Speed estimation of a Doubly Fed Induction Machine controlled by a Field Oriented Control Strategy

Tahar Djellouli and Mohamed Seghir Boucherit

Abstract−This paper studies the estimation problem of speed in a Doubly Fed Induction Machine (DFIM) controlled by a Field Oriented Control (FOC) Strategy. The DFIM is the most responsive in variable speed. The chosen configuration uses two voltage inverters connected to the stator and rotor windings, to adopt the power distribution between them through the pulses distribution of the stator and the rotor in motor operating mode. It is necessary to model the DFIM in three-phase equations and then in two-phase equations faithfully representing the characteristics of the machine. From this model, we can design and simulate the control. The control by oriented rotor flux can be realized by using the speed provided by sensors or estimators. In this paper, we have used the Extended Kalman Filter (EKF) in order to avoid problems caused by the motor speed sensor and improve the robustness of the control and its performance without using any speed sensor.

***Keywords*− Doubly Fed Induction Machine, Field Oriented Control, speed sensor, voltage inverter**

NOMENCLATURE

Msr, M	Mutual inductance between a stator phase and a rotor phase, M:maximum value of the Mrs
Ls, Lr	Stator and Rotor self-inductancesrespectively
σ	dispersion coefficient (σ=1-M^2/L_sL_r)
R_s,R_r	stator and rotor resistances.
T_s, T_r	Stator and rotor time-constants (Ts = Ls,/Rs ;Tr = Lr,/Rr)
θ_s ,θ_r	Angle tracking of the stator flux and rotor relative to the benchmark
θ	Electrical angle between the axis of the stator windings and the rotor windings
I_{ds}, I_{qs}	d-axis and q-axis component of stator current in stationary reference frame
I_{dr}, I_{qr}	d-axis and q-axis component of rotor current in stationary reference frame
V_{ds}, V_{qs}	d-axis and q-axis component of stator voltage in stationary reference frame
V_{dr}, V_{qr}	d-axis and q-axis component of rotor voltage in stationary reference frame
ω_s ,ω_r	The stator and rotor pulsation
Ω	Mechanical speed of rotor
ϕ_{ds},ϕ_{qs}	Stator flux two phase in a rotating frame
ϕ_{dr},ϕ_{qr}	Rotor flux two phase in a rotating frame
T_{em}	Electromagnetic Torque.
C_r	Load torque.
J	Total inertia.
k_f	Coefficient of friction
p	Number of pole pairs of the machine
T	Sampling time, =0.00001s

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I. INTRODUCTION

The Doubly Fed Induction Machine (DFIM) presents several advantages as well as a generator mode in wind energy conversion systems, like wind-turbine or pumped storage systems, and as a motor mode in high power applications such as traction and marine propulsion [1]. The DFIM operates in motor mode and is powered by two voltage inverters, one is feeding the stator and the other is for the rotor [2] (Fig.1). The inverters are controlled by the Pulse Width Modulation (PWM) technique [3]. The control strategy proposed in this paper is a Field Oriented Control (FOC). This control strategy is applied to ensure good dynamic performance, stability and motor current decoupling in synchronous reference frame (d, q) [4]. The strategy is achieved without using any information about the rotor's position or speed.

In most cases, a mechanical sensor measures the speed. Although this requires a location installation that causes difficulties access and requires additional space that reduces reliability in harsh environments and increases the cost of the machine [5]. To remove this sensor, the most technical ones are based on estimation theory combined with the mathematical machine model. The extended Kalman filter is used to estimate the speed of the DFIM as a function of the measured stator and rotor currents and voltages. The estimated speed is used overall. The simulation results obtained by the control with speed sensor and by estimated speed are presented in a comparative table.

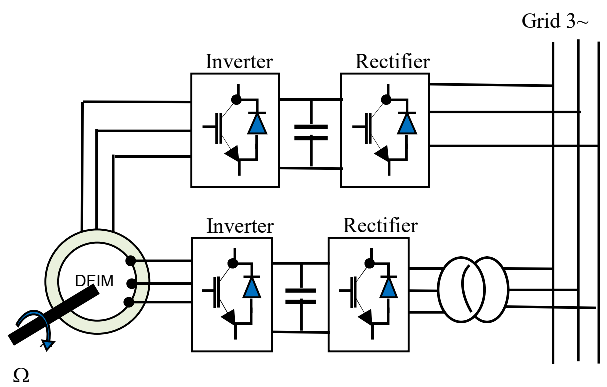

Fig. 1: General principle of a DFIM powered by two inverters.

The paper is organized as follows: Section II and III summarize the mathematical model and vector control by rotor field oriented of the DFIM with speed sensor. Section IV is devoted to estimate the rotor speed by the extended Kalman filter used in the developed strategy.

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II. Mathematical Machine Model

To achieve good dynamic performance in the control of a DFIM, it is necessary to have a model that faithfully represents the machine's behavior, not only in permanent regimes, but also in transient regimes.
The induction machine consists of three windings located symmetrically in the notches of stator and rotor. DFIM comprises three stator coils and three rotor coils offset by an identical distribution angle.
Vectors equations of voltages, currents and total stator and rotor fluxes are given as follow [6]:

$$\begin{cases} [V_s] = [R_s][I_s] + \frac{d}{dt}[\varphi_s] \\ [V_r] = [R_r][I_r] + \frac{d}{dt}[\varphi_r] \end{cases} \quad (1)$$

$$Where \begin{cases} [R_s] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \\ [R_r] = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \end{cases} \quad (2)$$

$$\begin{cases} [V_s] = [V_{as}\ V_{bs}\ V_{cs}]^T \\ [V_r] = [V_{ar}\ V_{br}\ V_{cr}]^T \neq [0\ 0\ 0]^T \end{cases} \quad (3)$$

$$\begin{cases} [I_s] = [I_{as}\ I_{bs}\ I_{cs}]^T \\ [I_r] = [I_{ar}\ I_{br}\ I_{cr}]^T \end{cases} \quad (4)$$

$$\begin{cases} [\phi_s] = [\phi_{as}\ \phi_{bs}\ \phi_{cs}]^T \\ [\phi_r] = [\phi_{ar}\ \phi_{br}\ \phi_{cr}]^T \end{cases} \quad (5)$$

The following matrix relations give the expressions of the total fluxes through the stator and rotor windings:

$$\begin{bmatrix} [\Phi_s] \\ [\Phi_r] \end{bmatrix} = \begin{bmatrix} [L_{ss}][M_{sr}] \\ [M_{rs}][L_{rr}] \end{bmatrix} \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} \quad (6)$$

$[M_{rs}] = [M_{sr}]^T$.

$[L_{ss}], [L_{rr}], [M_{sr}]$ and $[M_{rs}]$ are sub-matrices of inductances given by:

$$\begin{cases} [L_{ss}] = \begin{bmatrix} L_{ss} & M_s & M_s \\ M_s & L_{ss} & M_s \\ M_s & M_s & L_{ss} \end{bmatrix} \\ [L_{rr}] = \begin{bmatrix} L_{rr} & M_r & M_r \\ M_r & L_{rr} & M_r \\ M_r & M_r & L_{rr} \end{bmatrix} \end{cases} \quad (7)$$

$$[M_{sr}] = M \begin{bmatrix} \cos\theta & \cos(\theta + \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{2\pi}{3}) & \cos\theta & \cos(\theta + \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & \cos\theta \end{bmatrix} \quad (8)$$

The modeling of the DFIM is based on the general equations in the Park transformation applied on the stator and rotor windings, these equations are resulted as following [6]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \end{cases} \quad (9)$$

$$\begin{cases} V_{dr} = R_r I_{dr} + \frac{d\phi_{dr}}{dt} - \omega_r \phi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d\phi_{qr}}{dt} + \omega_r \phi_{dr} \end{cases} \quad (10)$$

$$\begin{cases} \phi_{ds} = L_s I_{ds} + M I_{dr} \\ \phi_{qs} = L_s I_{qs} + M I_{qr} \end{cases} \quad (11)$$

$$\begin{cases} \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (12)$$

where ω_s, ω are the stator and rotor pulsations respectively, $\omega = p\Omega$; Ω is the mechanical rotating speed.
The dynamical equation and the electromagnetic torque T_{em} are given by equations (13) and (14) respectively:

$$J\frac{d\Omega}{dt} = T_{em} - C_r - K_f.\Omega \quad (13)$$

$$T_{em} = p\frac{M}{L_r}(\phi_{dr} I_{qs} - \phi_{qr} I_{ds}) \quad (14)$$

The machine is powered directly by double three phase voltages perfect sources: as it is represented in Fig. 1.

III. Field Oriented Control Of Dfim

For the Field Oriented Control (FOC) of the DFIM, it is necessary to choose a reference frame (d, q) for obvious reasons of simplifications. This technique consists of the orientation of the stator and rotor flux.
The (d) axis orientation in the direction of the stator flux is the most used in DFIM control as shown in (Fig. 2) [7,8].

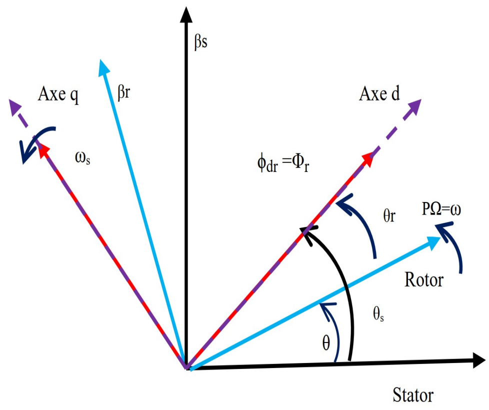

Fig. 2: DFIM axis orientation in d-q reference

The relative angular position of the (d) axis of the rotating reference d-q is given by:

$$\theta_s = \theta_r + \theta \tag{15}$$

Where,
θ_r: is the angular position relative to d axis
θ : represents the electrical angular position of the rotor relative to the stator reference frame.
With,

$$\begin{cases} \frac{d\theta_s}{dt} = \omega_s \\ \frac{d\theta}{dt} = \omega \\ \omega_s = \omega + \omega_r \end{cases} \tag{16}$$

From equations (9) and (10), and by replacing the fluxes by their values and introducing the intermediate voltages [7], we obtain the follow equations:

$$\begin{cases} V_{tds} = V_{ds} - \frac{M}{L_r} V_{dr} \\ V_{tdr} = V_{dr} - \frac{M}{L_r} V_{ds} \\ V_{tqs} = V_{qs} - \frac{M}{L_r} V_{qr} \\ V_{tqr} = V_{qr} - \frac{M}{L_r} V_{qs} \end{cases} \tag{17}$$

$$\begin{cases} V_{tds} = V_{tdsc} + V_{tdsc1} = R_s I_{ds} + \sigma L_s \frac{dI_{ds}}{dt} + V_{tdsc} \\ V_{tqs} = V_{tqsc} + V_{tqsc1} = R_s I_{qs} + \sigma L_s \frac{dI_{qs}}{dt} + V_{tqsc} \\ V_{tdr} = V_{tdrc} + V_{tdrc1} = R_r I_{dr} + \sigma L_r \frac{dI_{dr}}{dt} + V_{tdrc} \\ V_{tqr} = V_{tqrc} + V_{tqrc1} = R_r I_{qr} + \sigma L_r \frac{dI_{qr}}{dt} + V_{tqrc} \end{cases} \tag{18}$$

With: $T_s = \frac{L_s}{R_s}$; $T_r = \frac{L_r}{R_r}$.
Where: V_{tdsc1} V_{tqsc1}; V_{tdrc1}; V_{tqrc1} are compensation terms given by

$$\begin{cases} V_{tdsc1} = -\frac{M}{L_r} R_r I_{dr} - \omega_s \phi_{qs} + \omega_r \frac{M}{L_r} \emptyset_{qr} \\ V_{tqsc1} = -\frac{M}{L_r} R_r I_{qr} + \omega_s \phi_{ds} - \omega_r \frac{M}{L_r} \emptyset_{dr} \\ V_{tdrc1} = -\frac{M}{L_s} R_s I_{ds} + \omega_s \frac{M}{L_s} \phi_{qs} - \omega_r \emptyset_{qr} \\ V_{tqrc1} = -\frac{M}{L_s} R_s I_{qs} - \omega_s \frac{M}{L_s} \phi_{ds} + \omega_r \emptyset_{dr} \end{cases} \tag{19}$$

This method gives us the transfer functions between currents and voltages of the stator and the rotor respectively :

$$\begin{cases} \frac{I_{qs}(s)}{V_{tqsc}(s)} = \frac{I_{ds}(s)}{V_{tds}(s)} = \frac{1}{R_s + \sigma L_s . s} \\ \frac{I_{qr}(s)}{V_{tqrc}(s)} = \frac{I_{rd}(s)}{V_{tdr}(s)} = \frac{1}{R_r + \sigma L_r . s} \end{cases} \tag{20}$$

With s is Laplace operator.
Hence, the application of stator FOC allows us to obtain the following equation

$$\{\Phi_{dr} = \Phi_r, \ \Phi_{qr} = 0 \tag{21}$$

This choice makes it possible to write system equations as follows:

$$\begin{cases} \Phi_{dr} = \Phi_r \\ \Phi_{qr} = 0 \end{cases} \rightarrow \begin{cases} I_{qr} = -\frac{M}{L_r} I_{qs} \\ I_{dr} = \frac{V_{dr}}{R_r} \\ i_{ds} = \frac{1}{M}\left(\phi_r - \frac{L_r}{R_r} V_{dr}\right) \end{cases} \tag{22}$$

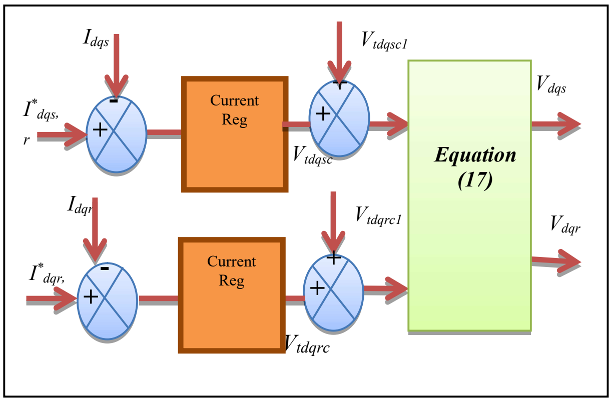

Fig. 3: Compensation terms in FOC strategy of DFIM

The different references of the currents to be regulated for an orientation of the rotor flux and unit power factor operation (with cos φ = 1) at the rotor are given by [9].

$$T^*_{em} = P \frac{M}{L_r} \phi^*_r I^*_{qs} \tag{23}$$

$$\begin{cases} I^*_{ds} = \frac{1}{M} \phi^*_r \quad ; \quad I^*_{dr} = \frac{V_{dr}}{R_r} \\ I^*_{qs} = \frac{L_r}{PM\phi^*_r} T^*_{em}; \ I^*_{qr} = -\frac{1}{P\phi^*_r} C^*_{em} \end{cases} \tag{24}$$

The stator flux depends on rotor flux.

Finally, one can summarize the vector control strategy with oriented rotor flux of the machine in the overall diagram presented in Fig. 4.

IV. Estimation of Speed By the Kalman Filter

The position or the speed of the DFIM information on the rotor is very important in the control. It is generally obtained through a mechanical speed sensor. However, this sensor requires a place for its installation and leads to difficulties in its mounting; it is sensitive to noises and vibrations. Several strategies have been proposed in the literature to eliminate this mechanical sensor. Among these strategies, there is the estimation by the Extended Kalman Filter (EKF). This Kalman filter is an observer for a nonlinear closed-loop with a variable gain matrix. At each calculation step, this Kalman filter predicts the new values of state variables of the DFIM. The prediction of values is made by minimizing the noise effects and modeling errors of the parameters or variables state. The noises are supposed to be white, Gaussian, and not correlated with the estimated states [10].

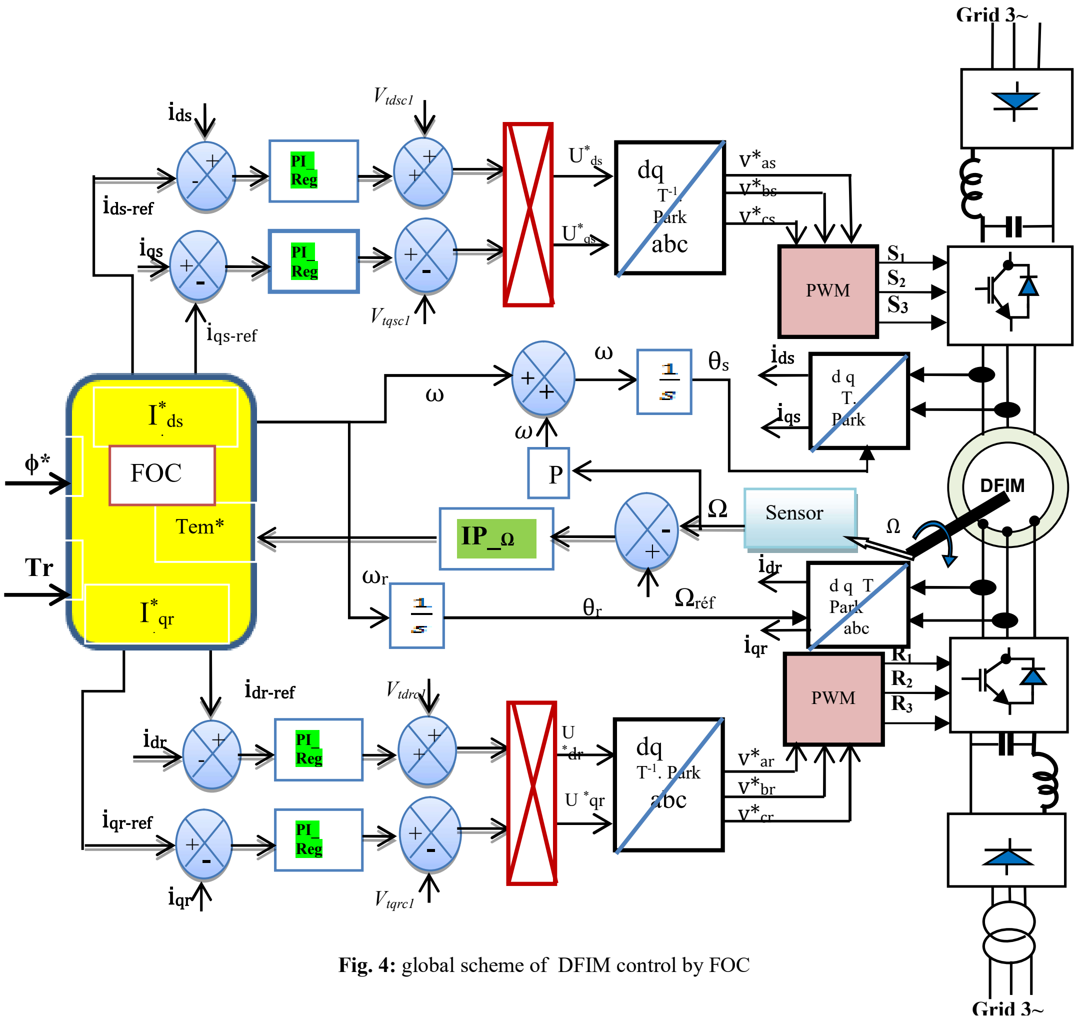

Fig. 4: global scheme of DFIM control by FOC

IV.1. Selection Of DFIM Model

The state equation of motor model is given as following [11]:

$$\dot{x} = f(x,u) = Ax + Bu \tag{25}$$

$$y = Cx \tag{26}$$

$$A = \begin{bmatrix} a_1 & a_2 p\Omega & a_3 & a_4 p\Omega & 0 \\ -a_2 p\Omega & a_1 & -a_4 p\Omega & a_3 & 0 \\ a_5 & -a_6 p\Omega & a_7 & -a_8 p\Omega & 0 \\ a_6 p\Omega & a_5 & a_8 p\Omega & a_7 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{27}$$

$$B = \begin{bmatrix} b_1 & 0 & b_2 & 0 \\ 0 & b_1 & 0 & b_2 \\ b_2 & 0 & b_3 & 0 \\ 0 & b_2 & 0 & b_3 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{28}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{29}$$

Where a_i and b_i parameters are given by:

$$a_1 = -\frac{R_s}{\sigma L_s};\quad a_2 = \frac{(1-\sigma)}{\sigma};\ a_3 = \frac{R_r M}{\sigma L_s L_r};\quad a_4 = \frac{M}{\sigma L_s},$$
$$a_5 = \frac{R_s M}{\sigma L_s L_r};\quad a_6 = \frac{-M}{\sigma L_r};\quad a_7 = -\frac{R_r}{\sigma L_r};\quad a_8 = \frac{1}{\sigma}.$$
$$b_1 = \frac{1}{\sigma L_s};\quad b_2 = -\frac{M}{\sigma L_s L_r};\quad b_3 = \frac{1}{\sigma L_r}$$

The dimension of the state vector is increased by adding the angular speed of the rotor, in this case, the angular speed of the rotor is considered in the state variable. The state vector becomes:

$$x = [i_{\alpha s}\ i_{\beta s}\ i_{\alpha r}\ i_{\beta r}\ \omega]^T \tag{30}$$

$$u = [v_{\alpha s}\ v_{\beta s}\ v_{\alpha r}\ v_{\beta r}\ ]^T \tag{31}$$

IV. 2. Discretization Of The Model

The time-discrete state space model of the DFIM model obtained from equations (25) and (26) can be written as follow [11]:

$$\begin{cases} X_{k+1} = f(k, X_k, U_k, W_k) = A_k X_k + B_k U_k + W_k \\ Y_k = h(k, X_k, V_k) = C_k X_k + V_k \end{cases} \tag{32}$$

k: represents the number of an iteration in the discrete of state equation

W *and* V are the state noise which corresponds to the non-deterministic part the measurement noise respectively

With: $X_k = \begin{bmatrix} I_{\alpha s}(k) \\ I_{\beta s}(k) \\ I_{\alpha s}(k) \\ I_{\beta s}(k) \\ \omega(k) \end{bmatrix}$; $X_{k+1} = \begin{bmatrix} I_{\alpha s}(k+1) \\ I_{\beta s}(k+1) \\ I_{\alpha s}(k+1) \\ I_{\beta s}(k+1) \\ \omega(k+1) \end{bmatrix}$, $U_k = \begin{bmatrix} V_{\alpha s}(k) \\ V_{\beta s}(k) \\ V_{\alpha r}(k) \\ V_{\beta r}(k) \end{bmatrix}$

Where A_k, B_k and C_k are the discrete system matrix, input matrix and output matrix respectively:

$$\begin{cases} A_k = I + T.A \\ B_k = T.B \\ C_k = C \end{cases} \quad (33)$$

In the equation (33), T and I are the sampling time and the identity matrix respectively. The discrete state space model is therefore defined by:

$$\begin{cases} A_k = \begin{bmatrix} 1+a_1T & a_2p\Omega T & a_3T & a_4p\Omega T & 0 \\ -a_2p\Omega T & 1+a_1T & -a_4p\Omega T & a_3T & 0 \\ a_5T & -a_6p\Omega T & 1+a_7T & -a_8p\Omega T & 0 \\ a_6p\Omega T & a_5T & a_8p\Omega T & 1+a_7T & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\ B_k = T\begin{bmatrix} b_1 & 0 & b_2 & 0 \\ 0 & b_1 & 0 & b_2 \\ b_2 & 0 & b_3 & 0 \\ 0 & b_2 & 0 & b_3 \\ 0 & 0 & 0 & 0 \end{bmatrix} \\ C_k = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{cases} \quad (34)$$

The Kalman filter considers that the state and the measurement noises vector as Gaussian white noise of zero mean.

The covariance matrices are, respectively, Q and R*;* defined by:

$$\begin{cases} Q_k = cov(W_k) = E\{W_k W_k^T\} \\ R_k = cov(V_k) = E\{V_k V_k^T\} \end{cases} \quad (36)$$

With the noises W_k and V_k are white noises uncorrelated Gaussian, characterized by zero mean of the covariance matrices Q_k and R_k

IV.3. IMPLEMENTATION OF THE KALMAN FILTER ALGORITHM

In the first time, it is necessary to use initial values of the covariance system matrices of the measurement noises and the state noises (*Q)* and (*R)*, respectively, to obtain the best considerable speed value [12]. They have important results on the stability filter and convergence time. These matrices are supposed diagonal covariances.

Initialization: There are two steps to implement the EKF algorithm, the first is the prediction, the second is the correction, and these two steps are introduced by an initialization of state vector X_0 and the covariance matrix P_0,Q_0 and R_0.

- State vector prediction at time (k +1):

- The filtering algorithm contains two principal steps, a prediction step and a filtering step [12*;* 13]. In the first one, the predicted states values $\hat{X}(k+1)$ are obtained by using a mathematical model (state-variable equations), and also the previous values of the estimated states:

$$\hat{X}(k+1) = f[\hat{X}(k), U(k), k] \quad (37)$$

Therefore, the predicted state covariance matrix (*P*) is obtained before the new measurement values.

At the end, the mathematical model and also the covariance matrix of the system (Q) are used.

- During the second step, which is the filtering, the estimated states $\hat{X}(k+1)$ are obtained from the predicted ones, they estimate $X(k+1)$ by adding a correction term $K(y-\hat{y})$ to the predicted value. This correction term is a weighted variety between the current output vector y and the predicted output vector $\hat{y}$. Here K is the Kalman gain [13].

V. RESULTS AND DISCUSSION

The simulations of the DFIM control and speed estimation method with the extended Kalman filter have been done using the MATLAB/Simulink software. Simulation results are shown in Figures from Fig5 to Fig8. Figure 5(a) represents the speed response using the mechanical sensor after applying a reference step of speed at (t = 0.1s); then the load torque is applied at (t = 0.6s). After that, the reversal of the rotation direction is applied at (t = 1.2s). Figure 5(b) presents the estimated speed by EKF resembling to the real speed it. Electromagnetic torque with a sensor of speed and with EKF are shown in Figures 6(a) and 6(b) respectively.

The same things are applied in the stator Currents in Figures 7 (a) and 7(b), and Rotor currents in Figures 8 (a) and 8(b). Except in the case of a sensor-less control, there is a small fluctuation due to the estimation by the Kalman filter. These results are shown in the diagram; we develop a speed estimation of the DFIM using the EKF, eliminating the mechanical speed sensor. Note that the Kalman Filter estimator presents a good tracking for the rotor speed with a weak error in steady state, the EKF is still robust during the load application and reversal of the speed.

VI. CONCLUSION

In this paper, a vector Control strategy of DFIM with and without mechanical sensor by estimation using EKF is presented. It has been shown that oriented rotor flux vector control combined with a speed sensor has been realized in order to obtain good decoupling between flows and a good regulation of motor currents, in order to ensure a good dynamic performance of the global system. In the same time, it solves the problems of the speed control with mechanical sensor. The interesting simulation results obtained on the control show the efficiency, the convergence and the stability of the system in case of load noise or change variation. The use of the EKF in the vector control allows obtaining a good decoupling and a good regulation of the currents in order to ensure a good dynamic performance of the global system in the speed control by estimation .In this work a robust sensor-less control combined with an EKF approach has been shown.

FOC results **with** speed sensor	**FOC** results **with** speed estimation

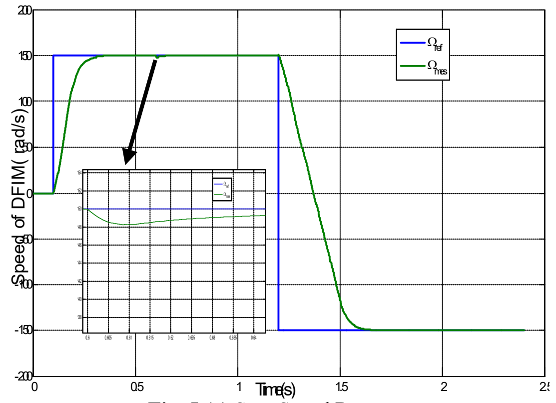

Fig .5 (a) Step Speed Response

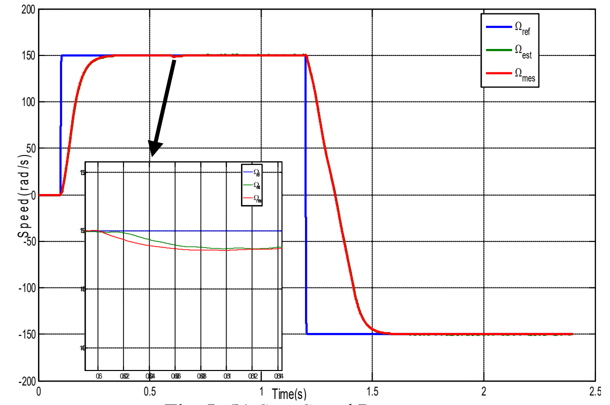

Fig .5. (b) Step Speed Response

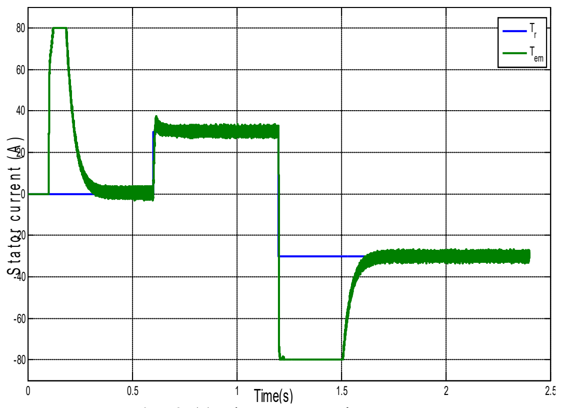

Fig .6. (a) Electromagnetic Torque

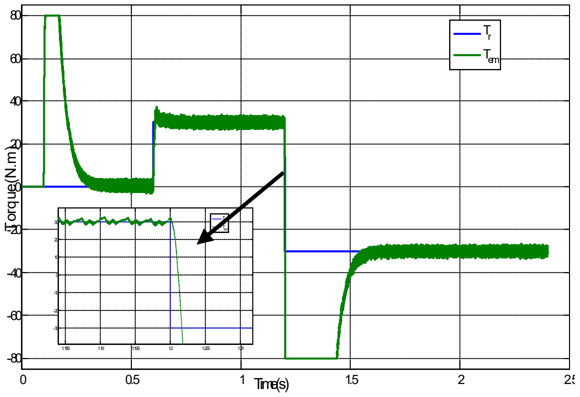

Fig .6. (b) Electromagnetic Torque

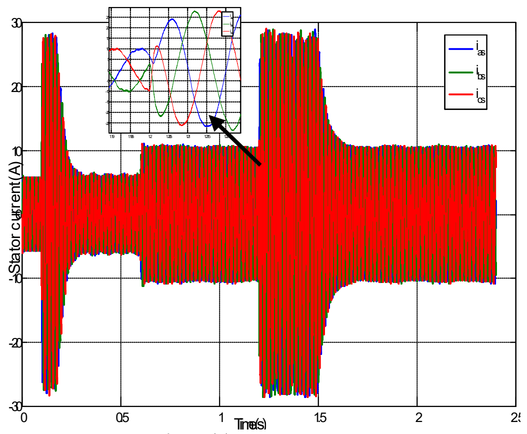

Fig .7 (a) Stator current

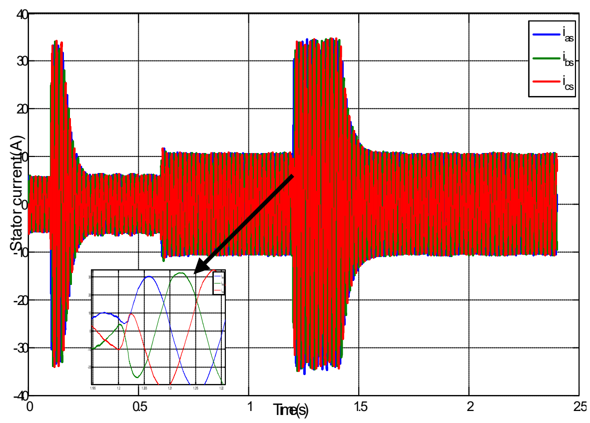

Fig .7. (b) Stator current

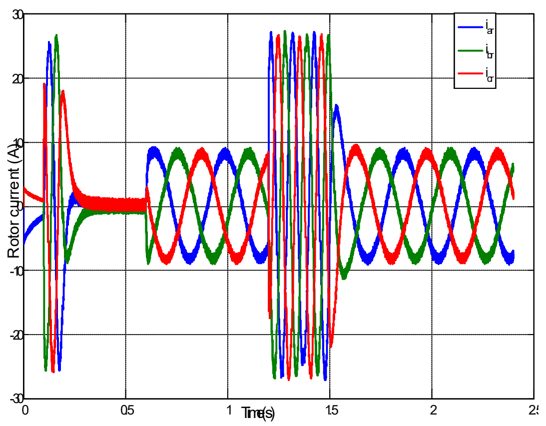

Fig .8 (a) Rotor current

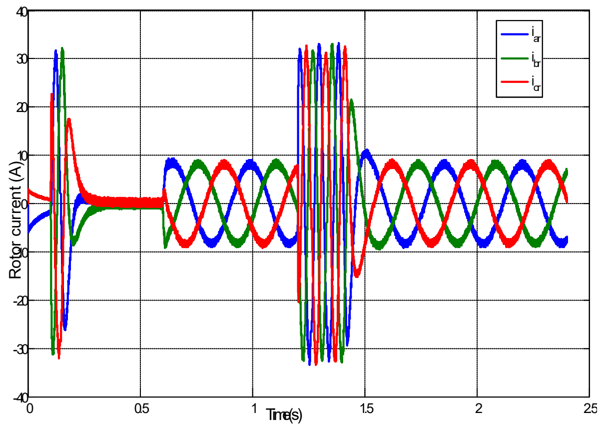

Fig .8. (b) Rotor current

APPENDIX

- DFIM parameters used in simulation

Stator resistance	Rs=1.20 Ω
Rotor resistance	Rr=1.80 Ω
Stator inductance	Ls = 0.1568 H
Rotor inductance	Lr = 0.1554 H
mutual inductance	M=0.150H
Inertia moment	J=0.070 $Kg.m^2$
Coefficient of viscous	f=0.001
Number of pairs of poles	P=2

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