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Robust speed sensorless indirect field-oriented control of induction motor drive using LQR controller

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***Abstract*— A robust sensorless speed control is proposed to improve the trajectory tracking performance of induction motors. The proposed design employs the Linear Quadratic Regulator (LQR). The indirect field oriented control theory for the induction motor drive is based on LQR algorithm that overcomes the system uncertainties.**
In this paper, to achieve accurate performance of speed control of IM, a newly designed optimal control method is presented. The new proposed controller is designed by combining PI controller and linear quadratic regulator (LQR). This is a new technique fully matches the merits of the easy design of the LQR and the strong robustness of the PI. Simulation results and experimental results show that the proposed approach gives good results.

***Index Terms*— Induction motor (IM), Linear Quadratic Regulator (LQR)., indirect field Oriented Control (IFOC).**

I. INTRODUCTION

The indirect field oriented control (IFOC) technique is very useful for implementing high performance induction motor drive systems [l-5]. In the IFOC technique the shaft speed, that is usually measured, and the slip speed, that is calculated based on the machine parameters, are added to define the angular frequency of the rotor flux vector. Then, the standard IFOC technique is essentially a feed forward scheme which has the drawbacks of being dependent of the parameters that vary with the temperature and the level of magnetic excitation of the motor. Several authors proposed methods of compensation of the changes of parameters. [5-16]. In this paper the speed control in the indirect VC is achieved using a LQR –PI regulator. The LQR method is a powerful technique for designing controllers for complex systems that have stringent performance requirements. The LQR method seeks to find the optimal controller that minimizes a given cost functions. This cost function is parameterized by two matrices, Q and R, that weight the state vector and the system input respectively. Considering the LQR method is an easy way to decide the demand control law to satisfy the requirements. It is based on the state-space model. To find the control law, a relative Riccati equation is first solved, and an optimal feedback gain, which will lead to optimal results evaluating from the defined cost function (performance index), is obtained. For testing this technique one has used an reduced-order linear observer for speed and rotor flux estimation of induction motors [17-22]. Simulations and experimental results show that, the LQR-PI controller strategy associated to sensorless IFOC control provide good performance, maintaining good performance levels under realistic conditions.

II. INDUCTION MOTOR MODEL

The dynamic model for the induction motor in a rotating reference frame d-q can be described by equation (1).

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R}{\sigma L_s} i_{sd} + \omega_s i_{sq} + \frac{M}{\sigma L_s L_r}\left(\frac{1}{T_r}\emptyset_{rd} + \omega\emptyset_{rq}\right) + \frac{1}{\sigma L_s}V_{sd} \\ \frac{di_{sq}}{dt} = -\frac{R}{\sigma L_s} i_{sq} - \omega_s i_{sd} + \frac{M}{\sigma L_s L_r}\left(\frac{1}{T_r}\emptyset_{rq} - \omega\emptyset_{rd}\right) + \frac{1}{\sigma L_s}V_{sq} \\ \frac{d\emptyset_{rd}}{dt} = \frac{M}{T_r} i_{sd} - \frac{1}{T_r}\emptyset_{rd} + (\omega_s - \omega)\emptyset_{rq} \\ \frac{d\emptyset_{rq}}{dt} = \frac{M}{T_r} i_{sq} - \frac{1}{T_r}\emptyset_{rq} - (\omega_s - \omega)\emptyset_{rd} \\ T_e = \frac{p.M}{L_r}\left(i_{sq}\emptyset_{rd} - i_{sd}\emptyset_{rq}\right) \end{cases} \quad (1)$$

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - T_l - f.\omega) \quad (2)$$

$$\sigma = 1 - \frac{M^2}{L_s L_r} \quad ; \quad R = R_s + \frac{M^2}{L_r^2}R_r \quad ; \quad T_r = \frac{L_r}{R_r}$$

The model of induction machine drive in stationary reference frame α - β may be written as given by equation (2).

III. INDIRECT FIELD ORIENTED CONTROL

The aim of this work is to design and test a new speed controller, which allow operating at low speed range and exhibit good dynamic and steady state performances. As shows in Eq (2) the expression of the electromagnetic torque in the dynamic regime presents a coupling between stator current and rotor flux. The main objective of the vector control of induction motors is, as in DC machines, to independently control the torque and the flux; this is done by using a d-q rotating reference frame synchronously with the

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rotor flux space vector. The d-axis is then aligned with the rotor flux space vector. Under this condition we get:

$$\phi_{rd} = \phi_r \text{ and } \phi_{rq} = 0 \tag{3}$$

From equation (1) the rotor dynamics are given by following equations:

$$\frac{d\emptyset_r}{dt} = \frac{M}{T_r} i_{sd} - \frac{1}{T_r}\emptyset_r \tag{4}$$

$$\frac{d\omega}{dt} = \frac{3p^2 M}{2J L_r}\left(\emptyset_r i_{sq}\right) - \frac{f}{J}\omega - \frac{p}{J}T_l \tag{5}$$

$$T_e = \frac{3pM\emptyset_r}{2L_r} i_{sq} \tag{6}$$

The orientation angle of rotor flux is given by:

$$\theta_s = \int \omega_s dt = \int \left(\omega + \frac{R_r M i_{sq}^*}{L_r \emptyset_r^*}\right) dt \tag{7}$$

The rotor flux magnitude is related to the direct axis stator current by a first order differential equation so it can be controlled by controlling the direct axis stator current. Under steady state operation rotor flux is constant, so (4) becomes

$$\emptyset_r = M i_{sd} \tag{8}$$

The modified indirect vector control can be implemented using the following equations:

$$i_{sd}^* = \frac{\emptyset_r^*}{M} \tag{9}$$

$$i_{sq}^* = \frac{2}{3p}\frac{L_r}{M}\frac{T_e^*}{\emptyset_r^*} \tag{10}$$

The principal scheme of the modified indirect vector control is shown in figure (1) in which the function blocks F1 and $F2$ are presented by the equations (9) and (10) respectively. The speed control in the IFOC in Figure (1) is achieved using a (LQR-PI) controller.

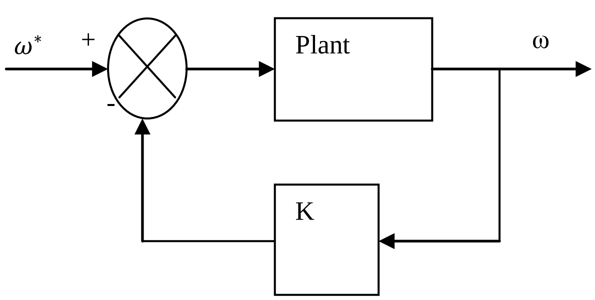

Figure 2: Block Diagram of LQR Controller

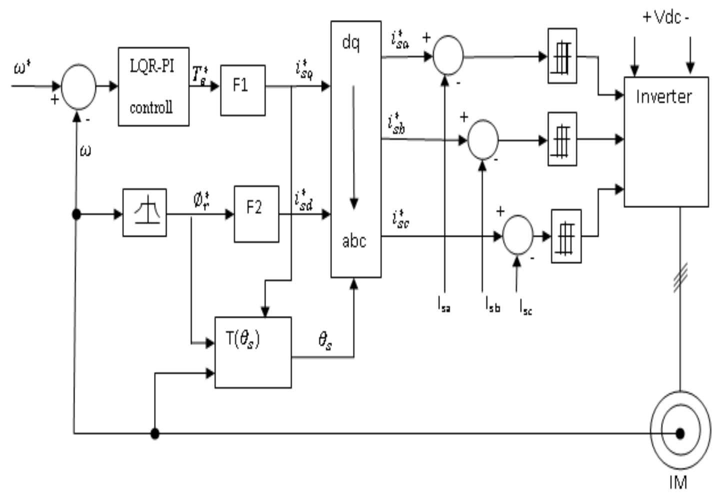

Figure 1: Modified Indirect Field Oriented Control

III.1 SPEED REGULATION USED LQR-PI CONTROLLER

In this section, we show the designed procedure for the speed control of IM system which is under the control of combining the PI and LQR. LQR is an optimal control method. The block diagrams of state feedback controller displayed in Figure 2. The system that represents the speed regulation using the (PI) controller is displayed in Figure 3, whose transfer function is given by equation (11) [25].

$$\frac{\omega}{\omega^*} = \frac{K_i K_T}{J s^2 + (f + K_p K_T)s + K_i K_T} \tag{11}$$

where $K_T = \left(\frac{3pM^2}{2L_r}\right) i_{sd}^*$

From the equation (13) we can write**:**

$$\omega = \frac{1}{s}\left[-\frac{(f + K_p K_T)}{J}\omega + \frac{K_i K_T}{J}\omega^* + \frac{1}{s}\frac{K_i K_T}{J}(\omega^* - \omega)\right]$$

Let us pose:

$$X_1 = \frac{1}{s}\frac{K_i K_T}{J}(\omega^* - \omega) \tag{12}$$

$$X_2 = \frac{1}{s}\left[-\frac{(f + K_p K_T)}{J}\omega + \frac{K_i K_T}{J}\omega^* + X_1\right] \tag{13}$$

The equations (12-13) can be written in the following form:

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\end{bmatrix} = \begin{bmatrix}0 & -1\\ 1 & -\frac{(f + K_p K_T)}{J}\end{bmatrix}\begin{bmatrix}X_1\\ X_2\end{bmatrix} + \frac{K_i K_T}{J}\omega^*\begin{bmatrix}1\\ 1\end{bmatrix} \tag{14}$$

IV. CONCEPT OF LQR

The LQR is a powerful technique for designing controllers for complex systems that have stringent performance requirements. The standard theory of the optimal control is presented in [23-24]. Under the assumption that all state variables are available for feedback, the LQR design method starts with a defined set of states which are to be controlled. In general, the system (14) can be written in state space equation as follows:

$$\dot{X} = AX + BU \qquad (15)$$

A is the state matrix; B is the control matrix. Also, We assume here that all the states are measurable and seek to find a state-variable feedback control. The LQR design is a method of reducing the performance index to a minimize value. The minimization of it is just the means to the end of achieving acceptable performance of the system. For the design of a LQR, the performance index (J) is given by:

$$J = \int_0^{\infty} (X^T Q X + u^T R U) dt \qquad (17)$$

Where Q is symmetric positive semi-definite state weighting matrix, and R is symmetric positive definite control weighting matrix.

The choice of the element Q and R allows the relative weighting of individual state variables and individual control inputs as well as relative weighting state vector and control vector against each other. The term in the brackets in equation (17) above are called quadratic forms and are quite common in matrix algebra. Also, the performance index will always be a scalar quantity, whatever the size of Q and R matrices. The conventional LQR problem is to find the optimal control input law U^* that minimizes the performance index under the constraints of Q and R matrices. The closed loop optimal control law is defined as:

$$U^* = -KX \qquad (18)$$

Where K is the optimal feedback gain matrix, and determines the proper placement of closed loop poles to minimize the performance index in (17). The matrix K depends on the matrices A, B, Q, and R. There are two main equations which have to be calculated to achieve K. Where P is a symmetric and positive definite matrix obtained by solution of the Algebraic Riccati Equation is defined as:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \qquad (19)$$

Then the feedback gain matrix is given by:

$$K = R^{-1} B^T P \qquad (20)$$

Moreover, The number of matrices Q and R elements are dependent on the number of state variable (n) and the number of input variable (m), respectively. The diagonal-off elements of these matrices are zero for simplicity. If diagonal matrices are selected, the quadratic performance index is simply a weighted integral of the squared error of the states and inputs.

Substituting (16) into (18), we obtain

$$\dot{X} = AX - BKX = (A - BK)X \qquad (21)$$

Where:

$$A = \begin{bmatrix} 0 & -1 \\ 1 & -\frac{(f + K_p K_T)}{J} \end{bmatrix}; \; B = \frac{K_i K_T}{J} \omega^* \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

If the Eigen values of the matrix (A-BK) have negative real parts, such a positive definite solution P always exits. To investigate the stability of this system the Nyquist method is applied and the result is presented in Figure(3), One can say that the system (21) is stable.

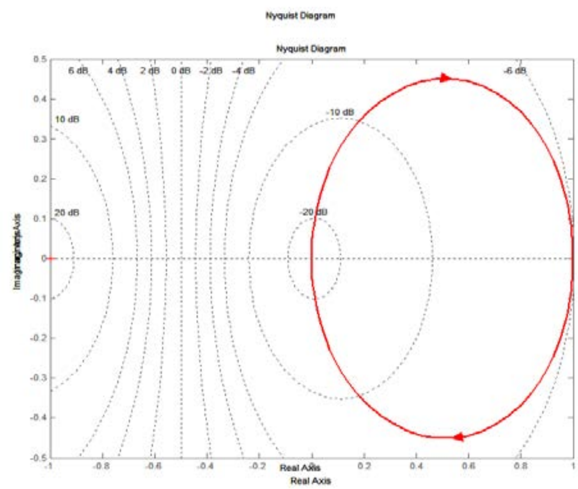

Figure (3) : The Nyquist diagram plot.

V. REDUCED-ORDER STATE OBSERVER

A large number of estimation methods have been proposed since early nineties [14-18]. In this paper, a reduced-order observer is used to estimate the speed and rotor flux. The state equation of the induction motor in the stationary reference frame is used for the observer design:

$$\hat{\dot{X}} = \hat{A}_{22}\hat{X} + A_{21}\bar{\imath}_s + G(\bar{\imath}_s - \hat{\imath}_s) \qquad (22)$$

where:

$$\hat{A}_{22} = \begin{bmatrix} \frac{-1}{T_r} & -\hat{\omega} \\ \hat{\omega} & \frac{-1}{T_r} \end{bmatrix}; A_{21} = \begin{bmatrix} \frac{M}{T_r} & 0 \\ 0 & \frac{M}{T_r} \end{bmatrix}; \; G = \begin{bmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{bmatrix}$$

where A means the estimated values and G is the observer gain matrix which is decided so that (22) can be stable.

$$\hat{X} = \hat{\dot{\phi}}_r = \begin{bmatrix} \hat{\phi}_{r\alpha} \\ \hat{\phi}_{r\beta} \end{bmatrix}; \; \bar{\imath}_s = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}; \; \hat{\imath}_s = \begin{bmatrix} \hat{\imath}_{s\alpha} \\ \hat{\imath}_{s\beta} \end{bmatrix}$$

The development of the Eq (22) gives by using the Eq (3):

$$\hat{\dot{\phi}}_r = \hat{A}_{22}\hat{\dot{\phi}}_r + A_{21}\bar{\imath}_s + G(A_{11}\bar{\imath}_s + A_{12}\hat{\dot{\phi}}_r + BU - \hat{\imath}_s) \qquad (23)$$

Where

$$A_{11} = \begin{bmatrix} \frac{-R}{\sigma L_s} & 0 \\ 0 & \frac{-R}{\sigma L_s} \end{bmatrix};\ A_{12} = \begin{bmatrix} \frac{M}{\sigma L_s L_r T_r} & \frac{M}{\sigma L_s L_r}\omega \\ \frac{-M}{\sigma L_s L_r}\omega & \frac{M}{\sigma L_s L_r T_r} \end{bmatrix};$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix}$$

Lyapunov's theorem is utilized. From (23) and (24), the estimation error of the rotor flux is described by the following equation:

$$e = \left(\hat{\bar{\emptyset}}_r - \bar{\emptyset}_r\right) = [e_{\emptyset r\alpha} \quad e_{\emptyset r\beta}]^T \qquad (24)$$

The differential equation representing the error in estimation of the states is established by carrying out the difference between the equations (3) and (17), one has then:

$$\hat{\dot{e}} = (A_{22} + GA_{12})e + \Delta A_{22}\emptyset_r \qquad (25)$$

Where

$$\Delta A_{22} = \hat{A}_{22} - A_{22}$$

Now, we define the following Lyapunov function candidate.

$$V = e^T e + k_v(\hat{\omega} - \omega)^2 \qquad (26)$$

Where k_v is a positive constant.
The time derivative of V becomes

$$\frac{dV}{dt} = e^T\left\{\left(\hat{A}_{22} + G\hat{A}_{12}\right)^T + \left(\hat{A}_{22} + G\hat{A}_{12}\right)\right\}e$$
$$-2c\Delta\omega\left(e_{\emptyset r\beta}\hat{\emptyset}_{r\alpha} - e_{\emptyset r\alpha}\hat{\emptyset}_{r\beta}\right) + 2k_v\Delta\omega\frac{d\hat{\omega}}{dt} \qquad (27)$$

From (27), we can find the following adaptive scheme for the speed estimation by equalizing the second term to the third term

$$\frac{d\hat{\omega}}{dt} = \frac{\sigma L_s L_r}{M k_v}\left(e_{\emptyset r\beta}\hat{\emptyset}_{r\alpha} - e_{\emptyset r\alpha}\hat{\emptyset}_{r\beta}\right) \qquad (28)$$

If we decide the observer gain matrix G so that the first term of (27) can be negative-semi definite, the proposed speed adaptive flux observer is stable.

$$\begin{cases} l_{12} = l_{21} = 0 \\ l_{11} = l_{22} < 0 \end{cases} \qquad (29)$$

The motor speed can change quickly. Therefore, the following proportional and integral adaptive scheme is used practically in order to improve the response of the speed estimation.

$$\hat{\omega} = \left(K_p + \frac{K_I}{s}\right)\left(e_{\emptyset r\beta}\hat{\emptyset}_{r\alpha} - e_{\emptyset r\alpha}\hat{\emptyset}_{r\beta}\right) \qquad (30)$$

where K_p, K_I : are arbitrary positive gain.

TABLE:1: INDUCTION MACHINE PARAMETERS

R_s : 5.72 Ω	stator Resistance
R_r : 4.2 Ω	rotor Résistance rotor
L_s : 0.462 H	stator Inductance
L_r : 0.462 H	rotor Inductance
M : 0.44 H	mutual Inductance
J : 0.0049 Kgm^2	moment of inertia
P : 2	Number of pair of pole
f : 0.003 Nm.s/rad	damping coefficient
Power	1.5 Kw

VI. SIMULATION RESULTS

Simulations, using Matlab-Simulink software package, have been carried out to verify the effectiveness of the proposed control method. The results are shown in figures 4a-4g . The block diagram of the sensorless indirect field oriented control of induction motor drive incorporating the speed estimator combined to LQR controller is shown in Fig. 5. The accuracy of the estimation algorithm and response of the sensorless indirect field oriented control of induction motor drive is verified under fully loaded condition at various operating speeds. Fig .3 shows the Nyquist diagram . It is also observed that stability is also analyzed after applying the proposed LQR-PI controller. To determine the feedback gain K, the elements of matrices Q and R are chosen as: Q=[0.1 0;0 0.1] and R =0.1. By using lqr command in Matlab, the control feedback gain K can be obtained as K = [0.99881 0. 23595] .
The results of simulation are shown in Fig. 4. These results are obtained by the simulation under the condition that the load torque is (4.4 Nm). The motor speed (ω) , estimated speed $(\hat{\omega})$ and reference speed (ω^*) are shown in Fig.4.a. The estimated speed always followed the reference. The step change of the speed reference does not affect the performance of the system. Good speed estimation accuracy was obtained under both dynamic and steady state conditions under various operating conditions.

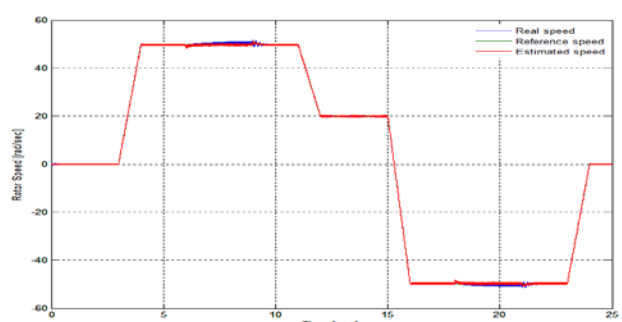

Fig.4a: Reference, estimated and real speed.

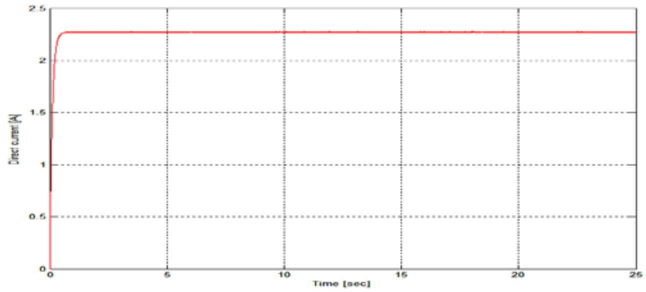

Fig. 4b: Direct current isd .

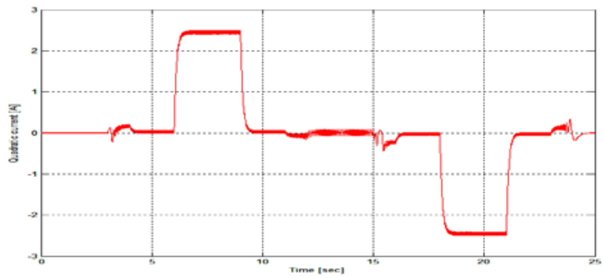

Fig. 4c: Quatratic current i_{sq}.

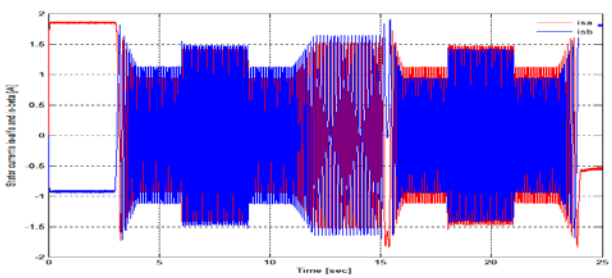

Fig. 4d: Stator currents $i_{s\alpha}$ and $i_{s\beta}$.

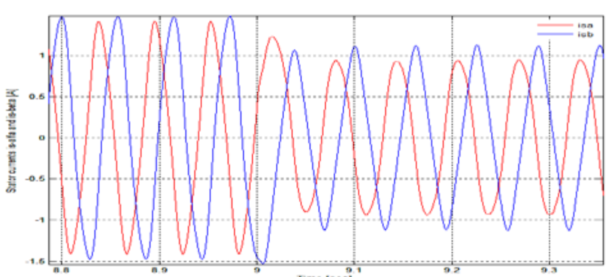

Fig. 4e: Stator currents $i_{s\alpha}$ and $i_{s\beta}$. (Zoom)

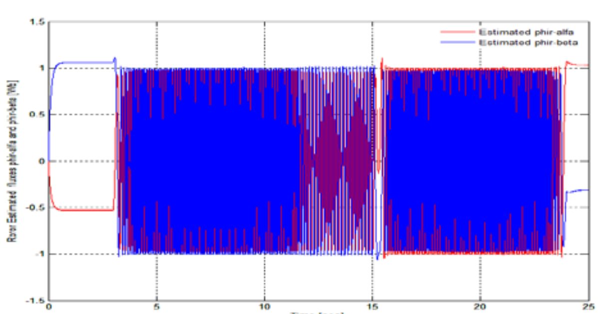

Fig.4f: Estimated rotor fluxes $\widehat{\emptyset}_{r\alpha}\widehat{\emptyset}_{r\beta}$.

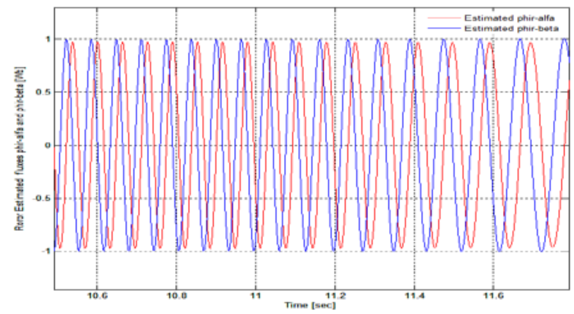

Fig.4g: Estimated rotor fluxes $\widehat{\emptyset}_{r\alpha}\widehat{\emptyset}_{r\beta}$ (Zoom).

VII. EXPERIMENTAL RESULTS

Experimental setup based on real-time control in dSPACE environment provides the interface between the Simulink environment variables and the real system. the laboratory (LTI,EA 3899) IUT of Soissons (french)) associated to a coprocessor (ADMC201) dedicated to the control of IM. Experimental setup, as shown in figure.6.

Figure.5 depicts the experimental motor speed and the estimated speed, while Figs. 5b and 5c show the real direct and quadratic current for a trapezoidal speed profile with a steady state at 50 rpm and a speed inversion, Fig5a. It can be noticed that that the tracking capacities are good. fig 5g show the estimated rotor flux. From this result it can be noted good similarity between simulation and experimental results.

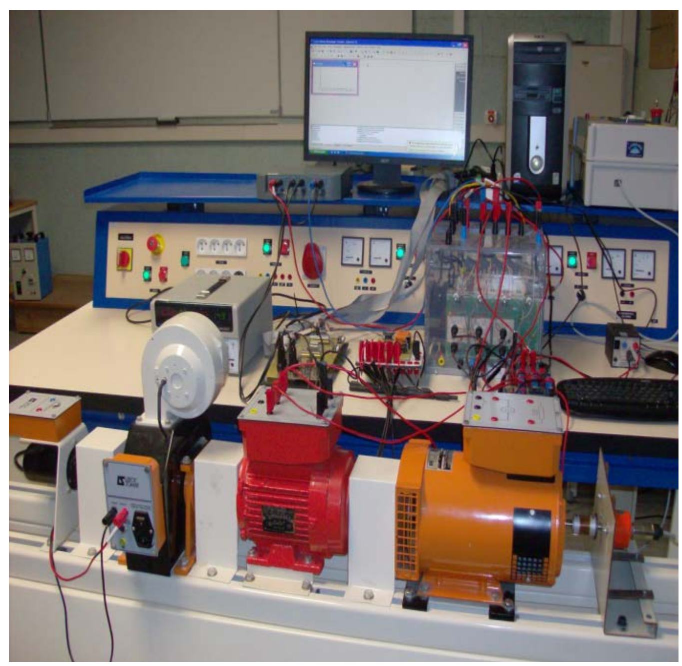

Fig.6 : Experimental system in the L.T.I laboratory, consisting of a 1.5 Kw induction motor, a voltage-source inverter, and a digital signal processor (DSP).

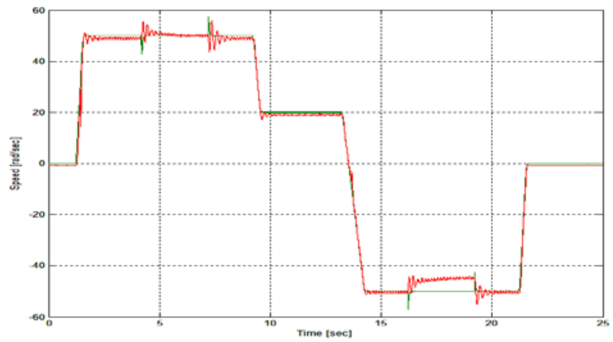

Fig.5a: Reference, estimated and real speed.

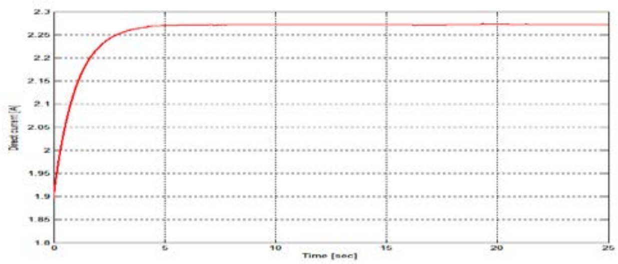

Fig.5b: Direct current I_{sd}.

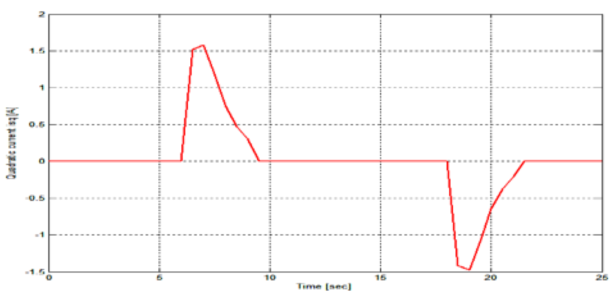

Fig.5c: Quatratic current i_{sq}.

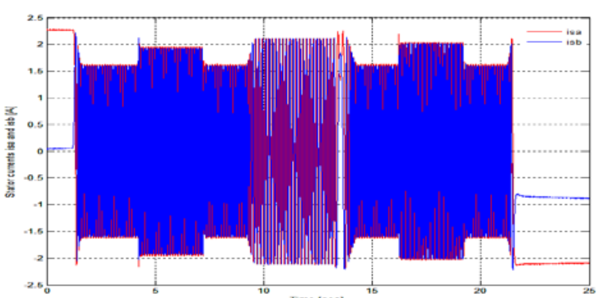

Fig.5e: Stator currents I_{sa} and I_{sb}.

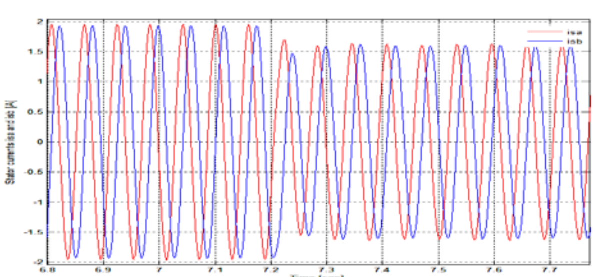

Fig.5f: Stator currents I_{sa} and I_{sb} (Zoom).

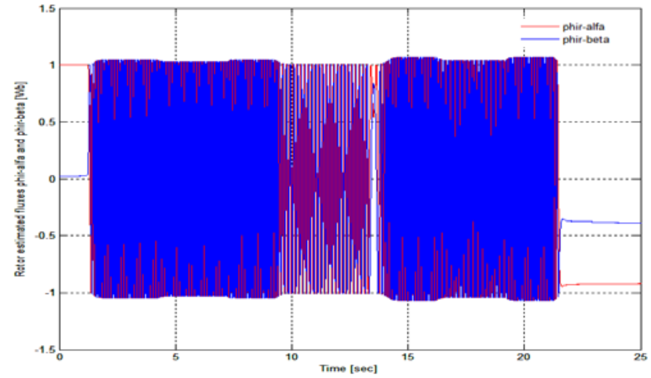

Fig.5g: Rotor estimated fluxes $\widehat{\emptyset}_{r\alpha}$ *and* $\widehat{\emptyset}_{r\beta}$.

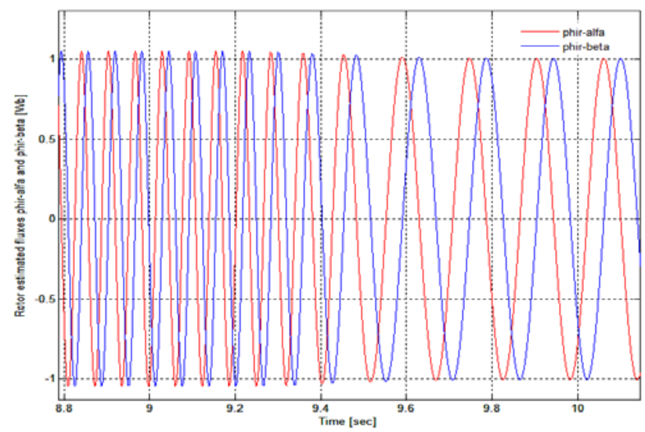

Fig.5h: Rotor estimated fluxes $\widehat{\emptyset}_{r\alpha}$ *and* $\widehat{\emptyset}_{r\beta}$. (Zoom).

VIII. CONCLUSION

In this paper, a new methodology that combines LQR withPI is submitted to design the speed sensorless controller for IM To validate the the new controller strategy, we provided a series of simulations . A reduced-order observer for sensorless control of induction machines using LQR-PI controller has been simulated and implemented successfully. Both simulation and experimental results have shown the performance of the method.

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