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Experimental Implementation of Sensorless Vector Control for IM Drive Using EKF Observer and Fuzzy Logic Controller

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Keywords

«Induction motor», « Sensorless vector control », «Extended kalman Filter», «Fuzzy logic controller», «dSpace 1104».

Abstract

This paper presents an implementation of an intelligent control of induction motor (IM) drive. The strategy is based on field-oriented control (FOC) and fuzzy logic approach. The fuzzy logic controller (FLC) will be proposed for rotor speed, direct and quadratic current regulation to cover the drawbacks of the conventional PI controller and to ensure an accurate reference tracking; a robust response against different uncertainties. An Extended Kalman Filter (EKF) is used for rotor speed and flux estimation. This observer can improve the performance of the controlled system by increasing its reliability and decreasing the cost of the speed sensor. The Proposed sensorless strategy will be examined through Hardware implementation with dSpace 1104 board. The experimental results are presented as a comparative study of the control scheme using PI and fuzzy controllers.

I. Introduction

The induction motor is one of the most used machines for industrial application, where it is necessary to speed control and load mobility, due to their ruggedness, a simplicity of construction, reduced maintenance, low cost and standardization [1]. However, the difficulty of using IM in control-loop lies in the fact of the nonlinearity mathematical model, multivariable, strongly coupled and doesn't inherently capable of providing variable speed operation. This problem has been overcome thanks to field-oriented control [1], [2]. The FOC has been designed in order to acquire high-performance and robustness control for IM in variable speed application[2], [3]. Unfortunately, the use of PI controllers needs particular information of control system modeling. Moreover, under these conditions, PI controllers have limitation provoked by the presence of time-varying parameters, disturbances and uncertainties which affect the stability and the dynamic of the control system. Then, the choice of the gains is not easy, particularly in the real-time implementation.

To remedy this problem, several control techniques have been proposed in literature such as the variable structure control (VSC) [4], and nonlinear control [5], [6]. Others focused their attention on the artificial intelligent techniques [7]. Among different intelligent algorithms, fuzzy logic controllers (FLC) is the simplest, and it does not require the exact knowledge of the mathematical modeling. The FLC can offer a high-robustness with good reference tracking, insensitivity to the external influential and mechanical vibration [8], [9].

Generally, an observer is used in the synthesis control of the machines. Many structures of observers have been suggested for different parameters estimation in order to minimize the cost of the control system by reducing the number of sensors such as, model reference adaptive system MRAS [10], sliding mode observer [11], Luenberger observer [12] and Extended Kalman Filter (EKF) [13]. The EKF has high convergence rate and good disturbance rejection, which can handle the model uncertainties and the effect of unmeasured disturbances, unlike the other observer schemes. The

estimation of the motor state variables by EKF requires just the stator voltages and currents [13]. The accuracy of the estimated speed depends on the accuracy of machine parameters and measured signals. This work presents a comparative evaluation of PI and FLC controllers in the sensorless FOC control of the IM drive based on EKF observer. The effectiveness of the sensorless control strategy with various controllers will be investigated by experimental test bench using MATLAB/Simulink environment with dSpace 1104 board.

II. Induction machine model

Under the hypotheses of the magnetic circuit linearity and overlooking iron losses, the nonlinear model of the induction motor is expressed in the stationary reference frame (α, β) in the form [4]:

$$\begin{cases} \frac{di_{\alpha s}}{dt} = \frac{M_{sr}R_r}{\sigma L_s L_r^2} \phi_{r\alpha} + \frac{n_p M_{sr}}{\sigma L_s L_r} \omega \phi_{r\beta} - \frac{M_{sr}^2 R_r + L_r^2 R_s}{\sigma L_s L_r^2} i_{\alpha s} + \frac{1}{\sigma L_s} V_{\alpha s} \\ \frac{di_{\beta s}}{dt} = \frac{M_{sr}R_r}{\sigma L_s L_r^2} \phi_{r\beta} - \frac{n_p M_{sr}}{\sigma L_s L_r} \omega \phi_{r\alpha} - \frac{M_{sr}^2 R_r + L_r^2 R_s}{\sigma L_s L_r^2} i_{\beta s} + \frac{1}{\sigma L_s} V_{\beta s} \\ \frac{d\phi_{r\alpha}}{dt} = -\frac{R_r}{L_r} \phi_{r\alpha} - n_p \omega \phi_{r\beta} + \frac{R_r}{L_r} M_{sr} i_{\alpha s} \\ \frac{d\phi_{r\beta}}{dt} = -\frac{R_r}{L_r} \phi_{r\beta} + n_p \omega \phi_{r\alpha} + \frac{R_r}{L_r} M_{sr} i_{\beta s} \\ \frac{d\omega}{dt} = \frac{n_p M_{sr}}{2JL_r} (\phi_{r\alpha} i_{\beta s} - \phi_{r\beta} i_{\alpha s}) - \frac{T_L}{J} \end{cases} \quad (1)$$

Where $i_{\alpha s}, i_{\beta s}$ are stator current components; $\phi_{r\alpha}, \phi_{r\beta}$ are stator flux components; R_s, R_r are stator and rotor resistance, respectively; L_s, L_r are stator and rotor inductance, respectively; $\sigma = 1 - \frac{M_{sr}}{L_s L_r}$ is Blondel's coefficient; and M_{sr} is the mutual stator-rotor inductance.

III. Field oriented control of IM

The FOC has been developed to allow varying IM speed over a wide range. It separates the stator currents of IM into flux and torque components in the (d, q) coordinate reference frame. The model Eq.1 is a heavily coupled, multivariable and nonlinear system. These properties complicate the control design of the IM. The rotor flux-oriented coordinate is applied in order to simplify the model of the IM, where the rotor flux is aligned to the direct axis (d) and the electromagnetic torque is aligned to the quadratic axis (q). In this coordinate system the rotor flux is assumed as [2]:

$$\begin{cases} \phi_{rd} = \phi_r \\ \phi_{rq} = 0 \end{cases} \quad (2)$$

The electromagnetic torque expression becomes:

$$T_e = n_p \frac{M_{sr}}{L_r} \phi_{rd} i_{qs} = K_t \cdot \phi_{rd} i_{qs} \quad (3)$$

where:

$$K_t = n_p \frac{M_{sr}}{L_r}$$

The new model motor dynamics is described by the following space vector differential equations:

$$\begin{cases} \frac{di_{ds}}{dt} = \frac{V_{ds}}{\sigma L_{sc}} - \eta_1 i_{ds} + n_p \omega i_{qs} - \left(\eta_2 i_{ds} + \alpha \beta \phi_{rd} + \alpha M_{sr} \frac{i_{qs}^2}{\phi_{rd}} \right) \\ \frac{di_{qs}}{dt} = \frac{V_{qs}}{\sigma L_{sc}} - \eta_1 i_{qs} - n_p \omega i_{ds} - \beta n_p \omega \phi_{rd} - R_r \left(\eta_2 i_{qs} + \alpha M_{sr} \frac{i_{qs} i_{ds}}{\phi_{rd}} \right) \\ \frac{d\omega}{dt} = \mu \phi_{rd} i_{qs} - \frac{T_L}{J} \\ \frac{d\phi_{rd}}{dt} = \alpha M_{sr} R_r i_{ds} - \alpha R_r \phi_{rd} \end{cases} \quad (4)$$

as:

$$\mu = \frac{3n_p M_{sr}}{2JL_r}; \quad \eta_1 = \frac{R_s}{\sigma L_r}; \quad \eta_2 = \frac{M_{sr}^2}{\sigma L_s L_r^2}; \quad \alpha = \frac{1}{L_r}; \quad \beta = \frac{M_{sr}}{\sigma L_s L_r}$$

IV. Fuzzy logic control design

FLC is a method to incarnate human-like thinking into a control system, where, it does not require exact system modeling and parameters; this makes FLC very suitable for motor drive control [1]. Separated FLCs are designed in the sensorless FOC control to getting rid the drawback of PI controller and generate the reference's voltages in the synchronous frame. Another controller is considered in outer loop for speed regulation and generating the reference electromagnetic torque in order to achieve good reference tracking, fast response and high robustness against load disturbance [7]. The block diagram of the applied Fuzzy logic control for speed, direct and quadratic currents is shown in Fig. 1.

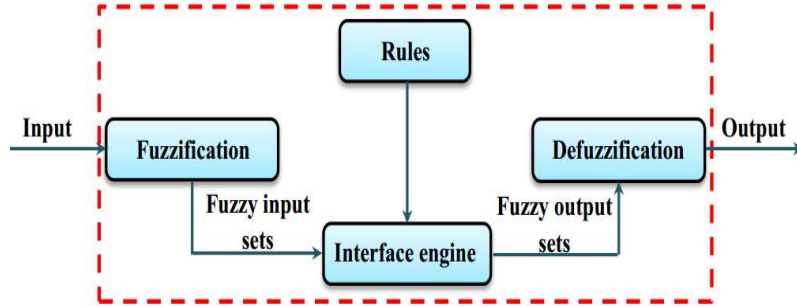


Fig. 1 Fuzzy logic system

The FLC system composed of three principal steps: fuzzification of the input system, linguistic of rules and defuzzification of the output system. The tracking error and its time derivative of the speed, direct or quadratic currents are the input of the separate FLCs. During fuzzification, there are seven variables for the input signal quantities are transformed to fuzzy sets, while the inference step determines the output controller decision developer by Mamdani (table I), according to the set belonging to the rule base. The defuzzification step provides in real quantity the incremental duty cycle. Moreover, Extra variables are added in the fuzzy sets for the output to enhance the dynamic performance. To simplify computation, equilateral triangle membership functions are selected for both input and output as depicted in Fig. 2. The symmetric triangle and overlapped forms are chosen, where accuracy improvement can be treated through a membership focus at zero.

Table I: Fuzzy Rules of the FLCs controllers

e	ce	NB	NM	NS	ZE	PS	PM	PB
NB		NB	NB	NBM	NM	NMS	NS	ZE
NM		NB	NBM	NM	NMS	NS	ZE	PS
NS		NBM	NM	NMS	NS	ZE	PS	PMS
ZE		NM	NMS	NS	ZE	PS	PMS	PM
PS		NMS	NS	ZE	PS	PMS	PM	PBM
PM		NS	ZE	PS	PMS	PM	PBM	PB
PB		ZE	PS	PMS	PM	PBMH	PB	PB

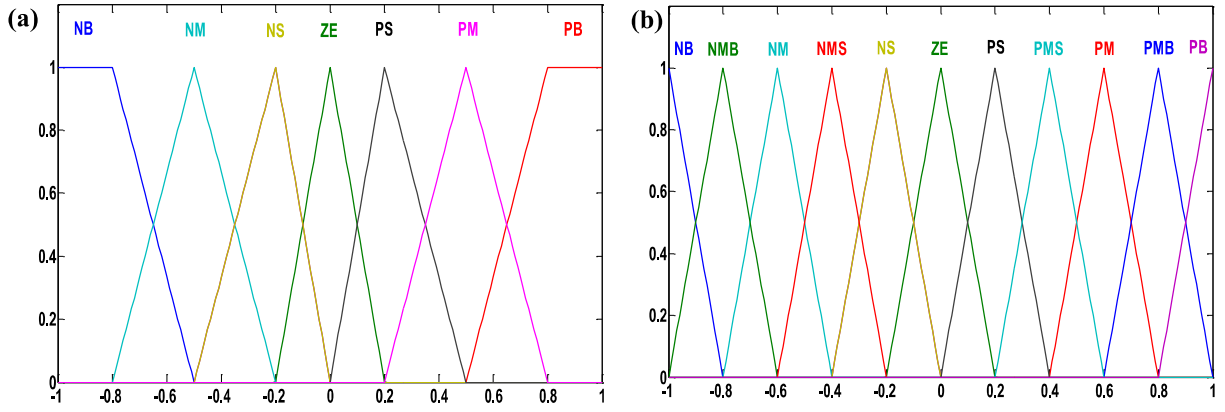


Fig. 2 Membership function a) input, b) output

V. Extended Kalman Filter design

The EKF is linked to the stochastic systems; it uses system noise and statistical characteristics of measurement noise in order to obtain an estimate \hat{x} of the state x of the nonlinear system Eq. 5.

The nonlinear stochastic systems are described by:

$$\begin{cases} \dot{x} = f(x, u) + w(t) (\text{System}) \\ y = Cx + v(t) (\text{Measurement}) \end{cases} \quad (5)$$

Where x and u are the state and the input of the system, $w(t)$ illustrates the disturbances applied on the system input and the output effected by the random noise $v(t)$

The estimation procedure as follow [13]:

- The prediction of the extended state vector:

$$\dot{x}(k+1/k) = f(\dot{x}(k/k), u(k)) \quad (6)$$

- The prediction of the covariance matrix:

$$P(k+1/k) = A(k)P(k/k)A^T(k) + Q \quad (7)$$

where:

$$A(k) = \left. \frac{\partial f}{\partial x}(x(k), u(k)) \right|_{x=\hat{x}(k/k)} \quad (8)$$

- Computation of Kalman gain:

$$K(k+1) = P(k+1/k)C^T(k) \left(C(k)P(k+1/k)C^T(k) + R \right)^{-1} \quad (9)$$

- State update:

$$\dot{x}(k+1/k+1) = \dot{x}(k+1/k) + K(k+1) \left[y(k+1) - C(\dot{x}(k+1/k)) \right] \quad (10)$$

- Estimation covariance computation:

$$P(k+1/k+1) = (I - K(k+1)C(k))P(k+1/k) \quad (11)$$

EKF can be used for extra states which are added in the state vector, where the rotor speed estimator based on EKF is given by:

$$\begin{cases} \dot{x} = Ax(t) + Bu \\ y = Cx(t) \end{cases} \quad (12)$$

where:

$$A = \begin{bmatrix} -(\eta_1 + \eta_2) & 0 & \frac{\beta}{T_r} & n_p \beta \omega & 0 \\ 0 & -(\eta_1 + \eta_2) & -n_p \beta \omega & \frac{\beta}{T_r} & 0 \\ \frac{M_{sr}}{T_r} & 0 & -\frac{1}{T_r} & -n_p \omega & 0 \\ 0 & \frac{M_{sr}}{T_r} & n_p \omega & -\frac{1}{T_r} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{\sigma L_{sc}} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_{sc}} & 0 & 0 & 0 \end{bmatrix}^T, C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}^T$$

$$x = [i_{as} \quad i_{\beta s} \quad \phi_{ar} \quad \phi_{\beta r} \quad \omega_r]^T, u = [V_{as} \quad V_{\beta s}]^T, y = [i_{as} \quad i_{\beta s}]^T$$

Considering the process noise and measure noise, assume the sampling time T_e , the discrete and linearized for the Eq.12 is obtained from the following equation:

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k) + w(k) \\ y(k+1) = C_d(k) + v(k) \end{cases} \quad (13)$$

As:

$$A_d = \begin{bmatrix} 1 - T_e \cdot (\eta_1 + \eta_2) & 0 & T_e \cdot \frac{\beta}{T_r} & T_e \cdot n_p \beta \omega & 0 \\ 0 & 1 - T_e \cdot (\eta_1 + \eta_2) & -T_e \cdot n_p \beta \omega & T_e \cdot \frac{\beta}{T_r} & 0 \\ T_e \cdot \frac{M_{sr}}{T_r} & 0 & 1 - T_e \cdot \frac{1}{T_r} & T_e \cdot n_p \omega & 0 \\ 0 & T_e \cdot \frac{M_{sr}}{T_r} & T_e \cdot n_p \omega & 1 - T_e \cdot \frac{1}{T_r} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B_d = \begin{bmatrix} T_e \cdot \frac{1}{\sigma L_{sc}} & 0 & 0 & 0 & 0 \\ 0 & T_e \cdot \frac{1}{\sigma L_{sc}} & 0 & 0 & 0 \end{bmatrix}^T$$

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

Based on Eq.13 and using the EKF algorithm, the model state can be estimated at different times and thus estimate rotor speed of IM. The covariance matrixes that pass the different states measured, predicted and estimated. Their main objective is to minimize the errors related to the modeling approximation and the presence of noise on the measurements. The choice of these matrixes are selected by trial-and-errors for achieving the desired estimation performance, as below:

$$Q = \text{diag} [10^{-3} \quad 10^{-3} \quad 10^{-5} \quad 10^{-5} \quad 10^{-1}], R = \text{diag} [10^{-3} \quad 10^{-3}]$$

The global sensorless fuzzy FOC control scheme of IM based on EKF filter is shown in Fig. 3.

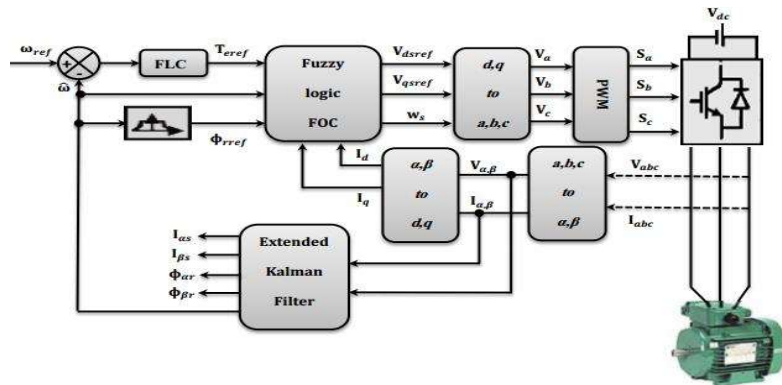


Fig 3: Sensorless fuzzy FOC control of the IM

VI. Experimental results

The proposed sensorless fuzzy FOC control using EKF filter observer have been investigated and compared with the classical PI controller for different variable reference speed and mechanical load torque application. The algorithm implementation was done in the laboratory equipped with dSpace 1104 board. The experimental setup is shown in Fig. 4, consisting of 1) 1.1 kW squirrel-cages IM, The parameters of the motor are given in the appendix. 2) A magnetic powder brake with the control unit, 3) a Semikron voltage converter and adaptation interfaces ($5V-15V$). 4) Speed sensor. 5) Hall type current sensors, voltage sensors. 6) Auto transformer ($0-450V$). 7) dSpace 1104 connected with a personal computer equipped with control desk software.

The chosen sampling frequency for the Real-Time implementation is 5kHz .

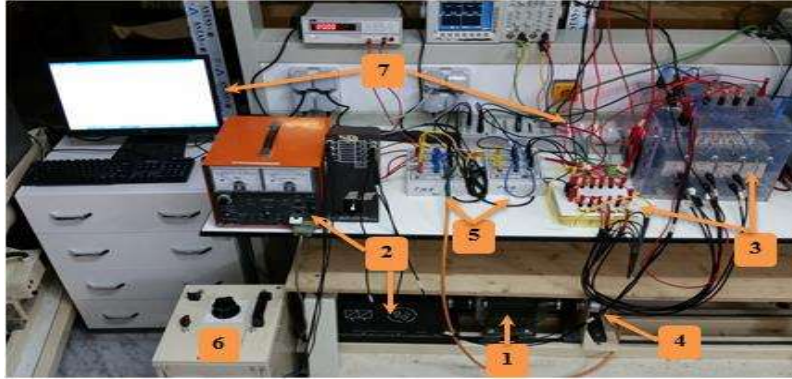


Fig 4. Experimental setup

The figures below (Figs. 5 to 10) show the experimental validation of sensorless FOC control in different operation modes such as transient and steady state, load application, reverse speed test and low speed, for the classical PI and FLC controllers. The figures are specified by (a) for PI FOC control and (b) for Fuzzy FOC control.

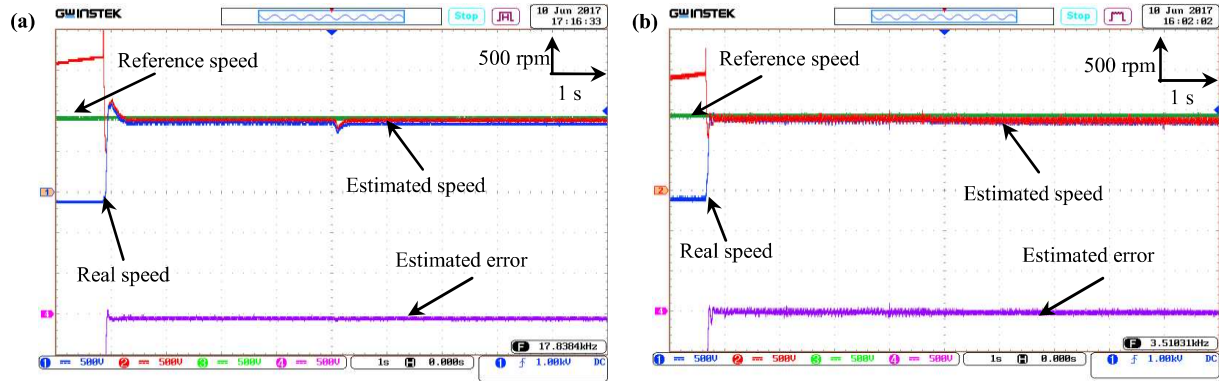


Fig. 5: Rotor speed and estimated error with load application

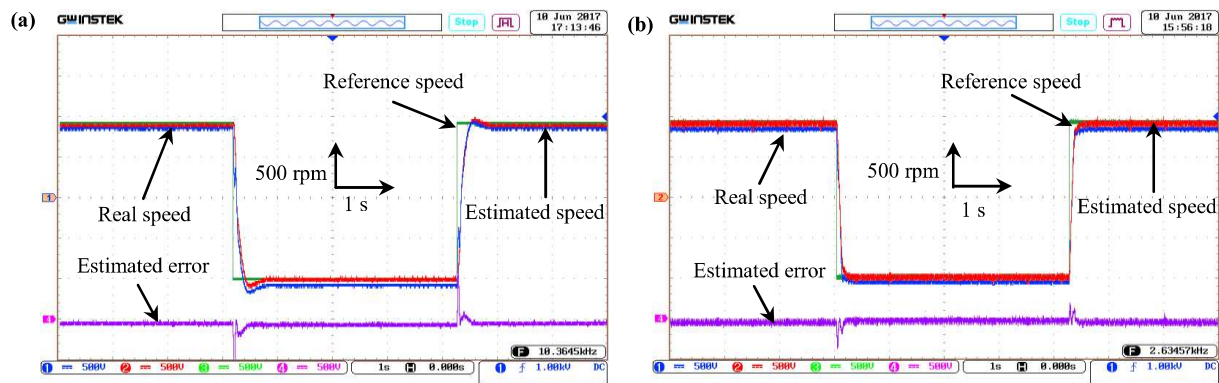


Fig. 6: Rotor speed and estimated error with reverse speed test

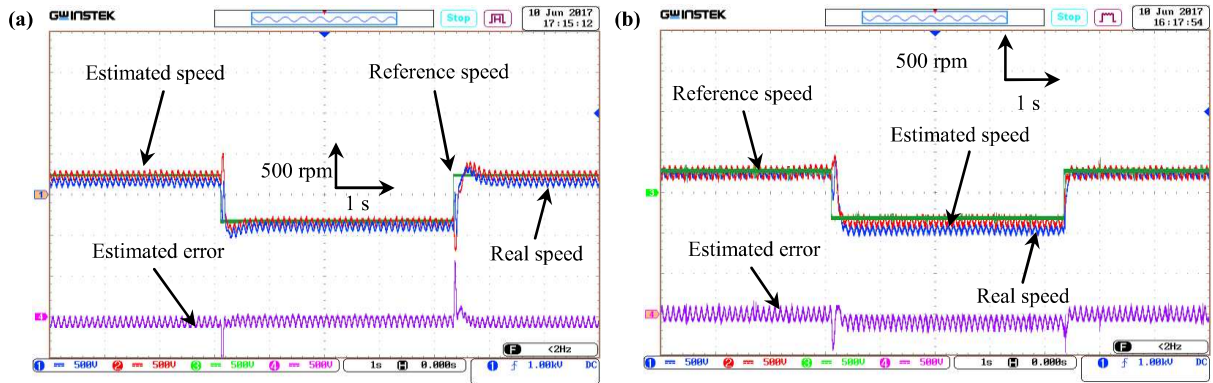


Fig. 7: Rotor speed and estimated error with reverse speed test

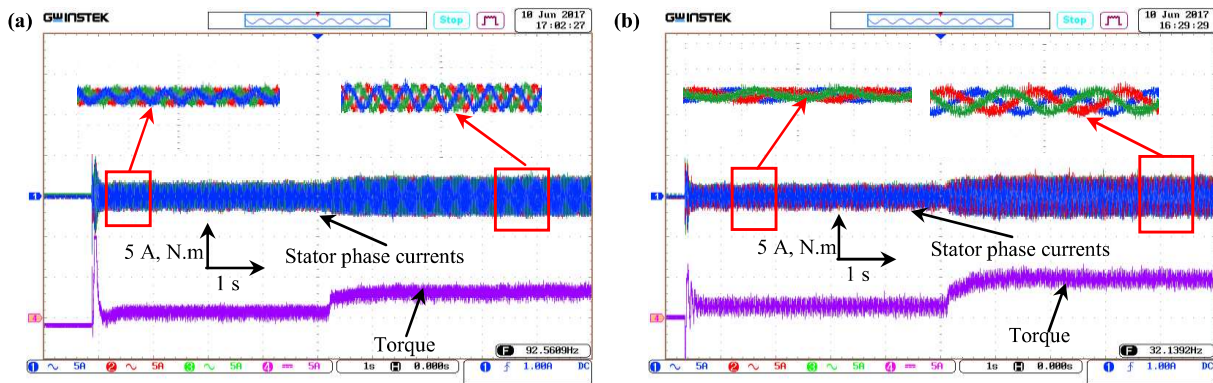


Fig. 8: Stator phase currents and torque with rated load introduction

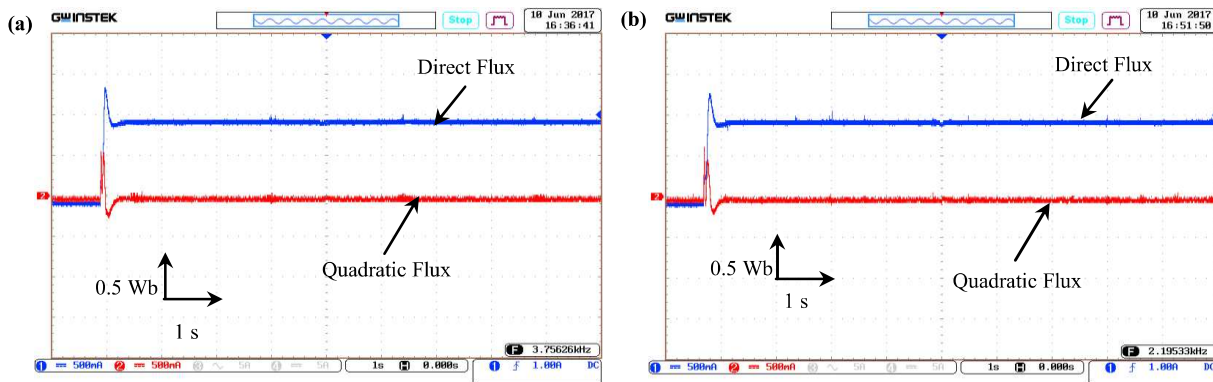


Fig. 9: Direct and Quadratic flux components

In Figs. 5-7, the experimental results of estimated rotor speed of sensorless FOC control of the IM using EKF observer, and the estimated error in the different speed region have been employed, (a) PI FOC and (b) fuzzy FOC respectively. The rotor speed in FLC controller (Fig. 5b) presents the fast response of time 0.06s; good reference tracking without overshoot, whereas, a small overshoot is observed in Fig. 5a of the PI controller with a time response of 0.1s. From Figs. 6 and 7, a good estimated speed following performance test in different working in inverse (1000 rpm to -1000 rpm) and low speed (200 rpm to -200 rpm) is observed. While the FLC controller provides better superposition Fig. 6b and 7b. Furthermore, the estimated errors converge always to zero.

Fig. 8 depicts the stator phase currents and electromagnetic torque with load application. It is noted that good sinusoid waveform of the stator current; fast and good dynamic in the torque; there is a reduction of ripples in FLC controller compared with PI controller.

Fig. 9, illustrate the direct and quadratic flux components of the sensorless FOC controlled IM. The direct rotor flux is stabilized at rated value (1Wb), while the quadratic rotor flux is maintained at almost zero. Hence, the decoupled control is kept.

VII. Conclusion

This paper deals with an experimental implementation of sensorless Field oriented control based on fuzzy logic approach and EKF observer for induction motor drive. EKF observer is used for rotor speed estimation in order to achieve a sensorless control algorithm. The FLC controller has been employed for rotor speed, direct and quadratic currents regulation. The experimental results have been compared to the traditional PI controller. The obtained results show a good dynamic and reference tracking with perfect decoupling for the FOC control strategy. The EKF has an accurate estimation which improves the reliability by dispense with the use of the speed sensor. The fuzzy logic controller proves high robustness; present a fast response and gives acceptable performance for different speed operating the machine.

Appendix

Table II. Induction Motor Parameters

Specifications		Parameters	
Rated power [kW]	1.1	R_s [Ω]	6.75
Rated voltage [V]	230/400	R_r [Ω]	6.21
Rated current [A]	2.5	L_s [H]	0.5192
Rated frequency [Hz]	50	L_r [H]	0.5192
Number of pole pairs	2	M_{sr} [H]	0.4957
Rated speed [rpm]	1450	J [Kg.m ²]	0.0124
		f [Nm.s.rad ⁻¹]	0.002

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