A Robust Position Control for Induction Motors using a Load Torque Observer

Oscar Barambones, Patxi Alkorta, Jose Maria Gonzalez de Durana and Enrique Kremers

***Abstract*— The design of a robust position control scheme for an induction motor drive using the field oriented control theory is proposed. The proposed sliding-mode control law incorporates an adaptive sliding gain in order to adjust the sliding gain to the system uncertainties. Moreover, the sliding gain adaptation avoids having to calculate the upper limit for the system uncertainties. The design also incorporates a load torque observer in order to obtain the load torque applied to the induction motor without the use of the load torque sensor. The proposed observer is based on the system dynamical equation and uses the rotor speed and the stator current in order to obtain the load torque.**

The stability analysis of the proposed controller under parameter uncertainties and load torque variations is provided using the Lyapunov stability theory. Finally experimental results show that the proposed controller with the proposed observer provides high-performance dynamic characteristics and that this scheme is robust with respect to plant parameter uncertainties and load torque variations.

I. INTRODUCTION

Induction motor drives based on digital control technology have reached a high utilization in a broad range of applications ranging from low-cost to high-performance systems.

The field oriented control theory (FOC) have been used in the design of induction motor drives for high-performance applications. Using this control method, the dynamic behavior of the induction motor is rather like that of a separately excited direct current (DC) motor. However, like a DC motors occurs, the control performance of the induction motor is still influenced by the plant parameter variation and external disturbance. Therefore, many studies have been made on the motor drives in order to preserve the performance under these parameter variations and external load disturbance, such as nonlinear control, optimal control, predictive control, variable structure system control, adaptive control, fuzzy control and neural control [1]-[5].

The sliding-mode control strategy has been focussed on many studies and research for the position control of the induction motors [6]-[8]. However the traditional sliding control schemes requires the prior knowledge of an upper bound for the system uncertainties since this bound is employed in the switching gain calculation. This upper bound should be determined as precisely as possible, because as higher is the upper bound, higher value should be considered for the sliding gain, and this implies a high control effort which is undesirable in a practice. In order to surmount this drawback, in the present paper it is proposed an adaptive law to calculate the sliding gain which avoids the necessity of calculate an upper bound of the system uncertainties.

On the other hand in the last decade remarkable efforts have been made to reduce the number of sensors in the control systems. The sensors increases the cost and also reduces the reliability of the control system, because this elements are generally expensive, delicate and difficult to instal [9]-[11].

This paper presents a position control scheme consisting, on the one hand of a load torque estimation algorithm in order to avoid the load torque sensor, and on the other hand, of an adaptive sliding mode control algorithm that overcome the system uncertainties and load disturbances. Moreover, the proposed control scheme do not present a high computational cost and therefore can be implemented easily in a real time applications over a low-cost DSP processor.

This manuscript is organized as follows. The load torque observer is introduced in Section 2. The proposed adaptive variable structure robust position control is presented in Section 3. Then, some simulation results are presented in Section 4. Finally, concluding remarks are stated in Section 5.

II. LOAD TORQUE OBSERVER

In the traditional sliding mode control schemes, the load torque should be known or should be measured using a torque sensors in order to compensate this load torque. On the other hand the load torque could be considered as a system uncertainty but in this cases the control system should be robust under all load torque values that would appear along the time.

Therefore, in the case of that the load torque is unknown or is very variable along the time, and the system has no torque sensors a good solution could be the use of a load torque estimator. In this paper a second order Luenberger observer is proposed, in order to obtain the load torque applied to the induction motor without the use of the load torque sensor.

The mechanical equation of an induction motor can be written as:

$$J\ddot{\theta}_m + B\dot{\theta}_m + T_L = T_e \tag{1}$$

Oscar Barambones is with Dpto. Ingeniería de Sistemas y Automática EUI de Vitoria. Nieves Cano 12. 01006 Vitoria, Spain. oscar.barambones@ehu.es

Patxi Alkorta is with Dpto. Ingeniería de Sistemas y Automática EUITI de Eibar. Avda. Otaola, 29. 20600 Eibar, Spain. patxi.alkorta@ehu.es

Jose Maria Gonzalez de Durana is with Dpto. Ingeniería de Sistemas y Automática EUI de Vitoria. Nieves Cano 12. 01006 Vitoria, Spain. josemaria.gonzalezdedurana@ehu.es

Enrique Kremers is with European Institute for Energy Research (EIFER). Karlsruhe Institute of Technology. Karlsruhe, Germany. Enrique.Kremers@eifer.uni-karlsruhe.de

where J and B are the inertia constant and the viscous friction coefficient of the induction motor respectively; T_L is the external load; θ_m is the rotor mechanical position, which is related to the rotor electrical position, θ_r, by $\theta_m = 2\,\theta_r/p$ where p is the pole numbers and T_e denotes the generated torque of an induction motor, defined as [12]:

$$T_e = \frac{3p}{4}\frac{L_m}{L_r}(\psi_{dr}^e i_{qs}^e - \psi_{qr}^e i_{ds}^e) \tag{2}$$

where ψ_{dr}^e and ψ_{qr}^e are the rotor-flux linkages, with the subscript 'e' denoting that the quantity is refereed to the synchronously rotating reference frame; i_{ds}^e and i_{qs}^e are the d-q stator current components, and p is the pole numbers.

The relation between the synchronously rotating reference frame and the stationary reference frame is performed by the so-called reverse Park's transformation [13]:

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & -\sin(\theta_e) \\ \cos(\theta_e - 2\pi/3) & -\sin(\theta_e - 2\pi/3) \\ \cos(\theta_e + 2\pi/3) & -\sin(\theta_e + 2\pi/3) \end{bmatrix} \begin{bmatrix} x_d^e \\ x_q^e \end{bmatrix} \tag{3}$$

where θ_e is the angle position between the d-axis of the synchronously rotating reference frame and the a-axis of the stationary reference frame, and it is assumed that the quantities are balanced.

Using the field-orientation control principle [13], the current component i_{ds}^e is aligned in the direction of the rotor flux vector $\bar{\psi}_r$, and the current component i_{qs}^e is aligned in the perpendicular direction to it. At this condition, it is satisfied that:

$$\psi_{qr}^e = 0, \qquad \psi_{dr}^e = |\bar{\psi}_r| \tag{4}$$

Taking into account the results presented in equation (4), the equation of induction motor torque (2) is simplified to:

$$T_e = \frac{3p}{4}\frac{L_m}{L_r}\psi_{dr}^e i_{qs}^e = K_T\, i_{qs}^e \tag{5}$$

where K_T is the torque constant, defined as follows:

$$K_T = \frac{3p}{4}\frac{L_m}{L_r}\psi_{dr}^{e^*} \tag{6}$$

where $\psi_{dr}^{e^*}$ denotes the command rotor flux.

With the above mentioned proper field orientation, the dynamics of the rotor flux is given by [12]:

$$\frac{d\psi_{dr}^e}{dt} + \frac{\psi_{dr}^e}{T_r} = \frac{L_m}{T_r}\, i_{ds}^e \tag{7}$$

where $T_r = L_r/R_r$ is the rotor time constant.

From the mechanical system equation 1 and the induction motor torque equation 5, the following dynamic equation is obtained:

$$\dot{w}_m = -\frac{B}{J}w_m + \frac{K_T}{J}\, i_{qs}^e - \frac{1}{J}T_L \tag{8}$$

where $w_m = \dot{\theta}_m$

It is assumed that the load torque only changes at certain moments, and therefore the load torque can be considered as a quasi-constant signal:

$$\dot{T}_L = 0 \tag{9}$$

Then, the previous equations can be collected in the next estate equation:

$$\dot{z} = A_z z + B_z i_{qs}^e \tag{10}$$

where:

$$\begin{aligned} z &= [w_m \quad T_L]^T \\ A_z &= \begin{bmatrix} -\frac{B}{J} & -\frac{1}{J} \\ 0 & 0 \end{bmatrix} \\ B_z &= \begin{bmatrix} \frac{K_T}{J} & 0 \end{bmatrix}^T \end{aligned}$$

Considering the rotor speed as the system output, the output equation is:

$$y = w_m = C_z\, z \tag{11}$$

where

$$C_z = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

Then, the states observer, which estimates the states (rotor speed and load torque), is defined by means of the following equation (Luenberger observer):

$$\begin{aligned} \dot{\hat{z}} &= A_z\hat{z} + B_z i_{qs}^e + H\,(y - \hat{y}) & (12) \\ &= A_z\hat{z} + B_z i_{qs}^e + H(y - C_z\hat{z}) & (13) \\ &= (A_z - HC_z)\hat{z} + B_z i_{qs}^e + Hy & (14) \end{aligned}$$

where the symbol $(\hat{\cdot})$ represents the estimated values and H is the observer gain matrix.

Therefore, if the observer gain H is adequately chosen, then the estimation error converges to zero. Consequently the estimated states $\hat{w}_m, \hat{T}_L$ converges to the real states w_m, T_L as t tends to infinity. Hence, the load torque may be obtained from the states observer given by equation (14), that uses the rotor speed and the stator current in order to obtain the load torque applied to the induction motor.

III. ADAPTIVE VARIABLE STRUCTURE POSITION CONTROL

From eqn. (1) and eqn. (5), the mechanical equation of an induction motor can be written, taking into account the parameter uncertainties, as follows:

$$\ddot{\theta}_m = -(a + \triangle a)\dot{\theta}_m - (f + \triangle f) + (b + \triangle b)i_{qs}^e \tag{15}$$

where the parameters are defined as:

$$a = \frac{B}{J}, \quad b = \frac{K_T}{J}, \quad f = \frac{\hat{T}_L}{J}; \tag{16}$$

and the terms $\triangle a$, $\triangle b$ and $\triangle f$ represents the uncertainties of the terms a, b and f respectively.

It should be noted that the load torque T_L has been replaced by the estimated load torque $\hat{T}_L$ and the difference between them is taken as an uncertainty.

Let us define the position tracking error as follows:

$$e(t) = \theta_m(t) - \theta_m^*(t) \tag{17}$$

where θ_m^* is the rotor position command.

Taking the second derivative of the previous equation with respect to time yields:

$$\ddot{e}(t) = \ddot{\theta}_m - \ddot{\theta}_m^* = -a\,\dot{e}(t) + u(t) + d(t) \tag{18}$$

where the following terms have been collected in the signal $u(t)$,

$$u(t) = b\, i_{qs}^e(t) - a\,\dot{\theta}_m^*(t) - f(t) - \ddot{\theta}_m^*(t) \tag{19}$$

and the uncertainty terms have been collected in the signal $d(t)$,

$$d(t) = -\triangle a\, w_m(t) - \triangle f(t) + \triangle b\; i_{qs}^e(t) \tag{20}$$

Now, we are going to define the sliding variable $S(t)$ as:

$$S(t) = \dot{e}(t) + k\, e(t) \tag{21}$$

where k is a positive constant gain.

Then, the sliding surface is defined as:

$$S(t) = \dot{e}(t) + k\, e(t) = 0 \tag{22}$$

The variable structure position controller is designed as:

$$u(t) = -(k-a)\,\dot{e}(t) - \hat{\beta}\gamma\,\mathrm{sgn}(S) \tag{23}$$

where the k is the previously defined gain, β is the switching gain, S is the sliding variable defined in eqn. (21) and $\mathrm{sgn}(\cdot)$ is the sign function.

Finally, the switching gain $\hat{\beta}$ is adapted according to the following updating law:

$$\dot{\hat{\beta}}(t) = \gamma\,|S(t)| \qquad\qquad \hat{\beta}(0) = 0 \tag{24}$$

where γ is a positive constant that let us choose the adaptation speed for the sliding gain.

In order to obtain the position trajectory tracking, the following assumption should be formulated:

($\mathcal{A}\,1$) There exits an unknown finite and positive switching gain β such that

$$\beta > d_{max} + \eta \qquad \eta > 0$$

where $d_{max} \geq |d(t)| \quad \forall\; t$ and η is a positive constant.

Note that this condition only implies that the system uncertainties are bounded magnitudes.

Theorem 1: Consider the induction motor given by equation (15). Then, if the assumption ($\mathcal{A}\,1$) are verified, the control law (23) leads the rotor mechanical position $\theta_m(t)$ so that the position tracking error $e(t) = \theta_m(t) - \theta_m^*(t)$ tends to zero as the time tends to infinity.

The proof of this theorem will be carried out using the Lyapunov stability theory.

Proof : Define the Lyapunov function candidate:

$$V(t) = \frac{1}{2}S(t)S(t) + \frac{1}{2}\tilde{\beta}(t)\tilde{\beta}(t) \tag{25}$$

where $S(t)$ is the sliding variable defined previously and $\tilde{\beta}(t) = \hat{\beta}(t) - \beta$.

Its time derivative is calculated as:

$$\begin{aligned}
\dot{V}(t) = {} & S(t)\dot{S}(t) + \tilde{\beta}(t)\dot{\tilde{\beta}}(t) \\
& = S\cdot[\ddot{e} + k\,\dot{e}] + \tilde{\beta}\dot{\hat{\beta}} \\
& = S\cdot[(-a\,\dot{e} + u + d) + k\,\dot{e}] + \tilde{\beta}\,\gamma|S| \\
& = S\cdot[(k-a)\,\dot{e} + u + d] + (\hat{\beta} - \beta)\gamma|S| \\
& = S\cdot\Big[(k-a)\,\dot{e} - (k-a)\,\dot{e} - \hat{\beta}\gamma\,\mathrm{sgn}(S) + d\Big] \\
& \quad + (\hat{\beta} - \beta)\gamma|S| \\
& = d\,S - \hat{\beta}\gamma|S| + \hat{\beta}\gamma|S| - \beta\gamma|S| && (26) \\
& \leq |d||S| - \beta\gamma|S| \\
& \leq |d||S| - (d_{max} + \eta)\gamma|S| \\
& = |d||S| - d_{max}\,\gamma|S| - \eta\,\gamma|S| \\
& \leq -\eta\,\gamma|S| && (27)
\end{aligned}$$

then

$$\dot{V}(t) \leq 0 \tag{28}$$

It should be noted that the eqns. (18), (21), (23) and (24), and the assumption ($\mathcal{A}\,1$) have been used in the proof.

Using the Lyapunov's direct method, since $V(t)$ is clearly positive-definite, $\dot{V}(t)$ is negative semidefinite and $V(t)$ tends to infinity as $S(t)$ and $\tilde{\beta}(t)$ tends to infinity, then the equilibrium at the origin $[S(t), \tilde{\beta}(t)] = [0, 0]$ is globally stable, and therefore the variables $S(t)$ and $\tilde{\beta}(t)$ are bounded. Since $S(t)$ is bounded then it is deduced that $e(t)$ and $\dot{e}(t)$ are bounded.

On the other hand, making the derivative of equation (21) it is obtained,

$$\dot{S}(t) = \ddot{e}(t) + k\dot{e}(t) \tag{29}$$

then, substituting the equation (18) and (23) in the above equation,

$$\begin{aligned}
\dot{S}(t) &= -a\dot{e}(t) + u(t) + d(t) + k\dot{e}(t) \\
&= (k-a)\dot{e}(t) + d(t) + u(t) \\
&= (k-a)\dot{e}(t) + d(t) - (k-a)\dot{e}(t) - \hat{\beta}\gamma\,\mathrm{sgn}(S) \\
&= d(t) - \hat{\beta}\gamma\,\mathrm{sgn}(S) && (30)
\end{aligned}$$

From equation (30) we can conclude that $\dot{S}(t)$ is bounded because $d(t)$, γ and $\hat{\beta}$ are bounded.

Now, from equation (26) it is deduced that

$$\ddot{V}(t) = d\,\dot{S}(t) - \beta\,\gamma\frac{d}{dt}|S(t)| \tag{31}$$

which is a bounded quantity because $\dot{S}(t)$ is bounded.

Under these conditions, since $\ddot{V}$ is bounded, $\dot{V}$ is a uniformly continuous function, so Barbalat's lemma let us conclude that $\dot{V} \to 0$ as $t \to \infty$, which implies that $S(t) \to 0$ as $t \to \infty$.

Therefore $S(t)$ tends to zero as the time t tends to infinity. Moreover, all trajectories starting off the sliding surface $S = 0$ must reach it in finite time and then will remain on this surface. This system's behavior once on the sliding surface is usually called *sliding mode* [1].

When the sliding mode occurs on the sliding surface (22), then $S(t) = 0$, and therefore the dynamic behavior of the tracking problem (18) is equivalently governed by the following equation:

$$\dot{S}(t) = 0 \quad \Rightarrow \quad \dot{e}(t) = -k\, e(t) \tag{32}$$

Then, like k is a positive constant, the tracking error $e(t)$ and its derivative $\dot{e}(t)$ converges to zero exponentially.

It should be noted that, a typical motion under sliding mode control consists of a *reaching phase* during which trajectories starting off the sliding surface $S = 0$ move toward it and reach it in finite time, followed by *sliding phase* during which the motion will be confined to this surface and the system tracking error will be represented by the reduced-order model (32), where the tracking error tends to zero.

Finally, the torque current command, $i_{qs}^{e*}(t)$, can be obtained directly substituting eqn. (23) in eqn. (19):

$$i_{qs}^{e*}(t) = \frac{1}{b}\left[a\,\dot{\theta}_m^* + \ddot{\theta}_m^* + f(t) - (k-a)\,\dot{e} - \hat{\beta}\gamma\,\mathrm{sgn}(S)\right] \tag{33}$$

Therefore, the proposed variable structure control resolves the position tracking problem for the induction motor in presence of some uncertainties in mechanical parameters and load torque variations.

IV. SIMULATION RESULTS

In this section we will study the position regulation performance of the proposed sliding-mode control with the proposed load torque estimator versus reference and load torque variations by means of simulation examples.

The induction motor used in this case study is a 50 HP, 460 V, four pole, 60 Hz motor having the following parameters: $R_s = 0.087\,\Omega$, $R_r = 0.228\,\Omega$, $L_s = 35.5\,mH$, $L_r = 35.5\,mH$, and $L_m = 34.7\,mH$.

The system has the following mechanical parameters: $J = 1.662\,kg.m^2$ and $B = 0.1\,N.m.s$. It is assumed that there is an uncertainty around 20 % in the system parameters, that will be overcome by the proposed adaptive sliding mode control.

In addition the following values have been chosen for the controller parameters: $k = 50$, $\gamma = 30$ and $\hat{\beta}(0) = 0$.

In this example the motor starts from a standstill state and we want that the rotor position follows a smooth step command, that starts from 0 rad and finish at 2 rad. The system starts with an initial load torque $T_L = 100\,N.m$, then at time $t = 1.5\,s$, the load torque steps from $T_L = 100\,N.m$ to $T_L = 250\,N.m$, and finally at time $t = 2.5\,s$, the load torque steps from $T_L = 250\,N.m$ to $T_L = 350\,N.m$.

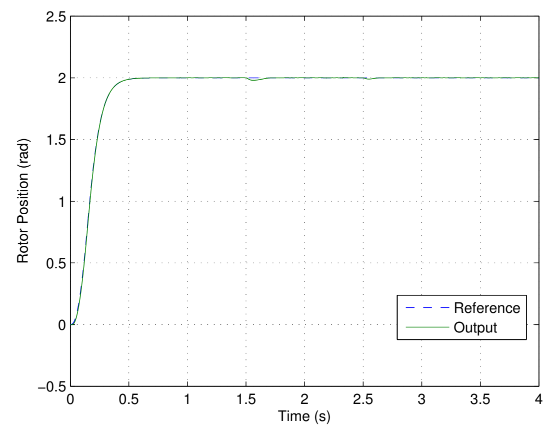

Fig. 1. Reference and real rotor position signals (rad)

Figure 1 shows the desired rotor position (dashed line) and the real rotor position (solid line). As it may be observed, after a transitory time in which the sliding gain is adapted, the rotor position tracks the desired position in spite of system uncertainties. Nevertheless, at time $t = 1.5\,s$ and $t = 2.5\,s$ a little position error can be observed. This error appears because there is a torque increment at this time, and then the controlled system lost the so called 'sliding mode', because the actual sliding gain is too small for the new uncertainty introduced in the system due to the load torque increment. But, after a small time, the sliding gain is adapted so that this gain can compensate for the new system uncertainties and then the rotor position error is eliminated.

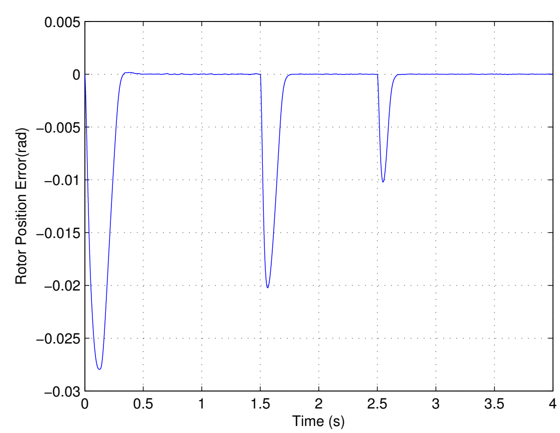

Fig. 2. Rotor position error (rad)

Figure 2 shows the rotor position tracking error. As in the previous figure, a small position error can be observed at time $t = 1.5\,s$ and $t = 2.5\,s$ due to the load torque increment at this time.

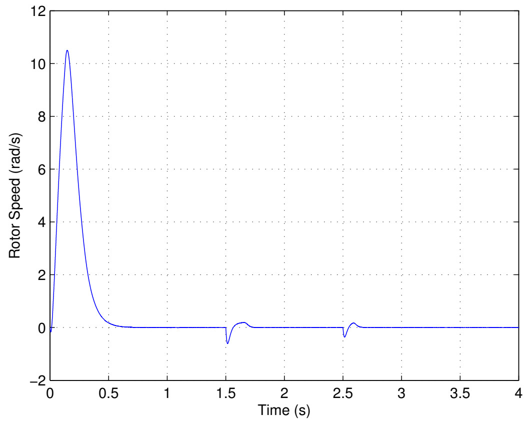

Fig. 3. Rotor Speed

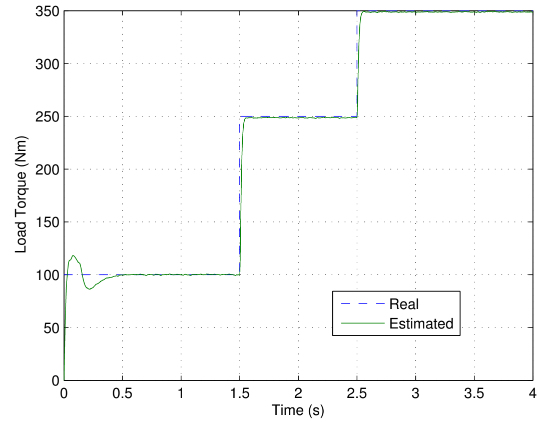

Fig. 5. Load Torque (N.m)

Figure 3 shows the rotor speed. This figure presents an increasing initial speed value but after $t = 0.2\,s$ the value decreases until zero because the rotor position reach the reference value.

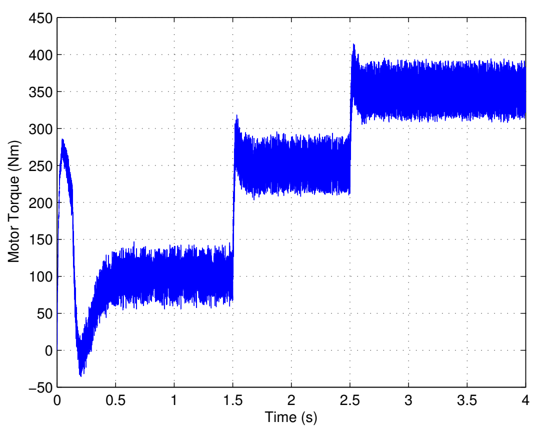

Fig. 4. Motor torque (N.m)

Figure 4 shows the motor torque. The motor torque has a high initial value in the speed acceleration zone because it is necessary a high torque to increment the rotor speed and then the value decreases in a deceleration region. Later at time $t = 1.5\,s$ and $t = 2.5\,s$ the torque increases due to the load torque increment. This figure shows that the so-called chattering phenomenon appears in the motor torque. Although this high frequency changes in the torque will be reduced by the mechanical system inertia, they could cause undesirable vibrations in the rotor, which may be a problem for certain systems. However, for the systems that do not support this chattering, it may be eliminated substituting the sign function by the saturation function in the control signal.

Figure 5 shows the estimated load torque (dashed line) and the real load torque (solid line). This figure shows that after a transitory time the load torque observer estimates the load torque. Then at time $t = 1.5\,s$ and and $t = 2.5\,s$ there is an increment in the load torque but the proposed estimator estimates the new load torque value quickly.

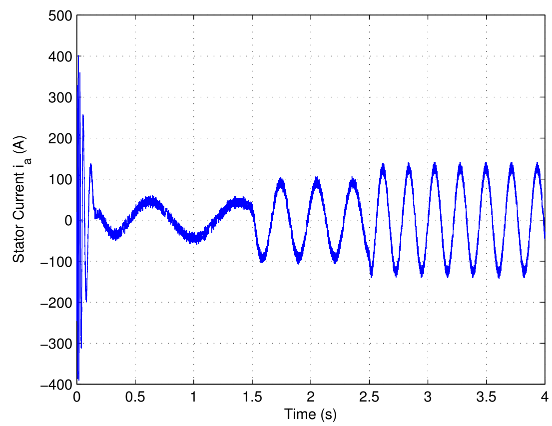

Fig. 6. Stator Current i_{sa} (A)

Figure 6 shows the stator current i_{sa}. As in the case of the motor torque, the current signal presents a high value in the initial state. Next, in the constant position region the current is lower because the motor torque only has to compensate the load torque. Then, at time $t = 1.5\,s$ and $t = 2.5\,s$ the current increases due to the load torque increment.

Figure 7 shows the time evolution of the sliding variable. In this figure it can be seen that the system reach the sliding condition $(S(t) = 0)$ at time $t = 0.3\,s$, but the system lost this condition at time $t = 1.5\,s$ and $t = 2.5\,s$ due to the load torque increment which produces an increment in the system uncertainties that could not be compensated by the actual value of the sliding gain.

Figure 8 presents the time evolution of the adaptive sliding gain. The sliding gain starts from zero and then it is increased until its value is high enough in order to compensate for the system uncertainties. Then, after $t = 0.3\,s$, the sliding gain is remained constant because the system uncertainties remain constant as well. Later at time $1.5\,s$ and $t = 2.5\,s$ there is an

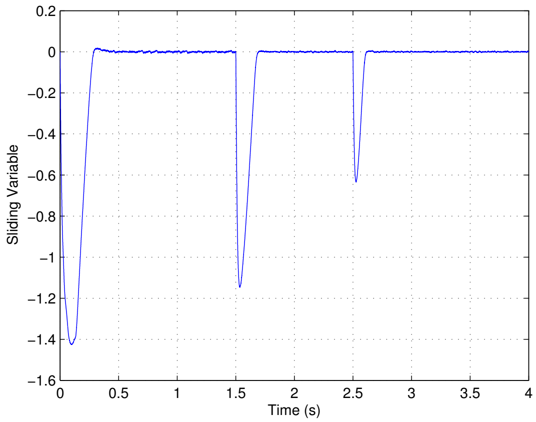

Fig. 7. Sliding Variable

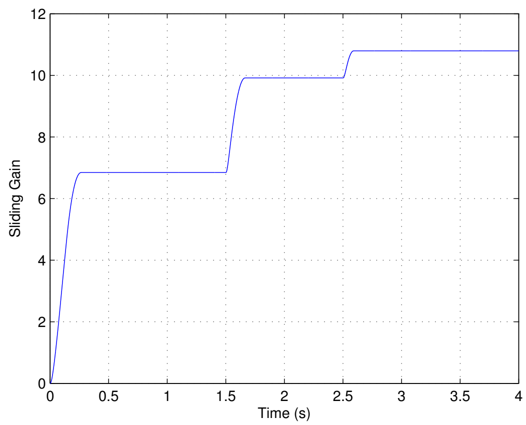

Fig. 8. Sliding Gain

increment in the system uncertainties caused by the rise in the load torque. Therefore the sliding gain is adapted once again in order to overcome the new system uncertainties. As it can be observed in the figure after this adaptation the sliding gain remains constant again, since the system uncertainties remain constant as well.

It should be noted that the adaptive sliding gain allows to employ a smaller sliding gain, because the sliding gain does not have to be chosen high enough to compensate for all the possible uncertainties that may appear in the system. In this way in the proposed adaptive scheme the sliding gain will be adapted (if necessary) when a new uncertainty appears in the system in order to surmount this uncertainty.

V. CONCLUSIONS

In this paper a robust position regulation for an induction motors using an adaptive sliding mode vector control has been presented. The proposed variable structure control incorporates an adaptive algorithm to calculate the sliding gain value. The the sliding gain adaptation, on the one hand avoids the necessity of calculate the upper bound for the system uncertainties, and on the other hand allows to employ a smaller sliding gain in order to overcome the system uncertainties. Therefore, the control signal of the proposed variable structure control schemes will be smaller that the control signals of the traditional variable structure control schemes, because in the last one the sliding gain value should be chosen high enough to overcome all the possible uncertainties that could appear in the system along the time.

A load torque observer is proposed, in order to obtain the load torque applied to the induction motor without the use of the load torque sensor. The proposed observer is based on the system dynamical equation and uses the rotor speed and the stator current in order to obtain the load torque.

The proposed control scheme do not present a high computational cost and therefore could be implemented in a low cost DSP-processor.

Finally, by means of simulation examples, it has been shown that the proposed position control scheme performs reasonably well in practice, and that the position tracking objective is achieved under uncertainties in the system parameters and under load torque variations.

ACKNOWLEDGMENTS

The authors are very grateful to the UPV/EHU by the support of this work through the project GUI10/01.

REFERENCES

[1] Utkin V.I., 1993, Sliding mode control design principles and applications to electric drives, *IEEE Trans. Ind. Electron.*, vol. 40, no. 1, pp. 2335, Feb. 1993.

[2] Cirrincione M., Pucci M., Cirrincione G., Capolino G., "Sensorless control of induction machines by a new neural algorithm: the TLS EXIN neuron", *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 1916-1924, May. 2007.

[3] YAZDANPANAH R., SOLTANI J., ARAB MARKADEH G.R. , Nonlinear torque and stator flux controller for induction motor drive based on adaptive inputoutput feedback linearization and sliding mode control *Energy Conversion and Management*, vol. 49, 541-550. 2008.

[4] T. Orłowska-Kowalska and M. Dybkowski, "Stator-Current-Based MRAS Estimator for a Wide Range Speed-Sensorless Induction-Motor Drive", *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1296-1308, April. 2010.

[5] H. Miranda, P. Corts, J. I. Yuz and J. Rodrguez, "Predictive Torque Control of Induction Machines Based on State-Space Models", *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 1916-1924, Jun. 2009.

[6] A. Benchaib and C. Edwards, "Nonlinear sliding mode control of an induction motor", *Int. J. of Adaptive Control and Signal Procesing*, vol. 14, 201-221. 2000

[7] W.J. Wang, and J.Y. Chen , "Passivity-based sliding mode position control for induction motor drives" *IEEE Trans. on Energy conversion*, vol. 20, 316-321. 2005

[8] M. A. Fnaiech, F. Betin, G.A. Capolino, and F. Fnaiech, "Fuzzy Logic and Sliding-Mode Controls Applied to Six-Phase Induction Machine With Open Phases", *IEEE Trans. Ind. Electron.*, vol. 57, no. 1, pp. 354-364, Jan. 2010.

[9] K. Ohyama, G. M. Asher, and M. Sumner,, "Comparative analysis of experimental performance and stability of sensorless induction motor drives", *IEEE Trans. Ind. Electron.*, vol. 53, no. 1, pp. 178-186, Feb. 2006.

[10] M. Ghanes and G. Zheng, "On Sensorless Induction Motor Drives: Sliding-Mode Observer and Output Feedback Controller", *IEEE Trans. Ind. Electron.*, vol. 56, no. 9, pp. 3404-3413, Sep. 2009.

[11] M. Comanescu, "An Induction-Motor Speed Estimator Based on Integral Sliding-Mode Current Control", *IEEE Trans. Ind. Electron.*, vol. 56, no. 9, pp. 3414-3423, Sep. 2009.

[12] B.K. Bose, B.K., 2001, *Modern Power Electronics and AC Drives.*, Prentice Hall, New Jersey.

[13] P. Vas, *Vector Control of AC Machines*. Oxford Science Publications, Oxford. 1994.