Nonlinear Control of an Induction Motor Using a Reduced-Order Extended Sliding Mode Observer for Rotor Flux and Speed Sensorless Estimation

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Abstract

This article proposes an innovative strategy to the problem of non-linear estimation of states for electrical machine systems. This method allows the estimation of variables that are difficult to access or that are simply impossible to measure. Thus, as compared with a full-order sliding mode observer, in order to reduce the execution time of the estimation, a reduced-order discrete-time Extended sliding mode observer is proposed for on-line estimation of rotor flux, speed and rotor resistance in an induction motor using a robust feedback linearization control. Simulations results on Matlab-Simulink environment for a 1.8 kW induction motor are presented to prove the effectiveness and high robustness of the proposed nonlinear control and observer against modeling uncertainty and measurement noise.

Keywords: Robust Nonlinear Control, Induction Motor, Reduced-Order Extended Sliding Mode Observers, Parameter Estimation

1. Introduction

The induction motors (IM) become very popular for motion control applications due to its reasonable cost, simple and reliable construction. However, the control of IM is proved very difficult since the dynamic systems are non linear, the electric rotor variables are not usually measurable or the transducers are expensive (such as torque, speed, flux transducers) and the physical parameters are often imprecisely known or variable. For instance, the rotor resistance drifts with the temperature of the rotor current frequency.

This naturally structure of non-linear and multivariable state of IM models induces the use of the non-linear control methods and in particular the robust feedback linearization strategy [1-3] to permit a decoupling, assure a good dynamic performance and stability of the IM.

However, a variation of the rotor resistance can induce a state-space “coupling” which can induce a degradation of the system. In order to achieve better dynamic performance, an on-line estimation of rotor fluxes, speed and rotor resistance is necessary. An approach proposed in [4,5] to estimate with success the state variables in an IM is the use of the full-order Sliding Mode Observer (SMO). This latter, built from the dynamic model of the IM by adding corrector gains with switching terms, is used to provide not only the unmeasurable state variable estimation (rotor fluxes and speed) 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 accuracy and the computation rate of the estimation algorithms, the measured parameters estimation is not necessary.

Thus a Reduced-Order Discrete-Time Extended Sliding Mode Observer (RDESMO) for the IM is presented in this paper to solve only and specially the problem of the unmeasurable parameters estimation (rotor fluxes, speed and rotor time constant).

So after a brief review of the IM model, a robust input-output linearization and decoupling control of induction motor is presented in Section 2. A reduced-order
discrete-time Extended Sliding Mode Observer (ESMO) is developed in Section 3. Section 4 describes the simulation results carried out on a 1.8 kW IM drive system. Finally, conclusions are summarized in Section 5.

2. Induction Motor Model and Robust Feedback Control

By assuming that the saturation of the magnetic parts and the hysteresis phenomenon are neglected, the classical dynamic model of the IM in a \((d, q)\) synchronous reference frame can be described by [6]:

\[
\begin{align*}
V_{ds} &= R_s I_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} ; \\
V_{qs} &= R_s I_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} ; \\
\Phi_{ds} &= L_m \Phi_{ds} + \sigma_s I_{ds} \\
\Phi_{qs} &= L_m \Phi_{qs} + \sigma_s I_{qs}
\end{align*}
\]

The load mechanical equation is:

\[
\frac{J}{p} \frac{d\omega}{dt} + f \omega = C_m - C_r \quad \text{where} \quad C_m = p \frac{L_m}{L_r} (\Phi_{ds} I_{qs} - \Phi_{qs} I_{ds})
\]

The application of (1.a) to (1.c) returns a system of fifth-order non-linear differential equation, with as state variables the stator currents \((I_{ds}, I_{qs})\), the rotor fluxes \((\Phi_{ds}, \Phi_{qs})\) and the rotor pulsation \((\omega)\):

\[
x_c = f_c(x_c) + g_c u \quad \text{where} \quad x_c = [I_{ds}, I_{qs}, \Phi_{ds}, \Phi_{qs}, \omega] \; , \; u = [V_{ds}, V_{qs}]
\]

\[
f_c(x_c) = -\lambda I_{ds} + \omega_s I_{qs} + \sigma_s \beta \Phi_{qs} + \beta \omega_s \Phi_{qs} \\
\quad -\omega_s I_{qs} - \lambda I_{ds} + \beta \omega_s \Phi_{qs} + \beta \sigma_s \Phi_{qs} \\
\quad \sigma_s L_m I_{ds} - \sigma_s \Phi_{ds} + \omega_s \Phi_{qs} \\
\quad \sigma_s L_m I_{qs} - \sigma_s \Phi_{qs} + \omega_s \Phi_{ds} \\
\quad p^2 L_m \frac{L_m}{L_r} (\Phi_{qs} I_{ds} - \Phi_{ds} I_{qs}) - \frac{p}{J} C_r - \frac{f}{J} \omega
\]

\[
g_c = \begin{bmatrix}
\frac{1}{\sigma L_r} & 0 \\
0 & \frac{1}{\sigma L_s} \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]

\[
\sigma_s = \frac{1}{T_r} ; \quad \lambda = \lambda(\sigma_r) = \frac{1}{\sigma} \left( \frac{1}{T_r} (1 - \sigma) \right) ; \\
\beta = \frac{1 - \sigma}{\sigma L_m} ; \quad \sigma_r = 1 - \frac{L_m^2}{L_r L_s}
\]

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:

\[
\Phi_{ds} = \Phi_r = \text{Constant and } \Phi_{qs} = 0
\]

Thus the dynamic model of the IM, completed with the output equation, can be rewritten as:

\[
\dot{x} = f(x) + g u ; \quad y = [h_1(x) \; h_2(x)] = [\Phi_r \; \omega]
\]

\[
x = [I_{ds} \; I_{qs} \; \Phi_r \; \omega] \; , \; u = [V_{ds} \; V_{qs}]
\]

\[
f(x) = \begin{bmatrix}
-\lambda_1 I_{ds} + \omega_s I_{qs} + \sigma_1 \beta \Phi_{qs} + \beta \omega_s \Phi_{qs} \\
\quad -\omega_s I_{qs} - \lambda_1 I_{ds} + \beta \omega_s \Phi_{qs} + \beta \sigma_1 \Phi_{qs} \\
\quad \sigma_1 L_m I_{ds} - \sigma_1 \Phi_{ds} + \omega_s \Phi_{qs} \\
\quad \sigma_1 L_m I_{qs} - \sigma_1 \Phi_{qs} + \omega_s \Phi_{ds} \\
\quad p^2 L_m \frac{L_m}{L_r} (\Phi_{qs} I_{ds} - \Phi_{ds} I_{qs}) - \frac{p}{J} C_r - \frac{f}{J} \omega
\end{bmatrix}
\]

From the expressions (2) and (3), one can write:

\[
\begin{bmatrix}
\frac{d I_{ms}}{dt} = \sigma_r I_{ds} - \sigma_r I_{ms} \\
\sigma_r = \omega_1 \frac{I_{ms}}{I_{qs}} \\
C_{ms} = \frac{p L_m}{L_r} \Phi_r I_{qs}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{d I_{ms}}{dt} = \sigma_r I_{ds} - \sigma_r I_{ms} \\
\sigma_r = \omega_1 \frac{I_{ms}}{I_{qs}} \\
C_{ms} = \frac{p L_m}{L_r} \Phi_r I_{qs}
\end{bmatrix}
\]

This relation (5) shows that the dynamic model of the IM can be represented as a non-linear function of the rotor time constant. A variation of this parameter can induce, for the IM, a lack of field orientation, performance and stability. Thus, to preserve the reliability, robustness performance and stability of the system under parameters variation (in particular the rotor time constant variations) and disturbances, we can use a robust feedback linearization strategy to regulate the motor states.

As a matter of fact, we can see that the system (4) has relative degree \(r_1 = r_2 = 2\) and can be transformed into a linear and controllable system by chosen [7]:

- a suitable change of coordinates given by:
the system (2). Assume that among the state variable, the stator currents \( (I_{ds}, I_{q}) \) are measurable, therefore their on-line estimation is not necessary. Thus from the expression (2), in order to estimate only the rotor flux (\( \Phi_{dr}, \Phi_{dq} \)) and speed (\( \omega_r \)), a reduced dimensional state vector defined by \( X_r = [\Phi_{dr}, \Phi_{dq}, \omega_r] \) \( T = [x_1, x_2, x_3] \), \( T \) can be introduced. The corresponding reduced-order state space equation becomes:

\[
\dot{x}_r(t) = J_r (x_r(t), v(t))
\]

Where \( v(t) = [I_{ds}, I_{dq}] \) \( T \) is the new input.

\[
J_r (x_r(t), v(t)) = \begin{bmatrix}
-\sigma_r x_1 + \omega_d x_2 + \sigma_r I_{ds} + \Gamma_1 I_s \\
-\omega_d x_1 - \sigma_r x_2 + \sigma_r I_{dq} + \Gamma_2 I_s \\
p^2 \frac{L_m}{L_r} (I_{dq} - I_{ds}) - \frac{P}{J} C_r - \frac{f}{J} x_3 + \Gamma_3 I_s
\end{bmatrix}
\]

(7)

The fact that the state vector only consists of the rotor flux and speed offers an advantage namely the reduction of the computational volume and complexity. Thus the rotor flux and speed can be more easily and rapidly estimated. Denote \( \hat{x}_1, \hat{x}_2 \) and \( \hat{x}_3 \) the estimates of the fluxes \( \Phi_{dr}, \Phi_{dq} \) and \( \omega_r \). The Reduced-order SMO is a copy of the model (7) by adding corrector gains with switching terms:

\[
\dot{\hat{x}}_1 = -\sigma_r \hat{x}_1 + \omega_d \hat{x}_2 + \sigma_r I_{ds} + \Gamma_1 I_s \\
\dot{\hat{x}}_2 = -\omega_d \hat{x}_1 - \sigma_r \hat{x}_2 + \sigma_r I_{dq} + \Gamma_2 I_s \\
\dot{\hat{x}}_3 = p^2 \frac{L_m}{L_r} (\hat{I}_{dq} - \hat{I}_{ds}) - \frac{P}{J} C_r - \frac{f}{J} \hat{x}_3 + \Gamma_3 I_s
\]

(8)

where \( \Gamma_1, \Gamma_2 \) and \( \Gamma_3 \) are the observer gains. The switching “Is” is defined as

\[
I_s = \begin{bmatrix}
\text{sign}(\hat{x}_1) \\
\text{sign}(\hat{x}_2)
\end{bmatrix} ; \quad S = \begin{bmatrix}
\hat{x}_1 \\
\hat{x}_2
\end{bmatrix} = M \hat{Z}_r ;
\]

\[
M = \begin{bmatrix}
\beta \sigma_r & \beta \hat{x}_3 \\
-\beta \hat{x}_3 & \beta \sigma_r
\end{bmatrix}^{-1}
\]

(9)

where \( \hat{Z}_r \) is a function depending on the parameters measurements (stator currents, voltages…).

Setting \( \hat{x} = x - \hat{x} \), the estimation error dynamics is given by:

\[
\begin{align*}
\dot{\hat{x}}_1 &= -\sigma_r \hat{x}_1 + \omega_d \hat{x}_2 - \Gamma_1 I_s \\
\dot{\hat{x}}_2 &= -\omega_d \hat{x}_1 - \sigma_r \hat{x}_2 - \Gamma_2 I_s \\
\dot{\hat{x}}_3 &= p^2 \frac{L_m}{L_r} (\hat{x}_1 I_{dq} - \hat{x}_2 I_{ds}) - \frac{f}{J} \hat{x}_3 - \Gamma_3 I_s
\end{align*}
\]

(10)

With the following observer gain matrices given by the expression (11), the estimation error \([\hat{x}_1, \hat{x}_2, \hat{x}_3] \) con-
verges to zero.

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix} = \begin{bmatrix}
r - \sigma_r & \omega_q & 0 \\
-\omega_q & r - \sigma_r & 0 \\
p^2 \frac{L_m J_{\psi_q}}{L_r J} & -p^2 \frac{L_m J_{\psi_d}}{L_r J}
\end{bmatrix} \Delta; \quad \Delta = \begin{bmatrix}
n & 0 \\
0 & n
\end{bmatrix} \tag{11}
\]

where \( r \) and \( n \) are positive adjusting parameters which play a critical role in the stability and the velocity of the observer convergence.

### 3.2. Reduced-Order Extended Sliding Mode Observer

In order to estimate the rotor time constant, a reduced dimensional extended state vector defined by \( X_e = [\Phi_{\psi_d}, \Phi_{\psi_q}, \omega_r, \sigma_r]^T = [x_1, x_2, x_3, x_4]^T \) has been introduced with \( \sigma_r = R_r/L_r \). The corresponding reduced-order extended state space equation becomes:

\[
\dot{x}_{re}(t) = J_{re}(x_{re}(t), \nu(t)) \quad \text{where}
\]

\[
J_{re}(x(t), \nu(t)) = \begin{bmatrix}
-\dot{x}_1 + \omega_q x_2 + x_4 L_m J_d - \dot{x}_4 J_s \\
-\omega_q x_1 + x_4 L_m J_q \\
p^2 \frac{L_m J_{\psi_q}}{L_r J} (I_{\psi_q} x_1 - I_{\psi_d} x_2) - \frac{p}{J} C_r - \frac{f}{J} x_3 \\
\epsilon
\end{bmatrix}
\]

\[
(12)
\]

where \( \epsilon \) presents the slow variation of \( \sigma_r \). The proposed Reduced-order ESMO is:

\[
\begin{align*}
\dot{x}_1 &= -\dot{x}_4 + \dot{x}_1 + \omega_q \dot{x}_2 + \dot{x}_4 L_m J_d - \dot{x}_4 J_s + \Gamma_1 J_s \\
\dot{x}_2 &= \omega_q \dot{x}_1 - \dot{x}_4 - \dot{x}_2 + \dot{x}_4 L_m J_q + \Gamma_2 J_s \\
\dot{x}_3 &= p^2 \frac{L_m J_{\psi_q}}{L_r J} (I_{\psi_q} \dot{x}_1 - I_{\psi_d} \dot{x}_2) - \frac{p}{J} C_r - \frac{f}{J} \dot{x}_3 + \Gamma_3 J_s \\
\dot{x}_4 &= \epsilon + \Gamma_4 J_s
\end{align*}
\]

\[
(13)
\]

where is, \( \Gamma_1 \), \( \Gamma_2 \) and \( \Gamma_3 \) are respectively defined by (9) and (11).

To determine observer gain \( \Gamma_4 \), it can be supposed that the observation errors of the fluxes converge to zero. The estimation errors of the fluxes \( \dot{x}_i, \dot{x}_i, \ldots \) \((i = 1, 2)\) are then given by:

\[
\begin{align*}
0 &= -\dot{x}_4 + \dot{x}_1 + \omega_q \dot{x}_2 + L_m J_d \dot{x}_4 - \Gamma_1 J_s \\
0 &= -\omega_q \dot{x}_1 - \dot{x}_2 + \dot{x}_4 L_m J_q \dot{x}_4 - \Gamma_2 J_s
\end{align*}
\]

\[
(14)
\]

By replacing the expressions of 1 and 2 in (14), the estimation error dynamics of the rotor time constant is given by:

\[
\begin{align*}
\dot{x}_4 &= -\Gamma_4 J_s = -\Gamma_4 \Delta^{-1} \begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} = -\Gamma_4 \Delta^{-1} \begin{bmatrix}
L_m J_{\psi_d} \dot{x}_4 - \dot{x}_1 \\
L_m J_{\psi_q} \dot{x}_4 - \dot{x}_2
\end{bmatrix}
\end{align*}
\]

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

\[
\Gamma_4 = m \frac{L_m J_{\psi_d} \dot{x}_4 - \dot{x}_1}{L_m J_{\psi_q} \dot{x}_4 - \dot{x}_2} \quad \text{with} \quad m > 0
\]

The parameter \( m \) is adjusted with respect to rotor time constant estimation.

Finally, from the expressions (11) and (15), it can be seen that there are three positive adjusting gains: \( r, n \) 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.

In order to implement the reduced-order ESMO algorithm in a DSP for real-time applications, the corresponding reduced-dimension state space equation defined in (12) must be discretized using Euler approximation (1st order). Thus the new discrete-time varying model represented by a function depending on the stator current is given by:

\[
\begin{align*}
x_{re}(k + 1) &= x_{re}(k) + T_e L_m J_{\psi_q} (x_{re}(k)) = x_{re}(k) + T_e q(x_{re}(k), \nu(k)) \\
y_{re}(k) &= y_{re}(k)
\end{align*}
\]

with

\[
q(x_{re}(k), \nu(k)) = \begin{bmatrix}
-\sigma_r(k) \Phi_{\psi_d}(k) + \omega_q(k) \Phi_{\psi_q}(k) + \sigma_r(k) L_m J_d(k) \\
-\omega_q(k) \Phi_{\psi_d}(k) - \sigma_r(k) \Phi_{\psi_q}(k) + \sigma_r(k) L_m J_q(k) \\
p^2 \frac{L_m J_{\psi_q}}{L_r J} (I_{\psi_q}(k) \Phi_{\psi_d}(k) - I_{\psi_d}(k) \Phi_{\psi_q}(k)) - \frac{p}{J} C_r - \frac{f}{J} \omega_q(k) \\
0
\end{bmatrix}
\]

\[
(16)
\]

where \( k \) means the kth 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 RDESMMO can be defined by the following equation:

\[
\begin{align*}
\dot{\tilde{x}}_{re}(k + 1) &= \tilde{x}_{re}(k) + T_e q(\tilde{x}_{re}(k), \nu(k)) + G(k) I_s(k)
\end{align*}
\]

\[
(17)
\]

where the prediction vector is:

\[
\tilde{x}_{re}(k + 1) = \tilde{x}_{re}(k) + T_e q(\tilde{x}_{re}(k), \nu(k))
\]

with \( \tilde{x}_{re}(k) = \begin{bmatrix} \hat{\Phi}_{\psi_d}(k) & \hat{\Phi}_{\psi_q}(k) & \hat{\omega}_r(k) & \hat{\sigma}_r(k) \end{bmatrix}^T \)

The switching vector \( I_s(k) \), deduced from the continuous case given by (9), can be written as: \[ \text{ENG} \]
\[ I_s(k) = \begin{bmatrix} \text{sign}(s_1(k)) \\ \text{sign}(s_2(k)) \end{bmatrix} \quad \text{with} \]
\[ S = \begin{bmatrix} s_1(k) \\ s_2(k) \end{bmatrix} = T_eM(k)\bar{Z}(k+1) \]

where
\[ M(k) = \begin{bmatrix} -\dot{\sigma}_s(k) & \omega_d(k) \\ -\omega_d(k) & -\dot{\sigma}_s(k) \end{bmatrix}, \]

\[ \dot{z}(k+1) = \begin{bmatrix} z_{\sigma}(k+1) - \dot{z}_{\sigma}(k+1) \\ z_{\nu}(k+1) - \dot{z}_{\nu}(k+1) \end{bmatrix} \]

Let us introduce the measure vector
\[ z,(k+1) = [z_{\sigma}(k+1), z_{\nu}(k+1)]^T \]

written as follows:
\[ z_{\sigma}(k+1) = \Phi_{\sigma}(k+1) - \Phi_{\sigma}(k) - T_e\omega_d(k) \Phi_{\nu}(k) \]
\[ z_{\nu}(k+1) = \Phi_{\nu}(k+1) - \Phi_{\nu}(k) + T_e\omega_d(k) \Phi_{\sigma}(k) \]

From the electrical Equation (1.a) of the IM, an approximate (1st order) discrete-time relation of the fluxes is given by:

\[ \begin{bmatrix} z_{\sigma}(k+1) \\ z_{\nu}(k+1) \end{bmatrix} = \begin{bmatrix} T_eL_s \left[ V_{ds}(k) - R_sI_{ds}(k) - \frac{\sigma L_s}{L_m} \left[ I_{ds}(k+1) - I_{ds}(k) - T_e\omega_d(k)I_{ds}(k) \right] \right] \\ T_eL_s \left[ V_{qs}(k) - R_sI_{qs}(k) - \frac{\sigma L_s}{L_m} \left[ I_{qs}(k+1) - I_{qs}(k) + T_e\omega_d(k)I_{ds}(k) \right] \right] \end{bmatrix} + \begin{bmatrix} \dot{\Phi}_{\sigma}(k+1) - \dot{\Phi}_{\sigma}(k) - T_e\omega_d(k) \Phi_{\nu}(k) \\ \dot{\Phi}_{\nu}(k+1) - \dot{\Phi}_{\nu}(k) + T_e\omega_d(k) \Phi_{\sigma}(k) \end{bmatrix} \]

\[ \begin{bmatrix} \dot{z}_{\sigma}(k) \\ \dot{z}_{\nu}(k) \end{bmatrix} = \begin{bmatrix} \Phi_{\sigma}(k+1) - \Phi_{\sigma}(k) - T_e\omega_d(k) \Phi_{\nu}(k) \\ \Phi_{\nu}(k+1) - \Phi_{\nu}(k) + T_e\omega_d(k) \Phi_{\sigma}(k) \end{bmatrix} \]

The proposed gain matrix representation \( G(k) \), deduced from the continuous case given by (11) and (15), can be defined as follows (discrete-time approach):

\[ G,(k) = \begin{bmatrix} T_e \omega_d(k) \\ r - T_e\dot{\sigma}_r(k) - T_e\omega_d(k) \end{bmatrix} \begin{bmatrix} r - T_e\dot{\sigma}_r(k) \\ -T_e\omega_d(k) \end{bmatrix} \Delta \]

Once the fluxes are estimated, it is easy to deduce the estimated torque defined by:

\[ \hat{\tau}_{em}(k) = p \frac{L_m}{L_s} \left[ \Phi_{\sigma}(k)I_{ds}(k) - \Phi_{\nu}(k)I_{ds}(k) \right] \]

4. Simulation 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 robust linearization via feedback algorithm (Figure 1). The nominal parameters of the induction motor are given in the Table 1.

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 15% noise on the simulated currents \( I_{ds} \), \( I_{qs} \) or speed. Thus, using a sampling period \( T_s = 1 \) ms, the simulations are realized at first in the nominal case with the nominal parameters of the induction motor (Table 1) and then, in the second case, with 50% variation of the nominal rotor time constant \( \sigma_r = 1.5 \sigma_{nm} \) in order to verify the rotor time constant tracking and flux estimation.

Figure 2 and Figure 3 show the simulation results for a step input of the rotor speed and flux. One can see that in both nominal (Figures 2(a), 2(c)) or non-nominal (Figures 3(a'), 3(c')) cases, the estimated values of fluxes and torque converge very well to their simulated values.

The observed fluxes (Figure 2(a)) indicate the good orientation \( \Phi_{sr} \) is constant and \( \Phi_{sq} \) converges to zero) which is due to a favorable rotor time constant estimation (Figures 2(b), 3(b')). The estimated torque (Figure 2(c)) is in good agreement with the simulated value.

Once the fluxes are estimated, we can deduce the algorithm of the feedback linearization control (Figure 1). The waveforms show the good uncoupling between the rotor flux and the speed because a step variation in \( \Phi_{sr} \) (Figure 2(a) and Figure 3(a')) can not generate a speed change (Figure 2(d) and Figure 3(d')). Thus the field orientation and the synthesis of robust linearization and decoupling control are well verified.

All those results show the satisfying tuning, the excellent performance of the robust decoupling control and RDESMO against rotor resistance variations and perturbations or noises.
Figure 1. Simulation scheme of the system.

Figure 2. (a, b, c, d): Nominal case (Rr = Rrn).

Figure 3. (a’, b’, c’, d’): Non nominal case (Rr = 1.5Rrn).
Table 1. Nominal parameters of the induction motor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmn</td>
<td>1.8 kW</td>
</tr>
<tr>
<td>Un</td>
<td>220/380 V</td>
</tr>
<tr>
<td>In</td>
<td>20.8/12 A</td>
</tr>
<tr>
<td>p</td>
<td>2</td>
</tr>
<tr>
<td>Fn</td>
<td>50 Hz</td>
</tr>
<tr>
<td>n</td>
<td>1420 rpm</td>
</tr>
<tr>
<td>Jn</td>
<td>0.15 kg.m²</td>
</tr>
<tr>
<td>fn</td>
<td>0.05 N.m.s/rad</td>
</tr>
<tr>
<td>Rsn</td>
<td>5.7</td>
</tr>
<tr>
<td>Rm</td>
<td>1.475</td>
</tr>
<tr>
<td>Lsn</td>
<td>0.1766 H</td>
</tr>
<tr>
<td>Lm</td>
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<tr>
<td>Lfn</td>
<td>0.0504 H</td>
</tr>
<tr>
<td>Lm</td>
<td>0.1262 H</td>
</tr>
</tbody>
</table>

5. Conclusions

We have shown in this paper that a robust feedback linearization strategy and RDESMO are used to permit a regulation and observation for the Induction motor states in order to assure a good dynamic performance and stability of the global system. In order to reduce the observation execution time, this RDESMO, based on the full-order SMO principle, permit only and specially for the reconstruction of the parameters non measurable in an IM (the fluxes, speed and the rotor time constant estimation).

The interesting simulation results obtained on the induction motor show the effectiveness, the convergence and the stability of this robust decoupling control and RDESMO against rotor resistance variations, measured noises and load. Thus, in order to validate the robustness of this non-linear control and RDESMO, Experimental results on a testing bench for a 1.8 kW induction motor will be present in the next research project.

6. References


Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cem, C:</td>
<td>Electromagnetic and load torques, N.m.</td>
</tr>
<tr>
<td>f:</td>
<td>Friction coefficient, Nm.s/rad.</td>
</tr>
<tr>
<td>Lds, Lqs</td>
<td>Stationary frame (d,q)-axis stator currents and rotor magnetizing current, A.</td>
</tr>
<tr>
<td>J:</td>
<td>Inertia, kg.m².</td>
</tr>
<tr>
<td>Lr, Ls, Lm, Lf:</td>
<td>Rotor, stator, mutual and leakage inductances, H.</td>
</tr>
<tr>
<td>p:</td>
<td>Pole pair number.</td>
</tr>
<tr>
<td>Rr, Rs:</td>
<td>Stator and rotor referred resistance, Ω.</td>
</tr>
<tr>
<td>Tc, Tm, Tmr:</td>
<td>Sampling period, rotor and stator time constant (Tc = Lc/Rc = 1/ωc, Tm = Lm/Rm), s.</td>
</tr>
<tr>
<td>Vds, Vqs:</td>
<td>Stationary frame d- and q-axis stator voltage, V.</td>
</tr>
<tr>
<td>Φdr, Φqr:</td>
<td>d-q components of rotor fluxes, Wb.</td>
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<td>d-q components of stator fluxes, Wb.</td>
</tr>
<tr>
<td>ωs, ωr, ωd:</td>
<td>Stator, rotor and slip pulsation (or speed), rad/s.</td>
</tr>
</tbody>
</table>