Journal of electrical systems Special Issue N° 01 : November 2009 pp: 42-47

The use of the Direct Control of Stator Flux and Kalman Filter for the Direct Torque Control of Induction Machine

Journal of Electrical Systems

A. Menacer, *A. Benakcha and B. Messaoudi*

Abstract **-- The direct torque control is a good solution to problems related to robustness and dynamics encountered in vector control with rotor flux oriented. The current research is directed towards improving the performance of this technique, whose the main problems are the evolution of the switching frequency, the ripples on the torque, on the flux and on the current. In this paper, the main object is the development of a structure for the direct torque sensor using the extended Kalman filter in order to estimate the mechanical speed. The simulation results show that this filter have a good performance (robustness) for different variations of the load and the noise measurement.**

Index Terms— Induction machine, Direct torque control, Kalman filter.

I. INTRODUCTION

Direct torque control (DTC) of induction motors has aroused significant interest among researchers looking for an efficient and high performance ac motor drive (robustness, low cost and ease of maintenance). In order to obtain the operation and accurate control, the regulation of the flux and speed is necessary [1], [3].

Indeed, the performed techniques of control, such as a vector control and direct torque control DTC, are based on knowledge of the mathematical machine model.This involves to know not only directly some electrical variables not measurable, example the flux in the machine, but to know also the parameters of the used model

If we search the optimal performances, it is necessary to estimate accurately the states and the parameters of the machine. These commands have been an important starting point of the research for the state and the parameters estimation of the induction machine [5, 7, 8].

The command without sensor allows:

• the reduction of the system complexity,
• the good mechanical robustness,
• the higher reliability.

The main of this work is the development of the speed regulation system using a Kalman filter with the DTC control.

II. MODEL OF THE INDUCTION MACHINE

The induction motor state space model with stator currents and stator flux as state variables can be written in d–q coordinates fixed to the stator as:

$$\begin{cases} \dot{x} = A\,x + B\,u \\ y = C\,x \end{cases} \tag{1}$$

where: x, u et y are respectively the state, input and output of the system such as:

$$x = \left[i_{s\alpha}\ i_{s\beta}\ \phi_{s\alpha}\ \phi_{s\beta}\right]^t$$
$$y = \left[i_{s\alpha}\ i_{s\beta}\right]^t$$
$$u = \left[u_{s\alpha}\ u_{s\beta}\right]^t$$

$$A = \begin{bmatrix} -\left(\frac{R_r}{\sigma L_r} + \frac{R_s}{\sigma L_s}\right) & -w_r & \frac{R_r}{\sigma L_r L_s} & \frac{w_r}{\sigma L_s} \\ -w_r & -\left(\frac{R_r}{\sigma L_r} + \frac{R_s}{\sigma L_s}\right) & -\frac{w_r}{\sigma L_s} & \frac{R_r}{\sigma L_r L_s} \\ -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma Ls} & 0 \\ 0 & \frac{1}{\sigma Ls} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

III. THE PRINCIPLE OF DIRECT TORQUE CONTROL

The direct torque control of the induction machine is based on the direct determination of the string command applied to the switchs of the voltage inverter. The choice is usually based on the use of hysteresis regulators whose function is to control the state of the system, the magnitude of stator flux and the electromagnetic torque. This type of strategy ranks in the category of control in magnitude, as opposed to the laws of the control in time, more traditional and based on adjusting the average voltage vector by pulse width modulation (PWM).

A. Action on the stator flux

The stator flux in the reference frame to the stator is given by the following equation:

$$\phi_s = \int_0^t \left(V_s - R_s . i_s\right) dt \tag{2}$$

Over a control period [0, Te], corresponding to a sampling period Te, the expression (2) can be written as follows:

$$\phi_s = \phi_{s0} + V_s T_e \quad \int_0^t R_s i_s dt \tag{3}$$

where: ϕ_{s0} is the flux vector at t=0

This work is realized at the LGEB laboratory (Laboratory of Electrical Engineering of Biskra, Algeria) by Dr Arezki Menacer, Dr Abedelhamid Benakcha and Messaoudi Boufateh, at the Department of Electrical Engineering, University Mohamed Khider, BP 145, 07000, Biskra, Algeria

A.Menacer (e-mail menacer_arezki@hotmail.com).
A.Benakcha (e-mail: benakcha_a@yahoo.fr).
B. Messaoudi (e-mail: boufateh.messaoudi@laposte.net).

Paper presented at the Third International Conference on Electrical Engineering-ICEE'09
19-21 May 2009, USTHB, Algiers, Algeria and selected for publication in "JES" by the ICEE 2009 Editorial Board

To simplify, we consider the term "$R_s i_s$" as negligible compared to the stator voltage "V_s", which occurs when the speed rotation is high enough.

From the equation (3), we find:

$$\frac{d\phi_s}{dt} = V_s \tag{4}$$

then :

$$\Delta\phi_s = \phi_s - \phi_{s0} = V_s T_e \tag{5}$$

B. Action on the torque

The electromagnetic torque is proportional to the vectorial product between the stator and rotor flux vector:

$$Ce = k.\left(\overline{\phi}_s . \overline{\phi}_r\right) = |\phi_s||\phi_r| \sin\theta_{sr} \tag{6}$$

C. Description of the control structure

Figure (1) shows the selection of the voltage vector V_s according the area defined by N_i.

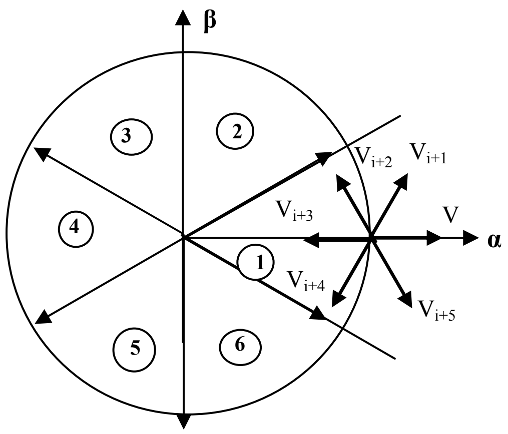


Fig.1 : Selection of voltage vector Vs according to the N = i

- if V_{i+1} (for $i \le 5$ or V_{i-5}) is selected then $\|\phi_s\|$ increase and C_e increase.
- if V_{i+5} (for $i \le 1$ or V_{i-1}) is selected then $\|\phi_s\|$ increase and C_e decrease.
- if V_{i+2} (for $i \le 4$ or V_{i-4}) is selected then $\|\phi_s\|$ decrease and C_e increase.
- if V_{i+4} (for $i \le 2$ or V_{i-2}) is selected then $\|\phi_s\|$ decrease and C_e decrease.

Whatever the evolution direction of the torque or the flux, in the area position $N=i$, the two voltage vectors V_i and V_{i+3} are never used because they can increase or decrease the torque according to the flux position ϕ_s in the sector i [2].

The command table is built in function of the state variables $\Delta\phi_s$, ΔC_e and the area N_i of the position of the flux ϕ_s

TABLE I
TABLE OF DIRECT TORQUE CONTROL

$\Delta\phi_s$	ΔC_e	N_1	N_2	N_3	N_4	N_5	N_6
1	**1**	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	**1**	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

IV. EXTENDED KALMAN FILTER

The Kalman filter allow to resolve in the time domain, the problem of statistical estimation for the linear systems. It uses the representation of state of the linear stochastic systems. It provides then an optima estimation in the sense of minimum variance and the variance of the estimation error [6]. The extended Kalman filter is used to estimate: $\hat{I}_{s\alpha}, \hat{I}_{s\beta}$, $\hat{\phi}_{s\alpha}$, $\hat{\phi}_{s\beta}$, $\hat{\omega}_r$.

The figure (2) shows the structure of Kalman filter.

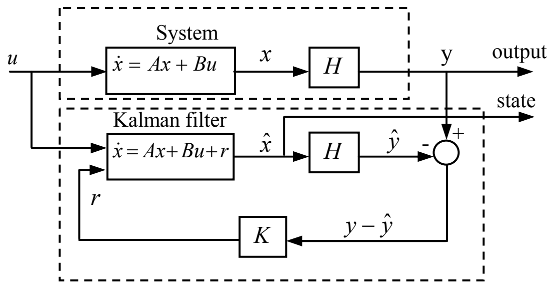


Fig.2 Structure of the Kalman filter estimator

The discrete model of IM is given as follows:

$$\begin{cases} x^e_{K+1} = f\left(x^e_K, u_K\right) + W^e_K \\ y_K = h\left(x^e_K\right) + V_K \end{cases} \tag{7}$$

with :

$$x^e_K = \left[x_K \quad \theta_K\right]$$

where

x_K : is the state vector to estimate

θ_K : is the parameters vector to estimate

and

W_k, V_k : respectively are the state and measurements noises.

Since:

$$Q_x = E\left(w_{xK}.w^t_{xi}\right) \quad \text{et} \quad Q_\theta = E\left(w_{\theta K}.w^t_{\theta i}\right)$$

where :

Q_x : covariance matrix state.

Q_θ : covariance matrix of the parameters.

Paper presented at the Third International Conference on Electrical Engineering-ICEE'09
19-21 May 2009, USTHB, Algiers, Algeria and selected for publication in "JES" by the ICEE 2009 Editorial Board

Assuming that the variations of the state and the parameters are independent, it follows that the matrix Q_θ is diagonal and is defined as follows:

$$Q = \begin{bmatrix} Q_x & 0 \\ 0 & Q_\theta \end{bmatrix}$$

A. *Application of the extended Kalman filter*

The process of observation of the extended Kalman filter is given in the following steps:

- The prediction of the extended state vector:

$$\hat{x}^e_{K+1/K} = f\left(x^e_{K/K}.u_K\right) \qquad (8)$$

where :

$$F = \begin{bmatrix} (1-T_e\gamma)i_{s\alpha} - T_e\omega_r i_{s\beta} + T_e K_1 \phi_{s\alpha} + T_e\omega_r\mu\phi_{s\beta} + \frac{T_e}{\sigma L_s}u_{s\alpha} \\ -T_e\omega_r i_{s\alpha} + (1-T_e\gamma)i_{s\beta} - T_e\omega_r\mu\phi_{s\alpha} + T_e K_1\phi_{s\beta} + \frac{T_e}{\sigma L_s}u_{s\beta} \\ -R_s i_{s\alpha} + \phi_{s\alpha} \\ -R_s i_{s\beta} + \phi_{s\beta} \\ \omega_r \end{bmatrix}$$

and:

$$\gamma = -\left(\frac{1}{\sigma T_r} - \frac{1}{\sigma T_s}\right) \; ; \; K_1 = \frac{1}{\sigma T_r L_s} \quad ; \quad \mu = \frac{1}{\sigma L_s}$$

- The prediction of the covariance matrix

The prediction covariance is represented by:

$$\hat{P}_{K+1/K} = F_K \hat{P}_{K/K} F_K^t + Q \qquad (9)$$

where: Q is the covariance matrix of the noise

and :

$$F_k = \left.\frac{\partial f(x^e_k, u_k)}{\partial x^e_k}\right|_{x^e_k = \hat{x}^e_{k/k}} \qquad (10)$$

where:

$$F_k = \begin{bmatrix} 1-T_e\gamma & -T_e\omega_r & T_e K_1 & T_e\mu\omega_r & -T_e i_{s\beta} + T_e\mu\phi_{s\beta} \\ T_e\omega_r & 1-T_e\gamma & -T_e\mu\omega_r & T_e K_1 & T_e i_{s\alpha} - T_e\mu\phi_{s\alpha} \\ -T_e R_s & 0 & 1 & 0 & 0 \\ 0 & -T_e R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- The Kalman gain calculus

The gain of the Kalman filter (matrix adjustment) is calculated by:

$$K_{K+1} = \hat{P}_{K+1/K} H_K^t (H_K \hat{P}_{K+1/K} H_K^t + R)^{-1} \qquad (11)$$

and

$$H_k = \left.\frac{\partial h\left(x^e_k\right)}{\partial x^e_k}\right|_{x^e_k = \hat{x}^e_{k/k}} \qquad (12)$$

with:

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

- The estimation of the extended state vector

$$\hat{x}^e_{K+1/K+1} = \hat{x}^e_{K+1/K} + K_{K+1}\left(y_{K+1} - H_K \hat{x}^e_{K+1/K}\right) \qquad (13)$$

- The estimation of the covariance matrix

$$\hat{P}_{K+1/K+1} = \hat{P}_{K+1/K+1} - K_{K+1}.H_K.\hat{P}_{K+1/K} \qquad (14)$$

B. *The choice of matrixes Q and R*

It is through these matrixes that pass the different states measured, predicted and estimated. Their main is to minimize the errors related to the modelisation approximation and the presence of noise on the measurements. This setting requires special attention and only a setting in line allows validating the operation of the filter. However, some main lines allow to understand the influence of adjustment of these values compared to the dynamic and stability of the filter [4].

The matrix Q, related to noise content in the state, adjusts the quality of our estimated model and its sampling. A greater value of Q gives a higher value of gain "*K*", reducing the importance of the modelisation and dynamic of the filter. The measure has then a relative weight greater. A high value of Q can create however the instability of the observer.

The matrix R adjusts the weight measurements. A high value indicates a large uncertainty of the measure.

A low value gives significant weight to the measure. However, it's being careful for the risk of instability at low values of R.

For a step of sampling time "T_e" equal to 10^{-4}, the values of Q and R are as follows:

$$Q = \text{diag}\left[10^{-2} \quad 10^{-2} \quad 10^{-3} \quad 10^{-3} \quad 10^{-3}\right]$$

$$R = \text{diag}\left[10^{-2} \quad 10^{-2}\right]$$

V. DIRECT TORQUE CONTROL (DTC) WITHOUT SPEED SENSOR USING THE EXTENDED KALMAN FILTER

The block control of the system using a direct torque control (DTC) with speed estimation by the extended Kalman filter is shown at Figure 3.

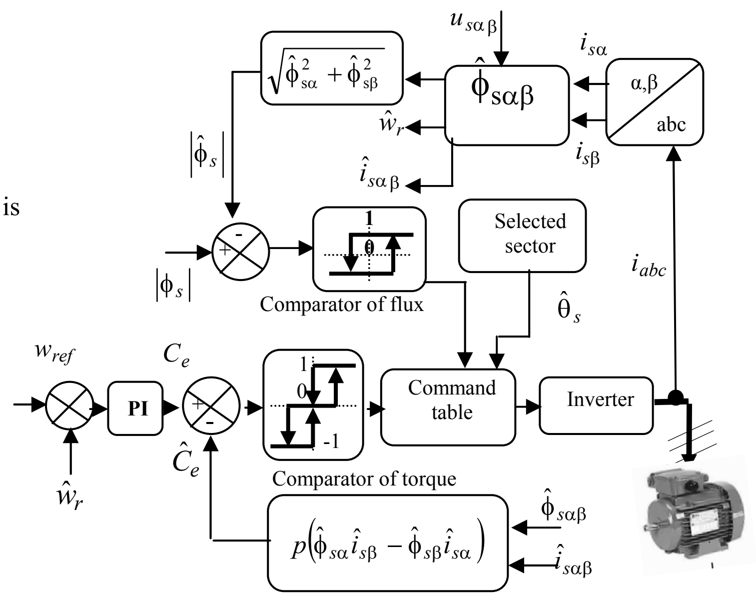


Fig.3 Direct torque control without speed sensor using the extended Kalman filter

Paper presented at the Third International Conference on Electrical Engineering-ICEE'09
19-21 May 2009, USTHB, Algiers, Algeria and selected for publication in "JES" by the ICEE 2009 Editorial Board

VI. Simulation results

In order to show the good performances and the robustness of the extended Kalman filter algorithm introduced in the direct torque control, many cases are considered in the following simulation:

A. Operating with no and full load

The Figures 4 to 9 represents the simulation results obtained from a no load operating. The application of a torque with 15 Nm is realized at t = 0.1s.

The estimated speed follows perfectly the command with a negligible error in the established regime. These results show the good performance of the filter used in the direct torque control DTC.

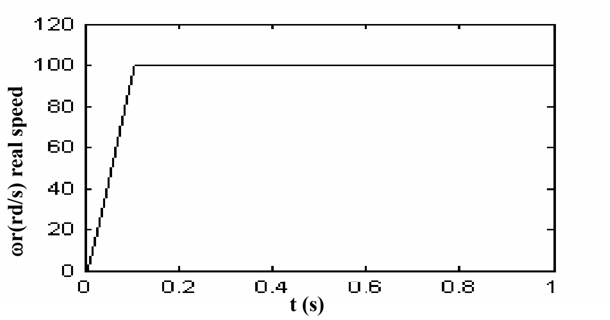


Fig.4 : Real **speed**

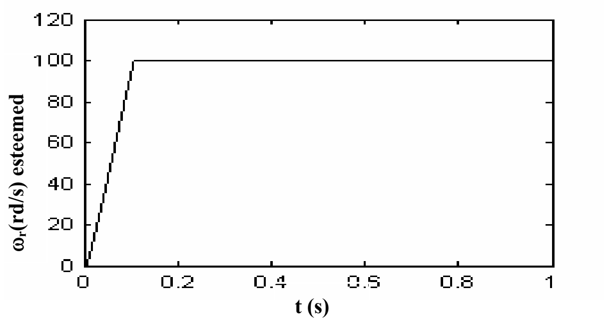


Fig.5 : Estimated speed

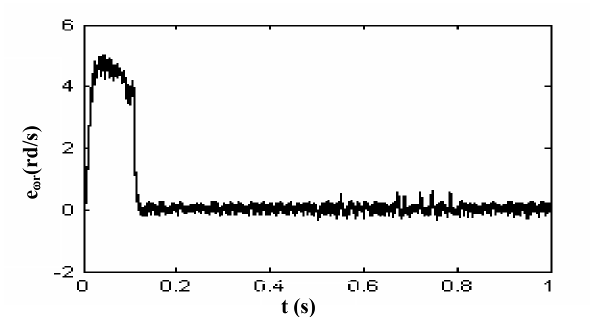


Fig.6 : Speed error

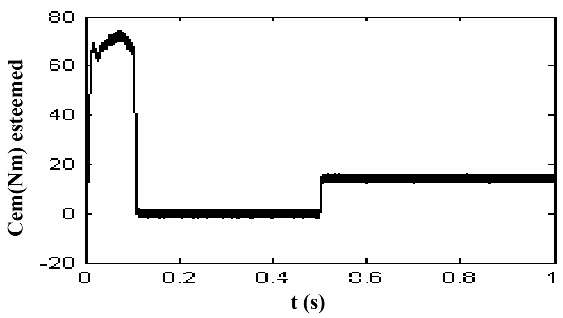


Fig.7 : Estimated electromagnetic torque

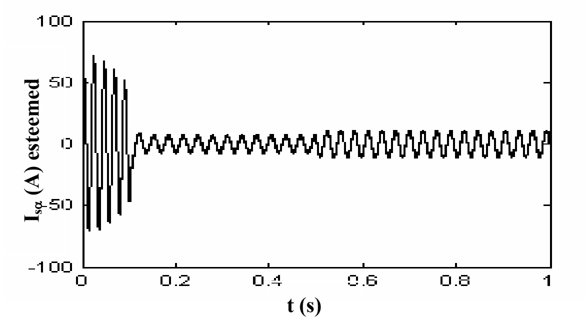


Fig.8 : Estimated current Isα

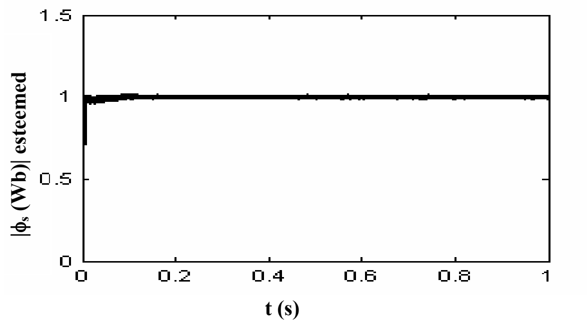
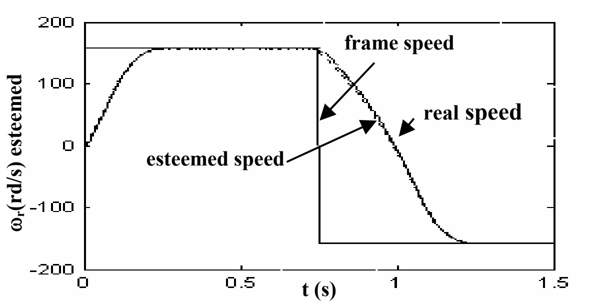


Fig.9 : Estimated flux magnitude

B. Operating with reverse speed rotation

In this case, a test of robustness of the control is realized by the reverse of the speed rotation.

The simulation results are illustrated by figures 10 and 11. We note that the estimated speed follows the reference with a slight variation at the moment of the reverse speed rotation, which is causes the oscillation of the flux.



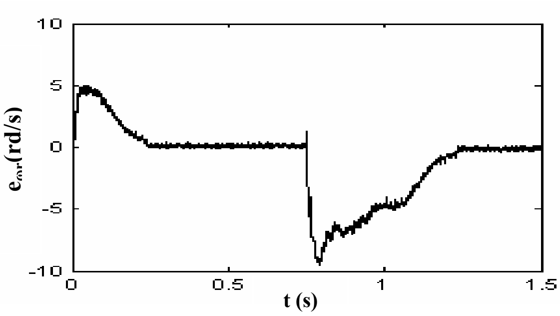


Fig.10: Speed error for a reverse turn

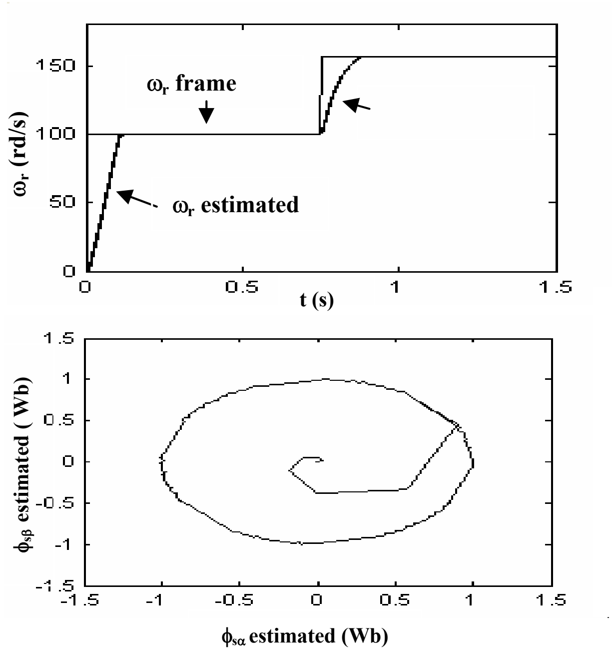


Fig.11: Path components of the estimated flux

C. *Estimated state for the low speeds*

In this case, the estimated speed is carried out for low speeds ± 50rd / s (Fig. 12). We note that the filter is stable.

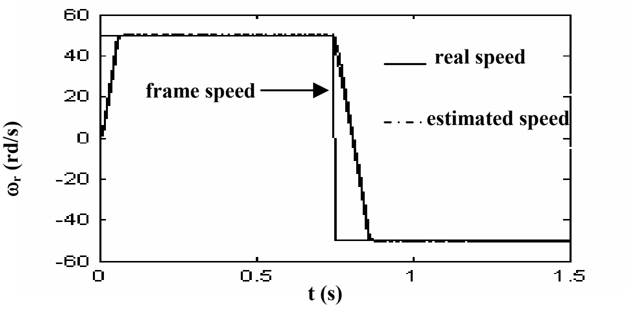


Fig.12 Filter performance at low speeds

D. *Estimate state with speed variation*

For a variation in the speed operating 100 rd / s to 157 rd / s, the estimated error is low at the start and at the moment of the variation (Figure 13).

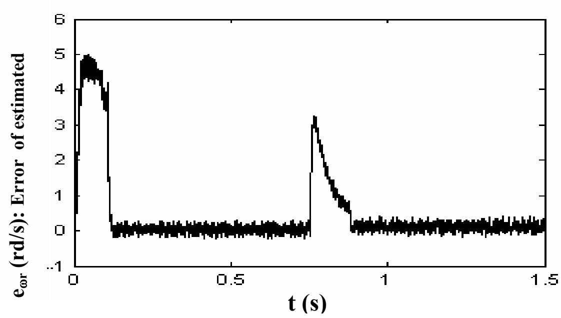


Fig.13 : Comparison of the level regulation of speed

E. *Injection of noise measurement in the stator currents*

The test of the robustness of the filter and the technique of control is realised for operating of the machine in a noisy environment. The noise is introduced in the measured stator current.

We note from the figure 14, the estimated speed is not too affected by the injection of the noise. The covariance noise of the speed can be increased with the increase in the covariance of measurement noise.

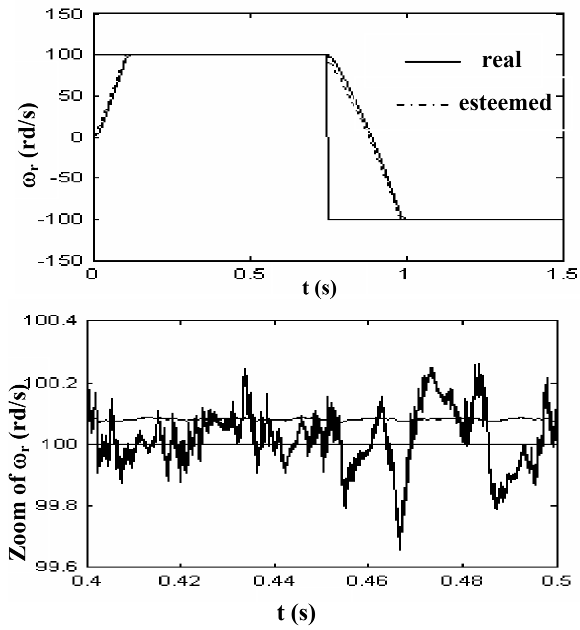


Fig.14 : Filter performance with a noise on the stator current

VII. CONCLUSION

In this paper we present the direct torque control using the extended Kalman filter (sensorless speed). This has provided a good performances for the training system overall. Indeed, the simulation results show the good performance from the filter at different situations: application the load torque, the operating for the reverse speed, the injection of the noise measurement for the stator currents and during the operation at low speeds.

VIII. APPENDIX

Parameters of asynchronous machine:

P = 4 kW, 220/380 V, f = 50 Hz, i_{sn} = 15 A, Ω = 1500 tr/min, C_r nom = 25 Nm, R_s = 1.2 Ω, R_r = 1.8 Ω, L_s =0.1554H, L_r = 0.1568 H, M = 0.15 H, J = 0.07 kg.m^2, 2p = 4.

.

IX. REFERENCES

[1] Takahashi, Youhichi Ohmori, "High-performance direct torque control of an induction motor", IEEE Transactions on industry applications, vol 25 N°.2, pp1603-1611.March/April 1989.

[2] A. Elebacha, M.T. Lanchich, M.cherkaoui", Contrôle directe de couple d'une machine asynchrone système de régulation de vitesse avec antiemballement", IEEE, 2000.

[3] S. Kaboli, M.R. Zolghadri, S. Hahbin, A. Honifar , "Effects of the flux value on torque ripple of the direct torque controlled induction motors drives determination» IEEE, pp 439- 444, 2003.

[4] H. R. Keyhani, M. R. Zoghadri, A.Homafar "An extended and improved discrete space vector modulation directed torque control for induction motors " IEEE, power conference pp 3414- 3420, 2004

[5] J. Rodriguez, J. Steinke, J. Pontt, M. Rotalla, P.Newman, "High power inverter motor drives with direct torque control " IEEE, 2004.

[6] F. Morand " Techniques d'observation sans capteur de vitesse en vue de la commande des machines asynchrones" Thèse doctorat école doctorale de Lyon, 7 Jan 2005.

[7] G. Bottiglieri, G. Scelba, and G. Scarcella, "Sensorless speed estimation in induction motor drives", IEEE Electric Machines, IEMDC'03, pp. 624– 630, June 2003.

[8] M. Barut, S. Bogosyan, and M. Gokasan, "EKF based sensorless direct torque control of IMs in the low speed range". IEEE Trans. On Industry Electronics, ISIE 2005., pp. 969 - 974, June 2005.

Menacer Arezki was born in Batna, Algeria, in 1968. He receives the B.Sc. degree in electrical engineering from the University of Batna, Algeria, in 1992, and the M.Sc. degree in electrical control from the Electrical Engineering Institute of Biskra University, Algeria, in 1996. He receives the Ph.D. degree in electrical control from the University of Batna and LAII Laboratory of Automatic and Industrial data processing, University of Poitiers, France, in 2007 and the "habilitation degree" in 2009 from University of Biskra Algeria. Currently, he is a Teaching Assistant with the Electrical Engineering Institute at the University of Biskra and member of LGEB Laboratory of Electrical Engineering of Biskra, Algeria. His major fields of interest in research are diagnosis, identification and control of electrical machines (menacer_arezki@hotmail.com).

Benakcha A/Hamid was born in 1961 in Arris, Algeria. He had achieved a M.sc. in 1980 and a B.Sc. in 1983 from the University of Batna, Algeria, and a Master of Science in 1985 and a Ph.D. in electronics from the University of Clermont-Ferrand, France. Since 1991, he teaches at the University of Biskra, Algeria. He is member of the Research Laboratory of electrotechnic of Biskra and the head of the research group: Simulation of sliding mode control of an asynchronous machine. His other research interests are: Electric machines (design, modelling, identification, control), power electronics, electromagnetism (antennas, free propagation), electronics (television). (benakch_a@yahoo.fr)

Paper presented at the Third International Conference on Electrical Engineering-ICEE'09
19-21 May 2009, USTHB, Algiers, Algeria and selected for publication in "JES" by the ICEE 2009 Editorial Board