New Lyapunov Approach For Second Order Sliding Mode Control of Induction Motor

H. Benderradji[1,3], A. Benamor[2,3], L. Chrifi-Alaoui[3],P. Bussy[3] & A. Makouf[4]

***Abstract*— This paper, deals with a second order sliding mode control of induction motor using a new analysis Lyapunov stability. This approach guarantees the robustness and dynamic performance than traditional first-order SMC algorithms, and simultaneously reducing the chattering phenomenon, which is the main drawback in the implementation of this technique. The rotor flux value is deduced from rotor flux observer using twisting algorithm. Simulation results are presented in order to validate the effectiveness of the proposed technique and to show the performance of second order sliding mode control for an induction motor drive system.**

I. Introduction

Induction motor (IM) is widely used in the industrial field for the reason that it is less expensive and more reliable than permanent magnet and dc motor. However, this machine is nonlinear process, highly coupled and time varying parameters. Therefore, to improve performance, many approaches of robust control have been used.

In the last few years, the variable structure control strategy using the sliding mode has received much attention in electrical drives control area. The main objective is to close dynamic system with a sliding surface. The most significant property of a SMC concerns its robustness, fast dynamic response and insensitivity to parameter variations [1-6]. Usually SMC has some intrinsic problems such as discontinuous control that often yields chattering which may be considered a problem for implementing in some real applications. Recently, different methods have been suggested to reduce the chattering using the continuous approximation techniques such as boundary layer [7-11].

The However, the standard sliding mode control suffers from the chattering phenomenon. In order to overcome this drawback, many methods have been proposed to reduce this phenomenon such as the saturation function, low pass filter, boundary layer and observer based solutions [12]. A research activity has been carried out in recent years, aimed at finding a continuous control action and guaranteeing the attainment of the same control objective of the standard SMC. A novel class of SMC algorithm, called the second-order SMC (SOSMC) algorithm, has been proposed [13,14]. This approach allows for finite-time convergence to zero of not only the sliding manifold but its derivative too.

The sliding mode observers are widely used due to the finite-time convergence, robustness with respect to uncertainties. A new generation of observers based on the second-order sliding-mode twisting and super twisting algorithms has been recently developed [15-19]. The twisting algorithm provides the finite time convergence and robustness in spite of the presence of external disturbances and parameter variations and attenuates the chattering phenomenon.

In this paper, we present a novel sliding mode approach for the stability analysis [7]. We use this approach to control the speed and flux of an induction motor. The paper, also proposes a second-order sliding mode observer for rotor flux and current estimation using twisting algorithm. Simulation results are presented to validate the effectiveness of the proposed control scheme.

II. Model description of induction motor

The two phase's equivalent model for an induction motor in the stationary reference frame of Park is given by:

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

$$f(x)=\begin{bmatrix} f_1(x)\\ f_2(x)\\ f_3(x)\\ f_4(x)\\ f_5(x)\end{bmatrix}=\begin{pmatrix} -\delta i_{s\alpha}+\alpha\beta\phi_{r\alpha}+p\beta\omega\phi_{r\beta}\\ -\delta i_{s\beta}-p\beta\omega\phi_{r\alpha}+\alpha\beta\phi_{r\beta}\\ \alpha M i_{s\alpha}-\alpha\phi_{r\alpha}-p\omega\phi_{r\beta}\\ \alpha M i_{s\beta}+p\omega\phi_{r\alpha}-\alpha\phi_{r\beta}\\ \mu(\phi_{r\alpha}i_{s\beta}+\phi_{r\beta}i_{s\alpha})-\dfrac{F}{J}\omega-\dfrac{T_L}{J}\end{pmatrix}$$

$$g(x)=\begin{bmatrix} b & 0 & 0 & 0\\ 0 & b & 0 & 0\end{bmatrix}^T=\begin{bmatrix} g_1(x) & 0 & 0 & 0\\ 0 & g_2(x) & 0 & 0\end{bmatrix}^T,$$

$$x=[i_{s\alpha}\quad i_{s\beta}\quad \phi_{r\alpha}\quad \phi_{r\beta}\quad \omega]^T$$

$f(x)$: is a vector of dimension n=5 the coefficients of which are non linear functions

For simplicity, we define the following variables:

$$\alpha=\frac{R_r}{L_r},\ \beta=\frac{M}{\sigma L_s L_r}, b=\frac{1}{\sigma L_s}\ \ \mu=\frac{pM}{J L_r},\ \delta=\frac{M^2 R_r}{\sigma L_s L_r^2}+\frac{R_s}{\sigma L_s}$$

[1] University of Msila Electrical Engineering department M'sila, Algeria, (e-mail: h_benderradji@yahoo.fr)

[2] Unité de recherche ATSI, ENIM, Monastir, Tunisia, (e-mail: anouar.benamor@yahoo.fr)

[3]University of Picardie Jules Verne, LTI (EA, 3899),13 av F. Mitterrand, 02880 Cuffies, France, (e-mail: larbi.alaoui@u-picardie.fr)

[4] Laboratory of induction and propulsion systems, Electrical Engineering Dept University of Batna, Algeria(e-mail: a_makouf@yahoo.fr)

Where $\phi_{r\alpha}$, $\phi_{r\beta}$ are the rotor flux dynamics and $i_{s\alpha}$, $i_{s\beta}$ are the stator currents. The control vector is defined by $u_s=[u_{s\alpha},u_{s\beta}]^T$ and T_L is the load torque, ω is the mechanical frequency of the electrical rotor speed, σ is total leakage factor. R_s and R_r denote stator and rotor resistance, L_s and L_r are stator and rotor self inductance, M is mutual inductance, p is the number of pole pairs and J is the moment of inertia.

The objective of the proposed control scheme is to control independently the rotor speed and the square of the rotor flux and in the same time we attenuate of the chattering phenomenon.

III. SECOND ORDER SLIDING MODE SPEED AND FLUX CONTROL

A. Problem formulation

Consider the uncertain nonlinear system

$$\dot{x} = \hat{f}(x) + \Delta f(x) + (\hat{g}(x) + \Delta g(x))u_s$$

$$f(x) = \begin{bmatrix} \hat{f}_1(x) + \Delta f_1 \\ \hat{f}_2(x) + \Delta f_2 \\ \hat{f}_3(x) + \Delta f_3 \\ \hat{f}_4(x) + \Delta f_4 \\ \hat{f}_5(x) + \Delta f_5 \end{bmatrix}$$

$$g(x) = \begin{bmatrix} \hat{g}_1(x) + \Delta g_1 & 0 \\ 0 & \hat{g}_2(x) + \Delta g_2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The functions of the matrix $f(x) = \hat{f}(x) + \Delta f$ and $g(x) = \hat{g}(x) + \Delta g$ are not exactly known, but estimated by the nominal part $\hat{f}(x)$ and $\hat{g}(x)$. Δf and Δg represent the uncertain function. u_s is the input control bounded as $|u_s| \le u_{\max}$

Let e_1 and e_2 the speed and flux tracking error between the reference and the actual induction motor model with

$$\varphi = \phi_{r\alpha}^2 + \phi_{r\beta}^2$$

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} \omega_{ref} - \omega \\ \varphi_{ref} - \varphi \end{bmatrix} \tag{2}$$

where ω_{ref} and φ_{ref} are the desired reference signals of the speed and rotor flux respectively.
The error dynamics are given by

$$\begin{aligned} \dot{e}_1 &= \dot{\omega}_{ref} - \mu(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}) + \frac{T_L}{J} - \Delta f_5 \\ \ddot{e}_1 &= \hat{h}_1(x) + \Delta h_1 + (\hat{D}_1(x) + \Delta D_1)u_s \end{aligned} \tag{3}$$

$$\begin{aligned} \dot{e}_2 &= \dot{\varphi}_{ref} + 2\alpha\varphi - 2\alpha M(\phi_{r\alpha} i_{s\alpha} + \phi_{r\beta} i_{s\beta}) \\ \ddot{e}_2 &= \hat{h}_2(x) + \Delta h_2 + (\hat{D}_2(x) + \Delta D_2)u_s \end{aligned} \tag{4}$$

where:

$$\hat{h}_1(x) = \ddot{\omega}_{ref} + p\mu\,\omega(\phi_{r\alpha} i_{s\alpha} + \phi_{r\beta} i_{s\beta}) + \mu(\delta + \alpha)(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}) + p\mu\beta\omega\varphi + \frac{\dot{T}_L}{J}$$

$$\hat{h}_2(x) = \ddot{\varphi}_{ref} + 2M(\delta + 3\alpha^2)(\phi_{r\alpha} i_{s\alpha} + \phi_{r\beta} i_{s\beta}) - 2\alpha^2(2+M)\varphi - 2pM\alpha\omega(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}) - 2M^2\alpha^2(i_{s\alpha}^2 + i_{s\beta}^2)$$

$$\hat{D}_1 = [\mu b\,\phi_{r\beta} \quad -\mu b\,\phi_{r\alpha}]$$

$$\hat{D}_2 = [-2\alpha M b\,\phi_{r\alpha} \quad -2\alpha M b\,\phi_{r\beta}]$$

$$\Delta h_1 = -\mu(\phi_{r\alpha}\Delta f_2 + i_{s\beta}\Delta f_3 - i_{s\alpha}\Delta f_4 - \phi_{r\beta}\Delta f_1) - \Delta f_5$$

$$\Delta D_1 = [-\phi_{r\alpha}\Delta g_1 \quad \phi_{r\beta}\Delta g_2]$$

$$\Delta h_2 = (4\alpha\phi_{r\alpha} - 2\alpha M i_{s\alpha})\Delta f_3 + (4\alpha\phi_{r\beta} - 2\alpha M i_{s\beta})\Delta f_4 - 2\alpha M(\phi_{r\alpha}\Delta f_1 + \phi_{r\beta}\Delta f_2)$$

$$\Delta D_2 = -2\alpha M\,[\phi_{r\alpha}\Delta g_1 \quad \phi_{r\beta}\Delta g_2]$$

B. Proposed sliding mode control

Consider the sliding surface defined by:

$$S = \begin{bmatrix} s_\omega \\ s_\varphi \end{bmatrix} = q\int e + e = \begin{bmatrix} q_\omega \int e_1 + e_1 \\ q_\varphi \int e_2 + e_2 \end{bmatrix} \tag{5}$$

With $q = \begin{bmatrix} q_\omega & 0 \\ 0 & q_\varphi \end{bmatrix}$

$S \in R^2$, q_ω, q_φ positive constant

Note that the choice of the sliding surface S = 0 has been made to ensure an exponential convergence of ω and φ to their references where the system evolves on the sliding surface.

The second derivative of the sliding surface S is:

$$\ddot{S} = q\dot{e} + \ddot{e} \tag{6}$$

To determine the control law that leads the sliding functions (5) to zero in finite time, one has to consider the dynamics of

$$S_\omega + \ddot{S}_\omega = \hat{H}_1(x) + \Delta H_1 + (\hat{D}_1(x) + \Delta D_1)u_s$$

$$S_\varphi + \ddot{S}_\varphi = \hat{H}_2(x) + \Delta H_2 + (\hat{D}_2(x) + \Delta D_2)u_s$$

With

$$\hat{H}_1(x) = q\int e_1 dt + e_1 + q\dot{e}_1 + q_\omega(\dot{\omega}_{ref} - f_5) + h_1(x)$$

$$\Delta H_1 = \Delta h_1 - q_\omega \Delta f_5$$

$$\hat{H}_2(x) = q\int e_2 dt + e_2 + q_\varphi \dot{e}_2 + h_2(x)$$

$$\Delta H_2 = \Delta h_2$$

We can write:

$$S + \ddot{S} = H(x) + D(x)u_s \tag{7}$$

Where $H(x) = \hat{H}(x) + \Delta H(x)$, $D(x) = \hat{D}(x) + \Delta D(x)$

C. Lyapunov stability analysis for the proposed control

Proposition 1

We consider in this first proposition that the uncertain functions *ΔH(x)* and *ΔD(x)* are negligible

The control law for the SOSMC of the system (1) is defined by [15]:

$$u_s = -D^{-1}(x)(H(x) + \lambda sng(\dot{S})) \tag{8}$$

$$\lambda = \begin{bmatrix} \lambda_\omega & 0 \\ 0 & \lambda_\varphi \end{bmatrix}, \quad \lambda_\omega, \lambda_\varphi > 0,$$

D is invertible.

With the developed nonlinear sliding-mode controller (8) and a stable sliding surface (5), the reaching Lyapunov function condition $\dot{V} \le 0$ is satisfied, and the controlled system will be stabilized.

Proof

We can verify the stability of the sliding surface by using the new positive Lyapunov function as fellow:

$$V = \frac{1}{2}(S^T S + \dot{S}^T \dot{S}) = \frac{1}{2}(S^2 + \dot{S}^2) \tag{9}$$

The derivative of V is:

$$\dot{V} = (\dot{S}\, S + \dot{S}\, \ddot{S}) = \dot{S}^T (S + \ddot{S}) \tag{10}$$

The expression (7) becomes

$$S + \ddot{S} = H(x) + D(x)u_s = -\lambda sng(\dot{S}) \tag{11}$$

The derivative of V becomes:

$$\dot{V} = -\lambda \dot{S}^T \; sng(\dot{S}) \tag{12}$$

then

$$\dot{V} = -\lambda \left|\dot{S}\right| \le 0 \tag{13}$$

With this condition the sliding surfaces s_ω and s_φ and their derivative tends to zero involving. the existence of second order sliding mode.

IV. Robustness to the uncertainties and external disturbances

In this case the uncertain functions ΔH(x) and ΔD(x) are taken into account. The expression of the derivative of the sliding function takes the following form:

$$S + \ddot{S} = \hat{H}(x) + \Delta H(x) + (\hat{D}(x) + \Delta D(x))u_S \tag{14}$$

The expression of the derivative of the sliding surface takes the following form:

$$S + \ddot{S} = \hat{H}(x) + \hat{D}(x)u_S + \Delta H(x) + \Delta D(x)u_S \tag{15}$$

where Δ*H(x)* and Δ*D(x)* are assumed to be bounded by some known matrixesχ and ρ vector respectively.

Proposition 2

The control law defined by equation:

$$u = -\hat{D}^{-1}(x)[\hat{H}(x) + \lambda sng(\dot{s})] \tag{16}$$

$$\text{With } \lambda > \chi + \rho\, u_{\max} \tag{17}$$

$$\left|\Delta H(x)\right| < \chi, \; \left|\Delta D(x)\right| < \rho$$

Proof

Using equation (16) the derivative of the surface s is then written:

$$s + \ddot{s} = -\lambda sng(\dot{s}) + \Delta H(x) + \Delta D(x)u_S \tag{18}$$

If $\dot{s} > 0$, we must have $-\lambda + \Delta H(x) + \Delta D(x)u_S \langle 0$

$$\text{then } \lambda \rangle\, \Delta H(x) + \Delta D(x)u_S \tag{19}$$

If $\dot{s} < 0$, we must have $\lambda + \Delta H(x) + \Delta D(x)u_S \rangle 0$

$$\text{then } \lambda \rangle - (\Delta H(x) + \Delta D(x)u_S) \tag{20}$$

The conditions (19) and (20) are satisfied if $\lambda \rangle \chi + \rho u_{\max}$

So $\dot{V} \le 0$, is verified and the trajectory of state reached the surface $s = \dot{s} = 0$ in the finite time.

- *Remark*

From the above control law of (8), it can be see that the implementation of these algorithms requires the load torque and rotor flux estimations since stator current, stator voltages and speed rotor are available by measures. In the next section, we are interested by a robust estimation of rotor flux. The estimated load torque can be easily obtained by using the mechanical equation of the motor model with estimated rotor fluxes and measured.

V. Second order sliding-twisting flux observer

A system (1) can be written as follows [15]:

$$\begin{aligned} \frac{di_S}{dt} &= -\delta I i_S + \beta A \phi_r + bIu_S \\ \frac{d\phi_r}{dt} &= \alpha M I i_S - A\phi_r \end{aligned} \tag{21}$$

$i_s = [i_{s\alpha} \quad i_{s\beta}]^T$, $\phi_r = [\phi_{r\alpha} \quad \phi_{r\beta}]^T$,

$A = \begin{bmatrix} \alpha & p\omega \\ -p\omega & \alpha \end{bmatrix}$, $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

The corresponding sliding mode observer for the system of (21) can be written as a replica of the system with an additional non-linear auxiliary input term (Γ) as follows

$$\begin{aligned} \frac{d\hat{i}_S}{dt} &= -\delta I i_S + \beta A \hat{\phi}_r + bIu_S \\ \frac{d\hat{\phi}_r}{dt} &= \alpha M I \hat{i}_S - A\hat{\phi}_r + \Gamma \end{aligned} \tag{22}$$

$\hat{i}_s = [\hat{i}_{s\alpha} \quad \hat{i}_{s\beta}]^T, \hat{\phi}_r = [\hat{\phi}_{r\alpha} \quad \hat{\phi}_{r\beta}]^T$ are the estimated stator-current and the rotor flux components respectively, in the stationary reference frame.

$\Gamma(z_1) = [\Gamma_1 \quad \Gamma_2]^T$ is the observer matrix gains to be designed. The estimate errors are:

$$\begin{aligned} z_1 &= \hat{i}_s - i_s \\ z_2 &= \hat{\phi}_r - \hat{\phi}_r \end{aligned} \tag{23}$$

Where the observation error dynamics is obtained from (21) and (22)

$$\dot{z}_1 = \beta A z_2$$
$$\dot{z}_2 = \alpha M I z_1 - A z_2 + \Gamma \tag{24}$$

The sliding surface is defined as follows

$$s = \frac{1}{\beta} A^{-1} z_1 \tag{25}$$

The derivative of the sliding surface is:

$$\dot{s} = \frac{1}{\beta} A^{-1} \dot{z}_1 + \frac{d(A^{-1})}{dt} z_1 = z_2$$

The dynamics of ω is supposed to be constant compared to the dynamics of the currents and flux, we can then consider $\frac{d(A^{-1})}{dt} = 0$.

$$\dot{s} = z_2$$
$$\ddot{s} = \dot{z}_2 = \alpha M I z_1 - A z_2 + \Gamma \tag{26}$$

With this form we can apply the following control laws, called the twisting algorithm [15]:

$$\Gamma = \begin{cases} \lambda_m sng(s) & s\dot{s} \le 0 \\ \lambda_M sng(s) & s\dot{s} \rangle 0 \end{cases} \tag{27}$$

The sufficient conditions for finite time convergence are:

$$\lambda_m \rangle \left|\alpha M I z_1 - A z_2\right|_{\max}$$
$$\lambda_M \rangle \lambda_m + 2\left|\alpha M I z_1 - A z_2\right|_{\max} \tag{28}$$

The system evolve featuring a second order sliding mode, after a finite time, i.e. the trajectories of state reached the surface $s = \dot{s} = 0$.

VI. DISCUSSION AND RESULTS

The parameters of the IM used are listed in Table.1. The rated load (T_L=10 N.m) is applied at time t=2s during the whole simulation. In closed loop simulation, it is assumed that all the parameters are known and constant except for the rotor resistance which will change at t=4s during the simulation period. The parameter change will be introduced only in the plant.

The motor is required to track the reference speed and rotor flux magnitude. The reference flux is set to 0.8Wb. The parameters of the gain control in simulation are q_ω=150, q_φ=100, λ_ω=10, λ_φ=2. The parameters of the gain observer in simulation are: $\lambda_{m\omega}$= 4.10^{-5}, $\lambda_{M\omega}$= 5.10^{-5}, $\lambda_{m\varphi}$= 4.10^{-6}, $\lambda_{M\varphi}$= 5.10^{-6}.

The simulation results of the performance tracking are demonstrated in the following cases.

To test the speed tracking controller, the reference trajectory is in a step form varying from 0 to 120 rad/s, afterwards it is decelerate to the inverse speed -80 rad/s and accelerate again to 120 rad/s. In Fig.1 we can see the new control input $u_{s\alpha}$ for the SOSMC system. Fig.2 and Fig.5 show the best speed and flux tracking and well reject of the load torque is achieved and excellent robustness with 50% and 100% rotor resistance variations. It can be noted that the decoupling control is ensured and speed and flux tracking are very quite maintained. We can see In Fig.3 and Fig.4 the sliding surfaces s_φ and s_ω of SOSMC and S_1 of the flux observer converge towards zero and the chattering is negligible. This control gives good quality results.

To test the effectiveness of technique control with rotor flux observer at low speed, the reference trajectory is now accelerated from the standstill to 20 rad/s, afterwards it is stopped, then accelerated again to 10 rad/s.

Due to the accuracy and robustness of the twisting sliding-mode flux observer, all low-speed results, shown in Fig.6, Fig.7 and Fig.8 prove the good performance and negligible chattering effect.

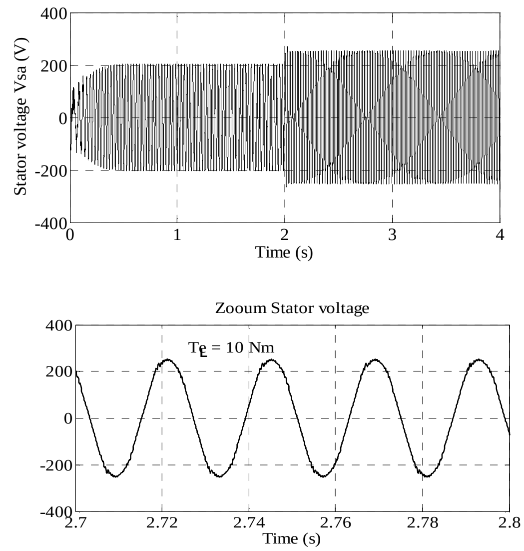
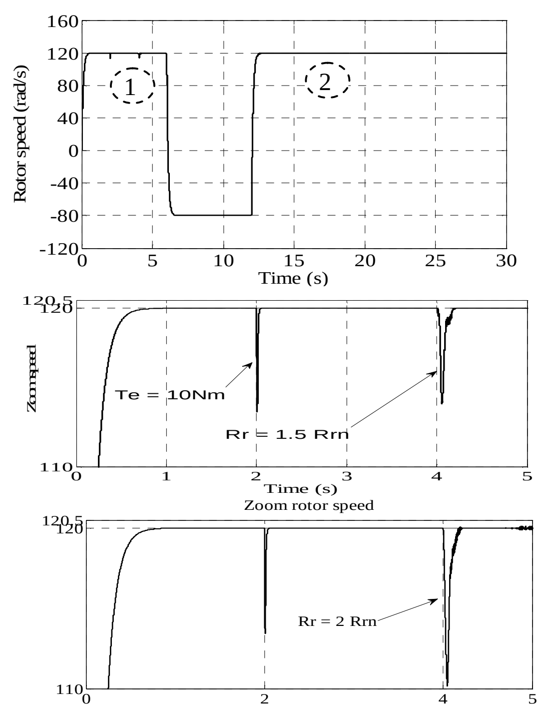


Figure 1. New control input $u_{s\alpha}$ of the SOSMC for IM



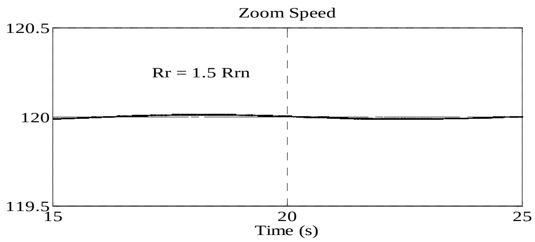


Figure 2. Dynamic responses of rotor speed variation under load torque T_L=10 Nm at 2s and variation of Rr at 4s (Rr=150%Rrn, Rr=200%Rrn).

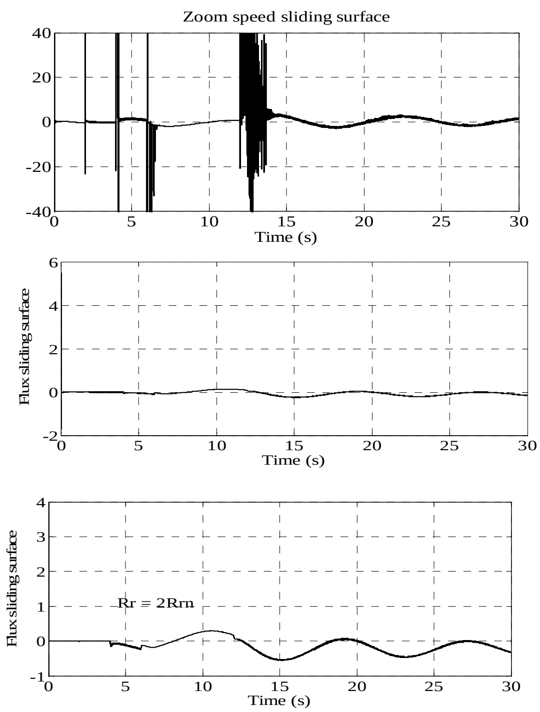


Figure 4. Sliding surfaces of speed Sω and flux Sφ SOSMC with speed variation under load torque and Rr variation

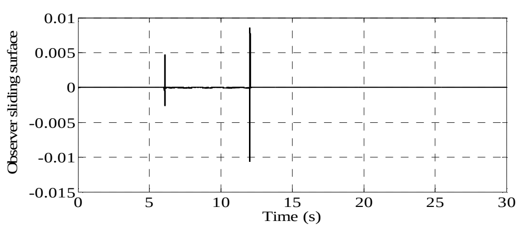
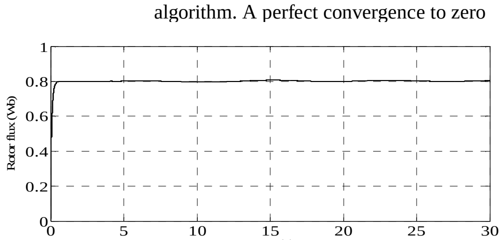


Figure 5. Sliding surface s of flux observer by twisting algorithm. A perfect convergence to zero



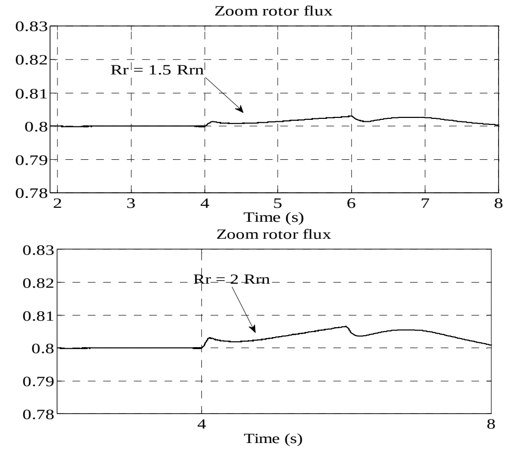


Figure 3. Rotor flux observer by twisting algorithm with speed variation under load torque and Rr variation

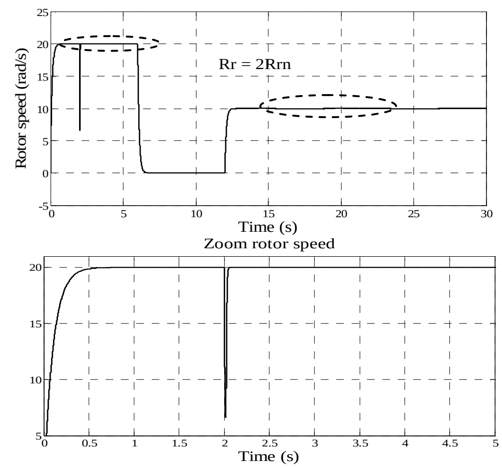


Figure 6. Dynamic responses of low speed test under T_L=10 Nm at 2s and 100% variation of Rr at 4s

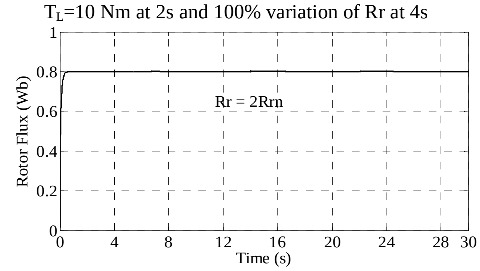
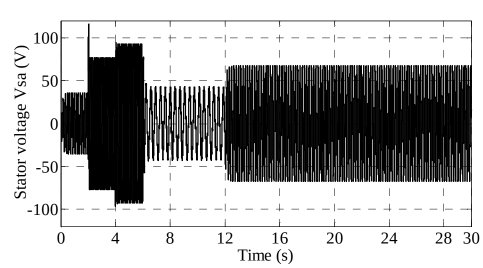


Figure 7. Rotor flux response under low speed with T_L=10 Nm at 2s and 100% variation of Rr at 4s



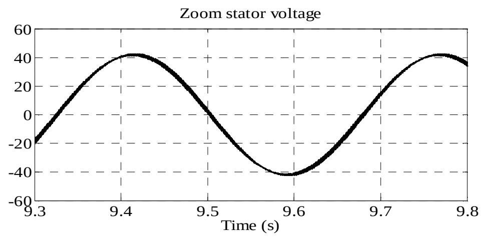


Figure 8. Control input usα for low speed test of SOSMC.

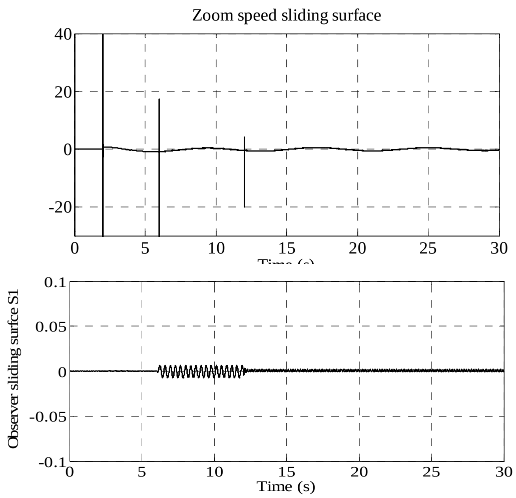


Figure 9. Speed sliding surface sω and sliding surface of rotor flux observer S1 by twisting algorithm for low speed test under T_L=10 Nm at 2s and 100% variation of Rr at 4s

VII. CONCLUSION

The proposed second order sliding mode technique demonstrates the very good performance and stability, especially; it is robustness under rotor resistance variation, external load disturbances and speed tracking. A twisting sliding mode observer is derived to estimate the rotor fluxes. Furthermore, it is shown that our observer is robust against uncertainties at low speed and in the same time the chattering effect is negligible. Simulations results prove successfully the validity of the current approach.

TABLE 1 1.5 KW, 220 V, 50 Hz Motor Parameters

R_s	5.72 Ω	L_s	0.462 H
R_r	4.2 Ω	L_r	0.462 H
M	0.4402 H	J	0.0049 Kg.m^2
p	2	F	0.003 Nms/rad

REFERENCES

[1] W. Perruquetti, J. P. Barbot, “Sliding mode control in engineering”, Control Engineering Series, Eds. Marcel Dekker, 2002.

[2] VI. Utkin, J. Guldner and J. Shi, “Sliding mode control in electromecanical systems”, Eds. Taylor-Francis, 1999.

[3] VI Utkin, “Sliding mode control design principles and applications to electric drives”. IEEE Trans on Industrial Electronics, Vol. 40, N^{0}1, pp 23–36, Feb. 1993.

[4] K-K Shyu, H-J Shieh, “A new switching surface sliding- mode speed control for induction motor drive systems”, IEEE Trans. Power Electronics, Vol. 11, N^0 4, pp. 660–667, 1996.

[5] H. Benderradji, L. Chrifi-Alaoui A. Makouf , “H∞ control using sliding mode linearization technique applied to an induction motor”, Systems, Signals and Devices (SSD11), on Power Elec. Systems (PES), 22-25 March, 2011.

[6] A. Benchaib, C. Edwards, “Nonlinear sliding mode control of an induction motor”, I. J. Adapt. Cont. Signal Process; Vol.14, pp 201-221, 2000.

[7]J.J. Slotine, “Sliding mode controller design for non-linear systems”, International Journal of Control, Vol. 40, pp. 421–434. 1984.

[8]M-H Park, K-S Kim “Chattering reduction in the position control of induction motor using the sliding mode”, IEEE Trans on Power Electronics, Vol.6 N0.3, pp 317–325, july 1991.

[9] H. Benderradji , A. Makouf , L. Chrifi-Alaoui “Field-oriented control using sliding mode linearization technique for induction motor”, IEEE *Conf on Control & Automation Congress (MED)*, Marrakech, Morocco, June 23-25, 2010.

[10] A. Benamor, L. Chrifi-Alaoui, M. Chabaane, P. Bussy, H. Messaoud, “A new second order sliding mode control approach for coupled MIMO nonlinear uncertain systems”, IEEE *Conf on Control & Automation Congress (MED*), Corfu, Greece, June 20-23, 2011.

[11] E. Etien, S. Cauet, L. Rambault and G. Champenois, “Control of an induction motor using sliding mode linearization”, Int. J. Appl. Math. Comput. Sci, Vol.12, N^o.4, pp. 523–531, 2002.

[12] M-H Park, K-S Kim “Chattering reduction in the position control of induction motor using the sliding mode”, IEEE Trans on Power Electronics, Vol.6 N^0.3, pp 317–325, july 1991.

[13] G. Bartolini, A. Damiano, G. Gatto, I. Marongiu, A. Pisano, and E. Usai “Robust speed and torque estimation in electrical drives by second order sliding modes”, IEEE Trans. Control. System Technol., vol. 11, pp. 84–90, Jan. 2003.

[14] T. Floquet, J.P. Barbot and W. Perruquetti, “Second order sliding mode control for induction motor”, 39thIEEE Conf. on Decision and Control, Sydney, Australia Dec., 2000.

[15] J. Davila, L. Fridman, and A. Levant, “Second order sliding mode observer for mechanical systems”, IEEE Trans. on Automatic Control, Vol. 50, N^{0}11, Nov. 2005.

[16] G. Bartolini, A. Ferrara, E. Usai and V.I. Utkin, “On multi–input chattering–free second order sliding mode control”, IEEE Trans. on Automatic Control, Vol. 45, N^0. 9, pp. 1711-1717, Sept. 2000.

[17] G.Bartolini, A.Ferrara and E.Usai, “Chattering Avoidance by Second-Order Sliding Mode Control”, IEEE Trans. On Automatic Control, Vol. 43, N^0. 2, pp. 241-246, Feb 1998.

[18] R. Benayache, S. M. Mhieddine, X. Dovifaaz, L. Chrifi-Alaoui, P. Bussy, “Robust second order sliding mode controller for nonlinear hydraulic system” IEEE International Conference on Control and Automation, 2009. ICCA 2009

[19] R. Benayache, L. Chrifi-Alaoui, A. Benamor, X. Dovifaaz and P. Bussy, “ Robust control of nonlinear uncertain systems via sliding mode with backstepping design”, American Control Conference (ACC), 2010