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GLOBAL STABILITY OF LINEARIZING CONTROL WITH A NEW ROBUST NONLINEAR OBSERVER OF THE INDUCTION MOTOR

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This paper mainly deals with the design of an advanced control law with an observer for a special class of nonlinear systems. We design an observer with a gain as a function of speed. We study the solution to the output feedback torque and rotor flux-tracking problem for an induction motor model given in the natural frame. We propose a new robust nonlinear observer and prove the global stability of the interlaced controller-observer system. The control algorithm is studied through simulations and applied in many configurations (various set points, flux and speed profiles and torque disturbances), and is shown to be very efficient.

Keywords: nonlinear observer, linearizing control, induction motor, global stability

1. Introduction

Induction motors are nonlinear, coupled, multivariable processes. Nevertheless, they become more and more appealing because of their reliability, robustness and low cost of maintenance (Van Raumer, 1994). We built a globally stable nonlinear control law with real effectiveness for the adopted strategies and we describe a speed dependent observer. We based the initial strategy on input-output linearization (Chiason, 1997; De Luca and Ulivi, 1989; Isidori, 1989). Here we redesign the observer based on a control law in order to ensure the global stability of the process-observer-controller system (Lubineau *et al.*, 1999). The main contributions of the paper are the following: First, we propose a new observer modified for a special class of nonlinear systems applied to the induction motor (Busawon *et al.*, 1998; Gauthier and Bornard, 1981). Secondly, a globally stable nonlinear observer based on a control law is designed. Lastly, intensive simulations in different conditions are performed to show that the general strategy proposed is very efficient.

We organize the paper as follows: we present in Section 2 the induction motor model. In Section 3, we present a nonlinear observer, an application to the induction motor, the control algorithm and the global stability proof. In Section 4, we give simulation results and comment on them with implementations in Matlab-Simulink.

2. Model of the Induction Motor

The model used is a traditional induction model of Park in a stator (α,β) fixed reference frame related to the stator, given by (Mansouri *et al.*, 2004):

$$\dot{x} = f(x) + g\,u, \tag{1}$$

with

$$x = [i_{s\alpha}, i_{s\beta}, \varphi_{r\alpha}, \varphi_{r\beta}, \Omega]^T, \quad u = [u_{s\alpha}, u_{s\beta}]^T.$$

Here x contains four electrical states (flux and current components, respectively $\varphi_{r\alpha}$, $\varphi_{r\beta}$ and $i_{s\alpha}, i_{s\beta}$) and one mechanical state Ω governed by a mechanical equation. The motor is driven by two voltage components, $u_{s\alpha}$ and $u_{s\beta}$. We define the control input matrix by

$$g = \begin{bmatrix} \dfrac{1}{\sigma L_s} & 0 & 0 & 0 & 0 \\ 0 & \dfrac{1}{\sigma L_s} & 0 & 0 & 0 \end{bmatrix}^T$$

with

$$T_r = \frac{L_r}{R_r}, \quad \sigma = 1 - \frac{M^2}{L_s L_r}, \quad K = \frac{M}{\sigma L_s L_r},$$

$$\gamma = \frac{R_s}{\sigma L_s} + \frac{R_r M^2}{\sigma L_s L_r^2},$$

$$f(x) = \begin{bmatrix} -\gamma i_{s\alpha} + \frac{K}{T_r}\varphi_{r\alpha} + p\Omega K \varphi_{r\beta} \\ -\gamma i_{s\beta} - p\Omega K \varphi_{r\alpha} + \frac{K}{T_r}\varphi_{r\beta} \\ \frac{M}{T_r} i_{s\alpha} - \frac{1}{T_r}\varphi_{r\alpha} - p\Omega\varphi_{r\beta} \\ \frac{M}{T_r} i_{s\beta} + p\Omega\varphi_{r\alpha} - \frac{1}{T_r}\varphi_{r\beta} \\ p\frac{M}{J_m L_r}(\varphi_{r\alpha} i_{s\beta} - \varphi_{r\beta} i_{s\alpha}) - \frac{f_m \Omega}{J_m} - \frac{\tau_L}{J_m} \end{bmatrix}, \tag{2}$$

where L_r, L_s, M are rotor, stator and mutual inductances, respectively, R_r and R_s are rotor and stator resistances, σ is the scattering coefficient, T_r is the time constant of the rotor dynamics, J_m is the rotor inertia, f_m is the mechanical viscous damping, p is the number of pole pairs, τ_L is the external load torque.

3. Nonlinear Control with Global Stability

We can solve the global stability problem using global tools such as Lyapunov functions. In this section, we first design an observer. It is an observer for a special class of nonlinear systems, applied to the induction motor and enriched for a further analysis. Secondly, we design a control law. We base this control law on linearizing control and we modify it in order to ensure global stability. We then establish global stability using a Lyapunov function (Lubineau *et al.*, 1999).

3.1. Nonlinear Observer and Application to the Induction Motor

In this section, based on extensions of the observer design strategy to the multi-output case (Busawon *et al.*, 1998) and the application to the induction motor, we propose a new observer with nonlinear terms. We are going to apply the result given in the preceding part to construct a full-order observer for an induction motor written in the α, β Park frame (Verghese and Sanders, 1988). The proposed observer uses the measurements of the stator voltage and current, and the rotor speed. More precisely, we design the observer up to an injection of the speed measurements so that only the electrical equations are considered. First, we define

$$\begin{aligned} x_e &= [i_{s\alpha}, i_{s\beta}, \varphi_{r\alpha}, \varphi_{r\beta}]^T, \\ \hat{x}_e &= \left[\hat{i}_{s\alpha}, \hat{i}_{s\beta}, \hat{\varphi}_{r\alpha}, \hat{\varphi}_{r\beta}\right]^T, \\ \tilde{x}_e &= x_e - \hat{x}_e, \end{aligned} \tag{3}$$

where x_e, $\hat{x}_e$ and $\tilde{x}_e$ are respectively the real state, estimated state and observation error vectors. We have

$$\dot{\hat{x}}_e = \begin{bmatrix} -\gamma & 0 & \frac{K}{T_r} & p\Omega K \\ 0 & -\gamma & -p\Omega K & \frac{K}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & -p\Omega \\ 0 & \frac{M}{T_r} & p\Omega & -\frac{1}{T_r} \end{bmatrix} \hat{x}_e + g\,u - \begin{bmatrix} -k_1 & 0 \\ 0 & -k_1 \\ -\frac{k_2}{T_r} & p\Omega k_2 \\ -p\Omega k_2 & -\frac{k_2}{T_r} \end{bmatrix} \begin{bmatrix} \tilde{i}_{s\alpha} \\ \tilde{i}_{s\beta} \end{bmatrix} + \begin{bmatrix} f_{i\alpha} \\ f_{i\beta} \\ 0 \\ 0 \end{bmatrix}, \tag{4}$$

where $f_{i\alpha}$ and $f_{i\beta}$ will be defined in Section 3.3, and

$$\begin{aligned} k_1 &= 2\theta, \\ k_2 &= \frac{T_r^2 \theta^2}{K[1 + (p\Omega T_r)^2]}. \end{aligned} \tag{5}$$

This leads to the following error equations:

$$\dot{\tilde{x}}_e = \begin{bmatrix} -\gamma - k_1 & 0 & \frac{K}{T_r} & p\Omega K \\ 0 & -\gamma - k_1 & -p\Omega K & \frac{K}{T_r} \\ \frac{M}{T_r} - \frac{k_2}{T_r} & p\Omega T_r k_2 & -\frac{1}{T_r} & -p\Omega \\ -p\Omega T_r k_2 & \frac{M}{T_r} - \frac{k_2}{T_r} & p\Omega & -\frac{1}{T_r} \end{bmatrix} \tilde{x}_e - \begin{bmatrix} f_{i\alpha} \\ f_{i\beta} \\ 0 \\ 0 \end{bmatrix}. \tag{6}$$

We show the diagram block of this observer in Fig. 1.

We shall perform the stability study in the next part by considering the whole system process-observer-controller.

3.2. Control Algorithm

We design a control algorithm based on feedback linearization (Marino *et al.*, 1993). The two controlled outputs of the system form the square of the flux norm in

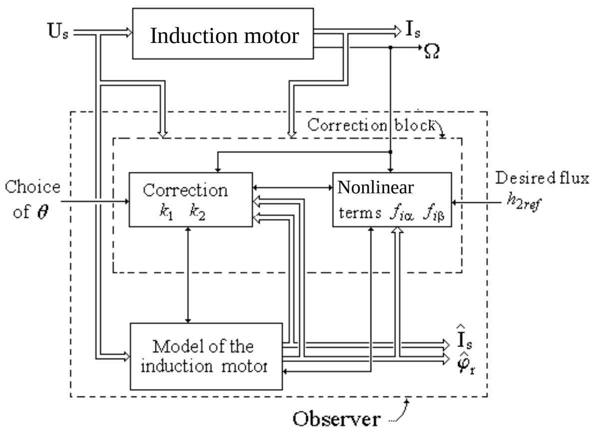

Fig. 1. Nonlinear observer block diagram.

the machine. This is to avoid magnetic saturation and to work in the mode of overspending where the limitation of the tension norm imposes the reduction in the flux norm $h_2(x)$ and the electromagnetic torque $h_1(x)$ (Grellet and Clerc, 1996). We express them as

$$
\begin{aligned}
h_1(x) &= p\frac{M}{L_r}\left(i_{s\beta}\varphi_{r\alpha} - i_{s\alpha}\varphi_{r\beta}\right), \\
h_2(x) &= \varphi_{r\alpha}^2 + \varphi_{r\beta}^2.
\end{aligned}
\tag{7}
$$

Both the variables are unknown. We define the observed outputs as

$$
\begin{aligned}
\hat{h}_1(x) &= p\frac{M}{L_r}\left(\hat{i}_{s\beta}\hat{\varphi}_{r\alpha} - \hat{i}_{s\alpha}\hat{\varphi}_{r\beta}\right), \\
\hat{h}_2(x) &= \hat{\varphi}_{r\alpha}^2 + \hat{\varphi}_{r\beta}^2.
\end{aligned}
\tag{8}
$$

We define the derivates of $\hat{h}_1$ and $\hat{h}_2$ as (Van Raumer, 1994; Lubineau *et al.*, 1999):

$$
\begin{aligned}
\dot{\hat{h}}_1 &= L_{\hat{f}}\hat{h}_1 + L_{g1}\hat{h}_1 u_{s\alpha} + L_{g_2}\hat{h}_1 u_{s\beta}, \\
\dot{\hat{h}}_2 &= L_{\hat{f}}\hat{h}_2,
\end{aligned}
\tag{9}
$$

where

$$
L_{\hat{f}}\hat{h}_1 = \frac{pM}{L_r}\left(-\hat{f}_1\hat{\varphi}_{r\beta} + \hat{\varphi}_{r\alpha}\hat{f}_2 + \hat{i}_{s\beta}\hat{f}_3 - \hat{i}_{s\alpha}\hat{f}_4\right), \tag{10}
$$

$$
\begin{aligned}
L_{g1}\hat{h}_1 &= -\frac{pM}{L_r}\frac{1}{\sigma L_s}\varphi_{r\beta}, \\
L_{g_2}\hat{h}_1 &= \frac{pM}{L_r}\frac{1}{\sigma L_s}\varphi_{r\alpha}, \\
L_{\hat{f}}\hat{h}_2 &= 2\hat{\varphi}_{r\alpha}\hat{f}_3 + 2\hat{\varphi}_{r\beta}\hat{f}_4,
\end{aligned}
\tag{11}
$$

with

$$
\begin{aligned}
\hat{f}_1 &= -\gamma\hat{i}_{s\alpha} + \frac{K}{T_r}\hat{\varphi}_{r\alpha} + p\Omega K\hat{\varphi}_{r\beta} + 2\theta\tilde{i}_{s\alpha} + f_{i\alpha}, \\
\hat{f}_2 &= -\gamma\hat{i}_{s\beta} - p\Omega K\hat{\varphi}_{r\alpha} + \frac{K}{T_r}\hat{\varphi}_{r\beta} + 2\theta\tilde{i}_{s\beta} + f_{i\beta}, \\
\hat{f}_3 &= \frac{M}{T_r}\hat{i}_{s\alpha} - \frac{1}{T_r}\hat{\varphi}_{r\alpha} - p\Omega\hat{\varphi}_{r\beta} + \frac{k_2}{T_r}\tilde{i}_{s\alpha} - p\Omega k_2\tilde{i}_{s\beta}, \\
\hat{f}_4 &= \frac{M}{T_r}\hat{i}_{s\beta} + p\Omega\hat{\varphi}_{r\alpha} - \frac{1}{T_r}\hat{\varphi}_{r\beta} + p\Omega k_2\tilde{i}_{s\alpha} + \frac{k_2}{T_r}\tilde{i}_{s\beta}.
\end{aligned}
$$

Since $L_{\hat{f}}\hat{h}_2$ is not a function of the control inputs, one should derive them once again. However, $L_{\hat{f}}\hat{h}_2$ contains terms which are functions of currents. The differentiation of those terms introduces terms of flux, which are unknown. To overcome this problem, we write this as (Isodori, 1989):

$$
L_{\hat{f}}\hat{h}_2 = -\frac{2}{T_r}\hat{h}_2 + \hat{h}_3 + \Delta, \tag{12}
$$

where

$$
\hat{h}_3 = 2\frac{M}{T_r}\left(\hat{i}_{s\alpha}\hat{\varphi}_{r\alpha} + \hat{i}_{s\beta}\hat{\varphi}_{r\beta}\right), \tag{13}
$$

$$
\begin{aligned}
\Delta &= 2\left(\frac{k_2}{T_r}\hat{\varphi}_{r\alpha} + k_2 p\Omega\hat{\varphi}_{r\beta}\right)\tilde{i}_{s\alpha} \\
&\quad + 2\left(-k_2 p\Omega\hat{\varphi}_{r\beta} + \frac{k_2}{T_r}\hat{\varphi}_{r\beta} +\right)\tilde{i}_{s\beta},
\end{aligned}
$$

$\hat{h}_3$ is an artificial auxiliary output to control. Let us differentiate $\hat{h}_3$:

$$
\dot{\hat{h}}_3 = L_{\hat{f}}\hat{h}_3 + L_{g1}\hat{h}_3 u_{s\alpha} + L_{g2}\hat{h}_3 u_{s\beta} \tag{14}
$$

with

$$
L_{\hat{f}}\hat{h}_3 = \frac{pM}{T_r}\left(\hat{\varphi}_{r\alpha}\hat{f}_1 + \hat{\varphi}_{r\beta}\hat{f}_2 + \hat{i}_{s\alpha}\hat{f}_3 + \hat{i}_{s\beta}\hat{f}_4\right), \tag{15}
$$

$$
\begin{aligned}
L_{g1}\hat{h}_3 &= \frac{2M}{T_r}\frac{1}{\sigma L_s}\varphi_{r\alpha}, \\
L_{g_2}\hat{h}_3 &= \frac{2M}{T_r}\frac{1}{\sigma L_s}\varphi_{r\beta}.
\end{aligned}
$$

This leads, finally, to

$$
\begin{aligned}
\dot{\hat{h}}_1 &= L_{\hat{f}}\hat{h}_1 + L_{g1}\hat{h}_1 u_{s\alpha} + L_{g_2}\hat{h}_1 u_{s\beta}, \\
\dot{\hat{h}}_2 &= L_{\hat{f}}\hat{h}_2, \\
\dot{\hat{h}}_3 &= L_{\hat{f}}\hat{h}_3 + L_{g1}\hat{h}_3 u_{s\alpha} + L_{g2}\hat{h}_3 u_{s\beta},
\end{aligned}
\tag{16}
$$

$$\begin{bmatrix} \dot{\hat{h}}_1 \\ \dot{\hat{h}}_2 \\ \dot{\hat{h}}_3 \end{bmatrix} = \begin{bmatrix} L_{\hat{f}}\hat{h}_1 + L_{g1}\hat{h}_1 u_{s\alpha} + L_{g_2}\hat{h}_1 u_{s\beta} \\ -\dfrac{2}{T_r}\hat{h}_2 + \hat{h}_3 + \Delta \\ L_{\hat{f}}\hat{h}_3 + L_{g1}\hat{h}_3 u_{s\alpha} + L_{g2}\hat{h}_3 u_{s\beta} \end{bmatrix}. \quad (17)$$

The errors between the desired trajectory of the outputs and the estimated outputs are

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \hat{h}_1 - h_{1\,\mathrm{ref}} \\ \hat{h}_2 - h_{2\,\mathrm{ref}} \\ \hat{h}_3 - h_{3\,\mathrm{ref}} \end{bmatrix}.$$

Let us design the control inputs as

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} L_{g1}\hat{h}_1 & L_{g2}\hat{h}_1 \\ L_{g1}\hat{h}_3 & L_{g2}\hat{h}_3 \end{bmatrix}^{-1} \begin{bmatrix} -L_{\hat{f}}\hat{h}_1 - k_{p1}e_1 + \dot{h}_{1\,\mathrm{ref}} \\ -L_{\hat{f}}\hat{h}_3 - e_2 - k_{p3}e_3 + \dot{h}_{3\,\mathrm{ref}} \end{bmatrix}. \quad (18)$$

This leads to

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -k_{p1}e_1 \\ -\dfrac{2}{T_r}\hat{h}_2 + \hat{h}_3 + \Delta - \dot{h}_{2\,\mathrm{ref}} \\ -e_2 - k_{p3}e_3 \end{bmatrix}, \quad (19)$$

where $h_{1\,\mathrm{ref}}$ and $h_{2\,\mathrm{ref}}$ are known references. The aim now is to define $h_{3\,\mathrm{ref}}$ as

$$h_{3\,\mathrm{ref}} = \frac{2}{T_r}\hat{h}_2 + \dot{h}_{2\,\mathrm{ref}} - k_{p2}e_2, \quad (20)$$

which leads to

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \end{bmatrix} = \begin{bmatrix} -k_{p1}e_1 \\ -k_{p2}e_2 + e_3 + \Delta \\ -e_2 - k_{p3}e_3 \end{bmatrix}. \quad (21)$$

An appropriate choice of the positive constants k_{p1}, k_{p2} and k_{p3} ensures the exponential convergence of the tracking errors.

We show a detailed scheme of the nonlinear control with the observer in Fig. 2.

3.3. Proof of Global Stability

We now consider all the elements together in order to build an ultimate observer based on the control law. Let us define the function

$$V_1(\tilde{x}_e) = \frac{\tilde{i}_{s\alpha}^2 + \tilde{i}_{s\beta}^2}{2} + \frac{\tilde{\varphi}_{r\alpha}^2 + \tilde{\varphi}_{r\beta}^2}{2\gamma_2}, \quad (22)$$

where γ_2 is a positive constant, and the function

$$V_2(e) = \frac{e_1^2 + e_2^2 + e_3^2}{2}. \quad (23)$$

We can choose a Lyapunov function candidate for the global system (process-observer-controller) as $V = V_1 + V_2$. Its derivate is

$$\begin{aligned} \dot{V} = {} & -k_{p1}e_1^2 - k_{p2}e_2^2 - k_{p3}e_3^2 + \Delta e_2 \\ & - (\gamma + k_1)\left(\tilde{i}_{s\alpha}^2 + \tilde{i}_{s\beta}^2\right) - \frac{1}{T_t\gamma_2}\left(\tilde{\varphi}_{r\alpha}^2 + \tilde{\varphi}_{r\beta}^2\right) \\ & + \left(\frac{K}{T_r} + \frac{M}{T_r\gamma_2} - \frac{k_2}{T_r\gamma_2}\right)\left(\tilde{i}_{s\alpha}\tilde{\varphi}_{r\alpha} + \tilde{i}_{s\beta}\tilde{\varphi}_{r\beta}\right) \\ & - \left[f_{i\alpha}\tilde{i}_{s\alpha} + f_{i\beta}\tilde{i}_{i\beta}\right] \\ & + p\Omega\left(K - \frac{k_2}{\gamma_2}\right)\left[\tilde{i}_{s\alpha}\tilde{\varphi}_{r\beta} - \tilde{i}_{s\beta}\tilde{\varphi}_{r\alpha}\right]. \end{aligned} \quad (24)$$

The following three conditions form a sufficient set of conditions ensuring $\dot{V} < 0$ by

$$\begin{aligned} & -\left[f_{i\alpha}\tilde{i}_{s\alpha} + f_{i\beta}\tilde{i}_{i\beta}\right] + \Delta\, e_2 = 0, \\ & k_1(\theta) > \frac{M^2}{4T_r\gamma_2} - \gamma \Rightarrow \theta > \frac{M^2}{8T_r\gamma_2} - \tfrac{1}{2}\gamma, \\ & k_2(\theta,\Omega) = K\,\gamma_2. \end{aligned} \quad (25)$$

Replacing Δ by its value (13) leads to the following equation:

$$\begin{aligned} \left[f_{i\alpha}\tilde{i}_{s\alpha} + f_{i\beta}\tilde{i}_{i\beta}\right] = {} & 2\left[\frac{k_2}{T_r}\tilde{\varphi}_{r\alpha} + k_2 p\Omega\tilde{\varphi}_{r\beta}\right]\tilde{i}_{s\alpha}\, e_2 \\ & + 2\left[-k_2 p\Omega\tilde{\varphi}_{r\alpha} + \frac{k_2}{T_r}\tilde{\varphi}_{r\beta}\right] e_2. \end{aligned} \quad (26)$$

Equation (26) is satisfied if $f_{i\alpha}$ and $f_{i\beta}$ are chosen as

$$\begin{aligned} f_{i\alpha} &= 2\left[\frac{k_2}{T_r}\hat{\varphi}_{r\alpha} + k_2 p\Omega\hat{\varphi}_{r\beta}\right] e_2, \\ f_{i\beta} &= 2\left[-k_2 p\Omega\hat{\varphi}_{r\alpha} + \frac{k_2}{T_r}\hat{\varphi}_{r\beta}\right] e_2. \end{aligned} \quad (27)$$

V is then a Lyapunov function for the overall system. Consequently, the whole process is stable and the convergence is exponential. We ensure flux and torque tracking. Then we can add a speed feedback loop to ensure the speed tracking.

4. Results and Simulations

4.1. Simulation Block Diagrams, Motor Data and a Benchmark

We design the general block diagram as shown in Fig. 3. In addition to that, we perform a simulation with Matlab-Simulink by using the benchmark in Fig. 4 and the motor

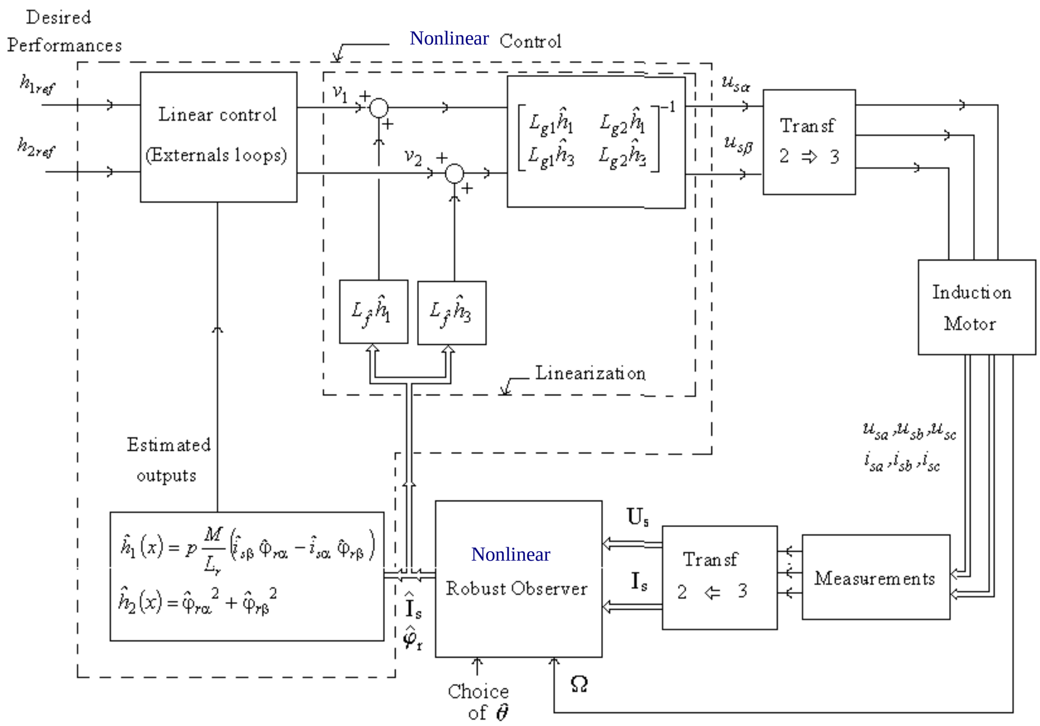

Fig. 2. Detailed scheme of the nonlinear control with an observer.

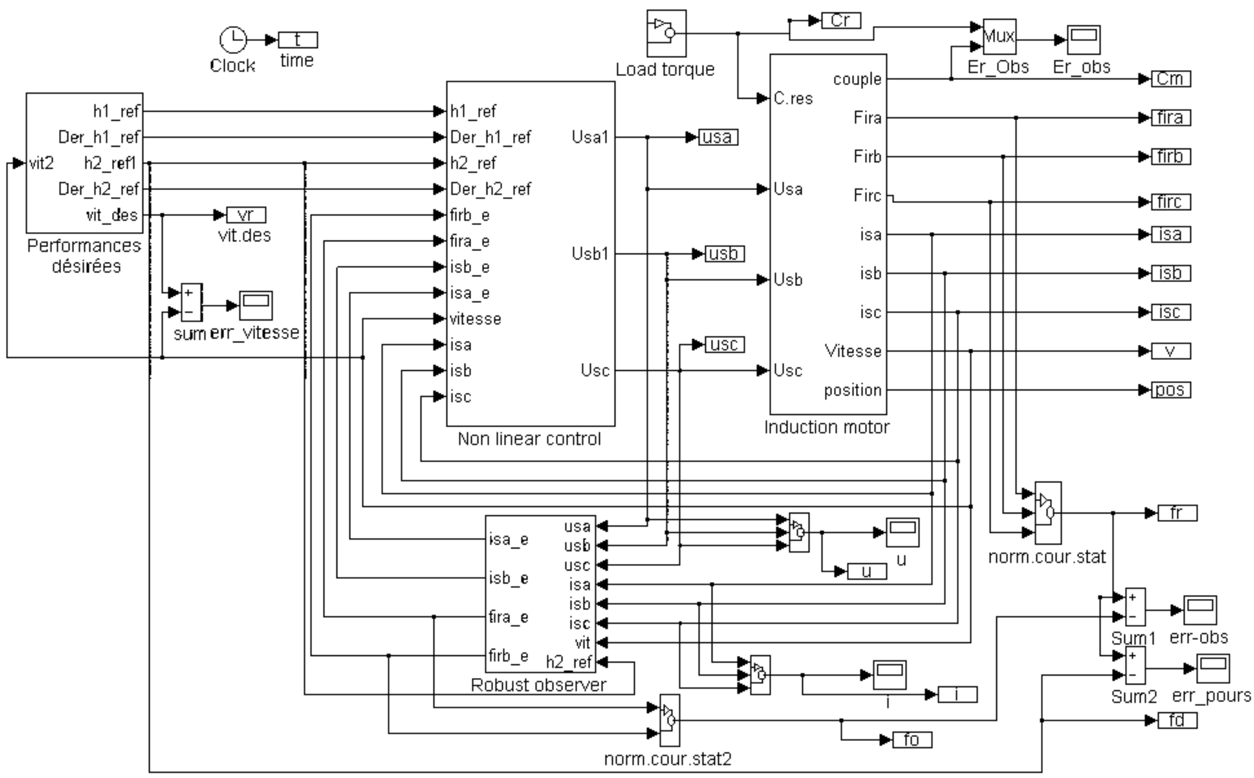

Fig. 3. General block diagram in Simulink.

Table 1. Parameters of the induction motor.

Designation	Parameter	Value
Rotor resistance	R_r	4.3047 Ω
Stator resistance	R_s	9.65 Ω
Mutual inductance	M	0.4475 H
Stator inductance	L_s	0.4718 H
Stator inductance	L_r	0.4718 H
Rotor inertia	J_m	0.0293 kg·m^2
Pole pair	p	2
Viscous friction coefficient	f_m	0.0038 N·m·sec·rad^{-1}
Mechanical power	P_{mec}	1.1 KW
Nominal voltage	V_{sn}	220 V
Nominal current	I_{sn}	2.6 A
Nominal speed	Ω_{sn}	1410 Nm

parameters given in Table 1 (Cauët, 2001). This benchmark (Bodson and Chiasson, 1992; Lubineau *et al.*, 1992) reveals the following profile: a rise in speed, a load, inversion speed and a load in recovery, and a return at a low speed.

We study the performance of the new nonlinear observer in an open loop. Then we associate it in a closed loop with the nonlinear control of the induction motor where we choose $\theta = 5$. This gives the dynamics of the observer close to those of the motor as shown in Fig. 5.

Figure 4 gives the reference trajectories of the speed, flux and load torque.

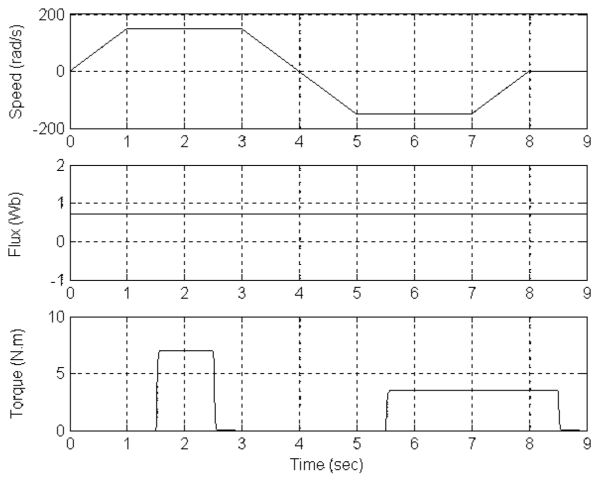

Fig. 4. Reference trajectories.

4.2. Study of the Nonlinear Observer in an Open Loop

First, we simulate the trajectory of the poles of the motor and the nonlinear observer, cf. (5), obtained with $\theta = 5$. Secondly, in Fig. 6 we show a good observation error of the rotor flux at different speeds (0.0125, 3.4 and 150 rad/s), simulated for $\theta = 30$.

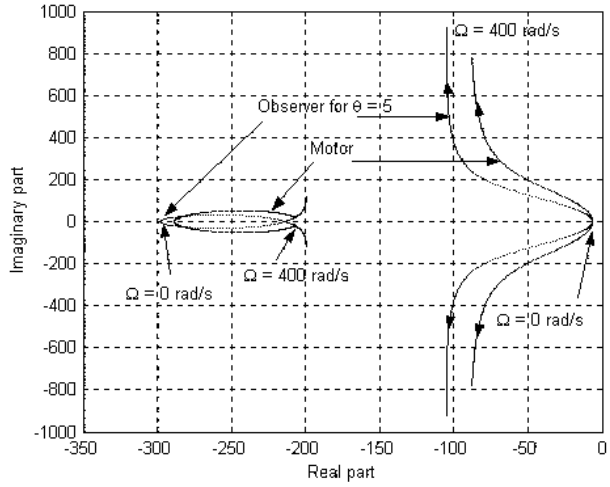

Fig. 5. Pole trajectory of the motor and the nonlinear observer.

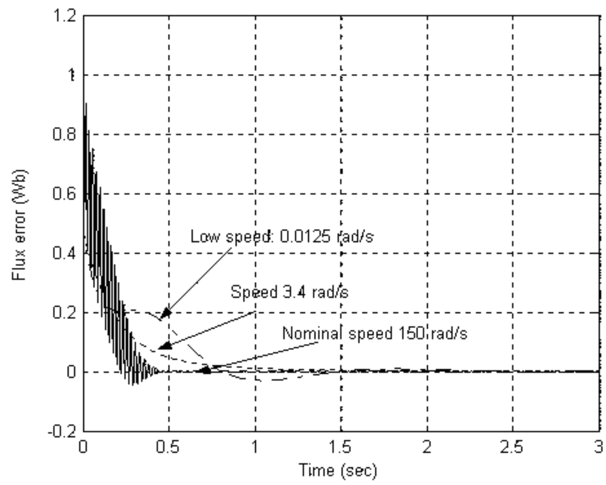

Fig. 6. Observation errors of the rotor flux ($\theta = 30$).

Note that we initialize the rotor flux in the observer with $\varphi_{r\alpha_0} = \varphi_{r\beta_0} = 0.5\,$Wb. Finally, in Fig. 7 we study sensitivity to rotor resistance disturbances for three values of $R_r = (4.3047, 6.4571, 8.034)\,\Omega$, i.e. an increase by 50% and 100%, respectively. We can show the robustness of the proposed nonlinear observer. Nevertheless, we note the existence of a static error, which increases with the variation of the rotor resistance.

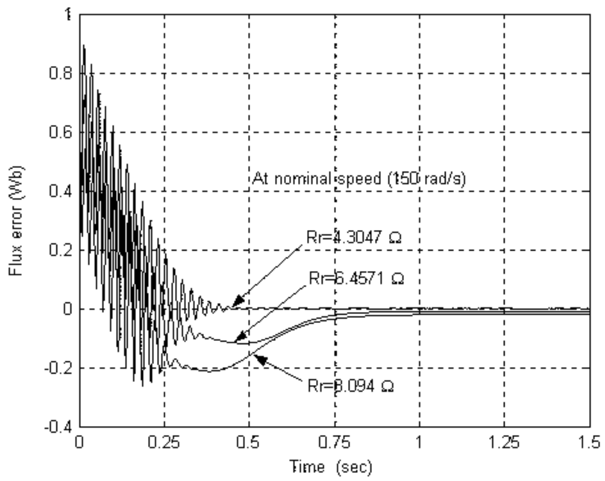

Fig. 7. Sensitivity to rotor resistance disturbances.

4.3. Performance of Linearizing Control Associated with the Nonlinear Observer

Speed error tracking

During an increase or a decrease in the speed, an error speed of ± 0.6 rad/s is observed. When the speed is constant, this error is cancelled. The peaks appear at the time of the abrupt variations in the load torque. Their amplitudes depend on its value, as shown in Fig. 8.

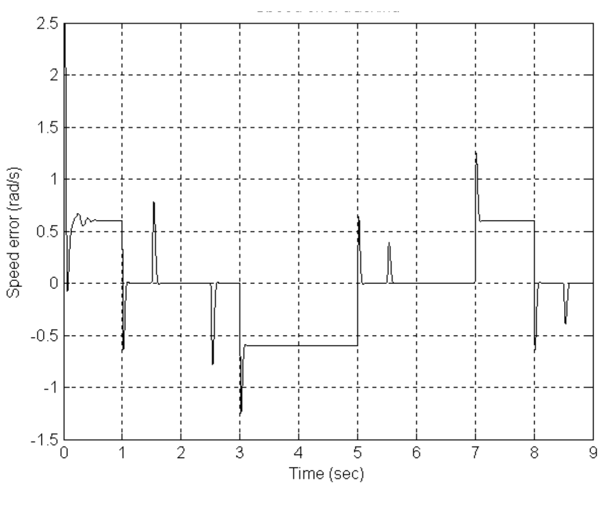

Fig. 8. Speed error tracking.

Torque

We note that the drive torque follows the load torque when the speed is constant. During an increase or decrease in the speed, a difference of ± 5 Nm appears between the two torques, as shown in Fig. 9.

Rotor flux errors

We note a very good tracking by looking at the two errors of observation and regulation as shown in Figs. 10–11. The transient response between $t = 0$ and 0.5 s is due to the initialization of the rotor flux norm with 0.707 Wb.

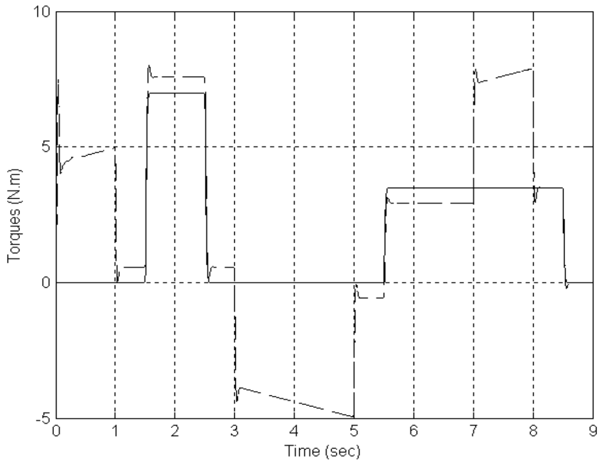

Fig. 9. Motor and load torques.

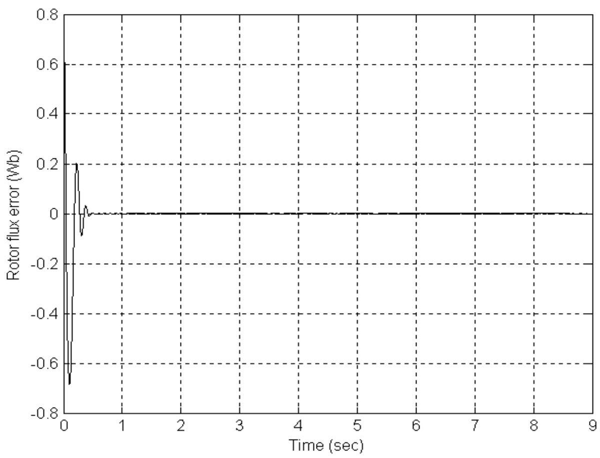

Fig. 10. Observation error of the rotor flux.

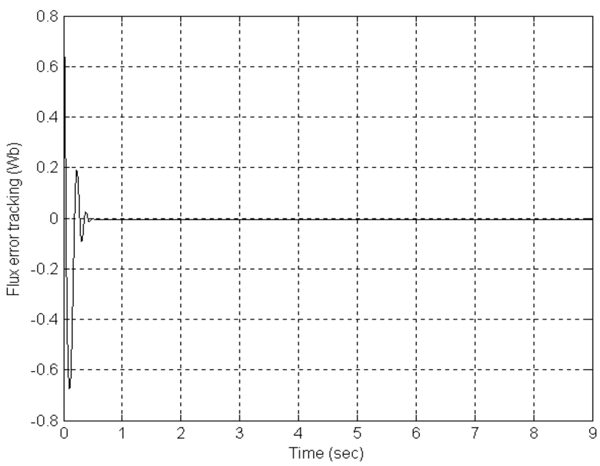

Fig. 11. Rotor flux error tracking.

Stator current norm

We show the plot of the norm stator current in Fig. 12. The norm of the current is equal to 3.5 A, in the interval of $t = [0\ 1]$ s, $t = [3\ 5]$ s because the speed increase and the load torque are zero. Between $t = [1\ 1.5]$ s, $[2.5\ 3]$ s, $[5\ 5.5]$ s and $[8.5\ 9]$ s, the norm is minimal and equal to 1.9 A. In this phase, the speed is constant and the load torque is zero. The amplitude of the current reaches a maximum value of 5 A at $t = [1.5\ 2.5]$ s, because a load torque of 7 Nm appears at that point. Speed remains always constant. Between $t = [5.5\ 7]$ s and $[8\ 8.5]$ s, the norm reaches 2.6 A and 2.8 A, respectively, because a load torque of 3.55 Nm takes place. Again speed remains constant. During this phase, and between $t = [7\ 8]$ s, the norm increases sharply because of the linear variation in speed.

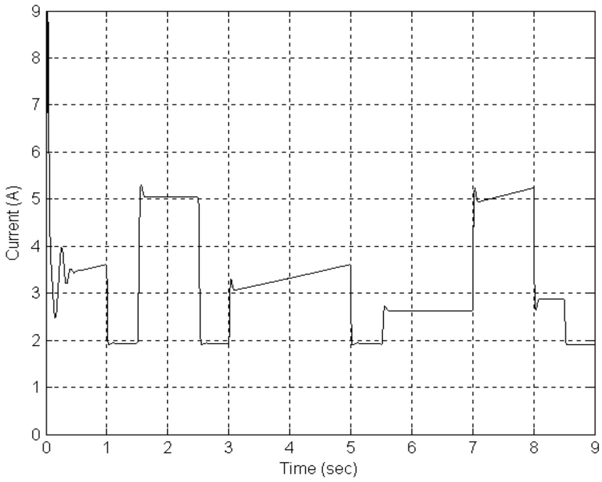

Fig. 12. Stator current norm.

Stator voltage control

The three stator control voltages follow the profile of the norm current, except if speed varies linearly. Their amplitude varies in the same proportions, as shown in Fig. 13.

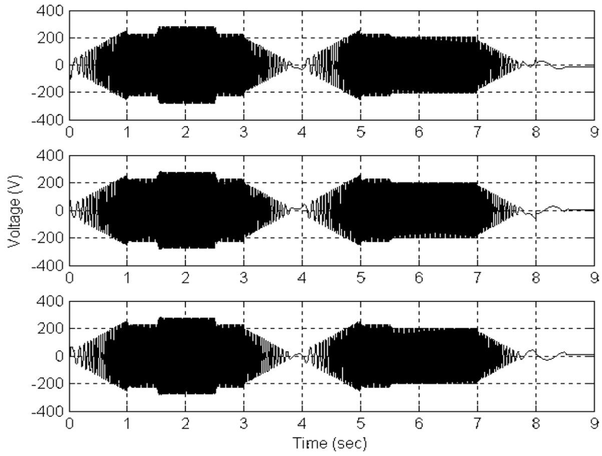

Fig. 13. Stator control.

5. Conclusion

In this paper, we presented a new robust observer based on a nonlinear control scheme for an induction motor. The observer proposed in this study offers the advantage of only one tuning parameter θ. The adaptation gain of the rotor flux depends on speed. The global stability (motor, controller, and observer) was established with a carefully built Lyapunov function that keeps the observer dynamics free. Intensive simulations in a wide operating domain such as low and high speed, constant flux and various torque disturbances were performed in Matlab-Simulink and justified the interest in such an observer based on linear control laws. The results of simulations regarding the observation of rotor flux, the robustness of the observer, the speed and torque tracking and the rotor flux tracking confirm the theory suggested. We wish to validate these results in real time.

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