Journal of Cybernetics and Informatics

published by

Slovak Society for Cybernetics and Informatics

Volume 6, 2006

http://www.sski.sk/casopis/index.php (home page)

ISSN: 1336-4774

Journal of Cybernetics and Informatics 6 (2006)
http://www.sski.sk/casopis/index.php

SLIDING MODE SPEED AND FLUX CONTROL OF AN INDUCTION MACHINE

M. Abid, Y. Ramdani, A. Aissaoui and A. Zeblah.

Faculty of Engineer science power Department
Laboratory IRECOM
University of Djillali Liabès BP 98 SIDI BEL ABBES, Algeria 22000
Email: irecomabid@ univ-sba.dz

Abstract
In this paper, a direct field-oriented induction motor drive with a sliding mode controller (SMC) is presented. The (SMC) technique finds its stronger justification in the utilization problem of a robust nonlinear control law to model uncertainties. The used control algorithm is sliding mode associated with a particular function "sat" to limit chattering effects that presents a serious problem to applications of variable structure systems. Simulation tests under load disturbances and parameter uncertainties are provided to evaluate the consistency and performance of the proposed control technique.
Keywords: Induction machine, Motor drives, sliding mode control

1 INTRODUCTION

The control of the induction machine (IM) must take into account machine specificities: the high order of the model, the nonlinear functioning as well as the coupling between the different variables of control. Furthermore, the machine parameters depend generally on the operating point and vary either on the temperature (resistance), or with the magnetic state of the induction machine, without taking into account the variation. These parametric variations modify the performances of the control system when we use a regulator or a control law with fixed parameters. The new industrial applications necessitate speed variators having high dynamic performances, a good precision in permanent regime, and a high capacity of overload on all the range of speed and a robustness to the different perturbations. Thus, the recourse to robust control algorithms is desirable in stabilization and in tracking trajectories. The variable structure control (VSC) possesses this robustness using the sliding mode control that can offer many good properties such as good performance against undemodled dynamics, insensitivity to parameter variation, external disturbance rejection and fast dynamic [5-10]. These advantages of sliding mode control can be employed in the position and speed control of an alternative current servo system.

Using field Oriented Control (FOC) of induction machine, the knowledge of rotor speed and flux is necessary. In this work the flux is obtained by the measurement of stator voltages and currents. However the estimation is depended on machine parameters. Therefore, although sensorless vector-controlled drives are commercially available at this time, the parameter uncertainties impose a challenge in the control performances. the speed is measured.

In this paper, we begin with the IM oriented model in view of the vector control, next the rotor flux Φ_r, is estimated. We, then, present the sliding mode theory and design of sliding mode rotor flux controller and motor speed. Finally, we give some conclusion remarks on the control proposed of IM using sliding mode.

2 INDUCTION MOTOR ORIENTED MODEL

The model of three phase squirrel cage induction motor in the synchronous reference frame whose axis d is aligned with the rotor flux vector, ($\Phi_{rd} = \Phi_r$ and $\Phi_{rq} = 0$), can be expressed as [1-4]:

$$\dot{I}_{sd} = -\gamma_{sd} + \omega_s I_{sq} + \frac{K}{T_r}\Phi_{rd} + \frac{1}{\sigma L_s}U_{sd} \tag{1}$$

$$\dot{I}_{sq} = -\omega_s I_{sd} - \gamma I_{sq} - P\Omega K \Phi_{rd} + \frac{1}{\sigma L_s} U_{sq} \tag{2}$$

$$\dot{\Phi}_{rd} = M_{sr} I_{sd} - \frac{1}{T_r} \Phi_{rd} \tag{3}$$

$$\dot{\Phi}_{rq} = \frac{M_{sr}}{T_r} I_{sq} - (\omega_s - P\Omega)\Phi_{rd} \tag{4}$$

$$\dot{\Omega} = \frac{PM_{sr}}{JL_r}(\Phi_{rd} I_{sq}) - \frac{C_r}{J} - f\Omega \tag{5}$$

With:

$$T_r = \frac{L_r}{R} \; ; \sigma = 1 - \frac{M_{sr}^2}{L_s L_r} \; ; \; K = \frac{M_{sr}}{\sigma L_s L_r} \; ; \; \gamma = \frac{R_s}{\sigma L_s} + \frac{R_r M_{sr}^2}{\sigma L_s L_r^2}$$

Where Φ_{rd}, Φ_{rq} are rotor flux components, U_{sd}, U_{sq} are stator voltage components, I_{sd}, I_{sq} are stator current components, σ is leakage factor and p is number of pole pairs. R_s and R_r are stator and rotor resistances, L_s and L_r denote stator and rotor inductances, whereas M_{sr} is mutual inductance. T_e is the electromagnetic torque, C_r is the load torque, J is the moment of inertia of the IM, Ω is mechanical speed, ω_s is stator pulsation, f is damping coefficient, T_r is rotoric time-constant.

FLUX ESTIMATOR

In order to estimate motor flux, we take an algorithm of estimation based on the integration of the stator voltage equations in the stationary frame. The flux estimator can be obtained by the following equations:

$$\dot{\hat{\Phi}}_{r\alpha} = \frac{L_r}{M_{sr}}\left(U_{s\alpha} - R_s I_{s\alpha} - \sigma L_s \dot{I}_{s\alpha}\right) \tag{6}$$

$$\dot{\hat{\Phi}}_{r\beta} = \frac{L_r}{M_{sr}}\left(U_{s\beta} - R_s I_{s\beta} - \sigma L_s \dot{I}_{s\beta}\right) \tag{7}$$

θ_s is the angle between rotoric vector flux Φ_r and the axis of the (α,β) frame

$$\theta_s = \arctan\left(\frac{\hat{\Phi}_{r\beta}}{\hat{\Phi}_{r\alpha}}\right) \tag{8}$$

3 SLIDING MODE CONTROL DESIGN

Sliding mode technique is developed from variable structure control to solve the disadvantages of other designing nonlinear control system. Sliding mode is the technique to adjust feedback by previously defining a surface so that the system which is controlled will be forced to that surface then the behavior system slides to the desired equilibrium point.

The main feature of this control is that we only need to drive the error to a "switching surface". When the system is in "sliding mode", the behavior system is not affected by any modelling uncertainties and/or disturbances.

The design of the control system will be demonstrated for a nonlinear system presented in the canonical form [5-9]

$$\dot{x} = f(x, t) + B(x, t)\; u(x, t), \quad x \in \Re^n, \; u \in \Re^m, \; rank(B(x, t)) = m \tag{9}$$

With control in sliding mode control, the goal is to keep the system motion on the manifold S, which is defined as:

$$S = \{x : \; e(x,t) = 0\} , \tag{10}$$

$$e = x^{d} - x \; . \tag{11}$$

Where e the tracking error vector, x^d is the desired state vector, x is the state vector.
The control input *u* has to grant that the motion of the system described in (5) is restricted to belong to the manifold S in the state space.
The sliding mode control should be chosen such that the candidate Lyapunov function satisfies the Lyapunov stability criteria:

$$V = \frac{1}{2} S(x)^2 \tag{12}$$

$$\dot{V} = S(x)\dot{S}(x) \tag{13}$$

This can be assured for:

$$\dot{V} = -\eta \; |S(x)| \tag{14}$$

Where η is a strictly positive. Essentially, equation (14) states that the squared “distance” to the surface, as measured by $e(x)^2$, decreases along all system trajectories.
Therefore (13, (14) satisfy the Lyapunov condition. With the selected Lyapunov function the stability of the whole control system is guaranteed. The control function will satisfy reaching conditions in the following form:

$$u^{com} = u^{eq} + u^{n} \; . \tag{15}$$

Where u^{com} is the control vector, u^{eq} is the equivalent control vector, u^n is the correction factor and must be calculated so that the stability conditions for the selected control are satisfied.

$$u^{n} = K \; sat(S(x)/\phi) \tag{16}$$

$sat(S(x)/\phi)$ is the proposed saturation function, ϕ is the boundary layer thickness
In this paper we propose J.J.Slotine method

$$S(X) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e \tag{17}$$

Where, *e* is the tracking error vector, λ is a positive coefficient and *n* is the system order.

3.1 Speed control and current limitation

To control the speed of the induction machine, three surfaces are chosen. Variables of control are the rotation speed and the flux Φ_r. The flux will be maintained at its nominal value to have a maximal torque.
We take n=1, the speed control manifold equations can be obtained as:

$$S(\Omega) = \Omega_{ref} - \Omega \tag{18}$$

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega} \tag{19}$$

Substituting the expression of $\dot{\Omega}$ equation 5 in equation (19), we obtain:

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} - \frac{PM_{sr}}{JL_r} (\Phi_{rd} I_{sq}) - \frac{C_r}{J} - f\Omega \tag{20}$$

We take

$$I_{sq} = I_{sq}^{eq} + I_{sq}^{n} \tag{21}$$

- During the sliding mode and in permanent regime, we have:

$S(\Omega) = 0, \; \dot{S}(\Omega) = 0, \; I_{sq}^{n} = 0$ where the equivalent control is.

$$I_{sq}^{eq} = \frac{JL_r}{PM_{sr}\Phi_{rd}} \left(\dot{\Omega}_{ref} + \frac{f}{J}\Omega + \frac{C_r}{J} \right) \tag{22}$$

- During the convergence mode, the condition $S(\Omega)\dot{S}(\Omega) \le 0$ must be verified. we obtain :

$$\dot{S}(\Omega) = -\frac{P^2 M_{sr}\Phi_{rd}}{JL_r} I_{sq}^n \quad (23)$$

Therefore, the correction factor is given by:

$$I_{sq}^n = Ki_{sq} sat(S(\Omega)) \quad (24)$$

To verify the system stability condition, the parameter Ki_{sq} must be positive.

3.2. Stator current limitation

In order to limit all possible overshoot of the current I_{qs}, we add a limiter of current defined by

$$I_{sq}^{lim} = I_{sq}^{max} sat(I_{sq}^{com}) \quad (25)$$

The current control manifold is

$$S(I_{sq}) = I_{sq}^{\lim} - I_{sq} \quad (26)$$

$$\dot{S}(I_{sq}) = \dot{I}_{sq}^{\lim} - \dot{I}_{sq} \quad (27)$$

Substituting the expression of $\dot{I}_{sq}$ equation 2 in equation (27), we obtain:

$$\dot{S}(I_{sq}) = \dot{I}_{sq}^{\lim} - \left(-\omega_s I_{sd} - \gamma I_{sq} - P\Omega K\Phi_{rd} + \frac{1}{\sigma L_s} U_{sq} \right) \quad (28)$$

The control voltage is

$$U_{sq}^{ref} = U_{sq}^{eq} + U_{sq}^{n} \quad (29)$$

$$U_{sq}^{eq} = \sigma L_s \left(\dot{I}_{sq}^{\lim} + \omega_s I_{sd} + \gamma I_{sq} + P\Omega K\Phi_{rd} \right) \quad (30)$$

$$U_{sq}^{n} = Ku_{sq} sat(S(I_{sq})) \quad (31)$$

To verify the system stability condition, the parameter K_{uqs} must be positive

3.3 Flux control

In order to appear control U_{sd}, we take n=2, the manifold equation can be obtained by:

$$S(\Phi_r) = \lambda_\Phi (\Phi_r^{ref} - \Phi_r) + (\dot{\Phi}_r^{ref} - \dot{\Phi}_r) \quad (32)$$

The control voltage

$$U_{sd} = U_{sd}^{eq} + U_{sd}^{n} \quad (33)$$

$$U_{sd}^{eq} = -\sigma L_s \left(\left(\dot{\Phi}_r^{ref} + \lambda_\Phi \dot{\Phi}_r^{ref} + \left(\frac{1}{T_r} - \lambda_\Phi \right) \dot{\Phi}_r \right) \frac{T_r}{M_{sr}} - \left(-\gamma_{sd} + \omega_s I_{sq} + \frac{K}{T_r} \Phi_{rd} \right) \right) \quad (34)$$

$$U_{sd}^{n} = Ku_{sd} \quad sat(S(\Omega)) \quad (35)$$

To verify the system stability condition, the parameter Ku_{sd} must be positive.

The selection of coefficients Ki_{sq} Ku_{sd}, Ku_{sq} and λ_Φ must be done in order to satisfy following requirements:

- Existence condition of the sliding mode, which requires that the state trajectories are directed toward the sliding manifold,
- Hitting condition, which requires that the system trajectories encounter the manifold sliding irrespective of their starting point in the state space(insure the rapidity of the convergence),
- Stability of the system trajectories on the sliding manifold,
- Not saturate the control to allow the application of the control discontinuous.

4. SIMULATION RESULTS

4.1. System description

The block diagram of the proposed robust control scheme is presented in figure 1.The blocks SMC1, SMC2, SMC3 represent the proposed sliding mode controllers. The block limiter limits the current within the limits values. The block 'Coordinate transform' makes the conversion between the synchronously rotating and stationary reference frame. The block 'Inverter' shows that the motor is voltage fed. The block 'I_{sq} and Φ_r Estimator' represents respectively the proposed the stator current I_{sq} and the rotor flux Φ_r. The block 'IM' represents the induction motor. The IM used in this work is a 7.5 kW, U=220V, 50 Hz, P=2, I_n=16A, Φ_n=0.9Wb. IM parameters: R_s=0.63Ω, R_r=0.4Ω, $L_r = M_{sr}$=0.097H, L_S=0.091H. The system has the following mechanical parameters: J=0.22kgm^2, f=0.001Nms/rd.

The global system is simulated in real time by the software Matlab/Simulink.

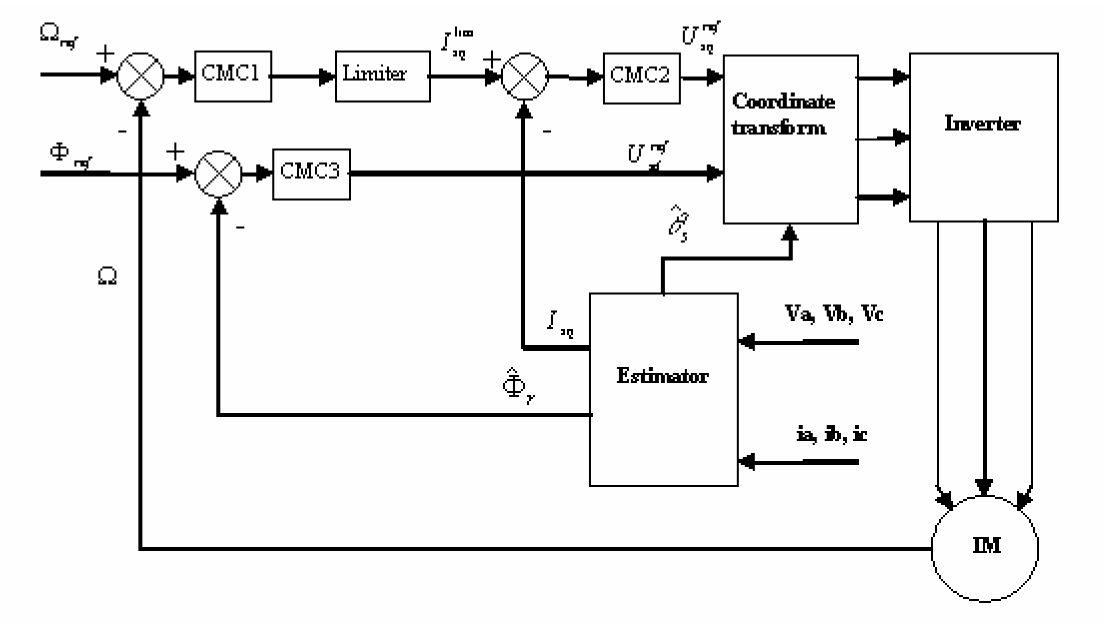

Fig. 1 Block diagram of the proposed control scheme of IM

4.2. Simulation results

To illustrate performances of control, we simulated a loadless starting up mode with the reference speed +Ω_n and an application and elimination of the load torque (C_r=30 Nm) at time 1s and 2s.

In order to test the robustness of the proposed control, we have studied the speed performances with current limitation. The introduced variations in tests look in practice to work conditions as the magnetic circuit overheating and saturation. Three cases are considered:

1. inertia variation,
2. Stator and rotor resistance variations
3. Stator and rotor inductance and mutual variations.

Figure 2 shows the robustness tests in relation to inertia variations. $J=m J_n$, $1 \leq m \leq 3$. Figure 3 shows the robustness tests to the stator and rotor resistance variations. Figure 4 shows the robustness tests to with stator and rotor inductance and mutual variations.

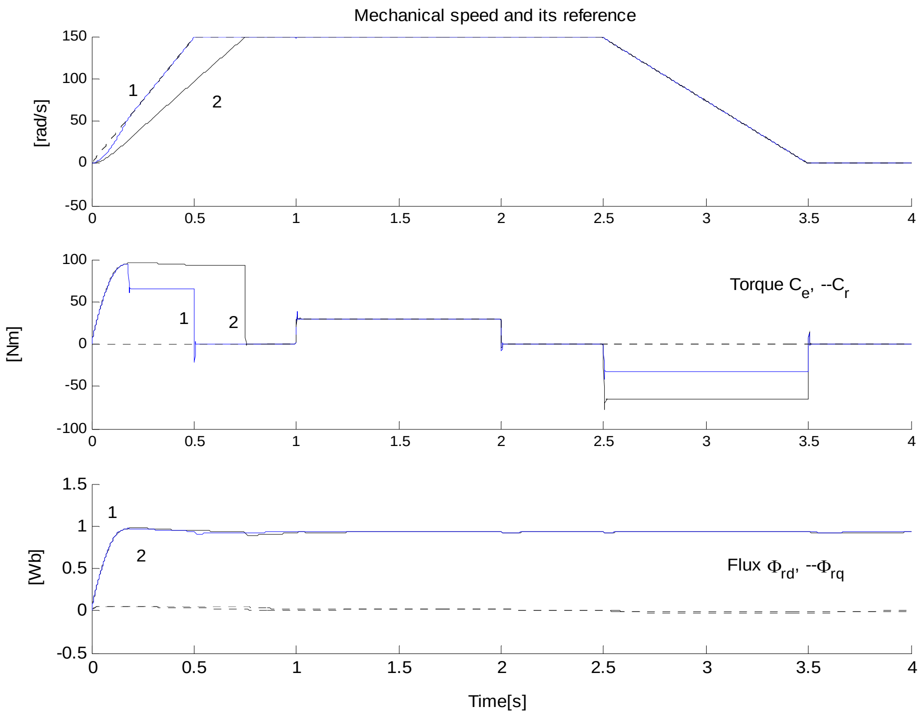

Fig.2 System responses
1: Nominal case, **2**: an increase of Inertia 2Jn

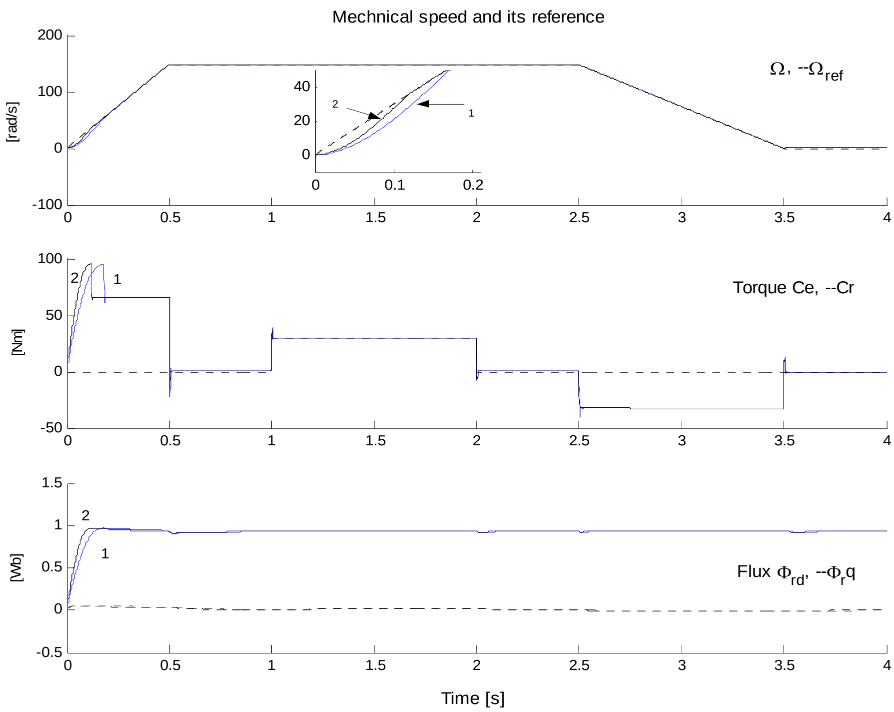

Fig.3 System responses
1: Nominal case, **2**: an increase of resistances 1.5R_s, 1.5R_r

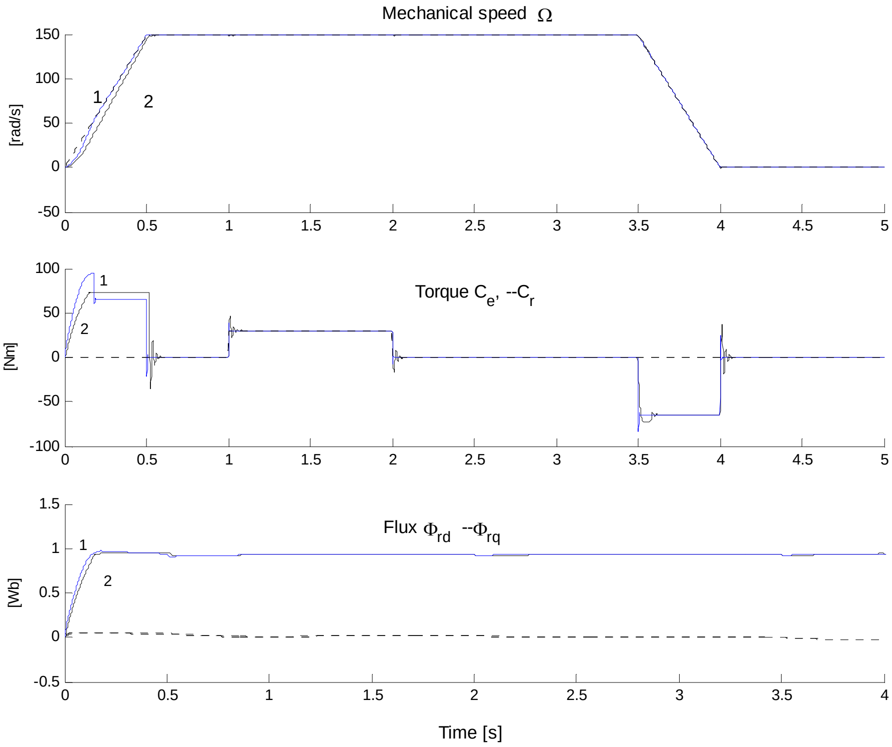

Fig. 4 System responses
1: Nominal case, **2**: an increase of resistances $1.5L_s$, $1.5L_r$

Figure2 shows the decoupling between the flux and torque. The flux tracks the desired flux and it is insensitive to outside parameter variations of the machine. It shows also the limited started torque and the speed is without overshoot and zero static error, the perturbation reject is instantaneous.

Figure3and Figure4 show the parameter variation does not allocate performances of proposed control. The speed response stays insensitive to parameter variations of the machine, without overshoot and without static error. The other performances stay maintained.

5 CONCLUSION

In this paper a speed, stator current and flux sliding mode control of induction machine using field Oriented Control has been presented. An algorithm to estimate the rotor flux is presented. Results of simulation show the robustness of proposed control in relation to the presence internal and external perturbations. The decoupling of torque and flux of IM is guaranteed. The rotor flux tracks the reference value. With a good choice of parameters of control and the smoothing out control discontinuity, the chattering effects are reduced, and the torque fluctuations are decreased. The speed tracking is without overshoot and zero static error. Furthermore, this regulation presents a simple robust control algorithm that has the advantage to be easily implantable in calculator

6 REFERENCES

[1] A. Mansouri, *Contribution à la commande des système non linéaire : Application aux robots et aux moteur asynchrone*. Thèse de doctorat d'état, USTO, Oran, 2004.

[2] A. Meroufel, *Commande découplée d'une machine asynchrone Sans capteur mécanique*. Thèse de doctorat d'état, Université de Sidi Bel Abbes, 2004.

[3] Jean Bornal and Guy Séguier, *Entraînement électrique à vitesse variable*, Lavoisier Technique et Documentation, 1998

[4] Buhler H, *Réglage de systèmes d'électronique de puissance*, Vol1 et 2, Presses polytechniques romandes, Lausanne, 1997
[5] V.I. Utkin, "Sliding mode control design principles and applications to electric drives," *IEEETrans. Ind. electronic*., vol. 40, pp.23-36, Feb.1977.
[6] Slotine, J.J.E. Li, W, *Applied nonlinear control*. Prence Hall, USA, 1998
[7] Karel jezernik, Miran rodie, Asif sabanovic, "Sliding mode application in speed sensorless torque control of an induction motor," *15th Triennial world congres*, Barcelona, Spain, 2002
[8] T. Zaharieva, *Commande à structure variable appliquée à un moteur synchrone*. Diplôme de recherche de l'INSA de Toulouse (DRUT), 2000.
[9] A.Ghazel, B. de Fornel and J.C.Hapiot, " Robustesse d'un contrôle vectorielle de structure minimale d'une machine asynchrone, " *J.Phys.III France* (1996)943-958.
[10] Buhler H. *Réglage par mode de glissement*. Presses polytechniques romandes (Lausanne, 1986)