \omega_{sl}.\Phi_{qr} + \sigma_r.L_m.I_{ds} \\ -\omega_{sl}.\Phi_{dr} - \sigma_r.\Phi_{qr} + \sigma_r.L_m.I_{qs} \\ \sigma_r.\beta.\Phi_{dr} + \beta.\omega_r.\Phi_{qr} - \lambda.I_{ds} + \omega_s.I_{qs} \\ -\beta.\omega_r.\Phi_{dr} + \beta.\sigma_r.\Phi_{qr} - \omega_s.I_{ds} - \lambda.I_{qs} \end{bmatrix}; g = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \dfrac{1}{\sigma.L_s} & 0 \\ 0 & \dfrac{1}{\sigma.L_s} \end{bmatrix} \qquad (2)$$

$$\sigma_r = \frac{1}{T_r}; \quad \lambda = \lambda(\sigma_r) = \frac{1}{\sigma}\left(\frac{1}{T_s} + (1-\sigma).\sigma_r\right); \quad \beta = \frac{1-\sigma}{\sigma.L_m} \quad ; \quad \sigma = 1 - \frac{L_m^2}{L_s.L_r}$$

λ, σ and β are parameters used to simplify the equations. Moreover, by choosing a rotating reference frame (d, q) so that the direction of axe d is always coincident with the direction of the rotor flux representative vector (field orientation), it is well known that this rotor field orientation in a rotating synchronous reference frame realizes:

$$\Phi_{dr} = \Phi_r = \text{Constant and } \Phi_{qr} = 0 \tag{3}$$

Assume that among the state variable, only the stator currents noted z_1, z_2 are measurable.

Denote $\hat{x}_1$ and $\hat{x}_2$ the estimates of the fluxes Φ_{dr} and Φ_{qr}. Consider that $\hat{z}_1$ and $\hat{z}_2$ are the estimates of the stator currents I_{ds} and I_{qs}. The classical full-order sliding mode observer is a copy of the model (Equations 2) by adding corrector gains with switching terms [4]:

$$\begin{cases} \dot{\hat{x}}_1 = -\sigma_r.\hat{x}_1 + \omega_{sl}.\hat{x}_2 + \sigma_r.L_m.z_1 + \Gamma_1.I_s \\ \dot{\hat{x}}_2 = -\omega_{sl}.\hat{x}_1 - \sigma_r.\hat{x}_2 + \sigma_r.L_m.z_2 + \Gamma_2.I_s \\ \dot{\hat{z}}_1 = \beta.\sigma_r.\hat{x}_1 + \beta.\omega_r.\hat{x}_2 - \lambda.z_1 + \omega_s.z_2 + \frac{1}{\sigma.L_s}V_{ds} + \Lambda_1.I_s \\ \dot{\hat{z}}_2 = -\beta.\omega_r.\hat{x}_1 + \beta.\sigma_r.\hat{x}_2 - \omega_s.z_1 - \lambda.z_2 + \frac{1}{\sigma.L_s}V_{qs} + \Lambda_2.I_s \end{cases} \tag{4}$$

where Γ_1, Γ_2 and Λ_1, Λ_2 are the observer gains.

The switching "Is" that depends on the estimated currents, is given by:

$$I_s = \begin{bmatrix} \text{sign}(s_1) \\ \text{sign}(s_2) \end{bmatrix} \quad \text{with } S = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} \beta.\sigma_r & \beta.\omega_r \\ -\beta.\omega_r & \beta.\sigma_r \end{bmatrix} \begin{bmatrix} z_1 - \hat{z}_1 \\ z_2 - \hat{z}_2 \end{bmatrix} \tag{5}$$

Setting $\tilde{x} = x - \hat{x}$, $\tilde{z} = z - \hat{z}$, the estimation error dynamics is defined by:

$$\begin{cases} \dot{\tilde{x}}_1 = -\sigma_r.\tilde{x}_1 + \omega_{sl}.\tilde{x}_2 - \Gamma_1.I_s \\ \dot{\tilde{x}}_2 = -\omega_{sl}.\tilde{x}_1 - \sigma_r.\tilde{x}_2 - \Gamma_2.I_s \\ \dot{\tilde{z}}_1 = \beta.\sigma_r.\tilde{x}_1 + \beta.\omega_r.\tilde{x}_2 - \Lambda_1.I_s \\ \dot{\tilde{z}}_2 = -\beta.\omega_r.\tilde{x}_1 + \beta.\sigma_r.\tilde{x}_2 - \Lambda_2.I_s \end{cases}$$

The conditions for convergence is verified by chosen the observer gain matrices (Equations 6) where **q** and **n** are two positive adjusting parameters:

$$\begin{bmatrix} \Lambda_1 \\ \Lambda_2 \end{bmatrix} = \begin{bmatrix} \beta.\sigma_r & \beta.\omega_r \\ -\beta.\omega_r & \beta.\sigma_r \end{bmatrix} .\Delta \quad ; \quad \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \end{bmatrix} = \begin{bmatrix} q-\sigma_r & \omega_{sl} \\ -\omega_{sl} & q-\sigma_r \end{bmatrix} .\Delta \, ; \; \Delta = \begin{bmatrix} n & 0 \\ 0 & n \end{bmatrix} \tag{6}$$

3. Reduced-order Discrete-Time Extended Sliding Mode Observer

As previously underline, a variation of the rotor resistance can induce performance degradation of the system. Also the stator currents are measurable therefore their on-line estimation is not necessary. Thus a Reduced-order Extended Sliding Mode Observer (RESMO) is introduced. In order to estimate the rotor flux and rotor time constant ($\sigma_r = 1/T_r = R_r/L_r$) variations, a three-dimensional state vector defined by $X_r = [\Phi_{dr} \quad \Phi_{qr} \quad \sigma_r]$ T = $[x_1 \quad x_2 \quad x_3]^T$ has been introduced. σ_r is assumed to be constant during a sampling period: $\frac{d\sigma_r}{dt} = 0$.

The corresponding reduced-order extended state space equation becomes Equation (7).

$$\begin{cases} \dot{x}_1 = x_3.L_m.I_{ds} - x_3.x_1 + \omega_{sl}.x_2 \\ \dot{x}_2 = x_3.L_m.I_{qs} - \omega_{sl}.x_1 - x_3.x_2 \\ \dot{x}_3 = 0 \end{cases} \tag{7}$$

The fact that the state vector only consists of the rotor flux and resistance offers an advantage namely the reduction of the computational volume and complexity. Thus the rotor flux and resistance can be easily and rapidly estimated.

Denote $\hat{x}_1$, $\hat{x}_2$ and $\hat{x}_3$ the estimates of the fluxes and rotor time constant. The proposed RESMO (Equation8) is a copy of the model (Equation 7) by adding corrector gains with switching terms:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_3.L_m.I_{ds} - \hat{x}_3.\hat{x}_1 + \omega_{sl}.\hat{x}_2 + \Gamma_1.I_{sr} \\ \dot{\hat{x}}_2 = \hat{x}_3.L_m.I_{qs} - \omega_{sl}.\hat{x}_1 - \hat{x}_3.\hat{x}_2 + \Gamma_2.I_{sr} \\ \dot{\hat{x}}_3 = \Gamma_3.I_{sr} \end{cases} \tag{8}$$

where Γ_1 and Γ_2 are the observer gains defined as in Equations 6.

The switching "I_{sr}" is in the form as described in Equations (9) where $\tilde{Z}_r$ is a function depending on the measures of stator currents, voltages and speed.

$$I_{sr} = \begin{bmatrix} \mathrm{sign}(s_1) \\ \mathrm{sign}(s_2) \end{bmatrix} \quad \text{with } S = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = M.\tilde{Z}_r \quad \text{and} \quad M = \begin{bmatrix} \beta.\sigma_r & \beta.\omega_r \\ -\beta.\omega_r & \beta.\sigma_r \end{bmatrix}^{-1} \tag{9}$$

In order to determine the observer gain matrix Γ_3, it can be supposed that the observation errors of the fluxes converge to zero. The estimation error dynamics of the fluxes $\tilde{x}_i = x_i - \hat{x}_i = 0$ (i=1, 2) are then given by:

$$0 = -\tilde{x}_3.\hat{x}_1 + \hat{x}_3.\tilde{x}_1 + \omega_{sl}.\tilde{x}_2 + L_m.I_{ds}.\tilde{x}_3 - \Gamma_1.I_{sr}$$
$$0 = -\omega_{sl}.\tilde{x}_1 - \tilde{x}_3.\hat{x}_2 + \hat{x}_3.\tilde{x}_2 + L_m.I_{qs}.\tilde{x}_3 - \Gamma_2.I_{sr}$$

$$\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = \frac{1}{q}.\begin{bmatrix} L_m.I_{ds} - \hat{x}_1 \\ L_m.I_{qs} - \hat{x}_2 \end{bmatrix}.\tilde{x}_3$$

The estimation error dynamics of the rotor time constant is given by Equation (10):

By replacing the expressions of Γ_1 and Γ_2, we obtain:

$$\tilde{x}_3 = -\Gamma_3.I_{sr} = -\Gamma_3.\Delta^{-1}\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = -\Gamma_3.\Delta^{-1}.\frac{1}{q}.\begin{bmatrix} L_m.I_{ds} - \hat{x}_1 \\ L_m.I_{qs} - \hat{x}_2 \end{bmatrix}.\tilde{x}_3 \tag{10}$$

We can see that this error dynamics is locally and exponentially stable by chosen:

$$\Gamma_3. = m.q.\begin{bmatrix} L_m.I_{ds} - \hat{x}_1 \\ L_m.I_{qs} - \hat{x}_2 \end{bmatrix}^T.\Delta \tag{11}$$

with $m > 0$.

The parameter *m* is adjusted with respect to rotor time constant estimation. In order to implement the RESMO algorithm in a DSP for real-time applications, the corresponding three-dimension state space equation defined in Equation (7) must be discretized using Euler approximation (2nd order) proposed in [10]. Thus the new discrete-time varying model represented by a function depending on the stator current is given by:

$$\begin{cases} x(k+1) = x(k) + T_e.J_1\big(x(k), v(k)\big) + \dfrac{T_e^2}{2!}.J_2\big(x(k), v(k)\big) \\ y(k) = x(k) \end{cases} \tag{12}$$

where

$$x(k) = \begin{bmatrix} \Phi_{dr}(k) & \Phi_{qr}(k) & \sigma_r(k) \end{bmatrix}^T \quad , \quad v(k) = \begin{bmatrix} I_{ds}(k) & I_{qs}(k) \end{bmatrix}^T$$

$$J_1\left(x(k),v(k)\right)=\begin{bmatrix}-\sigma_r(k).\Phi_{dr}(k)+\omega_{sl}(k).\Phi_{qr}(k)+\sigma_r(k).L_m.I_{ds}(k)\\-\omega_{sl}(k).\Phi_{dr}(k)-\sigma_r(k).\Phi_{qr}(k)+\sigma_r(k).L_m.I_{qs}(k)\\0\end{bmatrix};$$

$$J_2\left(x(k),v(k)\right)=\begin{bmatrix}\left(\sigma_r^2(k)-\omega_{sl}^2(k)\right).\Phi_{dr}(k)-2.\omega_{sl}(k).\sigma_r(k).\Phi_{qr}(k)\\ \qquad -\sigma_r^2(k).L_m.I_{ds}(k)+\sigma_r(k).L_m.\omega_{sl}(k).I_{qs}(k)\\2.\omega_{sl}(k).\sigma_r(k).\Phi_{dr}(k)+\left(\sigma_r^2(k)-\omega_{sl}^2(k)\right).\Phi_{qr}(k)\\ \qquad -\sigma_r(k).L_m.\omega_{sl}(k).I_{ds}(k)-\sigma_r^2(k).L_m.I_{qs}(k)\\0\end{bmatrix}$$

where k means the k^{th} sampling time, i.e. $t=k.T_e$ with T_e the adequate sampling period chosen without failing the stability and the accuracy of the discrete-time model.

The proposed RDESMO can be defined by the following equation:

$$\hat{x}(k+1)=\hat{x}(k)+T_e.J_1\left(\hat{x}(k),v(k)\right)+\frac{T_e^2}{2!}.J_2\left(\hat{x}(k),v(k)\right)+G(k).I_{sr}(k) \tag{13}$$

where the prediction vector is :

$$\breve{x}(k+1)=\hat{x}(k)+T_e.J_1\left(\hat{x}(k),v(k)\right)+\frac{T_e^2}{2!}.J_2\left(\hat{x}(k),v(k)\right)$$

with $\breve{x}(k)=\left[\breve{\Phi}_{dr}(k)\quad \breve{\Phi}_{qr}(k)\quad \breve{\sigma}_r(k)\right]^T$

The switching vector $I_{sr}(k)$, deduced from the continuous case given by Equation (9), can be written as :

$$I_{sr}(k)=\begin{bmatrix}\text{sign}(s_1(k))\\ \text{sign}(s_2(k))\end{bmatrix}\ \text{ with }\ S=\begin{bmatrix}s_1(k)\\ s_2(k)\end{bmatrix}=T_e.M(k).\widetilde{Z}(k+1) \tag{14}$$

Where
$$M(k)=\begin{pmatrix}-\hat{\sigma}_r(k)+\frac{T_e}{2}(\hat{\sigma}_r^2(k)-\omega_{sl}^2(k)) & \omega_{sl}(k)-T_e.\hat{\sigma}_r(k).\omega_{sl}(k)\\ -\omega_{sl}(k)+T_e.\hat{\sigma}_r(k).\omega_{sl}(k) & \hat{\sigma}_r(k)+\frac{T_e}{2}(\hat{\sigma}_r^2(k)-\omega_{sl}^2(k))\end{pmatrix}\ ;\ \widetilde{z}(k+1)=\begin{pmatrix}z_{rd}(k+1)-\hat{z}_{rd}(k+1)\\ z_{rq}(k+1)-\hat{z}_{rq}(k+1)\end{pmatrix}$$

By setting

$z_{rd}(k+1)=\Phi_{dr}(k+1)-\Phi_{dr}(k)-T_e.\omega_s(k).\Phi_{qr}(k)$

and $z_{rq}(k+1)=\Phi_{qr}(k+1)-\Phi_{qr}(k)+T_e.\omega_s(k).\Phi_{dr}(k)$,

from the electrical Equations (1a') and (1a''), an approximate discrete-time relation of the fluxes is given by Equations (15):

$$\begin{cases}z_{rd}(k+1)=\frac{T_e.L_r}{L_m}\left[V_{ds}(k)-R_s.I_{ds}(k)\right]-\frac{\sigma.L_s.L_r}{L_m}\left[I_{ds}(k+1)-I_{ds}(k)-T_e.\omega_s(k).I_{qs}(k)\right]\\ z_{rq}(k+1)=\frac{T_e.L_r}{L_m}\left[V_{qs}(k)-R_s.I_{qs}(k)\right]-\frac{\sigma.L_s.L_r}{L_m}\left[I_{qs}(k+1)-I_{qs}(k)+T_e.\omega_s(k).I_{ds}(k)\right]\end{cases}$$

and

$$\begin{pmatrix}\hat{z}_{rd}(k+1)\\ \hat{z}_{rq}(k+1)\end{pmatrix}=\begin{pmatrix}\breve{\Phi}_{dr}(k+1)-\hat{\Phi}_{dr}(k)-T_e.\omega_s(k).\hat{\Phi}_{qr}(k)\\ \breve{\Phi}_{qr}(k+1)-\hat{\Phi}_{qr}(k)+Te.\omega_s(k).\hat{\Phi}_{dr}(k)\end{pmatrix} \tag{15}$$

The proposed gain matrix representation G (k), deduced from the continuous case given by Equations (6) and (11), can be defined as follows (discrete-time approach):

$$G_r(k)=T_e.\begin{pmatrix}\Gamma_1(k)\\ \Gamma_2(k)\\ \Gamma_3(k)\end{pmatrix}=\begin{pmatrix} q-T_e.\hat{\sigma}_r(k) & T_e.\omega_{sl}(k)\\ -T_e.\omega_{sl}(k) & q-T_e.\hat{\sigma}_r(k)\\ T_e.(m.L_m.I_{ds}(k)-\hat{\Phi}_{dr}(k)) & T_e.(m.L_m.I_{qs}(k)-\hat{\Phi}_{qr}(k))\end{pmatrix}\Delta \quad (16)$$

Finally, from the expressions (16), it can be seen that there are three positive adjusting gains: *q, n* and *m* which play a critical role in the stability and the velocity of the observer convergence. These three adjusting parameters must be chosen so that the reduced observer satisfies robustness properties, global or local stability, good accuracy and considerable rapidity. Once the fluxes are estimated, it is easy to deduce the estimated torque defined by Equation (17):

$$\hat{C}_{em}(k)=p.\frac{L_m}{L_r}\left(\hat{\Phi}_{dr}(k).I_{qs}(k)-\hat{\Phi}_{qr}(k).I_{ds}(k)\right) \quad (17)$$

4. Simulation and experimental results

In order to verify the feasibility of the proposed RDESMO, the simulation on SIMULINK from Mathwork has been carried out for a 1.8 kW induction motor controlled with a field oriented vector strategy (**Figure 2**).

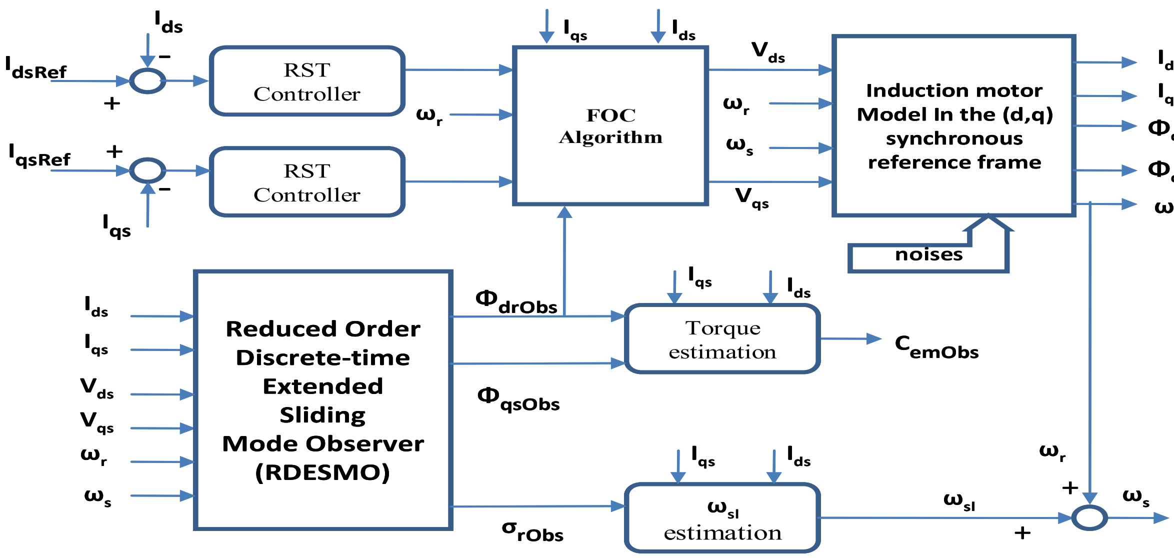

Figure 2. Simulation scheme

The nominal parameters of the induction motor are given in the **Table 1**.

Table I. Nominal parameters of the Induction motor

P_{mn} = 1.8 kW	U_n = 220 / 380 V	I_n = 20.8 / 12 A	p = 2
Fn = 50 Hz	Ω_n = 1420 rpm	J_n = 0.15 kg.N./m^2	f_n = 0.05 N.m.s/rad
R_{sn} = 5.7 Ω	R_{rn} = 1.475 Ω	L_{sn} = 0.1766 H	L_{rn} = 0.1262 H
L_{fn} = 0.0504 H	L_{mn} = 0.1262 H		

The RDESMO is implanted in a S_function using C language. In order to evaluate its performances and effectiveness, the comparisons between the observed state variables and the simulated ones have been realized for several operating conditions with the presence of about 20 % noise on the simulated currents.

Thus, using a sampling period T_e = 1 ms, the simulations are obtained at first in the nominal case with the nominal parameters of the IM (**Table I**) used to realize vector control orientation and then, in the second case, with 50 % variation of the nominal rotor time constant (σ_r = 1.5σ_{rn}) in order to verify the rotor time constant tracking and flux estimation. Two RST controllers are placed in the current loops I_{ds} and I_{qs} in order to realize the regulation of the flux and torque current respectively.

Figure 3 and **Figure 4** show the simulation results for a step variation of the currents reference (I_{dsRef} and I_{qsRef}).

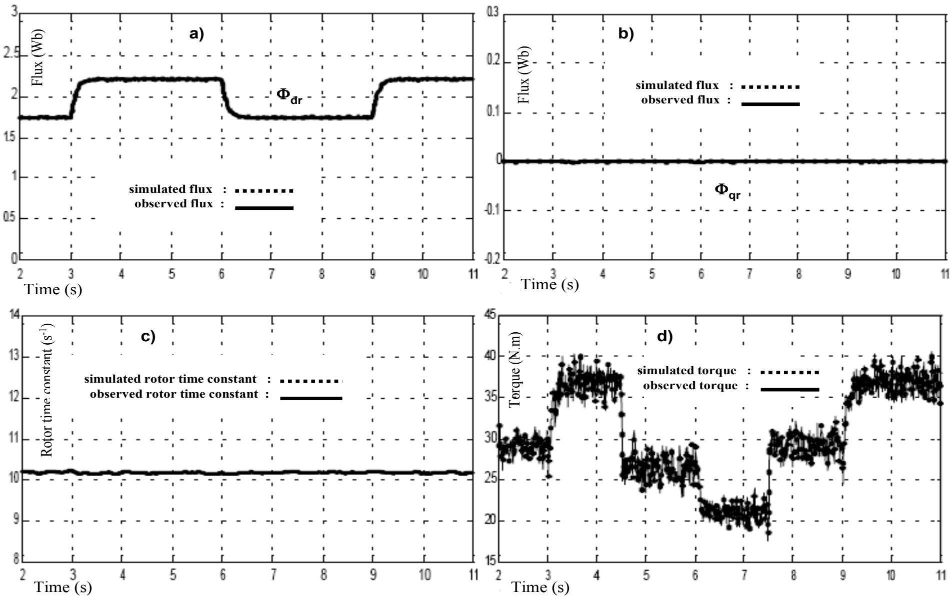

Figure 3. Nominal case ($R_r = R_{rn}$) with the presence of noises

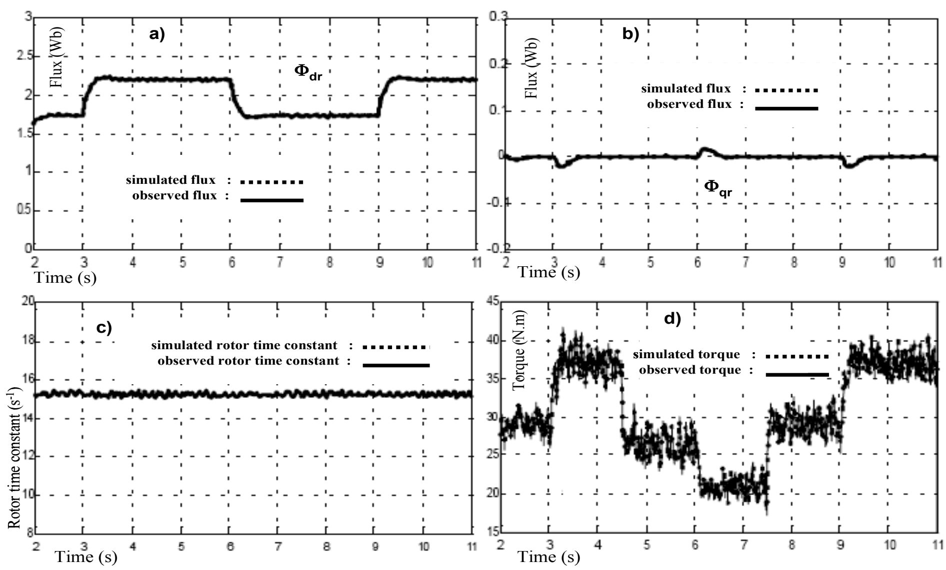

Figure 4. Non Nominal case ($R_r = 1.5R_{rn}$) with the presence of noises

In the case of rotor resistance variation where $R_r = 1.5R_{rn}$ (**Figure 4**), one can see perturbations on the flux orientation when the current I_{qs} varies in order to generate the required torque. However these waveforms remain acceptable and show that in both nominal (**Figure 3.a, 3.b, 3.c, 3.d**) and non-nominal cases (**Figure 4.a, 4.b, 4.c, 4.d**), the observed values of fluxes, rotor time constant and torque converge very well to their simulated values. Finally, the implementation in real-time of the proposed scheme is carried out on a testing bench. **Figure 5** shows the experimental set-up. It is composed of a 1.8 kW induction motor, a powder brake with load torque measurements, three LEM current sensors and a 2000 point incremental encoder. A PC-board and a Dspace1102 combined a TMS320C31/40MHz are used to implement PWM function, and control algorithms. Our proposed RDESMO has been implemented using Euler approximation. The PWM and the position measurement work at 10 kHz. Field-oriented control and RDESMO operate at 1 ms sampling period. A 15 kW three phase static inverter is supplied by a voltage source which provides about 0-400 V with current limitation of about 6 A.

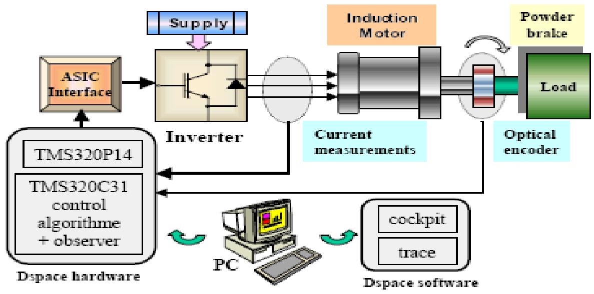

Figure 5. Experimental configuration diagram

Two kinds of tests have been performed (without and with load torque) in order to compare the behaviour of the reduced observer algorithm with respect to parameter variation:

- **Figure 6** shows the simulation and experimental results at a constant speed of 700 rpm, with a stator current I_{ds} = 4.3 A without load torque ($C_l \cong 0$ N.m)
- **Figure 7** illustrates the results where the motor speed is regulated at 1000 rpm with a load torque C_l=3 N.m and a stator current I_{ds} = 2.5 A.

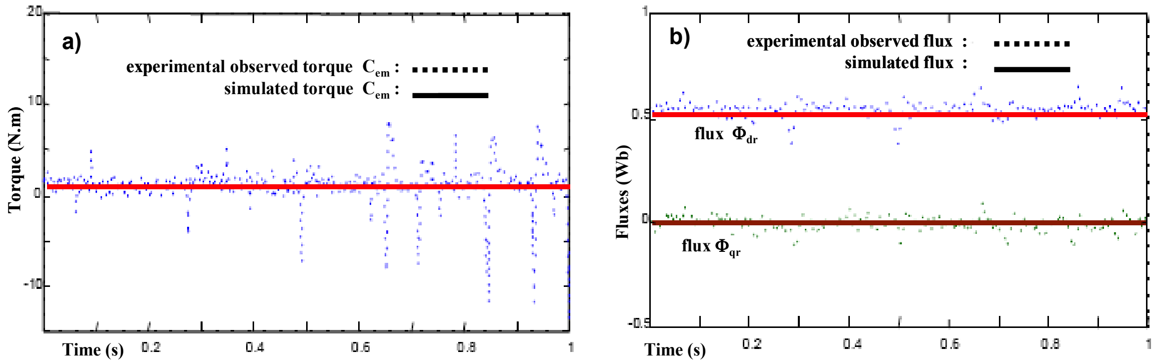

Figure 6. Results for regulating the motor speed to 700 rpm without load torque Cl ≅ 0 N.m

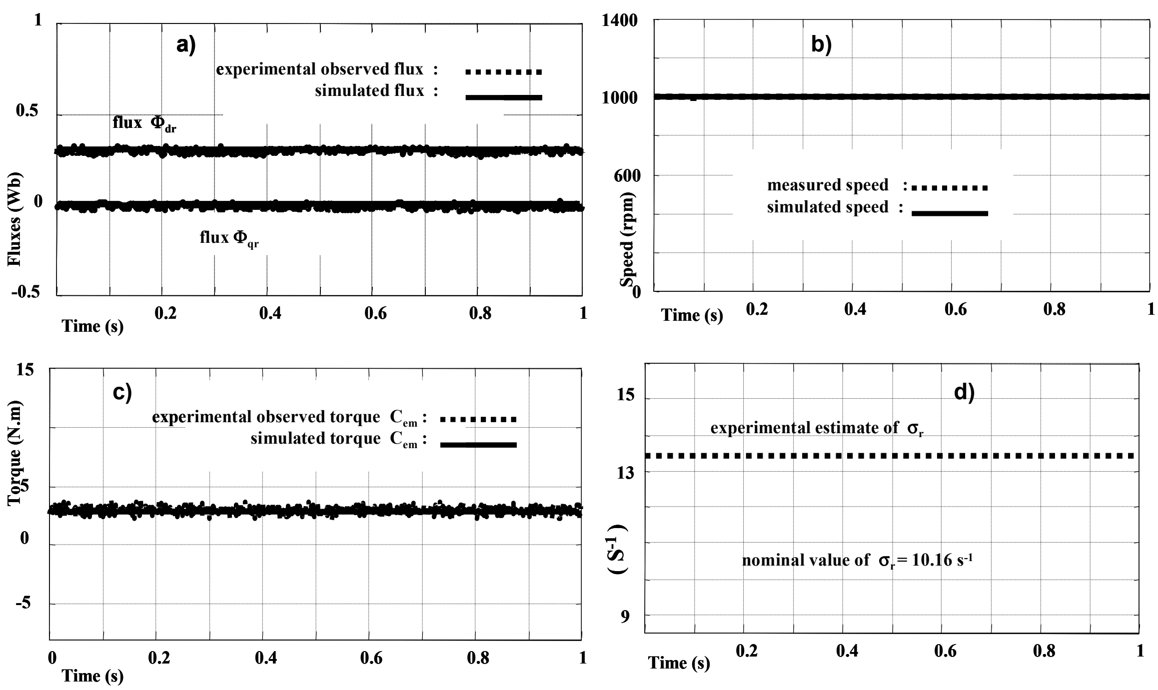

Figure 7. Results for regulating the motor speed to 1000 rpm with a load torque Cl ≅ 3 N.m

For each test, the comparative simulation and experimental results are presented. Better estimation performance yielded by the proposed reduced order sliding mode observer is obvious from the experimental results. Thus it can be seen that the experimental waves are quite similar to the simulation ones. The experimental observed fluxes (**Figure 6.b, 7.a**) indicates the good orientation (the flux Φ_{dr} is constant and Φ_{qr} converges to zero) which is due to a favorable rotor time constant estimation (**Figure 7.b**). The maximum relative error between experimental and simulated observed fluxes is less than 2%. Here the rotor time constant effectively drifts with the overheating of the IM because its estimated value is superior to the nominal one (σ_{rn} = 10.16 s^{-1}). The experimental estimated torque (**Figure 6.a, 7.c**) is in good agreement with the simulated value with a maximum gap around 0.2 N.m. The weak perturbations on the experimented fluxes or torque are probably tied to position noises and the inverter. The agreement between the experimental dynamic performance and the simulated ones is demonstrated.

5. Conclusion

A new approach for robust flux estimation en high-performance IM drive, namely, in sensorless control, was presented in this paper. It is based on a reduced order extended sliding mode observer algorithm and on an innovative methodology used in the state-space model discretization. The proposed RDESMO was successfully implemented for a direct rotor flux oriented IM drive. Very important and practical aspects and new improvements were introduced that strongly reduce the execution time of this new algorithm and simplify the tuning of gain matrices. In fact, the execution time of the RDESMO algorithm is about half of the full order extended SMO. The interesting simulation and experimental results obtained on the induction motor show the good performance and robustness of the RDESMO algorithm with respect to the rotor resistance variations, noises and load. The experimental results are in good agreement with the simulated value with a maximum relative error around 2% for fluxes and a maximum gap around 0.2 N.m for the torque. The main contribution of this work is that the well-known drawbacks of the full order extended SMO, like heavy computational effort for real-time applications; complexity and hard tuning of the algorithm are widely overcome using the proposed RDESMO.

Nomenclature

C_{em}, C_l	Electromagnetic and load torques (N.m)
I_{ds}, I_{qs}	Stationary frame (d, q)-axis stator currents (A)
I_{dr}, I_{qr}, I_{mr}	Stationary frame (d, q)-axis rotor currents and rotor magnetizing current (A)
p, J, f	p : pole pair No.; J : inertia ($kg.m^2$); f : friction coefficient (Nm.s/rad)
L_r, L_s, L_m, L_f	Rotor, stator, mutual and leakage inductances (H)
R_s, R_r	Stator and rotor referred resistance (Ω)
T_e , T_r , T_s	Sampling period, rotor and stator time constant: $T_r = L_r / R_r$; $T_s = L_s/R_s$, (s)
V_{ds}, V_{qs}	Stationary frame d- and q-axis stator voltage (V)
Φ_{dr}, Φ_{qr}, Φ_{ds}, Φ_{qs}	d-q components of rotor fluxes (Φ_{dr}, Φ_{qr}) and stator fluxes (Φ_{ds}, Φ_{qs}), (Wb)
ω_s, ω_r, ω_{sl}	Stator, rotor and slip pulsation (or speed), (rad/s)

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