Second order sliding mode control for induction motor

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Abstract

In the following paper, an output feedback tracking problem is solved for the asynchronous motor. The control is a second order sliding mode one whereas the observer is a first order based one. This output feedback has been implemented on an experimental set-up dedicated to horizontal handling and the experimental results are given in this paper.

1 Introduction

Nowadays, asynchronous motors (induction motors) are widely used in industrial fields. This increasing popularity is mainly due to a low maintenance cost (brushless motor), good mechanical performances and robustness. Moreover such electric drives have a wide range of real applications from which the following control problem can be formulated: speed, torque or flux regulation or tracking problems. In this paper we are interested in speed tracking and flux regulation.

Many different sorts of controllers have been designed by the control community: input/output linearization combined with some robust linear controller ([7]), adaptative control ([20], ..); field oriented control (FOC) (see [3], [17], [25]) which has been shown to be equivalent to some PBC (Passivity Based Control) controller ([19]); direct torque control (DTC) (see [8], [25]), which may be seen as a variable structure control scheme (see [14]); sliding mode control ([16]); etc...

All these designed controllers have to face four difficulties:

1. the process is inherently non linear (even if it is assumed that the magnetic components are unsaturated);

2. the physical parameters cannot be known up to some good accuracy and, even if it is sometimes the case, their values can drastically change with temperature and age;

3. rotor fluxes are not measurable;

4. the real input is of discontinuous kind (due to power electronics) and is often just approximately known (due to the dead zones,...);

To overcome difficulties (1–3), a sliding mode strategy (controller and observer) is presented in section 3. Indeed, such a strategy is known to be robust under perturbations and parametric uncertainities (see [21], [23], [24]). The authors of [16] designed a first order sliding mode controller for a benchmark dedicated to horizontal handling task, in Nantes, within the framework of the inter GdR CNRS "Automatique-Electrotechnique" ("Control electric engineering"). In this paper, a second order sliding mode controller is tested on the same benchmark. The goals are to achieve speed tracking (the reference has been chosen in accordance with horizontal handling specifications) and to minimize energy by constraining the square norm flux to be constant. One of the constraints for the control design is that only the stator current and rotor speed are available, which implies the design of a sliding mode observer to estimate the rotor flux. The paper is divided into 5 sections. The second section gives the model and the problem to be deal with. On this basis, section 3 is devoted to control, observer design, and closed loop stability analysis. Section 4 and 5 concern simulation and experimental results on the benchmark dedicated to horizontal handling task and lastly a conclusion sum up the obtained results compared to other ones.

2 Asynchronous motor model and problem formulation

Let us recall the well known model in the (α, β) frame and known as the Park model. For interpretation simplicity sake, the chosen model has been normalized: that is each variable is unit-normalized. More physical informations are available in [17], [25]. Under the hypothesis of magnetic circuit with linear caracteristics, the obtained model is the following five order non linear system:

$$\begin{cases} \dot{x}_1 = \alpha_1(x_2x_5 - x_3x_4) - \alpha_2 C_l - \alpha_3 x_1 \\ \dot{x}_2 = ax_4 - bx_2 - px_1x_3 \\ \dot{x}_3 = ax_5 - bx_3 + px_1x_2 \\ \dot{x}_4 = -\gamma_1 x_4 + \gamma_2 x_2 + \gamma_3 x_1 x_3 + \gamma_4 u_1 \\ \dot{x}_5 = -\gamma_1 x_5 + \gamma_2 x_3 - \gamma_3 x_1 x_2 + \gamma_4 u_2 \end{cases} \quad (1)$$

where $x = [x_1, x_2, x_3, x_4, x_5]^T = [\omega, \phi_{r\alpha}, \phi_{r\beta}, i_{s\alpha}, i_{s\beta}]^T$ is the state vector with components $i_{s\alpha}, i_{s\beta}$ (the stator currents), $\phi_{r\alpha}, \phi_{r\beta}$ (the rotor fluxes) and ω (the rotor angular velocity). In the following design control, it is assumed that only $i_{s\alpha}, i_{s\beta}$ and ω are measurable and the rotor flux will be estimated using an observer. Thus, in the following, the full state will be available to design the control $u = [u_1, u_2]^T \triangleq [V_{s\alpha}, V_{s\beta}]^T$, $V_{s\alpha}$ and $V_{s\beta}$ being the two stator voltages in the (α, β) frame. The variable C_l is the torque load which is supposed to be bounded as well as its time derivative $\dot{C}_l$.

Within the framework of the inter GdR CNRS "Automatique-Electrotechnique", several control problems for induction motor have been specified. In the following, we are interested in designing a controller well suited for horizontal handling: a benchmark in Nantes (IRCCyN) is dedicated to such a test. The control problem is to achieve speed tracking (the reference has been choosen in accordance with horizontal handling specifications) and to minimize energy by constraining the square norm flux $\phi^2 = x_2^2 + x_3^2$ to be constant. The flux reference is $\phi = 0.595\text{Wb}$, so $\phi^2 = 0.354$. The speed must track the following signal for which the maximum is $V_{nom} = 1430$ rnd/min (nominal speed).

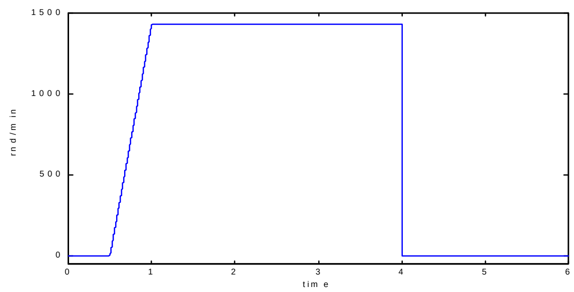

Figure 1: Reference speed

3 Second order sliding mode control

Sliding mode theory has received much attention these two last decades to design controllers for linear and nonlinear systems. The basic idea is to force the state to evolve on a prescribed manifold (called the sliding manifold $s(x) = 0$) chosen such that the corresponding zero dynamics performs some "good dynamical behaviour". In order to achieve a finite time convergence of the state on the sliding manifold, many reaching laws can be used (for example $\dot{s} = -k\,\text{sign}(s)$, $\dot{s} = -k_1 s - k_2\,\text{sign}(s)$, $\dot{s} = -k_1 s - k_2\,\text{sign}(s)\,|s|^a$ with $a \in]0, 1[$).

The main advantages of such a strategy are some dimension reduction by the number of inputs (which is usefull in designing the control parameters) and a robustness property with respect to perturbations and parametric uncertainities (for example the well known matching conditions see [11]). The drawback of this method is the well known chattering phenomenon (high frequency oscillations) which may cause damages to the actuators (for more informations see [6], [24]). To overcome this undesirable phenomenon, higher order sliding mode concept has been introduced by Levant et al. (see [13]) whose main idea is to obtain a finite time convergence onto the non empty manifold $s = \dot{s} = \ldots = s^{(r-1)} = 0$. Furthermore, a r^{th} order sliding mode control achieves a better precision with respect to chattering. For example, for a second order, if the sampling time τ is fixed, then the error is $o(\tau^2)$ whereas it is $o(\tau)$ for the first order. Here, according to the control problem, the surface S is defined in a natural way by

$$S = \begin{pmatrix} s_1 = \omega - \omega_{ref} \\ s_2 = \phi^2 - \phi_{ref}^2 \end{pmatrix} \tag{2}$$

(ω_{ref} and ϕ_{ref} will be given later). However, given that the chosen outputs are of relative degree two with respect to S, a finite time convergence to $S = 0$ can only be obtained with higher order sliding modes. Indeed, a first order sliding mode controller would provide an asymptotic convergence [22]. This fact is another motivation (with the chattering reduction) for the use of a second order sliding mode. A well-known second order algorithm is the twisting algorithm (see, [1], [18]). Here, a modified version of this algorithm is presented. It improves the convergence rate and leads to a global convergence, which is not the case with the twisting algorithm. Considering the system

$$\left\{ \begin{array}{l} \dot{x}_1 = x_2 \\ \dot{x}_2 = u + p(x, t) \end{array} \right. , \tag{3}$$

$p(t, x)$ being an uncertain function such that $|p(x, t)| \leq \Pi$, $\Pi > 0$, for all $(x, t) \in \mathbb{R}^2 \times \mathbb{R}$, the control algorithm

$$u = -\alpha^2 x_1 - 2\alpha\dot{x}_1 + \left\{ \begin{array}{ll} -\lambda_m\,\text{sgn}(x_1), & \text{if } x_1\dot{x}_1 \leq 0 \\ -\lambda_M\,\text{sgn}(x_1), & \text{if } x_1\dot{x}_1 > 0 \end{array} \right. , \tag{4}$$

where $\alpha > 0$ and

$$\lambda_m > \Pi, \tag{5}$$

$$\lambda_M > \lambda_m + 2\Pi, \tag{6}$$

is a sliding mode control of order two on the manifold $x_1 = 0$, for which the convergence rate increases with α.

3.1 Flux observer design

In order to design an output feedback second order sliding mode controller, we need to estimate the rotor flux. To do so, a first order sliding mode based observer given in [9] is used. This observer has already been implemented successfully on the induction motor benchmark in Nantes (IRCCyN). The principle is based on the equivalent method as proposed in [1] leading to the following observer:

$$\begin{cases} \dot{z}_1 = \alpha_1(z_2x_5 - z_3x_4) - \alpha_3 x_1 + \Lambda_1 I_s + q_1(x_1 - z_1) \\ \dot{z}_2 = ax_4 - bz_2 - px_1z_3 + \Lambda_2 I_s \\ \dot{z}_3 = ax_5 - bz_3 + px_1z_2 + \Lambda_3 I_s \\ \dot{z}_4 = -\gamma_1 x_4 + \gamma_2 z_2 + \gamma_3 x_1 z_3 + \gamma_4 u_1 + \Lambda_4 I_s \\ \dot{z}_5 = -\gamma_1 x_5 + \gamma_2 z_3 - \gamma_3 x_1 z_2 + \gamma_4 u_2 + \Lambda_5 I_s \end{cases}$$

where $z^T = [z_1, z_2, z_3, z_4, z_5]^T$ is the estimated state and $\Lambda_1 = [\lambda_{11}, \lambda_{12}]$, $\Lambda_2 = [\lambda_{21}, \lambda_{22}]$, $\Lambda_3 = [\lambda_{31}, \lambda_{32}]$, $\Lambda_4 = [\lambda_{41}, \lambda_{42}]$, $\Lambda_5 = [\lambda_{51}, \lambda_{52}]$, q_1 are the observer gains. This gains are designed according to the following. Let us select a sliding manifold $\{S_{obs} = 0\}$ with:

$$S_{obs} = \begin{bmatrix} s_{obs1} \\ s_{obs2} \end{bmatrix} = M \begin{bmatrix} x_4 - z_4 \\ x_5 - z_5 \end{bmatrix},$$

with

$$M^{-1} = \begin{bmatrix} \gamma_2 & \gamma_3 x_1 \\ -\gamma_3 x_1 & \gamma_2 \end{bmatrix}$$

and set $I_s = \begin{bmatrix} \text{sgn}(s_{obs1}) \\ \text{sgn}(s_{obs2}) \end{bmatrix}$.

Defining the observation error $e = x - z$ and letting

$$\begin{bmatrix} \Lambda_4 \\ \Lambda_5 \end{bmatrix} = M^{-1} \begin{bmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{bmatrix} \tag{7}$$

$$\Lambda_1 = \alpha_1 \begin{bmatrix} \delta_1 x_5 & -\delta_2 x_4 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} \Lambda_2 \\ \Lambda_3 \end{bmatrix} = \begin{bmatrix} -b + q_2 & -px_1 \\ px_1 & -b + q_3 \end{bmatrix} \begin{bmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{bmatrix} \tag{9}$$

where q_2, q_3, δ_1 and δ_2 are positive gains, we have the following result:

Theorem 1 *There exist gains (7), (8), (9) and*

$$\begin{aligned} \delta_1 &> |e_2|_{\max} \\ \delta_2 &> |e_3|_{\max} \end{aligned}$$

such that the error e converges asymptotically to zero whatever the controls are.

Remark 1 *While the sliding manifold $\{S_{obs} = 0\}$ is reached, the equivalent vector (see [15], [24]) is*

$$(I_s)_{eq} = \begin{bmatrix} \frac{e_2}{\delta_1} \\ \frac{e_3}{\delta_2} \end{bmatrix}$$

and thus the error dynamics becomes

$$\begin{cases} \dot{e}_1 = -q_1 e_1 \\ \dot{e}_2 = -q_2 e_2 \\ \dot{e}_3 = -q_3 e_3 \end{cases} . \tag{10}$$

Remark 2 *A new "step-by-step" sliding mode observer (see [2]) will be tested later on the benchmark.*

3.2 Control design

The first step is to select a "good" zero dynamics associated to S. Since the time derivative of the rotor speed has to be known, the sliding manifold variables are modified by replacing the flux by its estimated value. That is s_1 is changed into (renaming the variable)

$$s_1 = z_1 - \omega_{ref},$$

with time derivatives :

$$\begin{aligned} \dot{s}_1 &= -\alpha_3 x_1 + \alpha_1(z_2x_5 - z_3x_4) - \alpha_2 C_l - \dot{\omega}_{ref}, \\ \ddot{s}_1 &= A_{11}u_1 + A_{12}u_2 + B_1 e_2 + C_1 e_3 + D_1 - \frac{d\Lambda_1 I_s}{dt} \\ &\quad -\alpha_2 \dot{C}_l + \alpha_3 \alpha_2 C_l, \\ A_{11} &= -\alpha_1 \gamma_4 z_3, A_{12} = \alpha_1 \gamma_4 z_2, \\ B_1 &= -\alpha_1 \left(\gamma_3 x_1 z_2 + \gamma_2 z_3 - (q_1 - \alpha_3) x_5\right), \\ C_1 &= -\alpha_1 \left(\gamma_3 x_1 z_3 - \gamma_2 z_2 + (q_1 - \alpha_3) x_4\right), \\ D_1 &= -\alpha_1 (b + \gamma_1 + \alpha_3)(z_2x_5 - z_3x_4) - \alpha_1 \gamma_3 x_1 \hat{\phi}^2 \\ &\quad -\alpha_1 p x_1 (x_2x_4 + x_3x_5) + \alpha_3^2 x_1 \\ &\quad - \left(q_1 \Lambda_1 - \alpha_1 x_5 \Lambda_2 + \alpha_1 x_4 \Lambda_3\right) I_s, \end{aligned}$$

Thanks to the convergence rate of the observer, one can consider the control action once the surface $S_{obs} = 0$ has been reached. In this sliding mode, the equivalent dynamics is

$$(\Lambda_1 I_s)_{\text{eq}} = \alpha_1(e_2x_5 - e_3x_4),$$

leading to

$$\left(\frac{d\Lambda_1 I_s}{dt}\right)_{eq} = \alpha_1(-q_2 e_2 x_5 + q_3 e_3 x_4 + e_2 \dot{x}_5 - e_3 \dot{x}_4),$$

thus

$$\begin{aligned} \ddot{s}_1 &= A_{11}u_1 + A_{12}u_2 + \tilde{B}_1 e_2 + \tilde{C}_1 e_3 + D_1 \\ &\quad -\alpha_2 \dot{C}_l + \alpha_3 \alpha_2 C_l, \\ \tilde{B}_1 &= -\alpha_1 \left(\gamma_3 x_1 z_2 + \gamma_2 z_3 - (q_1 + q_2 - \alpha_3) x_5 - \dot{x}_5\right), \\ \tilde{C}_1 &= -\alpha_1 \left(\gamma_3 x_1 z_3 - \gamma_2 z_2 + (q_1 + q_3 - \alpha_3) x_4 + \dot{x}_4\right). \end{aligned}$$

Moreover, from s_2 one gets:

$$\begin{aligned} s_2 &= (z_2^2 + z_3^2) - \phi_{ref}^2, \\ \dot{s}_2 &= -2b\hat{\phi}^2 + a(z_2x_4 + z_3x_5) + (z_2\Lambda_2 + z_3\Lambda_3) I_s, \\ \ddot{s}_2 &= A_{21}u_1 + A_{22}u_2 + B_2 e_2 + C_2 e_3 + D_2 \\ &\quad +2\left(z_2 \frac{d\Lambda_2 I_s}{dt} + z_3 \frac{d\Lambda_3 I_s}{dt}\right) \\ A_{21} &= 2a\gamma_4 z_2, A_{22} = 2a\gamma_4 z_3, \\ B_2 &= 2(a\gamma_2 z_2 - a\gamma_3 x_1 z_3), \\ C_2 &= 2(a\gamma_2 z_3 + a\gamma_3 x_1 z_2), \\ D_2 &= -2a(3b + \gamma_1)(z_2x_4 + z_3x_5) + (4b^2 + 2a\gamma_2)\hat{\phi}^2 \\ &\quad +2a^2(x_4^2 + x_5^2) + 2apx_1(z_2x_5 - z_3x_4) \\ &\quad +4a(x_4\Lambda_2 + x_5\Lambda_3) I_s - 6b(z_2\Lambda_2 + z_3\Lambda_3) I_s \\ &\quad +2px_1(z_2\Lambda_3 - z_3\Lambda_2) I_s + 2(\Lambda_2^2 + \Lambda_3^2). \end{aligned}$$

Using the equivalent dynamics on $S_{obs} = 0$:

$$\begin{aligned}(\Lambda_2 I_s)_{eq} &= (q_2 - b)e_2 - px_1e_3, \\ (\Lambda_3 I_s)_{eq} &= (q_3 - b)e_3 + px_1e_2,\end{aligned}$$

leads to

$$\begin{aligned}\left(\frac{d\Lambda_2 I_s}{dt}\right)_{eq} &= -q_2(q_2 - b)e_2 + q_3px_1e_3 - p\dot{x}_1e_3, \\ \left(\frac{d\Lambda_3 I_s}{dt}\right)_{eq} &= -q_3(q_3 - b)e_3 - q_2px_1e_2 + p\dot{x}_1e_2,\end{aligned}$$

Thus

$$\begin{aligned}\ddot{s}_2 &= A_{21}u_1 + A_{22}u_2 + \tilde{B}_2e_2 + \tilde{C}_2e_3 + D_2, \\ \tilde{B}_2 &= 2\left((a\gamma_2 - q_2(q_2 - b))\, z_2 - (a\gamma_3 + q_2p)x_1z_3 + p\dot{x}_1\right), \\ \tilde{C}_2 &= 2\left((a\gamma_2 - q_3(q_3 - b))\, z_3 + (a\gamma_3 + q_3p)x_1z_2 - p\dot{x}_1\right).\end{aligned}$$

Now, using the static feedback

$$\begin{aligned}u &= A^{-1}\begin{bmatrix} -D_1 + v_1 \\ -D_2 + v_2 \end{bmatrix}, \\ A &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\end{aligned}$$

where $v = [v_1, v_2]^T$ is the new control vector, leads to:

$$\begin{aligned}\ddot{s}_1 &= v_1 + \tilde{B}_1e_2 + \tilde{C}_1e_3 - \alpha_2\dot{C}_l + \alpha_3\alpha_2C_l, \\ \ddot{s}_2 &= v_2 + \tilde{B}_2e_2 + \tilde{C}_2e_3.\end{aligned}$$

As C_l and $\dot{C}_l$ are assumed to be bounded and as e_2 and e_3 converge asymptotically to zero, there exists a finite time t_0 such that:

$$\left|\tilde{B}_1e_2 + \tilde{C}_1e_3 - \alpha_2\dot{C}_l + \alpha_3\alpha_2C_l\right| \leq K_1 \qquad (11)$$

$$\left|\tilde{B}_2e_2 + \tilde{C}_2e_3\right| \leq K_2 \qquad (12)$$

Then, one can apply the second order algorithm previously presented :

$$v_i = -\alpha_i^2 s_i - 2\alpha_i\dot{s}_i + \begin{cases} -\lambda_{m_i}\,\mathrm{sgn}(s_i), & \text{if } s_i\dot{s}_i \leq 0 \\ -\lambda_{M_i}\,\mathrm{sgn}(s_i), & \text{if } s_i\dot{s}_i > 0 \end{cases},\ i = 1, 2$$

with the $\alpha_i > 0$ and

$$\lambda_{M_i} > \lambda_{m_i}$$

$$\lambda_{m_i} > K_i$$

$$\lambda_{M_i} > \lambda_{m_i} + 2K_i$$

the K_i being defined in (11), (12). Finally, a sliding mode occurs on $S = 0$ leading to the desired tracking property for the rotor speed and the flux.

4 Simulation results

In order to test the validity of the controller before its implementation on the benchmark of the IRCCyN, some simulations have been made taking into account the nominal model of the motor set-up and all the constraints to which it is subject. The induction motor is a Leroy Somer A3L. The physical parameters of the motor are: $R_s = 1.633\Omega$, $R_r = 0.93\Omega$, $L_s = 0.142$H, $L_r = 0.076$H, $J = 0.029$Nm/rad/s^2, and the pole-pair number is $p = 2$.

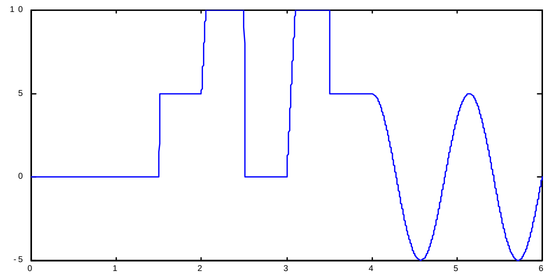

Figure 2: Load torque

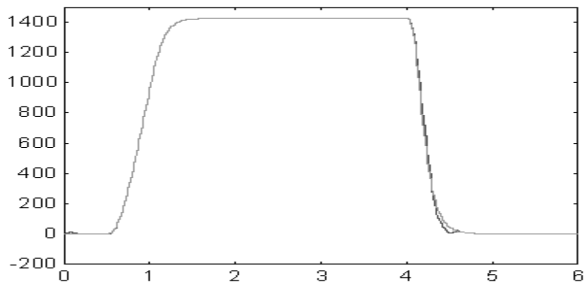

Figure 3: Reference and motor speed

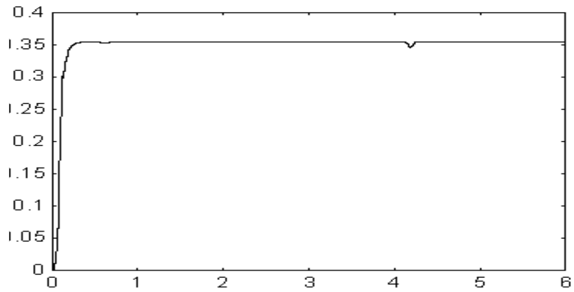

Figure 4: Stator flux (square norm)

The behaviour of the load torque C_l is given in Figure 2.

This corresponds to loading and unloading a conveyer belt. After $t = 4s$, an emergency stop is applied with a sinusoidal torque corresponding to the swing of the load on a travelling crane.

The observer parameters are $\delta_1 = \delta_2 = 5$, $q_1 = q_2 = q_3 = 15$, and the controller ones $\lambda_{M_1} = 5000$, $\lambda_{m_1} = 1000$, $\lambda_{M_2} = 500$, $\lambda_{m_2} = 100$. As seen on Figure 3, the tracking of the speed is correct in spite of the disturbance of the load torque. The curve of the reference speed is smooth since it has been filtred to limit the amplitude of the currents and the controllers during the transient time.

Figure 4 represents the evolution of the square of the flux, whose response is satisfying. Note that there is few chattering on the real speed and flux. The classical signum functions used here can be substituted by signum functions softened with dead zone or by sigmoid functions in order to improve the results, and particularly to reduce the actuator sollicitations.

5 Experimental results

The observer based sliding mode controller presented in this paper has been implemented on the experimental set-up "Horizontal handling", which is located in the IRCCyN's laboratory at Nantes and which is directed by Alain Glumineau and Robert Boisliveau (http://www.ircyn.prd.fr/Banc_Essai). One must note that all these experimentations were done after the setting of a new environment including a DSPACE 1103 card (power PC 333, 20 analogic inputs) allowing to work with Matlab 5.3 and Simulink 3. Several tests have been made, but these have to be completed in further experimentations. The figures 5 and 6 show the response of measured current and speed. Figure 5 concerns a test at half of the nominal speed and shows correct responses. In Figure 6, the reference speed has been taken in accordance with the benchmark specifications. The delay that appears in the response of the speed is due to the saturation of the convertors. However some solutions are proposed in the literature to solve this problem and will be implemented in the future. The tracking of speed is acceptable in spite of the very significant disturbance of load, which shows the robustness of the second order sliding mode control law. One can see that a peak of current appears when the motor stops. These overcurrents can be decreased by adjusting the filters or by decreasing the gains of the discontinuous control. The most important problem appearing here is the oscillations around the nominal speed. This comes from the fact that the observer is based on a first order sliding mode strategy and that the second order controller uses the estimated state. In order to counteract this chattering effect, a second order sliding mode observer will be implemented, allowing at the same time to provide a finite time convergence of both the observer and the controller. The filters and the different gains will also be optimized in order to improve the time response. Further tests will also be done to study the robustness of the control under parametric uncertainties.

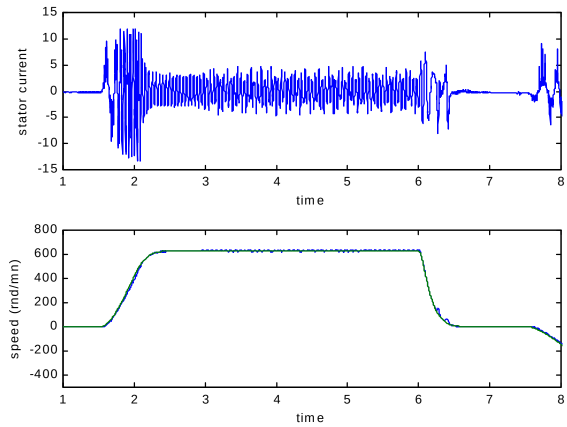

Figure 5: Stator current and rotor speed for $V_{ref_{\max}} = V_{nom}/2$

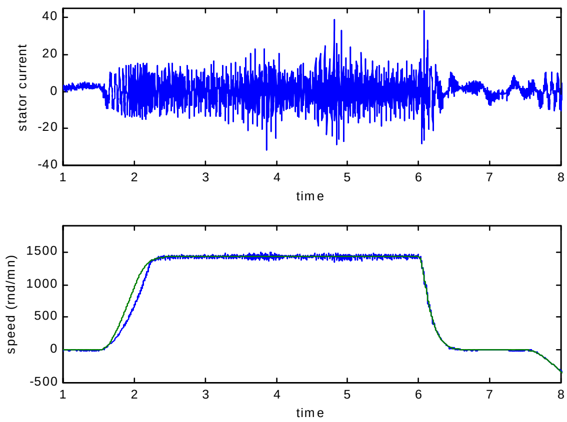

Figure 6: Stator current and rotor speed for $V_{ref_{\max}} = V_{nom}$

6 Conclusion

In this article, a second order sliding mode controller for the induction machine has been proposed and experimentally tested. Given that only the stator current and the rotor speed are available, a sliding mode observer has been designed to estimate the rotor flux. The controller has been designed taking into account the informations given by this observer. The closed-loop stability has also been shown. One can note that this stategy implies no torque estimation. The simulations show that the response are correct, which motivates the implementation on the benchmark of the IRCCyN laboratory. The experimentations highlight the efficiency of the higher order control scheme proposed in the paper. However, in order to improve the observer-based controller and to have a finite time convergence of the whole system (estimated and real states), another observer has to be developped. A higher order sliding mode observer seems to be an appropriate solution.

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