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An Output Feedback Passivity–based Controller for Sensorless Induction Motors

Jaime A. Moreno
II–UNAM
A.P. 70-472
04510 México D.F.
MEXICO
jmorenop@ii.unam.mx

Gerardo Espinosa–Pérez
DEPFI–UNAM
A.P. 70-256
04510 México D.F.
MEXICO
gerardoe@servidor.unam.mx

***Resumen*— In this paper the design of Sensorless Controllers for Induction Motors is approached from the perspective of establishing structural properties of the control law that allow for dealing with the observer design in a systematic way. In particular it is shown that sensorless Passivity–based Control (PBC) of this kind of machines leads to some Input–to–State Stability properties of the control error dynamics that establish a Separation principle for the closed–loop composed by the motor, the PBC and *any* sensorless observer. Considering this property a recently reported semiglobal sensorless observer is *numerically* evaluated operating together with the PBC. The dynamical performance that is obtained is remarkable even for operation conditions that include zero crossing speed trajectories. Derecho reservado © UNAM-AMCA.**

Palabras clave: Passivity control, Sensorless Control, Induction motors.

I. Introduction

Sensorless Control of Induction Motors (SCIM) is a topic that has attracted the attention due to its implications in the use of these kind of devices, namely, cost dropping and reliability improvement (Rajashekara et al, 1996). The main feature of this technique is the assumption about the immeasurability of the mechanical variables (position and speed) of the machine. This, in addition to the well–known limitation for using rotor (flux and/or current) sensors, makes natural to approach this problem from an estimation/observation perspective. However, the nonlinear nature of the IM makes finding a solution to be far from a trivial task.

The limitations for obtaining a solution of the SCIM have been established in the context of the observability properties of the motor model (Canudas et al, 2000), (Ibarra–Rojas et al, 2004). Thus, the current knowledge achieved about this topic allows for recognizing the *impossibility for solving it in a global way* due to the presence of several *unavoidable* obstacles like the existence of indistinguishable trajectories, i.e. pairs of different state trajectories with the same input/output behavior.

In order to deal with the complexity for designing sensorless controllers there have been some efforts in proposing a solution from a pure observer design perspective (Besancon et al, 2003), (Moreno and Espinosa, 2006) and from the viewpoint of designing, in an embedded way, the speed observer into the controller design (Marino et al, 2005). As expected the usefulness of these results is restricted to the ability for estimating the speed and rotor variables only for observable trajectories, leading to the fact that the stability properties are guaranteed only locally.

Another approach that has been followed is based on the possibility of having globally defined observability properties of the IM model assuming measurability of rotor variables (Ibarra, 2005). The objective in this case is to design globally defined controllers to later on substitute the unmeasurable rotor variables by some estimates obtained from open–loop observers. Evidently, the main limitation of these controllers comes from the lack of robustness that appears from the use of open–loop estimation schemes (Feemster et al, 2001), (Marino et al, 2004), (Montanari et al, 2004).

In spite of the important advances achieved in solving the sensorless control problem of IM, the main purpose of this paper is to contribute for improving the dynamic behavior of this kind of schemes. In this sense, the problem is viewed from a perspective that has not been considered in previous results, namely, the establishment of structural properties of the closed–loop system that allows for dealing with the observer–based controller design in a systematic way. The rational behind this approach is to consider that exploiting generic stability properties of the system composed by the plant and the control law would lead to observer designs that can be carried out first in a simpler way but, more important, in such a way that the desired dynamic response improvement would be achieved.

Regarding the aforementioned structural properties, the main contribution of this paper is to prove that the sensorless version, i.e. without measuring neither rotor variables nor motor speed and assuming unknown load torque, of the passivity–based control (PBC) reported in (Espinosa–Perez and Ortega, 1995) defines a mapping from the observation error (given as the difference between the actual and the estimated values of the unmeasurable variables) to the control error (defined as the difference between the actual and the desired behavior for the motor state) that is Input to State Stable (ISS).

The importance of establishing the ISS property comes from the well–known fact (Angeli et al, 2004) that for systems that enjoy it is possible to state (in a relatively simple way) a separation principle to prove the stability of a closed–loop system composed by the plant and an observer–based controller. Hence, the contribution of this paper is the establishment of a Separation Principle for passivity–based sensorless controlled induction motors.

It is important to notice that, as expected, the limitations imposed by the lack of global observability of the sensorless induction motor model are not removed by the establishment of the ISS property. Thus, the usefulness of the control scheme still depends on the observer performance, since the control error will tend to zero only if the observation error tends to zero, condition that depends in its turn on the operation regime considered for the machine. However, it must also noticed, on the other hand, that the ISS property indeed states that no matter how the sensorless observer is designed, stability for the closed–loop system is guaranteed. In this sense, a second contribution of the paper is the *numerical* evaluation of the mentioned above PBC operating with a recently reported sensorless observer (Moreno and Espinosa, 2006) that guarantees convergence to zero of the observation error for distinguishable trajectories while boundedness of this error when the motor operation generates undistinguishable trajectories. The performance exhibited by the motor under these conditions is remarkable, in spite of the fact that the evaluation considers reference speed trajectories that includes crossing zero operation.

The paper is organized as follows: The induction motor model considered for the analysis is presented in Section II. The sensorless PBC is developed in Section III where the ISS of the error dynamics is also presented. Section IV is devoted to quickly present the considered sensorless observer while the results obtained from the numerical evaluation are included in Section V. Some concluding remarks are presented in Section VI.

II. INDUCTION MOTOR MODEL

In order to develop the proposed sensorless controller, in this paper it is considered the standard 2ϕ equivalent model of the unsaturated IM given by (Meisel, 1966)

$$\mathcal{D}\dot{x} + \mathcal{C}(x)x + \mathcal{R}x = \mathcal{Q} \tag{1}$$

with $x^T = \left[i^T, \psi^T, \omega\right]$, $\mathcal{D} = diag\left\{L_r\sigma\mathcal{I}_2, \mathcal{I}_2, L_rJ\right\}$

$$\mathcal{C}(x) = \begin{bmatrix} 0 & 0 & n_pM\mathcal{J}\psi \\ 0 & -n_p\omega\mathcal{J} & 0 \\ -n_pM\psi^T\mathcal{J}^T & 0 & 0 \end{bmatrix} \tag{2}$$

$$\mathcal{R} = \begin{bmatrix} L_r\sigma\gamma\mathcal{I}_2 & -\beta_3\mathcal{I}_2 & 0 \\ -\beta_3\mathcal{I}_2 & \beta_1\mathcal{I}_2 & 0 \\ 0 & 0 & L_rB \end{bmatrix};\ \mathcal{Q} = \begin{bmatrix} L_ru \\ 0 \\ -L_rT_L \end{bmatrix} \tag{3}$$

where $i^T = [i_a, i_b] \in \mathcal{R}^2$ are the stator currents, $\psi^T = [\psi_a, \psi_b] \in \mathcal{R}^2$ are the rotor fluxes, $\omega \in \mathcal{R}$ is the rotor speed, $u^T = [u_a, u_b] \in \mathcal{R}^2$ are the stator (control) voltages and T_L is the (externally applied) load torque.

The (all positive) motor parameters are

$$\beta_1 = \frac{R_r}{L_r};\ \beta_3 = \frac{R_rM}{L_r}$$

$$\sigma = \frac{L_sL_r - M^2}{L_r};\ \gamma = \frac{M^2R_r + L_r^2R_s}{\sigma L_r^2}$$

with L_s, L_r the stator and rotor inductances, M the mutual inductance, R_s, R_r the stator and rotor resistances, J the rotor inertia, B the rotor friction coefficient and n_p the number of pole pairs.

The matrices $\mathcal{J} \in \mathcal{R}^{2\times2}$, $\mathcal{I} \in \mathcal{R}^{2\times2}$ are given by

$$\mathcal{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = -\mathcal{J}^T, \mathcal{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Under sensorless operation, the only available for measurement variables are the stator currents i and the control voltages u, i.e. the controller design must be carried out by assuming that the rotor fluxes ψ and the motor speed ω can not be measured. In addition, the external disturbance given by the load torque T_L is unknown.

Remark 1. Dealing with unknown T_L of general shape is a hard topic. As will be clear latter, the controller proposed in this paper will be able only to deal with unknown but constant load torque.

III. SENSORLESS PBC DESIGN

In this section the sensorless version of the PBC reported in (Espinosa–Perez and Ortega, 1995) is developed to later on establish the ISS properties of the error dynamics obtained as a result of this design. Although the followed methodology is the same as the presented in (Espinosa–Perez and Ortega, 1995), for the sake of clarity the complete design is included.

Define the *control error* as the difference between the actual and the desired state

$$e = x - x_d = \begin{bmatrix} e_s \\ e_r \\ e_\omega \end{bmatrix};\ x_d = \begin{bmatrix} i_d \\ \psi_d \\ \omega_d \end{bmatrix}$$

with x_d the desired behavior for the motor state. In terms of these variables the IM model (1) can be written as

$$\mathcal{D}\dot{e} + \mathcal{C}(x)e + \mathcal{R}e = \Phi \tag{4}$$

with

$$\Phi = \mathcal{Q} - \left\{\mathcal{D}\dot{x}_d + \mathcal{C}(x)x_d + \mathcal{R}x_d\right\} \tag{5}$$

For classical PBC, the purpose of the design is to exploit the passivity properties of the error dynamics (4) by defining the control law in such a way that $\Phi = -\mathcal{K}e$. This implies that the error dynamics takes the form

$$\mathcal{D}\dot{e} + \mathcal{C}(x)e + \left[\mathcal{R} + \mathcal{K}\right]e = 0 \tag{6}$$

Thus, by applying standard stability arguments, it can be shown that

$$\lim_{t\to\infty} e(t) = 0$$

whenever $[\mathcal{R}+\mathcal{K}]$ became a symmetric positive definite matrix.

For sensorless design, the classical PBC can not be longer applied since equality (6) is not satisfied. In the next proposition it is presented the structure of the error dynamics that is obtained when rotor and mechanical variables are not measurable.

Proposición 1: Consider the induction motor model (1). Assume that

A.1 The only available variables are stator currents i and stator voltages u.
A.2 The load torque T_L is an unknown disturbance.
A.3 The motor parameters are known.

Define the control law as

$$u=\sigma\frac{di_d}{dt}+\frac{n_pM}{L_r}\mathcal{J}\hat{\psi}\omega_d+\sigma\gamma i_d-\frac{\beta_3}{L_r}\psi_d-\frac{k_1}{L_r}e_s \quad (7)$$

where $\hat{\psi}$ is the estimate of the rotor fluxes ψ while the desired dynamic behavior for the rotor fluxes satisfies

$$\dot{\psi}_d=\left[n_p\hat{\omega}+\frac{R_r}{n_p\beta^2}T_d\right]\mathcal{J}\psi_d;\ \psi_d(0)=\begin{bmatrix}\beta\\0\end{bmatrix} \quad (8)$$

with $\beta=\|\psi_d\|$ the norm of the desired rotor flux vector.

The desired stator currents are such that

$$i_d=\beta_3^{-1}\left[\frac{R_r}{n_p\beta^2}T_d\mathcal{J}\psi_d+\beta_1\psi_d\right] \quad (9)$$

and the desired generated torque is given by

$$T_d=J\dot{\omega}_d+B\omega_d+\hat{T}_L-k_2(\hat{\omega}-\omega_d) \quad (10)$$

with $\hat{\omega}$ and $\hat{T}_L$ estimates for the motor speed and the load torque, respectively.

Under these conditions the error dynamics (4) can be written as

$$\mathcal{D}\dot{e}+\mathcal{C}(x)e+\bar{\mathcal{R}}e=\mathcal{M}\tilde{x} \quad (11)$$

with

$$\bar{\mathcal{R}}=\begin{bmatrix}(L_r\sigma\gamma+k_1)\mathcal{I}_2 & -\beta_3\mathcal{I}_2 & 0\\ -\beta_3\mathcal{I}_2 & \beta_1\mathcal{I}_2 & 0\\ 0 & -n_pMi_d^T\mathcal{J} & L_rB+k_2\end{bmatrix} \quad (12)$$

and

$$\mathcal{M}=\begin{bmatrix}n_pM\mathcal{J}\omega_d & 0 & 0\\ 0 & -n_p\mathcal{J}\psi_d & 0\\ 0 & -k_2 & L_r\end{bmatrix};\ \tilde{x}=\begin{bmatrix}\tilde{\psi}\\ \tilde{\omega}\\ \tilde{T}_L\end{bmatrix}$$

Demostración: The first two rows of (5) are given by

$$\Phi_1=L_ru-\left\{L_r\sigma\frac{di_d}{dt}+n_pM\mathcal{J}\psi\omega_d+L_r\sigma\gamma i_d-\beta_3\psi_d\right\} \quad (13)$$

which under the definition of the control law (7) takes de form

$$\Phi_1=n_pM\mathcal{J}\tilde{\psi}\omega_d-k_1e_s \quad (14)$$

Regarding the second two rows of (5), they are given by

$$\Phi_2=-\{\dot{\psi}_d-n_p\omega\mathcal{J}\psi_d-\beta_3i_d+\beta_1\psi_d\} \quad (15)$$

which in terms of the observation error for the rotor speed $\tilde{\omega}=\hat{\omega}-\omega$ can be written as

$$\Phi_2=-\{\dot{\psi}_d-n_p(\hat{\omega}-\tilde{\omega})\mathcal{J}\psi_d-\beta_3i_d+\beta_1\psi_d\}$$

Thus, if the dynamic desired behavior for the rotor fluxes is defined as (8) considering

$$T_d=-n_p\frac{M}{L_r}\psi_d^T\mathcal{J}i_d$$

then equation (15) takes the form

$$\Phi_2=-\{\frac{R_r}{n_p\beta^2}T_d\mathcal{J}\psi_d+n_p\tilde{\omega}\mathcal{J}\psi_d-\beta_3i_d+\beta_1\psi_d\}$$

Hence, substitution of the desired stator currents expression (9) leads to

$$\Phi_2=-n_pe_\omega\mathcal{J}\psi_d \quad (16)$$

Finally, the fifth row of equation (5) is given by

$$\Phi_3=-L_rT_L-\left\{L_rJ\dot{\omega}_d-n_pM\psi^T\mathcal{J}^Ti_d+L_rB\omega_d\right\} \quad (17)$$

which, by considering that $e_r=\psi-\psi_d$, can be written as

$$\Phi_3=-L_r\left\{T_L+J\dot{\omega}_d-T_d-n_p\frac{M}{L_r}e_r^T\mathcal{J}^Ti_d+B\omega_d\right\}$$

If (10) is considered, then equation (17) becomes

$$\Phi_3=-L_r\left\{-\tilde{T}_L-n_p\frac{M}{L_r}e_r^T\mathcal{J}^Ti_d+k_2(\hat{\omega}-\omega_d)\right\} \quad (18)$$

Noting that $\tilde{\omega}=\hat{\omega}-\omega$ equation (18) can be finally written as

$$\Phi_3=L_r\tilde{T}_L+n_pMi_d^T\mathcal{J}^Te_r-k_2\tilde{\omega}-k_2e_\omega \quad (19)$$

The proof is completed by noting that substitution of (14), (16) and (19) into equation (4) gives as a result expression (11). ■

The main result of the paper, i.e. the establishment of ISS properties for the error equation (11), is presented in the next

Proposición 2: Consider the induction motor model (1) in closed loop with the output feedback sensorless controller (7), (8), (9), (10). If the controller gains satisfy

$$k_1>\frac{\beta_3^2}{\beta_1}$$
$$k_2>\frac{n_p^2M^2}{4L_r\beta_1}\left[1+\frac{\beta_3^2}{\beta_1(L_r\sigma\gamma+k_1)}\right]\|i_d\|^2$$

then, the error dynamics (11) defines an input to state stable mapping considering $\tilde{x}$ as input and e as state.

Demostración: Consider the positive definite function

$$V=\frac{1}{2}e^T\mathcal{D}e$$

whose time derivative along the trajectories of (11) is given by

$$\dot{V}=-e^T\bar{\mathcal{R}}_se+e^T\mathcal{M}\tilde{x} \quad (20)$$

where $\bar{\mathcal{R}}_s$ is the symmetric part of matrix $\bar{\mathcal{R}}$ given in (12).

Noting that if the conditions imposed over the controller gains k_1 and k_2 are satisfied $\bar{\mathcal{R}}_s$ becomes, by a straightforward application of the Schur complement, positive definite, then it can be proved that $\tilde{x} = 0$ implies that $e = 0$ is globally exponentially stable since

$$\dot{V} = -e^T \bar{\mathcal{R}}_s e < 0$$

On the other hand, if $\tilde{x} \neq 0$ then equation (20) can be equivalently written as

$$\dot{V} = -(1-\theta)e^T \bar{\mathcal{R}}_s e - \theta e^T \bar{\mathcal{R}}_s e + e^T \mathcal{M} \tilde{x}$$

with θ a positive constant which belongs to the set $(0, 1)$.

Thus

$$\dot{V} \leq -(1-\theta)e^T \bar{\mathcal{R}}_s e$$

for all

$$\|e\| \geq \frac{\|\mathcal{M}\|}{\theta \lambda_{min}(\bar{\mathcal{R}}_s)} \|\tilde{x}\|$$

proving that the map $\Sigma : \tilde{x} \to e$ is input to state stable. ■

The following remarks about the presented result are in order:

Remark 2. The importance of the obtained ISS property of the error dynamics (11) can hardly be overestimated. This result states that no matter how the observer for obtaining $\tilde{x}$ is designed, convergence of this error to zero guarantees that the control error e will also tend to zero, i.e. a separation principle for the proposed PBC has been established.

Remark 3. Evidently, although strong, the presented ISS property does not remove the limitations imposed by the lack of globally defined observability properties of the induction motor model (1). However an interesting feature of ISS is related with the fact that if the input is bounded then the state will be also bounded. This characteristic will be exploited in the design of the controller evaluated in Section V by considering a recently reported observer, introduced in the next section, that guarantees bounded observation errors when the motor operates under undistinguishable trajectories.

IV. SENSORLESS OBSERVER

The study of the observability properties of the induction motor model (1) is a topic that has been recently developed in a detailed way (Ibarra, 2005). As a result, it is currently know that this machine, under sensorless operation, exhibits pairs of plant's trajectories that are indistinguishable, i.e. pairs of different state trajectories with the same input/output behavior. In fact, it has been shown in (Ibarra–Rojas et al, 2004) that the IM indistinguishable trajectories are not convergent, so that this machine is neither observable nor detectable for *every* trajectory.

The situation described above represents an obstacle to the existence of (global) observers, since no observer can converge for every plant's trajectory. Indeed, convergence of any observer could be guaranteed only for a subset of the plant's trajectories that excludes the diverging indistinguishable ones.

Although several observer structures can be found in the literature for dealing with the limitations imposed by the aforementioned lack of observability, in (Moreno and Espinosa, 2006) it is presented a study developed to identify the properties of an observer whose structure is given by a copy of the plant corrected with an output injection to stabilize the error dynamics. Interestingly enough, the analysis is carried out by exploiting – again – the passivity properties of the motor model.

The observer described above is presented in the next proposition since it will be used in Section V to illustrate how the ISS properties of the Sensorless PBC can be exploited to ensemble this controller with a given observer. The interested reader is referred to (Moreno and Espinosa, 2006) for a detailed analysis of its convergence properties.

Proposición 3: Consider the IM model (1). Assume

O.1 The only measurable signals are (i, u).
O.2 The load torque is constant but un*known*.
O.3 All parameters are known and $B > 0$.

Under these conditions, the sensorless observer defined by

$$\begin{aligned}
\frac{d\hat{\imath}}{dt} &= \beta\left[(a\mathbb{I}+n_p\hat{\omega}\mathbb{J})\,\hat{\psi} - (Ma+b)\,i + cu\right] - K_i\,(\hat{\imath}-i)\ , \\
\dot{\hat{\omega}} &= -\frac{B}{J}\hat{\omega} + \alpha\hat{\psi}^T\mathbb{J}i - \frac{\hat{T}_L}{J} - K_\omega\,(\hat{\imath}-i)\ , \qquad (21)\\
\dot{\hat{\psi}} &= -\,(a\mathbb{I}+n_p\hat{\omega}\mathbb{J})\,\hat{\psi} + Mai - K_\psi\,(\hat{\imath}-i)\ , \\
\dot{\hat{T}}_L &= -K_T\,(\hat{\imath}-i)\ ,
\end{aligned}$$

with output injection gains given as

$$\begin{aligned}
&K_i = k_i\mathcal{I};\ k_i \geq 0 \\
&K_\omega = \frac{\alpha}{\beta}i^T\mathcal{J} + k\left[n_p\beta\left(1+g^T(t)\,g(t)\right)\hat{\psi}^T\mathcal{J}^T + \right.\\
&\quad \left. -\,g_1^T(t)\left(a\mathcal{I}+n_p\hat{\omega}\mathcal{J}^T\right)\right]\ , \\
&K_z = k\left(-n_p\beta g_1(t)\,\hat{\psi}^T\mathcal{J}^T + a\mathcal{J} + n_p\hat{\omega}\mathcal{J}^T\right)\ , \\
&K_T = -kn_p\beta g_2(t)\,\hat{\psi}^T\mathcal{J}^T\ .
\end{aligned}$$

where

$$\begin{aligned}
g(t) &= \begin{bmatrix} g_1(t) \\ g_2(t) \end{bmatrix} \\
&= \exp\left(-\frac{B}{J}t\right)\int_0^t \exp\left(\frac{B}{J}\tau\right)\begin{bmatrix} \frac{\alpha}{\beta}\mathcal{J}^T i(\tau) \\ \frac{1}{J} \end{bmatrix} d\tau
\end{aligned}$$

and

$$a = \beta_1;\ \beta = \frac{\beta_3}{\sigma R_r};\ \alpha = \frac{n_p\beta_3}{JR_r};\ b = \frac{R_rR_s}{\beta_3};\ c = \frac{R_r}{\beta_3}$$

satisfies:

1. For every pair (r, ϵ), such that $r > \epsilon > 0$, and any trajectory of the plant with bounded state, if the initial estimation error belongs to the set $C_r =$

$\left\{|\tilde{\omega}| \le r\ ,\ \left\|\tilde{\psi} - \beta\tilde{i}\right\| \le r\right\}$, bounded in $\tilde{\omega}$ and $\tilde{\psi}-\beta\tilde{i}$, it will converge to the compact set $\mathcal{C}_\epsilon = \left\{\left\|\tilde{i}\right\| \le \epsilon\right\} \cap C_r$, and will stay there for all future times.
2. If the trajectory is distinguishable the observation error is finally and uniformly bounded.
3. Moreover, if the distinguishable trajectory is far enough from an indistinguishable one, the observation error converges uniformly and asymptotically.

In the next section the presented observer will be numerically evaluated operating in closed–loop with the PBC developed in Section III.

V. SIMULATION RESULTS

The usefulness of the proposed controller was validated via numerical simulations. To this end, there were considered the following motor parameters: $L_r = 0{,}076$ H, $L_s = 0{,}142$ H, $R_r = 0{,}93\ \Omega$, $R_s = 1{,}633\ \Omega$, $M = 0{,}099$ H, $n_p = 2$, $J = 0{,}029$ Kg m^2, $f = 0{,}13$ s^{-1}. The *unknown* Load Torque applied was constant of value $T_L = 5$ Nm.

Regarding the controller structure, the speed reference was set to $\omega_d(t) = 300\sin(0{,}25t)$ with a desired value for the rotor flux norm equal to $\beta = 0{,}8Wb$. This kind of reference establishes a challenge for the control scheme since it starts in a well-known unobservable trajectory, i.e zero motor speed. The experiment is further complicated by considering that the motor is at standstill at the beginning, condition that implies that the initial motor speed indeed corresponds with this unobservable trajectory.

Regarding the observer information, the considered initial values were: $\hat{\omega}(0) = 50rpm$ for the estimated motor speed, $\hat{\psi}(0) = 0{,}09Wb$ for the estimated rotor fluxes and $\hat{i}(0) = 1A$ for the estimated stator currents. The observer gains were set to $k_i = 1000$ and $k = 20$.

Under the conditions described above, in Figure 1 the motor speed response is presented. In this picture three important elements must be noticed. First, how the transient response due to uncertainty in the motor variables is quickly compensated. Second, that the control error is very small, and, third, that even that the reference trajectory crosses the zero level, the control objective is still achieved.

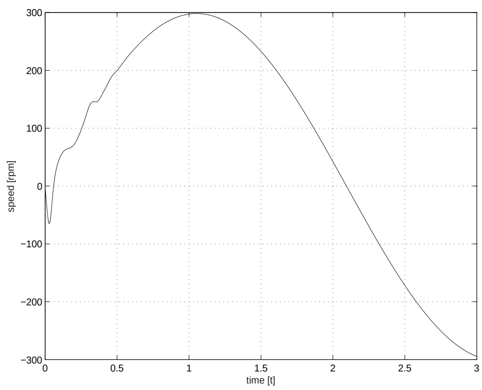

Figura 1. Motor speed response.

In order to illustrate the internal stability properties and, at the same time, the fact that the controller does not demand stringent requirements for its operation, in Figure 2 the rotor fluxes are presented while the stator currents are shown in Figure 3. The control signals are depicted in Figure 4. Notice that besides their boundedness, the maximum values that they reach correspond to a physical achievable operation.

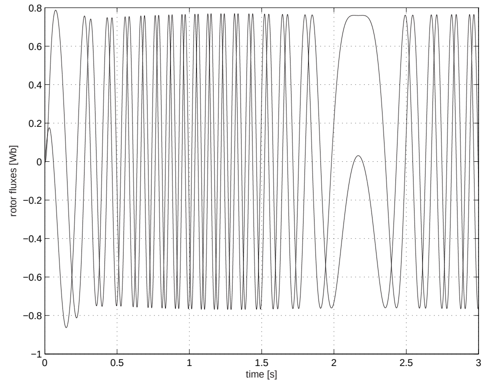

Figura 2. Rotor fluxes response.

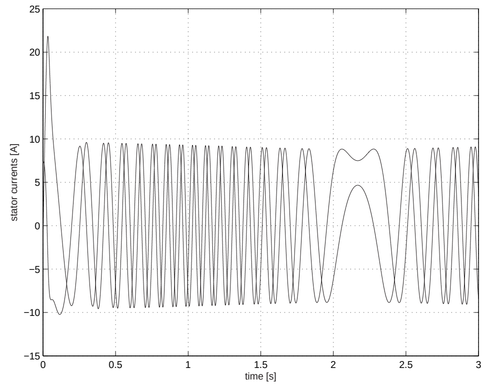

Figura 3. Stator currents response.

Finally, to illustrate the observer performance, in Figure 5, Figure 6 and Figure 7 the observation errors for the rotor fluxes, stator currents and load torque, respectively, are presented. From these figures, it is clear how the the actual value for the motor variables is achieved very quickly.

VI. CONCLUDING REMARKS

In this paper a separation principle for a passivity–based sensorless controller for induction motors has been established. This contribution was obtained by finding some Input–to–State Stability properties of the error dynamics that results from the closed–loop composed by the induction motor and the controller. The importance of this result lies in the fact that the separation principle is valid for every sensorless observer, although convergence of the control error still depends on the observer performance. The advantage of having this property was exploited to numerically

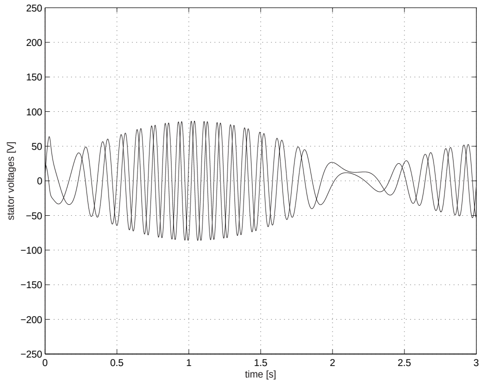

Figura 4. Stator voltages response.

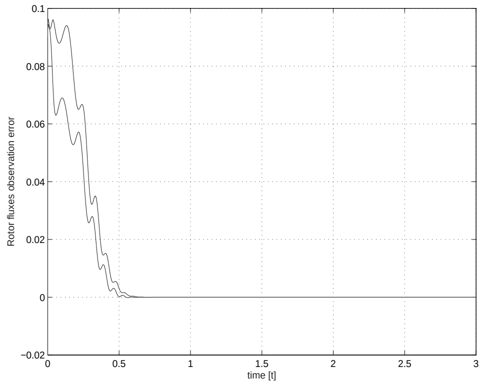

Figura 5. Rotor fluxes observation error response.

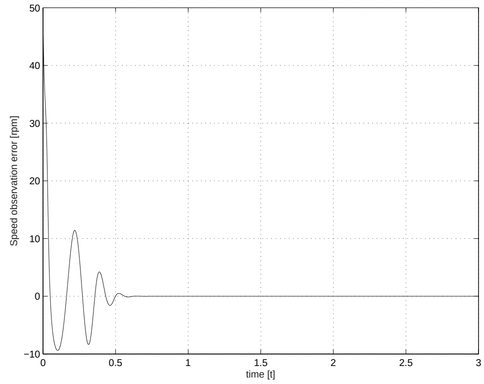

Figura 6. Speed observation error response.

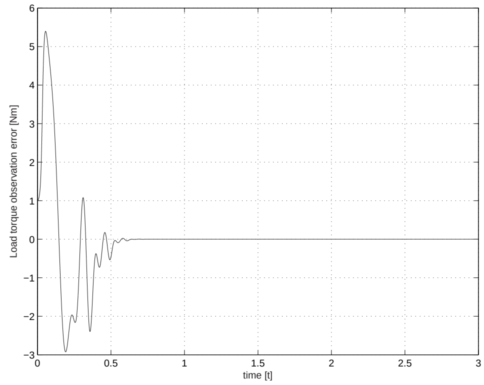

Figura 7. Load torque observation error response.

evaluate a semiglobal sensorless observer operating together with the proposed passivity–based controller. Remarkable performances were obtained even in the presence of zero crossing speed references.

VII. ACKNOWLEDGEMENTS

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