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Senserless Speed and Position of Direct Field Orientation Control Induction Motor Drive

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Abstract

Direct field-orientation Control (DFOC) of induction motor drives without mechanical speed sensors at the motor shaft has the attractions of low cost and high reliability. To replace the sensor, information on the rotor speed and position are extracted from measured stator currents and from voltages at motor terminals. In this paper presents direct field-orientation control (DFOC) with two type of kalman filter (complete order and reduced order extended kalman filter) to estimate flux, speed, torque and position. Simulated results show how good performance for reduced order extended kalman filter over that of complete order extended kalman filter in tracking performance and reduced time of state estimation.

Key words: *Sensorless , Direct Field Orientation Control, Kalman Filter, Complete order extended kalman filter, reduced order extended kalman filter.*

1. Introduction

Electric drives based on induction motors (IM) are widely used in industrial applications. High performance in terms of fast dynamics and load torque rejection, good tracking capability of speed reference in a wide speed range and high power efficiency are normally obtained with control algorithms based on speed feedback. On the other hand, there exist applications where low/medium performance are required, cost reduction and high reliability are mandatory, or hostile environment does not allow to use speed sensors. In these fields, speed sensorless IM control can be profitably applied [1]. Field orientation control of an induction motor (IM) allows for a more direct command of both torque and flux than was possible with other variable-frequency techniques. With field orientation, torque and flux are commanded in a decoupled manner, and the behavior of a dc motor is reproduced [2]. Sensorless induction motor drives have reached the status of a maturing technology in a broad range of applications ranging from low-cost to high performance systems. Eliminating the speed sensor on the motor shaft represents a cost advantage, which combines favorably with increased reliability due to the absence of this mechanical component and its sensor cable. A motor without speed sensor is indicated for operation in hostile environments [3]. In this paper, I will propose a stochastic observer of state (Kalman filter) to consider rotor flux, the speed, the load torque and the position of the rotor. Initially we present an observer of state in complete order EKF then of a reduced nature EKF. The introduction of this last makes it possible to reduce the dimension of the observer and thus computing time which facilitate the establishment of the operation of observation on a device in real time.

2. A Review of Previous Work

There are a lot of papers dealing with Kalman Filter, especially with Extended Kalman Filter (EKF). In [4] Murat Barut et al. described

Extended Kalman Filter (EKF) algorithm to be used for the direct vector control of induction motors. In [5] Murat Barut et al. presents extended-Kalman-filter-based estimation algorithms that could be used in combination with the speed-sensorless field-oriented control and direct-torque control of induction motors (IMs) . In [6] Américo Vicente Leite et al. presents speed estimation based on a reduced- order Extended Kalman Filter (EKF), instead of a full order EKF in induction motor. In [7]Américo Vicente Leite et al. presents an application of the extended Kalman filter (EKF) to the simultaneous on-line estimation of the dq rotor flux components and all the electrical parameters of a vector controlled induction motor. In [8] Mickaël Hilairet et al. presents effective implementation of an extended Kalman filter used for the estimation of both rotor flux and rotor velocity of an induction motor. In [9]Murat Barut presents extended Kalman filter (EKF) based estimation technique for the solution of the on-line estimation problem related to uncertainties in the stator and rotor resistances inherent to the speed-sensorless high efficiency control of induction motors (IMs) in the wide speed range as well as extending the limited number of states and parameter estimations possible with a conventional single EKF algorithm. In [10] Václav Šmídl et al .presents Performance of square-root extended Kalman filter (EKF) based on reduced order models for sensorless control of permanent magnet synchronous motor (PMSM) drives is studied. . In [11] S. Kumar et al. presents design and implementation of Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF) and Neural State Filter (NSF) for the state estimation of a three-phase induction motor.

3. Adjustment in Cascade Speed and Position by the Direct Field Orientation Control Induction Motor (DFOCIM)

One can proceed in the same way for the case where the speed regulation is made by the direct field orientation control fed in voltage, one adds in cascade, the loop of regulation of the position. The functional diagram of the loop of position is presented by Figure 1 [12].

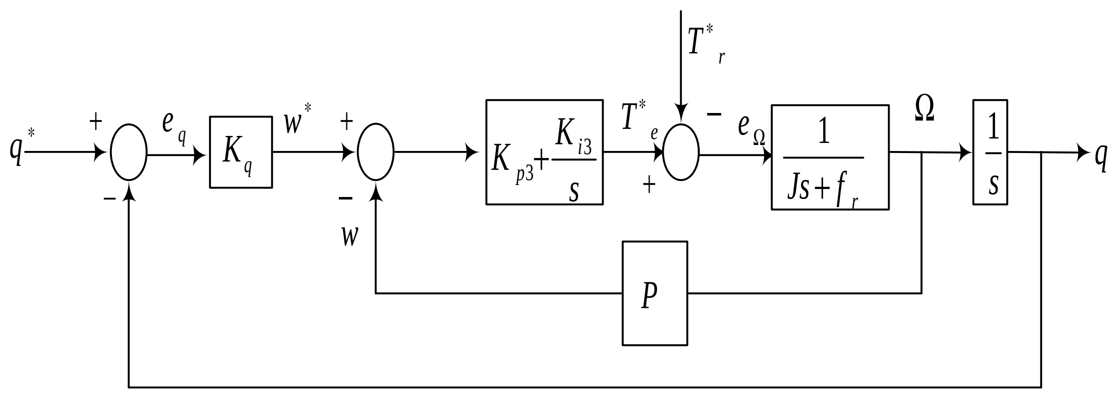


Fig. 1.Block Diagram of Position Regulation.

The transfer function in closed loop is:

$$\left.\frac{q(s)}{q^*(s)}\right|_{C_r=0} = \frac{K_q K_{p3} s + K_q K_{i3}}{Js^3 + (f_r + PK_{p3})s^2 + (PK_{i3} + K_q K_{p3}) + K_q K_{i3}} \quad \ldots(1)$$

The cascade position, speed and torque impose a dynamics of very slow position compared to that speed. Using MATLB/SIMULINK while basing oneself on the diagram block of Figure 1 one can determine the gain of position $K_q = 15$. The coefficients of speed regulator are given as follows

$K_{P3} = 4.1790 \quad K_{i3} = 19.8550$

4. Complete Order Extended Kalman Filter (EKF)

The extended kalman filter, allows the estimate of the state of a system extended to the speed. If one wants to estimate the load torque and the position of the rotor, a solution consists in extending the vector of state estimated with the load torque and the position of the rotor. The extended kalman filter in discrete time is given by the system of equation according to [13-15]

$$\begin{cases} X^e{}_{k+1} = A^e{}_k X^e{}_k + B^e{}_k U^e{}_k + W_k \\ Y^e{}_k = C^e{}_k X^e{}_k + V_k \end{cases} \quad \ldots(2)$$

$$\begin{cases} A^e{}_k = \exp(A^e(P\Omega)T_e) \approx I_7 + A^e(P\Omega)T_e + \dfrac{(A^e(P\Omega)T_e)^2}{2} \\ B^e{}_k = (A^e(P\Omega))^{-1}(A^e{}_k - I_7)B^e \approx T_e(I_7 + \dfrac{A^e(P\Omega)T_e}{2})B^e \\ C_k = C^e \end{cases} \quad \ldots(3)$$

When:

$$\begin{cases} X^e{}_k = \begin{bmatrix} I_{sa} & I_{sb} & \Phi_{ra} & \Phi_{rb} & \Omega & T_r & q \end{bmatrix}^T \\ U^e{}_k = \begin{bmatrix} V_{sa} & V_{sb} \end{bmatrix}^T \\ Y^e{}_k = \begin{bmatrix} I_{sa} & I_{sb} \end{bmatrix}^T \end{cases}$$

$$t'_s = s\,\frac{L_s}{R_s} \qquad K_r = \frac{M}{L_r} \qquad R_s = R_s + K_r{}^2.R_r$$

$$t_r = \frac{L_r}{R_r}$$

$$s = 1 - \frac{M^2}{L_s L_r}$$

$$A^e(P\Omega) = \begin{bmatrix} -\dfrac{1}{t'_s} & 0 & \dfrac{K_r}{t'_s R_s t_r} & \dfrac{K_r}{t'_s R_s} P\Omega & \dfrac{K_r}{t'_s R_s}\Phi_{rb} & 0 & 0 \\ 0 & -\dfrac{1}{t'_s} & -\dfrac{K_r}{t'_s R_s} P\Omega & \dfrac{K_r}{t'_s R_s t_r} & -\dfrac{K_r}{t'_s R_s}\Phi_{ra} & 0 & 0 \\ \dfrac{M}{t_r} & 0 & -\dfrac{1}{t_r} & -P\Omega & -\Phi_{rb} & 0 & 0 \\ 0 & \dfrac{M}{t_r} & P\Omega & -\dfrac{1}{t_r} & \Phi_{ra} & 0 & 0 \\ \left(\dfrac{P}{J}\right)K_r\Phi_{rb} & -\left(\dfrac{P}{J}\right)K_r\Phi_{ra} & -\left(\dfrac{P}{J}\right)K_r I_{sb} & \left(\dfrac{P}{J}\right)K_r I_{sa} & -\dfrac{f}{J} & -\dfrac{1}{J} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$C^e = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B^e = \begin{bmatrix} \dfrac{1}{t'_s R_s} & 0 \\ 0 & \dfrac{1}{t'_s R_s} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The algorithm of EKF in complete order in discrete time is given as [16]:

1- State Estimate (prediction):

$$\hat{X}^e{}_{k+1/k} = A^e{}_{k,k} X^e{}_{k/k} + B^e{}_{k/k} U^e{}_k \quad \ldots(4)$$

2- Calculation of the covariance matrix of the error of prediction:

$$P^e{}_{k+1/k} = A^e{}_{k,k} P^e{}_{k/k} A^e{}_{k,k}{}^T + Q^e{}_k \quad \ldots(5)$$

3- Calculation of the kalman filter gain (correction):

$$K^e{}_{k+1} = P^e{}_{k+1/k} C^e{}_k{}^T \left(C^e{}_k P^e{}_{k+1/k} C^e{}_k{}^T + R_k\right)^{-1} \quad \ldots(6)$$

4- Covariance Matrix of the error of the filter (correction):

$$P^e{}_{k+1/k+1} = \left(I_7 - K^e{}_{k+1} C^e{}_k\right) P^e{}_{k+1/k} \quad \ldots(7)$$

5- Estimate of the vector of state at the moment (k+1) (correction):

$$\hat{X}^e_{k+1/k+1}=\hat{X}^e_{k+1/k}+K^e_{k+1}\left(Y_{k+1}-C^e_k\hat{X}^e_{k+1/k}\right) \quad \ldots(8)$$

5. Reduced Order Extended Kalman Filter

In practice, so certain exits of the system are measurable (stator currents), it is preferable to use them to reach directly in certain states and to estimate the others by the means of an observer of state of a reduced order. The advantage of such observer is that it makes it possible to reduce the synthesis of the observer in terms of establishment and also in terms of computing time [14]

In order to obtain a simple model, we will adopt a model having rotor flux like state, the stator current like entry and the stator voltage like exit. The complex equations of the IM can be rearranged in order to express rotor flux and the stator voltage, according to the components of the current and flux. In the stationary reference frame, we can write [17]

$$\begin{cases}\dfrac{d\overline{\Phi}_r}{dt}=\dfrac{1}{t_r}\left(jP\Omega t_r-1\right)\overline{\Phi}_r+\dfrac{M}{t_r}\overline{I}_s\\ \overline{V}_s=\dfrac{K_r}{t_r}\left(jP\Omega t_r-1\right)\overline{\Phi}_r+R_s t'_s\dfrac{d\overline{I}_s}{dt}+R_s\overline{I}_s\end{cases} \quad \ldots(9)$$

$$\begin{cases}\dot{X}=AX+BU\\ Y=CX+DU+E\dot{U}\end{cases} \quad \ldots(10)$$

Where: $$\begin{cases}X=\left[\Phi_{ra}\quad \Phi_{rb}\right]^T\\ U=\left[I_{sa}\quad I_{sb}\right]^T\\ Y=\left[V_{sa}\quad V_{sb}\right]^T\end{cases}$$

$$A=\begin{bmatrix}-\dfrac{1}{t_r} & -P\Omega\\ P\Omega & -\dfrac{1}{t_r}\end{bmatrix} \qquad B=\begin{bmatrix}\dfrac{M}{t_r} & 0\\ 0 & \dfrac{M}{t_r}\end{bmatrix}$$

$$C=\begin{bmatrix}-\dfrac{K_r}{t_r} & -PK_r\Omega\\ PK_r\Omega & -\dfrac{K_r}{t_r}\end{bmatrix} \qquad D=\begin{bmatrix}R_s & 0\\ 0 & R_s\end{bmatrix}$$

$$E=\begin{bmatrix}t'_sR_s & 0\\ 0 & t'_sR_s\end{bmatrix}$$

The continuous model of a reduced order extended to the speed, the load torque and the position of the rotor are given by the system of equation according to:

$$\begin{cases}\dot{X}^e=F\left(X^e,U^e\right)\\ Y^e=H\left(X^e\right)\end{cases} \quad \ldots(11)$$

Where:

$$\begin{cases}X^e=\left[\Phi_{ra}\quad \Phi_{rb}\quad \Omega\quad T_r\quad q\right]^T\\ U^e=\left[I_{sa}\quad I_{sb}\right]^T\end{cases}$$

$$H\left(X^e\right)=\begin{bmatrix}-\dfrac{1}{t_r}\Phi_{ra}-P\Omega\Phi_{rb}\\ P\Omega\Phi_{ra}-\dfrac{1}{t_r}\Phi_{rb}\end{bmatrix}$$

$$F\left(X^e,U^e\right)=\begin{bmatrix}-\dfrac{1}{t_r}\Phi_{ra}-P\Omega\Phi_{rb}+\dfrac{M}{t_r}I_{sa}\\ P\Omega\Phi_{ra}-\dfrac{1}{t_r}\Phi_{rb}+\dfrac{M}{t_r}I_{sb}\\ \dfrac{1}{J}PK_rI_{sb}-\dfrac{1}{J}PK_rI_{sa}-\dfrac{f}{J}-\dfrac{1}{J}T_r\\ 0\\ \Omega\end{bmatrix}$$

$$Y^e=\begin{bmatrix}V_{sa}-t'_sR_s\dfrac{dI_{sa}}{dt}-R_sI_{sa}\\ V_{sb}-t'_sR_s\dfrac{dI_{sb}}{dt}-R_sI_{sb}\end{bmatrix}$$

The reduced order EKF in discrete time can be obtained as follows [19]:

$$\begin{cases}X^e_{k+1}=F\left(X^e_k,U^e_k\right)\\ Y^e_k=H\left(X^e_k\right)\end{cases} \quad \ldots(12)$$

F_K: The matrix of the discrete system is at every moment ritualized sampling by using the development in Taylor series to the order two.

The linearized model (13) is obtained, starting from the model extended in discrete times (12), by calculating Jacobeans given by equation (14) [20]

$$\begin{cases}X^e_{k+1}=A^e_kX^e_k+B^e_kU^e_k\\ Y^e_k=C^e_kX^e_k\end{cases} \quad \ldots(13)$$

Where:

$$\begin{cases} A^e{}_k = \left.\dfrac{dF_k}{dX^e}\right|_{X^e{}_k=\hat{X}^e{}_k} \\ B^e{}_k = \left.\dfrac{dF_k}{dU^e{}_k}\right|_{X^e{}_k=\hat{X}^e{}_k} \\ C^e{}_k = \left.\dfrac{dH_k}{dX^e}\right|_{X^e{}_k=\hat{X}^e{}_k} \end{cases} \quad \ldots(14)$$

One applies the same of EKF algorithm describes previously to estimate the vector of state in reduced order EKF.

6. The Block Diagram of DFOCIM with Complete Order and Reduced Order EKF

Figures 2 and 3 represent the blocks diagrams of the DFOCIM in complete and reduced order EKF. In order to evaluate the performances of the algorithms of estimate by the EKF of a complete order then of a reduced order and consequently the performances of the systems of total drive, we subjected our systems to various tests of simulation, for a direct FOCIM of speed and position.

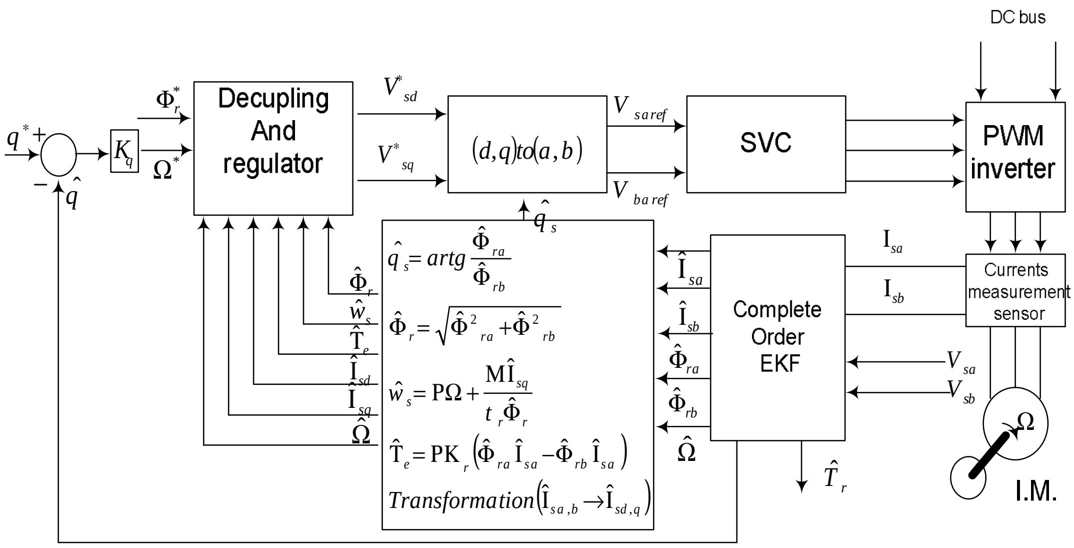


Fig. 2. Block Diagram of Direct Field Orientation Control Induction Motor (DFOCIM) with Complete Order Extended Kalman Filter.

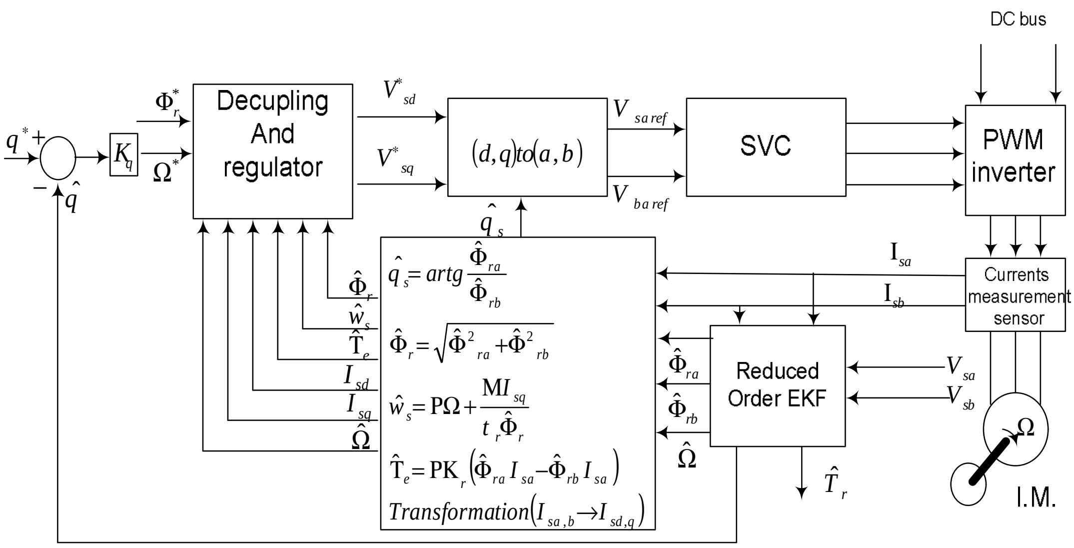


Fig. 3. Block Diagram of Direct Field Orientation Control Induction Motor (DFOCIM) with Reduced Order Extended Kalman Filter.

7. Simulation Results

7.A. Simulation Results in Speed Reference

1- No-Load Response

Figure 4 represents the estimate of the model of rotor flux (reference flux 0.85 Wb), position of the rotor, the speed and the torque as well as the estimation errors in the case of a no load for a level speed 1000tr/min.

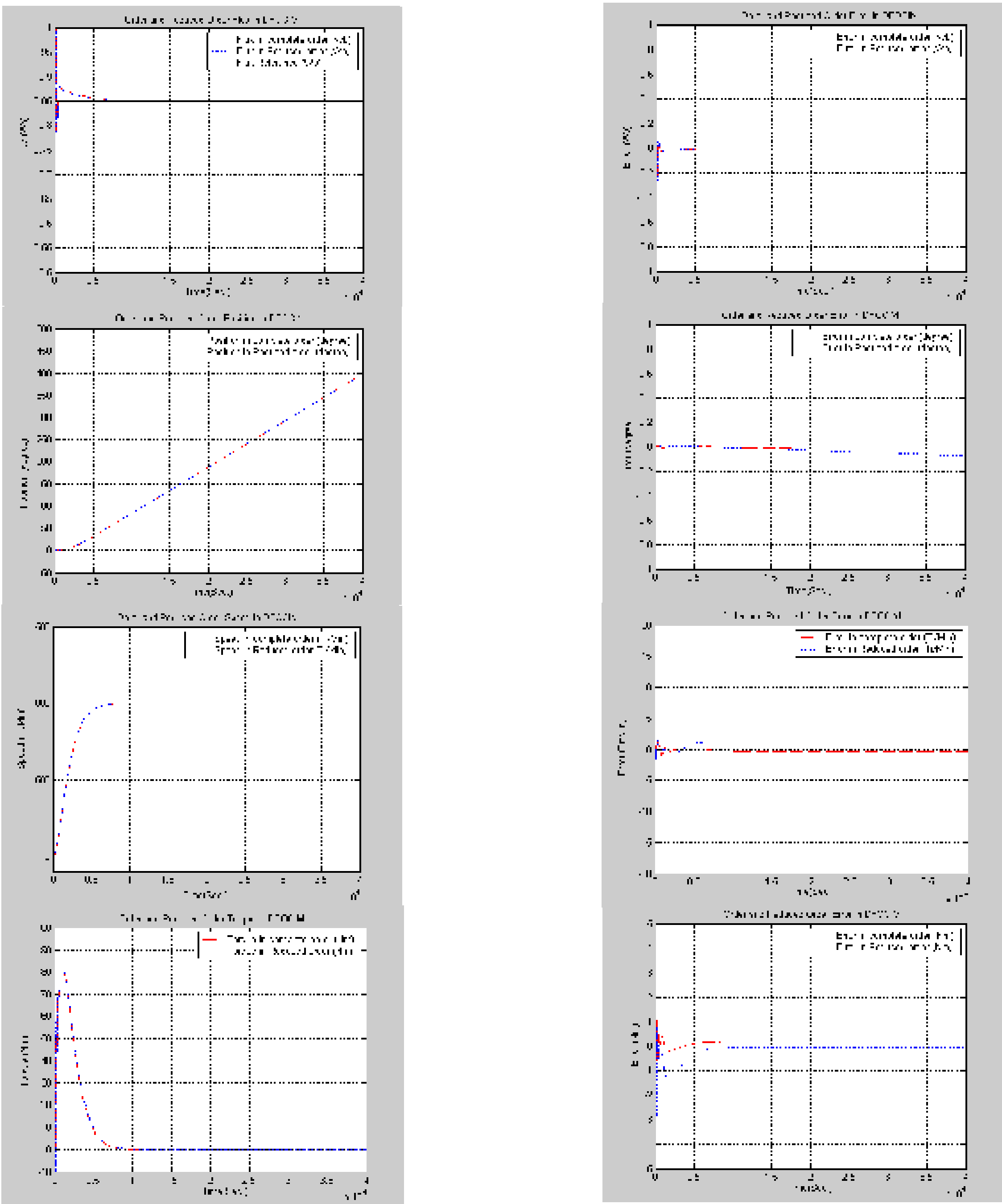


Fig. 4. Simulation Results Obtained with the Two Observers of Kalman Filter and Error for a Speed of Reference 1000 tr/min (No-Load).

2- Load Response

Figure 5 represents the estimate of the model of rotor flux (reference flux 0.85 Wb), the load torque, the position of the rotor, the speed and the torque as well as the estimation errors in the case of a no load starting for a level speed 1000tr/min followed of a level of the load torque 50Nm at the time t=1 sec. to 3 sec.

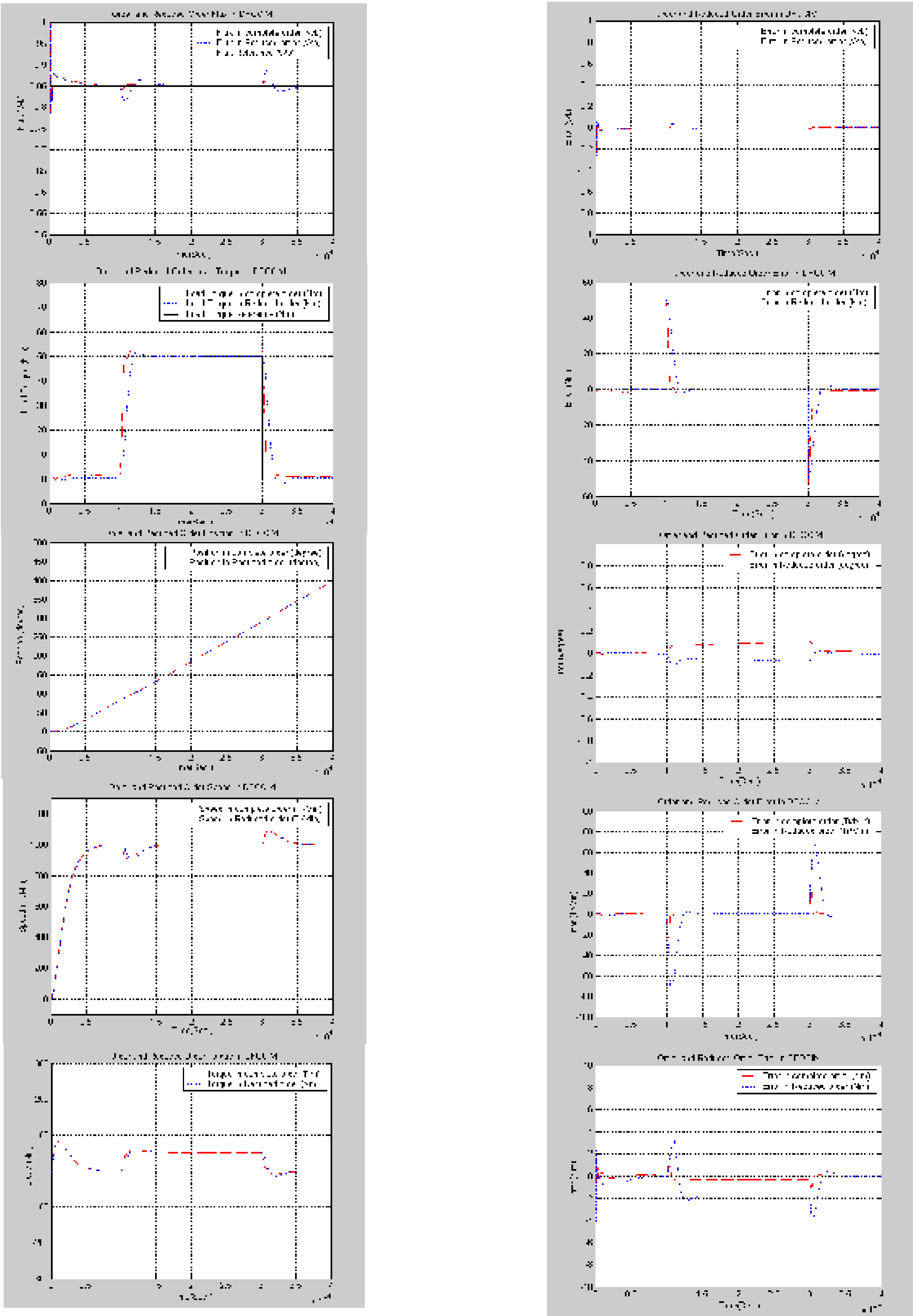


Fig. 5. Simulation Results Obtained with the Two Observers of Kalman Filter and Error for a Speed of Reference 1000 tr/min (Load of 50 Nm at t=1s to 3s).

3- No load Tracking Response

Figure 6 represents the estimate of model of rotor flux (reference flux 0.85 Wb), the position of the rotor ,the speed and the load torque as well as the estimation errors in the case of a no load for a level speed 1000tr/min and an inversion of direction of rotation at the moment T = 2sec.

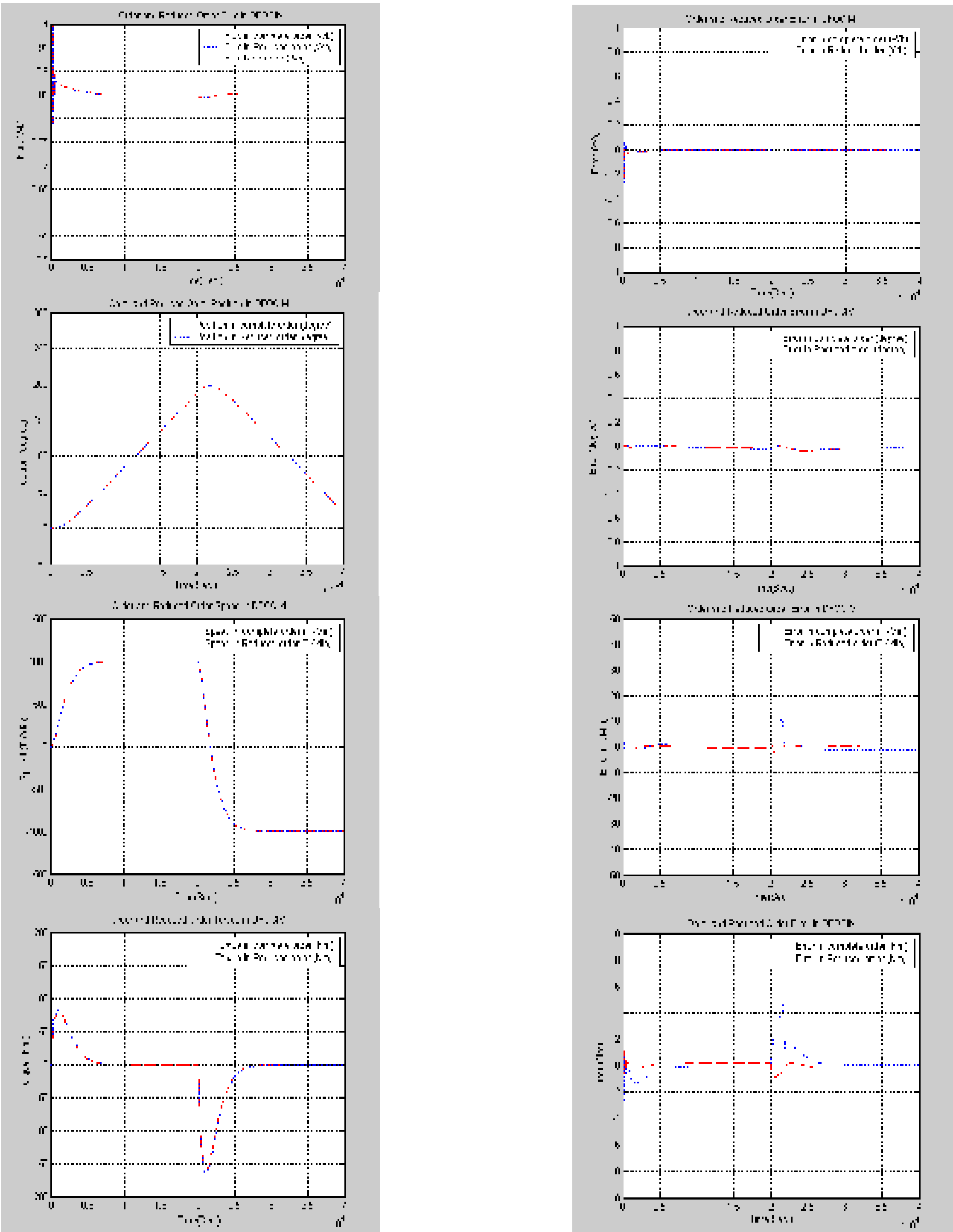


Fig. 6. Simulation Results Obtained with the Two Observers of Kalman Filter (Inversion of the Direction of Rotation of 1000 tr/min to -1000 tr/min to t=2s).

4- Load Tracking Response

Figure 7 represents the estimate of model of rotor flux (reference flux 0.85 Wb), the load torque, the position of the rotor and the speed as well as the estimation errors in the case of a no load starting for a level speed 1000tr/min followed of a level of the load torque 50Nm at the moment t=1 s, of an inversion of direction of rotation at the moment T = 2s and of a level of no load at the time t=3s.

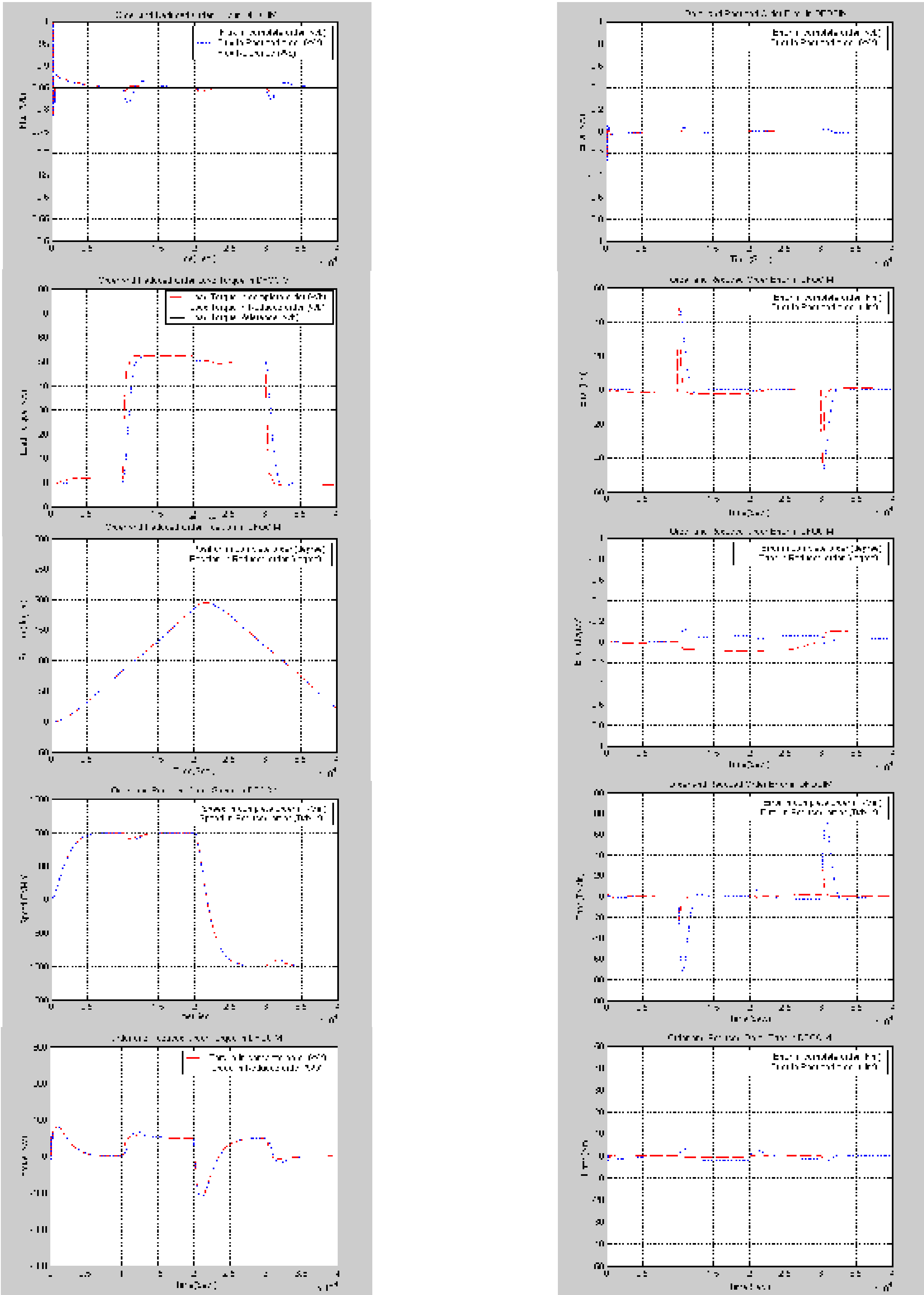


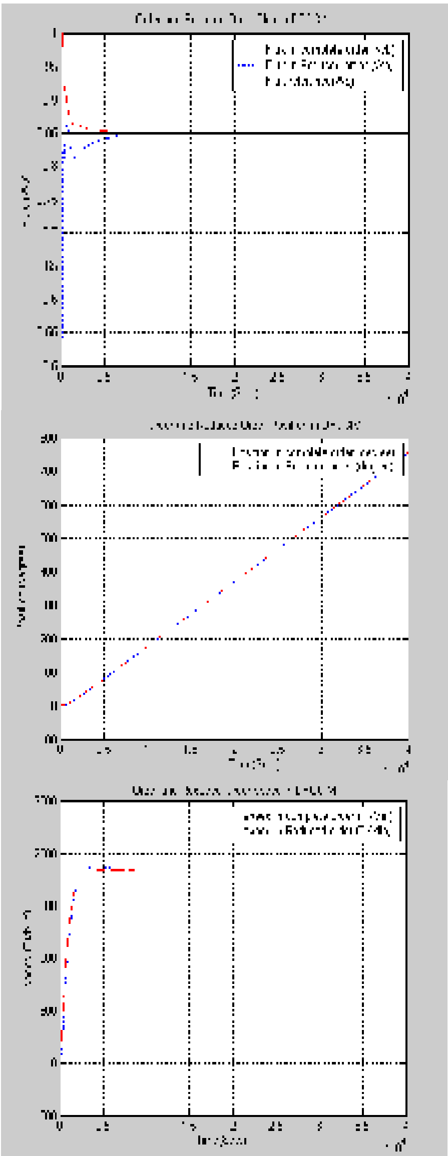
Fig. 7. Simulation Results Obtained with the Two Observers of Kalman Filter (inversion of the Direction of Rotation of 1000 tr/min to -1000 tr/min to t=2s and load 1 to 3 s).

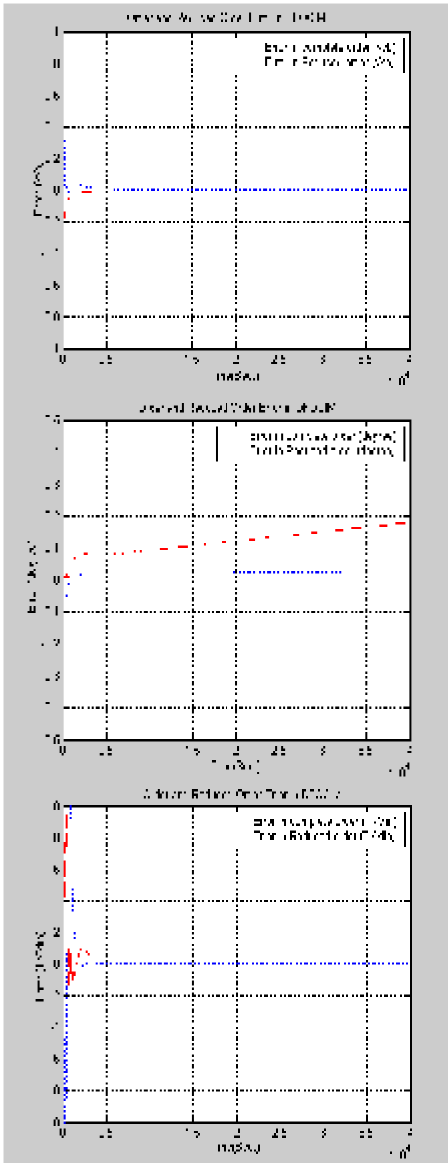
According to the all above, one notes that the two observers of EKF express well still robustness the abrupt variation the speed of reference. The estimate of rotor flux, speed, load torque and position of the rotor is always made satisfactory way. The EKF in a complete order has a better stability than the EKF in reduced Order. Moreover, this stability can be felt at the time of the adjustment of the covariance matrices. Indeed, the computing time for the methods of estimate which use the model of a complete order is largely more important than the time of estimate for the models of a reduced order. In more the errors in estimation obtained by the EKF of a reduced order always lower than those are obtained with the EKF in a complete order.

7.B. Simulation Results in Position Reference

1- No-Load Response

Figure 8 represents the estimate of model of rotor flux(reference flux 0.85 Wb), , position of the rotor, speed and the torque as well as the estimation errors in the case of a no load starting for an instruction of position in level ($q^* = 360^0$).





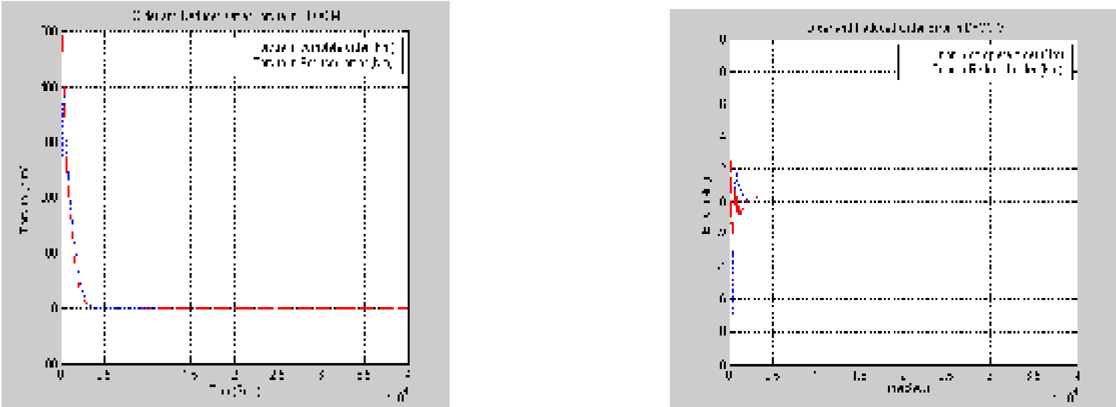
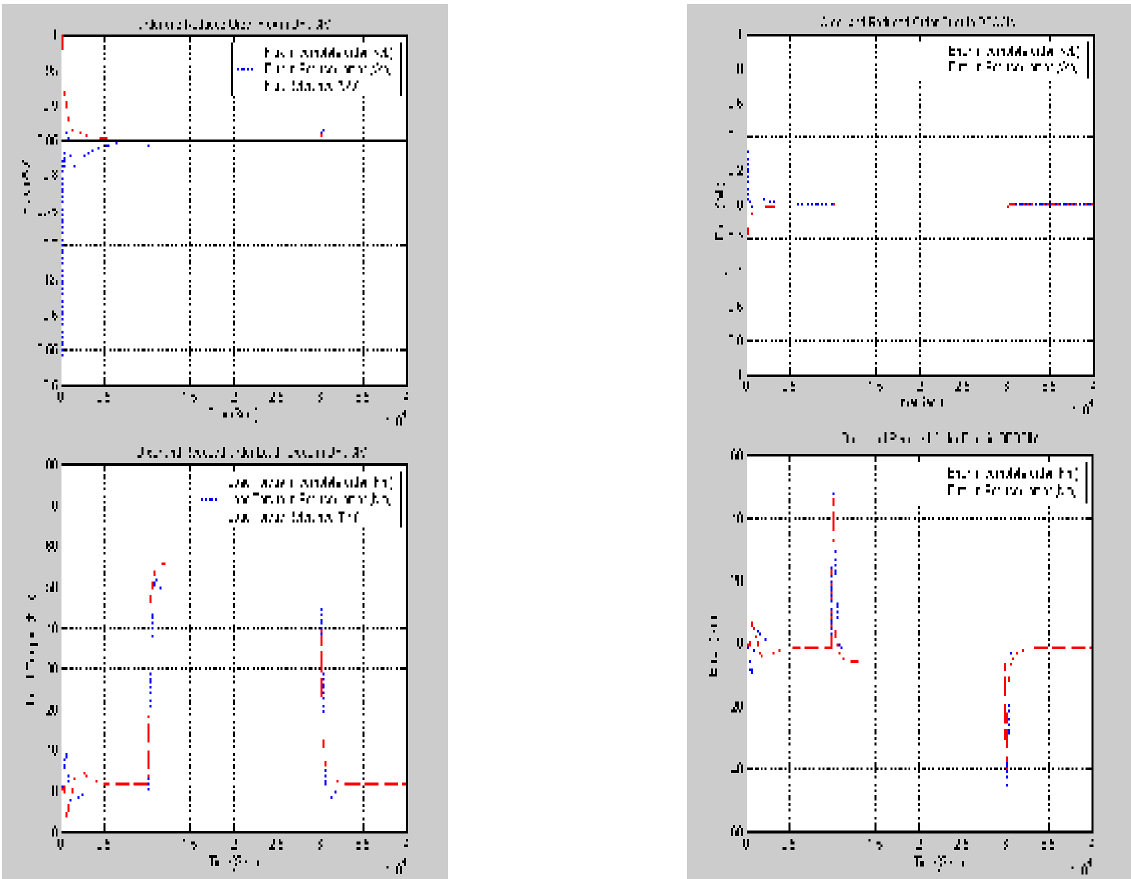


Fig. 8. Simulation Results Obtained with the Two Observers of kalman Filter and Error for a Position of Reference $q^* = 360^0$ (No-load).

2- Load Response

Figure 9 represents the estimate of model of rotor flux (reference flux 0.85 Wb), the load torque, the position of the rotor, the speed and the torque as well as the estimation errors in the case of a no load starting for an instruction of position in level ($q^* = 360^0$) follow-up of a level of the load torque 50Nm at the time t=1s to 3 s.



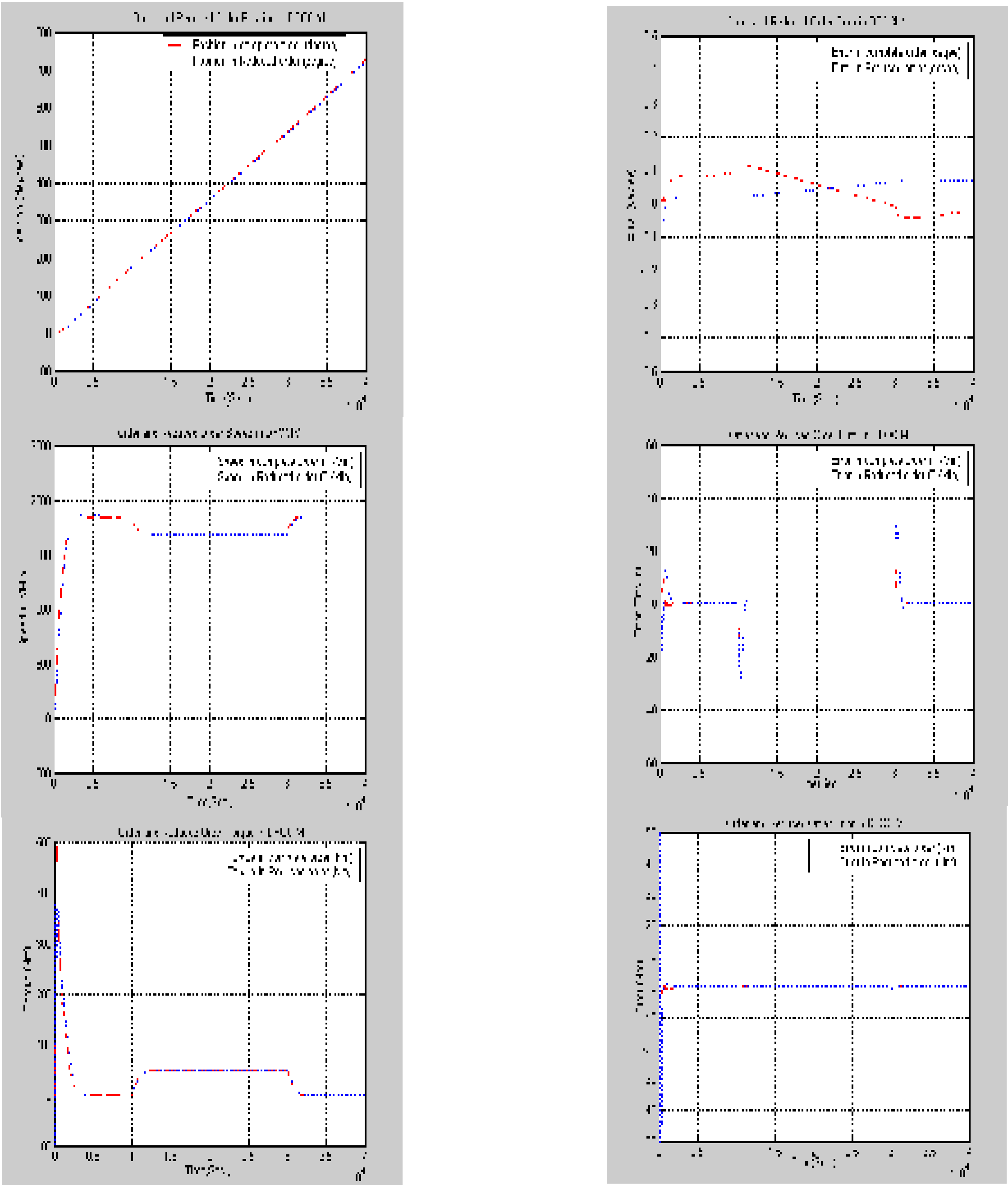


Fig. 9. Simulation Results Obtained with the Two Observers of kalman Filter and Error for a Position of Reference $q^* = 360^0$ (Load of 50 Nm at t=1s to 3s).

3- No load tracking Response

Figure 10 represents the estimate of model of rotor flux (reference flux 0.85 Wb), the position of the rotor ,speed and the load torque as well as the estimation errors in the case of a no load starting for an instruction of position in level ($q^* = 360^0$)follow-up of an inversion of instruction of position at the time t=2s .

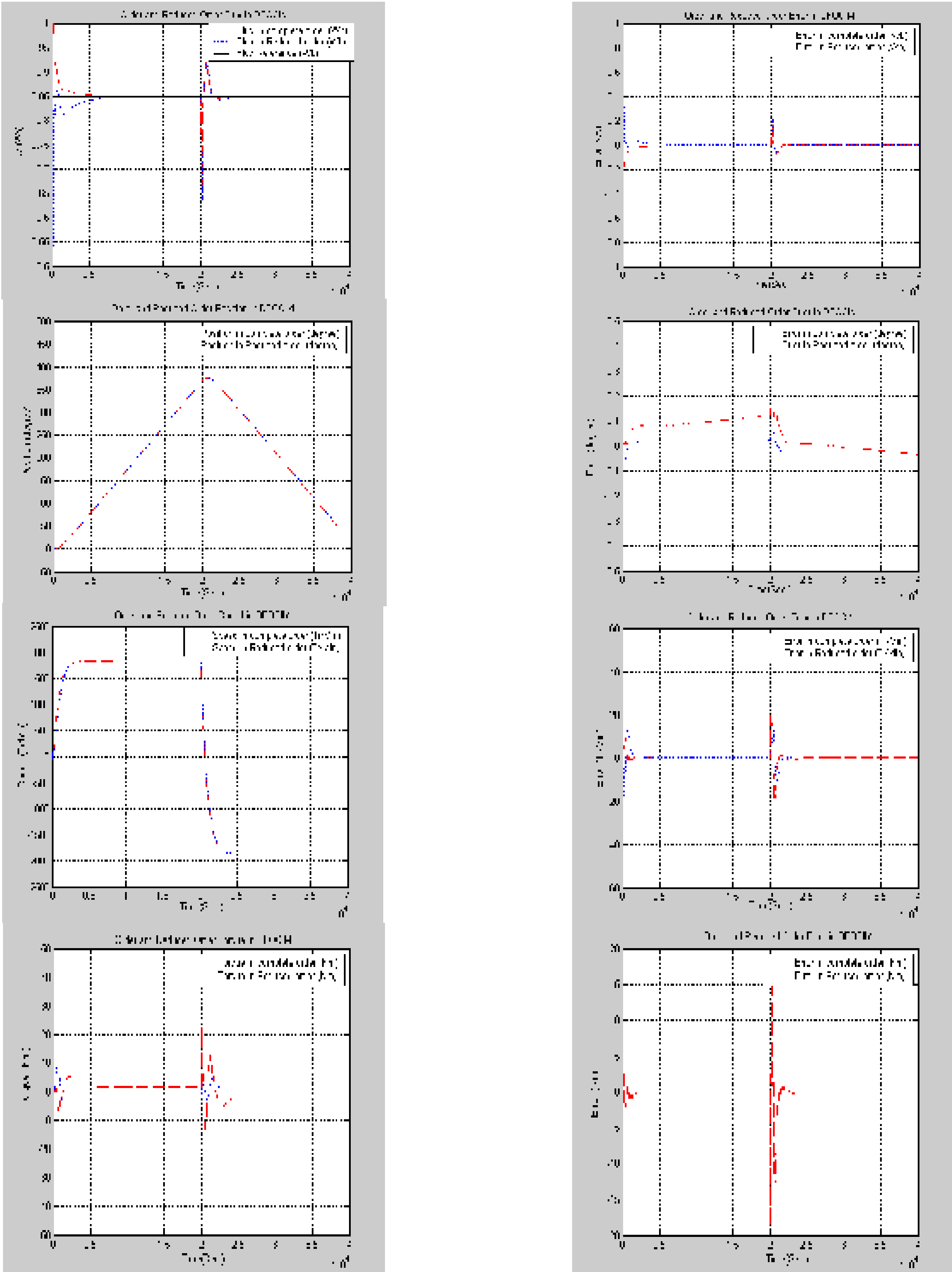
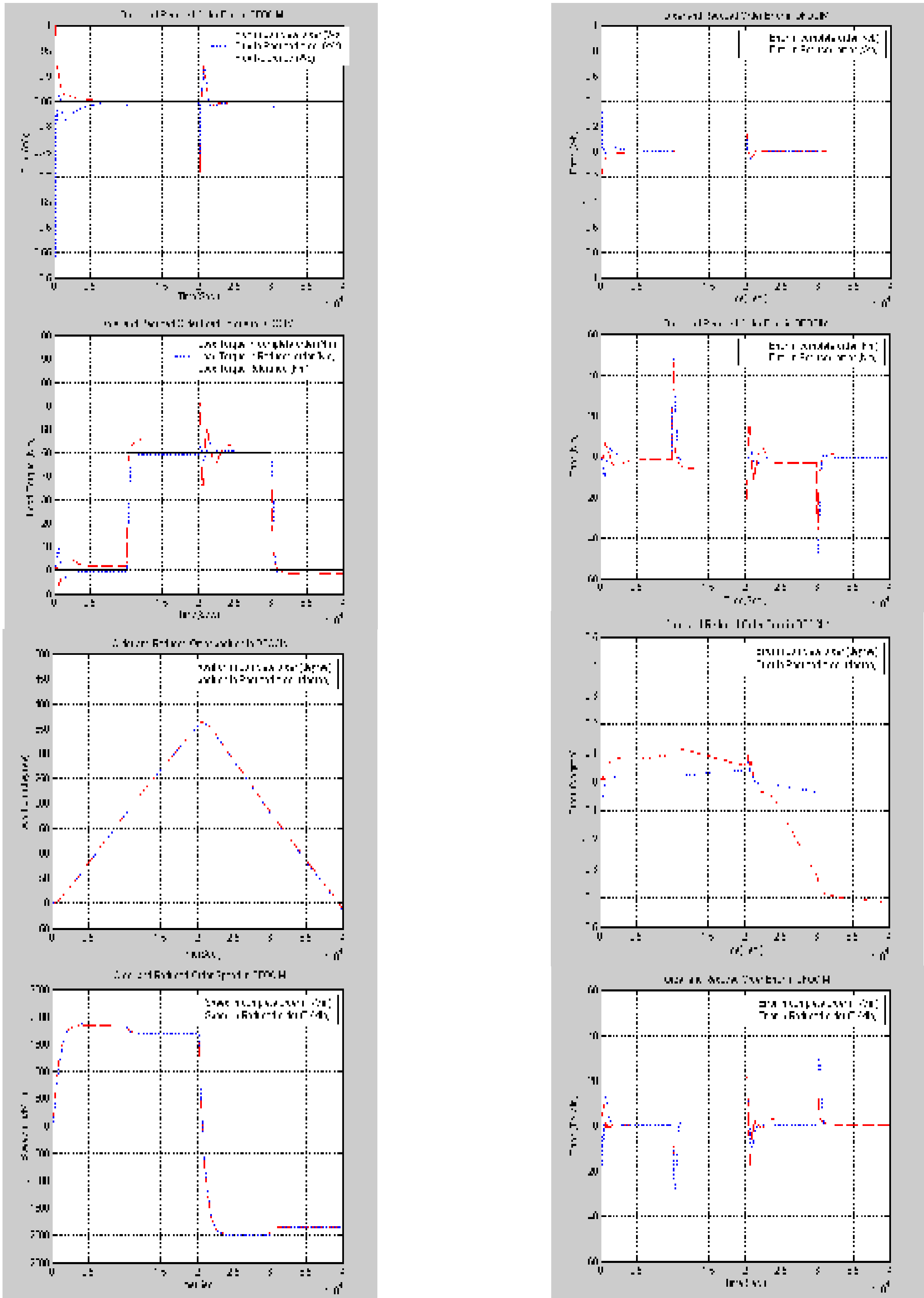


Fig. 10. Simulation Results Obtained with the Two Observers of Kalman Filter (Inversion of the Direction of Position Rotation of $q^* = 360^0$ to $q^* = -360^0$ to t=2s) .

4- Load Tracking Response

Figure 11 represents the estimate of model of rotor flux (reference flux 0.85 Wb), the load torque, the position of the rotor, the speed and the load torque as well as the estimation errors in the case of a no load starting for an instruction of position in level ($q^* = 360°$) follow-up of a level of the load torque 50Nm at the time t=1s, of an inversion of instruction of position at the time t=2s and of a level of no load at the moment t=3s



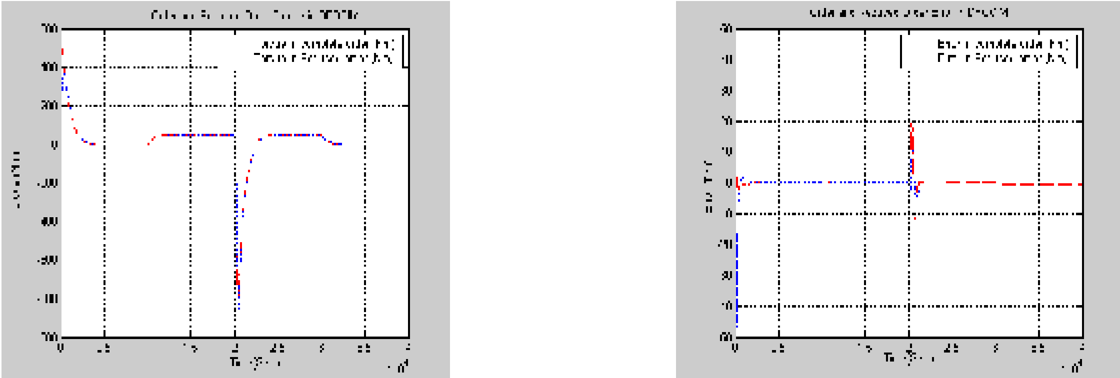


Fig. 11. Simulation Results obtained with the two observers of Kalman filter (inversion of the direction of position rotation of $q^* = 360^0$ to $q^* = -360^0$ to t=2s and load 1 to 3 s).

According to the all above the response in position obtained with the reduced order EKF is better than that obtained with the complete order EKF.

8. Conclusions

For the two observers of kalman filter (order and reduced order EKF) , the simulation results obtained for the estimate speed and position are satisfactory from error in estimation point of view of robustness and stability of the system of total drive under any operating condition (no load, load ,tracking and tracking load) and a significant result is that the small estimation errors occurring during transient and steady state operation do not jeopardize the system performance but estimation error and time of state estimation in reduced order EKF in speed and position in all state is better than complete order EKF . However, one can say that the reduced order EKF involves a reduction of the computing time facilitating the establishment of the operation of observation on a device real time.

Appendix I

The parameters IM are listed in Table (1).

Table 1,
Parameters of IM.

Nominal power	P_n	7,5	Kw
Nominal speed	Ω_n	1450	tr/min
Nominal torque	T	50	Nm
Number of pole Paris	P	2	p.u
Stator resistance	R_s	0,63	Ω
Rotor resistance	R_r	0,4	Ω
Stator inductance	L_s	0,097	H
Rotor inductance	L_r	0,091	H
Mutual inductance	M	0.091	H
moment of inertia	J	0,22	$Kg.m^2$

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تخمين السرعة والموقع لمسوق المحرك الحثي ذو سيطرة توجية المجال المغناطيسي المباشر

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الخلاصة

سيطرة توجيه المجال المغناطيسي المباشر (DFOC) لمسوق المحرك الحثي بدون محسسات سرعة ميكانيكية في العمود للمحرك الحثي يتمتع بالكلفة القليلة والثقة العالية . لاستبدال المحسس بأخذ المعلومات عن سرعة والموقع للجزء الدوار يؤخذ من فولتية وتيار الجزء الثابت للمحرك الحثي .في هذا البحث تم تقديم سيطرة توجيه الجال المغناطيسي المباشر مع نوعين من مرشحات الكالمان (Complete Order And Reduced Order Extended Kalman Filter) لتخمن الفيض، السرعة،العزم والموقع للمحرك الحثي. نتائج المحاكاه توضح الاداء الجيد ل (Reduced Order Extended Kalman Filter) على اداء (Complete Order Extended Kalman Filter) من حيث تتبع الاداء وتخفيض وقت تخمين المعطيات.