Induction motors vector control Drive using sliding mode flux observer

Cherif Mokhtar†, Azzedine Bendiabdellah†, Abdelkader Mezouar‡ and Ameur Fethi Aimer†
†Department of Electrical Engineering, University of Science and Technology Oran, Algeria.
(elt.cherif@yahoo.fr)
‡Department of Electrical Engineering, University Centre of Saida, Algeria.

Abstract — **The field oriented control emerged as an important approach for the control of AC machines, and continues to be explored and developed in the literature. The estimation of the rotor flux from the measurable variables was the only method used to implement the vector control of the induction machine. To replace the estimator based on the mathematical model of the system, which can lead to unintended errors due to uncertainties on the model and on the measures we use an appropriate observer.**

Keywords — **Induction machine, vector control, sliding mode control, nonlinear observer.**

I. INTRODUCTION

THE field orientation technique namely the Rotor flux orientation introduced by BLASCHKE in 1972, has made it possible to act independently on the rotor flux and the electromagnetic torque which gives us an induction machine as good in the areas of variable speed drive as a DC machine, but the aimed decoupling can not be insured in steady states when the rotor flux amplitude is kept constant, which presents a serious constraint especially for rotating machines at high speeds (higher than the nominal speed) [1].

A Nonlinear control is often necessary for best performance. The sliding mode control is a technique that works as well with the linear systems as with nonlinear systems. This technique has two stages: Forcing the variable control of the system to reach an hyper-surface as quickly as possible, then slides until it reaches a certain point, during its second phase, the system is in a sliding state and its dynamic behaviour is independent of system parameters, as well as disturbances, and therefore insensitive to parameter variations.

Whatever the technique used (classical or sliding mode control) knowledge of the values of state variables is required.

The use of sensors causes the congestion of the installation and creates fragility and disability of precision. Faced with these problems, we use a sliding mode observer.

II. INDUCTION MOTOR MODEL

The model of the induction machine can be presented in the following state variable form [1]:

$$\begin{cases} \dfrac{d}{dt}I_{ds} = \dfrac{1}{\sigma L_s}\left[-R_{sr}I_{ds} + \omega_s \sigma L_s I_{qs} + \dfrac{L_m R_r}{L_r^2}\phi_{dr} + \dfrac{L_m}{L_r}\omega\phi_{qr} + V_{ds}\right] \\[2mm] \dfrac{d}{dt}I_{qs} = \dfrac{1}{\sigma L_s}\left[-\omega_s \sigma L_s I_{ds} - R_{sr}I_{qs} - \dfrac{L_m}{L_r}\omega\phi_{dr} + \dfrac{L_m R_r}{L_r^2}\phi_{qr} + V_{qs}\right] \\[2mm] \dfrac{d}{dt}\phi_{dr} = \dfrac{L_m R_r}{L_r}I_{ds} - \dfrac{R_r}{L_r}\phi_{dr} + \omega_g \phi_{qr} \\[2mm] \dfrac{d}{dt}\phi_{qr} = \dfrac{L_m R_r}{L_r}I_{qs} - \dfrac{R_r}{L_r}\phi_{qr} - \omega_g \phi_{dr} \\[2mm] \dfrac{d\omega}{dt} = \dfrac{p}{J}C_{em} - \dfrac{f}{J}\omega - \dfrac{P}{J}C_r \end{cases}$$

where $\omega_g = \omega_s - \omega$; $R_{sr} = \left(R_s + R_r \dfrac{L_m^2}{L_r^2}\right)$; $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$

R_s and R_r: the stator and rotor resistances.
ω_g: the sliding of the angular speed.

The electromagnetic torque can be expressed by:

$$C_{em} = P\frac{L_m}{L_r}(\phi_{dr}I_{qs} - \phi_{qr}I_{ds}) \qquad (1)$$

where p is the number of pair poles.

III. FIELD ORIENTED CONTROL PRINCIPLE

In the induction machine, the principle of orientation is to align the rotor flux on the direct axis of Park's axes, see figure 1.
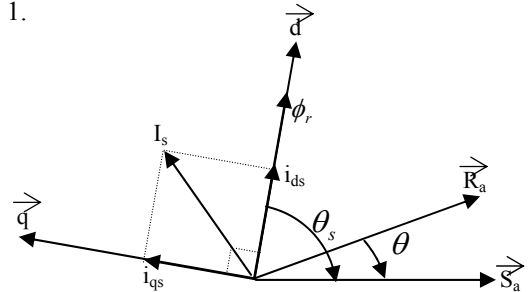

Fig. 1 Rotor flux orientation basic.

So: $\phi_{dr} = \phi_r$; $\phi_{qr} = 0$

We want to reach the following law [2]:

$$\frac{d}{dt}\phi_{qr} = 0 \quad \text{so} \quad \omega_s = \omega + \frac{L_m R_r}{L_r}\frac{I_{qs}}{\phi_r} \tag{2}$$

After Laplace transform, we can write:

$$\begin{cases} \phi_r = \frac{L_m}{1+T_r s}I_{ds} \\ C_{em} = \frac{pL_m}{L_r}\phi_r I_{qs} \end{cases} \quad \text{with} \quad T_r = \frac{L_r}{R_r} \tag{3}$$

To control the dynamics of the machine, knowledge of the position and the amplitude of the rotor flux is required. To obtain this information, we often use the model of the machine. A simple approach is to integrate the simplified rotor model equations as follows:

$$\frac{d}{dt}\phi_r = \frac{1}{T_r}(L_m I_{ds} - \phi_r)$$

$$\frac{d}{dt}\theta_s = \omega + \frac{L_m}{T_r \phi_r}I_{qs} \tag{4}$$

To avoid the coupling between the two equations, we use a static method of compensation. This method is concerned with the regulation of currents while neglecting the coupling terms. These are added to the output of the current correctors to obtain the reference voltages needed for the control.

The additional terms are determined so that the voltages are first-order relationship with the correspondent current. The voltage at the regulators output are given by [3]:

$$\begin{cases} V_{ds}^r = R_s I_{ds} + \sigma L_s s I_{ds} \\ V_{qs}^r = R_s I_{qs} + \sigma L_s s I_{qs} \end{cases} \tag{5}$$

The compensation voltage is given by:

$$\begin{cases} V_{ds}^c = \frac{L_m R_r}{L_r^2}s\phi_r - \sigma L_s \omega_s I_{ds} \\ V_{qs}^c = \frac{L_m}{L_r}\omega_s \phi_r + \sigma L_s \omega_s I_{qs} \end{cases} \tag{6}$$

In considering the steady state, the $\frac{L_m R_r}{L_r^2}s\phi_r$ term is eliminated, thus we obtain the reference voltage that is necessary for the control:

$$\begin{cases} V_{ds}^* = V_{ds}^c + V_{ds}^r \\ V_{qs}^* = V_{qs}^c + V_{qs}^r \end{cases} \tag{7}$$

We use PI regulators where dimensioned correction is made with the principle of poles placement. Figure 2 presents the main blocs of the direct field oriented control [4].

Simulation results

The simulation is achieved using MATLAB /SIMULINK. Figure 3 shows the orientation of the rotor flux by the direct method using a PWM inverter fed induction machine with the application of a 10 N.m load between t1= 0.5s and t2= 1.0s. We then apply a change of speed reference to -200 rad/s at t3=1.5s.
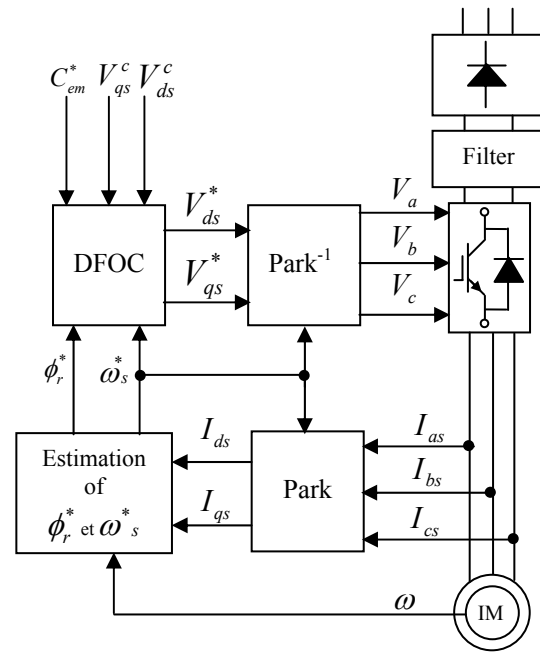
Fig. 2 The direct field oriented control principle.
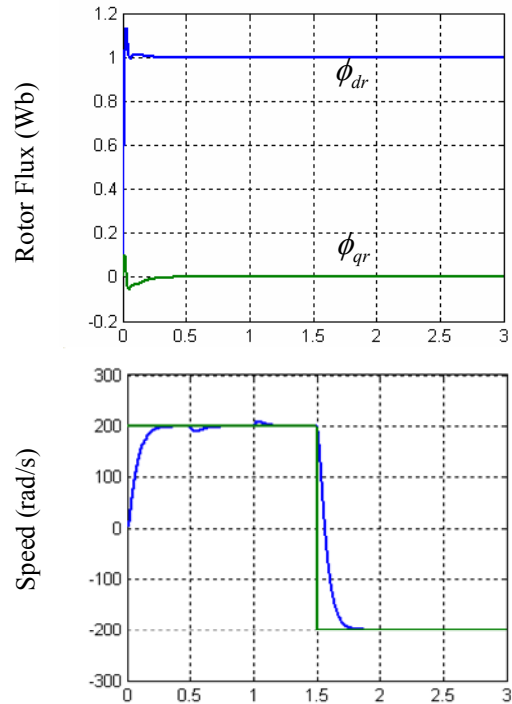
Fig. 3 Simulation results of the direct field oriented control.

In reference to these results we can concluded that:
- the decoupling is obtained between the rotor flux and the electromagnetic torque.
- the rotor fluxes (ϕ_{dr}, ϕ_{qr}) and the electromagnetic torque are maintained to their desired values, implying a good decoupling.

The use of PI regulator structure for the control of the speed induction machine has not yielded satisfactory results regarding the imposed disturbances. So it's necessary to introduce more powerful regulators, which are based on algorithms of modern techniques.

IV. SLIDING MODE CONTROL OF INDUCTION MACHINE

Two sliding surfaces are chosen giving the size of the command vector U, represented by voltage V_{ds} and V_{qs}, Figure 4, The variables to be resolved are the speed and the flux ϕ_r [1], [2], [5].

$$\begin{cases} S_\omega = \left(\dfrac{\partial}{\partial t} + \lambda_\omega \right) e(\omega) \\ S_{\phi_r} = \left(\dfrac{\partial}{\partial t} + \lambda_{\phi_r} \right) e(\phi_r) \end{cases} \tag{8}$$

With: $e(\omega) = \omega^* - \omega$ and: $e(\phi) = \phi_r^* - \phi_r$
The spins off surfaces are deduced as follows:

$$\begin{cases} \dot{S}_\omega = \ddot{\omega}^* + \lambda_\omega \dot{\omega}^* - \ddot{\omega} - \lambda_\omega \dot{\omega} \\ \dot{S}_{\phi_r} = \ddot{\phi}_r^* + \lambda_\phi \dot{\phi}_r^* - \ddot{\phi}_r - \lambda_\phi \dot{\phi}_r \end{cases} \tag{9}$$

According to the equation machine system we shall have:

$$\begin{cases} \dot{S}_\omega = \ddot{\omega}^* + \lambda_\omega \dot{\omega}^* + \dfrac{P}{J}\dot{C}_r + \left(\dfrac{f}{J} - \lambda_\omega\right)\dot{\omega} - \dfrac{P^2 L_m}{JL_r} i_{qs}\left(\dfrac{L_m}{T_r}i_{ds} - \dfrac{1}{T_r}\phi_r\right) \\ \quad - \dfrac{P^2 L_m}{JL_r}\dot{\phi}_r\left(-\omega_s i_{ds} - \dfrac{1}{\sigma}\left(\dfrac{1}{T_s} + \dfrac{L_m^2}{T_r L_s L_r}\right)i_{qs} - \dfrac{L_m}{\sigma L_s L_r}\phi_r\omega + \dfrac{1}{\sigma L_s}v_{qs}\right) \\ \dot{S}_{\phi_r} = \ddot{\phi}_r^* + \lambda_\phi \dot{\phi}_r^* + \left(\dfrac{1}{T_r} - \lambda_\phi\right)\dot{\phi}_r - \dfrac{L_m}{T_r}\left(-\dfrac{1}{\sigma}\left(\dfrac{1}{T_s} + \dfrac{L_m^2}{T_r L_s L_r}\right)i_{ds}\right) \\ \quad + \omega_s i_{qs} + \dfrac{L_m}{\sigma T_r L_s L_r}\phi_r + \dfrac{1}{\sigma L_s}v_{ds} \end{cases}$$

During the sliding mode, the derivatives have a zero value, which gives the equivalent commands V_{dseq} and V_{qseq}:

$$V_{dseq} = \dfrac{\sigma L_s T_r}{L_m}\left(\begin{array}{l} \ddot{\phi}_r^* + \lambda_\phi \dot{\phi}_r^* + \left(\dfrac{1}{T_r} - \lambda_\phi\right)\dot{\phi}_r - \dfrac{L_m}{T_r}\left(-\dfrac{1}{\sigma}\left(\dfrac{1}{T_s} + \dfrac{L_m^2}{T_r L_s L_r}\right)i_{ds}\right) \\ + \omega_s i_{qs} + \dfrac{L_m}{\sigma T_r L_s L_r}\phi_r \end{array} \right)$$

$$V_{qseq} = \dfrac{\sigma L_s J L_r}{P^2 L_m \phi_r}\left(\begin{array}{l} \ddot{\omega}^* + \lambda_\omega \dot{\omega}^* + \dfrac{P}{J}\dot{C}_r + \left(\dfrac{f}{J} - \lambda_\omega\right)\dot{\omega} - \dfrac{P^2 L_m}{JL_r} i_{qs}\left(\dfrac{L_m}{T_r}i_{ds} - \dfrac{1}{T_r}\phi_r\right) \\ - \dfrac{P^2 L_m}{JL_r}\dot{\phi}_r\left(-\omega_s i_{ds} - \dfrac{1}{\sigma}\left(\dfrac{1}{T_s} + \dfrac{L_m^2}{T_r L_s L_r}\right)i_{qs} - \dfrac{L_m}{\sigma L_s L_r}\phi_r\omega\right) \end{array} \right)$$

Fig. 4 Speed drive by the sliding mode control.

To check the condition of existence, we must put:

$$\begin{cases} V_{dsn} = K_{Vd} \cdot sign(S_{\phi_r}) \\ V_{qsn} = K_{Vq} \cdot sign(S_\omega) \end{cases}$$

In general, the value of command is:

$$U = U_{eq} + U_n$$

Simulation results and robustness tests

To illustrate the performance of the sliding mode control, Figure 5, we first simulate the machine at no load, for a rotor resistance variation R_r of +100%. We then apply a 10 N.m load between $t_1 = 0,5$s and $t_2 = 1$s. The machine is also subjected to an application of the command value between 200 and -200 (rad/s) at $t_3 = 1,5$s.

Fig. 5 Simulation results of speed drive by the sliding mode control.

It can be seen that the sliding mode control gives better performances regarding the continuation of the reference and the rejection of disturbances.

On the other hand, the robustness tests clearly show the effect of a misidentification of rotor parameters on the orientation of the rotor flux. This effect is primarily due to the error in the estimation of the rotor flux.

V. SLIDING MODE CONTROL WITH A NONLINEAR OBSERVER

The main idea of the observer is to find the best estimation of variables defining the state of the system from its inputs and outputs. For the estimated model, the observer has correction terms, which aim at minimizing the estimated error and accelerating the convergence to zero for this error.

A. Structure of a sliding mode observer

Consider the following non-linear system [2]:

$$\dot{x} = f(x,u,t) \qquad (10)$$

Consider also the vector y of the measurable variables which are connected linearly with the state variables:

$$y = C \cdot x \qquad (11)$$

If the system is an observable one, we define the observer by the following structure:

$$\dot{\hat{x}} = f(\hat{x},u,t) + A u_s \qquad (12)$$

with $\hat{x}$ having the same size as x (n). $\hat{f}$ being the estimation. A is the gain matrix with dimension $(n \times r)$ (r being the dimension of u). u_s is a vector defined by:

$$u_s = \begin{bmatrix} sign(s_1) & sign(s_2) & \cdots & sign(s_r) \end{bmatrix}^t$$

and $\hspace{5cm}$ (13)

$$\begin{bmatrix} s_1 & s_2 & \cdots & s_r \end{bmatrix}^t = S = \Gamma \begin{bmatrix} y - C\hat{x} \end{bmatrix}$$

Γ : is a square matrix $(r \times r)$ to be determined.

We also set the vector error $e = x - \hat{x}$ by subtracting (12) from (10), and we get:

$$\dot{e} = \Delta f - A u_s \qquad (14)$$

with $\hspace{1cm} \Delta f = f(x,u,t) - f(\hat{x},y,u,t)$

The vector surface $S = 0$ is attractive if:

$$S_i \dot{S}_i < 0 \quad \text{for:} \quad i = 1,r \qquad (15)$$

During the sliding mode, the switching term (13) is equal to zero because the vector surface and its derivative will be zero ($S \equiv \dot{S} \equiv 0$). The equivalent value of the switching term is given as follows:

$$\Gamma C(\Delta f - A \tilde{u}_s) = 0 \qquad (16)$$

where $\hspace{1cm} \tilde{u}_s = (\Gamma C A)^{-1} \Gamma C \Delta f \qquad (17)$

The matrix ΓCA must be invertible. This will constitute the first requirement for the choice of A and Γ. The error dynamic is governed by the following equation:

$$\dot{e} = (1 - A(\Gamma C A)^{-1}\Gamma C)\Delta f \qquad (18)$$

The choice of matrix Γ and A and the model $\hat{f}$ is therefore decisive to ensure the convergence of the error to zero.

B. Rotor flux sliding mode observer

The main purpose of the observer is to estimate the rotor fluxes ϕ_{dr} and ϕ_{qr} and the stator currents knowing the stator currents and voltages measurement, and the speed value. The output vector used for the estimation is given by [1]:

$$y = C \cdot x = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{pmatrix} x \qquad (19)$$

Consider now the induction motor system taking into account the variables $i_{ds}, i_{qs}, \phi_{dr}$ and ϕ_{qr}. The variables to be observed are $\hat{i}_{ds}, \hat{i}_{qs}, \hat{\phi}_{dr}$ and $\hat{\phi}_{qr}$. We give also the system's model to be observed and the observer's model.

The system to be observed is:

$$\begin{cases} \dot{i}_{ds} = -\dfrac{R_\alpha}{\sigma L_s}i_{ds} + \omega_s i_{qs} + \alpha\dfrac{1}{T_r}\phi_{dr} + \alpha\phi_{qr}\omega + \dfrac{1}{\sigma L_s}v_{ds} \\[2mm] \dot{i}_{qs} = -\omega_s i_{ds} - \dfrac{R_\alpha}{\sigma L_s}i_{qs} - \alpha\phi_{dr}\omega + \alpha\dfrac{1}{T_r}\phi_{qr} + \dfrac{1}{\sigma L_s}v_{qs} \\[2mm] \dot{\phi}_{dr} = \dfrac{L_m}{T_r}i_{ds} - \dfrac{1}{T_r}\phi_{dr} + \omega_g\phi_{qr} \\[2mm] \dot{\phi}_{qr} = \dfrac{L_m}{T_r}i_{ds} - \omega_g\phi_{dr} - \dfrac{1}{T_r}\phi_{qr} \end{cases} \qquad (20)$$

The observer's model is:

$$\begin{cases} \dot{\hat{i}}_{ds} = -\dfrac{R_\alpha}{\sigma L_s}i_{ds} + \omega_s i_{qs} + \alpha\dfrac{1}{T_r}\hat{\phi}_{dr} + \alpha\hat{\phi}_{qr}\omega + \dfrac{1}{\sigma L_s}v_{ds} + A_1^1 u_s \\[2mm] \dot{\hat{i}}_{qs} = -\omega_s i_{ds} - \dfrac{R_\alpha}{\sigma L_s}i_{qs} - \alpha\hat{\phi}_{dr}\omega + \alpha\dfrac{1}{T_r}\hat{\phi}_{qr} + \dfrac{1}{\sigma L_s}v_{qs} + A_1^2 u_s \\[2mm] \dot{\hat{\phi}}_{dr} = \dfrac{L_m}{T_r}i_{ds} - \dfrac{1}{T_r}\hat{\phi}_{dr} + \omega_g\hat{\phi}_{qr} + A_2^1 u_s \\[2mm] \dot{\hat{\phi}}_{qr} = \dfrac{L_m}{T_r}i_{ds} - \omega_g\hat{\phi}_{dr} - \dfrac{1}{T_r}\hat{\phi}_{qr} + A_2^2 u_s \end{cases} \qquad (21)$$

with $\hspace{1cm} R_\alpha = R_s + \dfrac{L_m^2}{L_r^2}R_r$ and $\alpha = \dfrac{L_m}{\sigma L_s L_r}$

$$u_s = \begin{bmatrix} sign(s1) & sign(s2) \end{bmatrix}^t \quad \text{and} \quad S = \begin{bmatrix} s1 \\ s2 \end{bmatrix} = \Gamma \bar{I}_s$$

By development, we obtain:

$$\Gamma = \dfrac{1}{\left(\alpha\dfrac{1}{T_r}\right)^2 + (\alpha\omega)^2} \begin{bmatrix} \alpha\dfrac{1}{T_r} & -\alpha\omega \\[2mm] \alpha\omega & \alpha\dfrac{1}{T_r} \end{bmatrix} \qquad (22)$$

$$A_1 = \begin{bmatrix} \delta_1\alpha\dfrac{1}{T_r} & \delta_1\alpha\omega \\[2mm] \delta_2\alpha\omega & \delta_2\alpha\dfrac{1}{T_r} \end{bmatrix} \qquad (23)$$

$$A_2 = \begin{bmatrix} \delta_1(q_1 - \dfrac{1}{T_r}) & \delta_1\omega_g \\[2mm] \delta_2\omega_g & \delta_2(q_2 - \dfrac{1}{T_r}) \end{bmatrix} \qquad (24)$$

Simulation results and robustness tests

We simulate the behavior of the observer by using Figure 6, for a variation of Rr by +50% at t_1=1s and for 100% at t_2=2s with the application of a load and the command value between 200 and -200 (rad/s) at time t_3=1,5s. We notice in Figure 7, that the regulation system with sliding mode observer shows a highly satisfactory performance regarding the convergence of the error to zero.
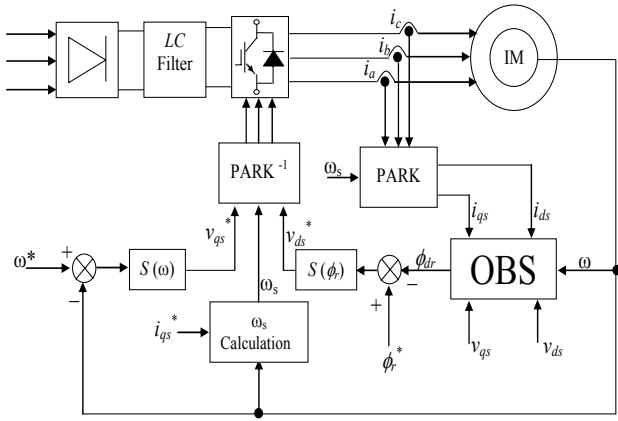
Fig. 6 Speed drive with a sliding mode observer.

VI. CONCLUSION

In this paper, we discussed the field oriented control technique of the rotor flux. This method makes it possible to decouple the flux control from that of the torque.

The PI regulator does not allow full control of the transient state. To correct this, we proposed the use of sliding mode control with non-linear switching surface; its algorithm has been synthesized from the nonlinear model by means of vector control.

We carried out tests that take into account the effect of the variation of different parameters of the machine. We found that speed control remains robust regarding to these variations, but it loses the decoupling possibility. This effect is primarily due to the error in the estimation of the rotor flux.

To solve these problems, we have proposed the replacement of the estimator by an observer whose role is to minimize the error about parametric variations. For this purpose, we have adopted an observer with derivatives corrective terms for variable system structure (sliding mode observer). This observer allows a good estimation of the rotor flux. However, it is very sensitive to the variations of the rotor resistance and inductance.

So, to have a high performance drive, it is proposed to continue this study for an on-line identification (real time) for the rotor parameters.

REFERENCES

[1] C.Mokhtar, A.Mezouar and A.F.Aimer "Commande vectorielle avec réglage de vitesse par mode de glissement de la machine asynchrone", *in Proceeding of the NCMES*, Boumerdes May 26-27, 2007 Algeria.

[2] A. Kerboua, *Commande et observateur par mode de glissement, application à une machine asynchrone alimentée en tension*. M.Sc Thesis, ENP, Algiers, Algeria 1999

[3] G. Grellet et G. Clerc, *Actionneurs électriques (Principes - Modèles - Commandes)*. EYROLLES Edition : 1997

[4] A. Boucheta, *Synthèse des contrôleurs par Baksteping de la machine asynchrone.* M.Sc Thesis, University Centre of Bechar, Algeria 2005

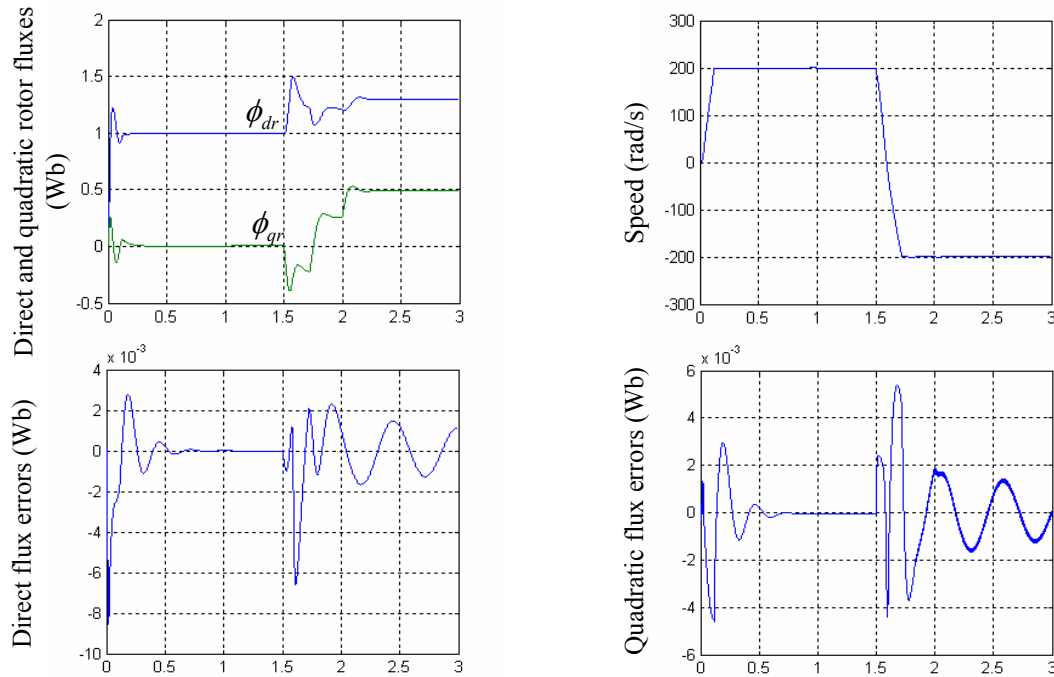[5] J. Slotine, *Applied non linear control 3.* Englewood Gliffs, NJ-Printice Hall : 1991

Fig.7 Simulation results of the speed drive with a sliding mode observer.