A Comparative Study of Rotor Time Constant Online Identification of an Induction Motor Using High Gain Observer and Fuzzy Compensator

ABDELHADI ELBACHA[1)], ZAKARIA BOULGHASOUL[1)2)], ELMOSTAFA ELWARRAKI[2)]
[1)] National School of Applied Sciences – ENSA of Marrakesh, Morocco
[2)] Faculty of Sciences and Technologies – FST of Marrakesh, Morocco
Cadi Ayyad University – Marrakesh, Morocco
a.elbacha@ucam.ac.ma, z.boulghasoul@gmail.com, elwarraki@fstg-marrakech.ac.ma

Abstract: - One of the most critical problems in induction motor drive is the knowledge of the current value of some induction motor parameters such as the rotor time constant, which depends strongly on temperature and frequency. This problem won't be easy to solve because of the high coupling between parameters in the nonlinear induction motor model. In order to determine the rotor time constant, this paper will focus on comparative study between two approaches to estimate this parameter using the indirect vector control of induction motor. The first identification is based on The High Gain Observer which ensures decoupling of the desired electrical variable, and requires less computational time. The second identification is based, on Fuzzy Compensator that uses the fuzzy logic principles. Possible exploitation of the proposed study in the fault detection issue is discussed through simulation of the rotor time constant variation and compensation using MATLAB/SIMULINK ®software, and, experimentally through a real time implementation using the dSPACE 1104 board.

Key-Words: - Induction Motor, Online Identification, High Gain Observer, Fuzzy Compensator, Rotor Time Constant, fault detection, Real Time Implementation, dSPACE 1104.

Nomenclature

v_{sd} , v_{sq}	*d, q* Axis Stator voltages
v_{rd} , v_{rq}	*d, q* Axis Rotor voltages
i_{sd} , i_{sq}	*d, q* Axis Stator currents
i_{rd} , i_{rq}	*d, q* Axis Rotor currents
ω_s , ω_r	Reference frame and the slip speed
ω	The Rotor speed
φ_{sd} , φ_{sq}	*d, q* Axis Stator fluxes
φ_{rd} , φ_{rq}	*d, q* Axis Rotor fluxes
L_s , L_r	Stator and Rotor Inductances
R_s , R_r	Stator and Rotor Resistances
T_s , T_r	Stator and Rotor time constants
M	Mutual inductance
σ	The Total leakage factor
θ_s , θ	*d, q* Reference frame and rotor position
ε_{rd} , ε_{rq}	Inputs of the Fuzzy Compensator
$\Delta\hat{T}_r$	The Output of the fuzzy Compensator
$\hat{T}_r$	Estimated value of the rotor time constant
T_e , T_l	Electromagnetic and Load torque
J_Δ	The total inertia
f_r	The friction coefficient
p	The number of pole pairs
*	Denotes reference value
$\hat{}$	Denotes an estimated value

1 Introduction

In recent decades, Induction Motors (IMs) has had a great success in many industrial fields. In comparison with DC motors which suffer from the drawbacks of the brushes-collector, the corrosion and the necessity of maintenance, the induction motors present high reliability, simple construction, low cost and highly reduced maintenance. However, IMs are nonlinear, multivariable and highly coupled [1]-[2]. Therefore, DC motors have been used especially for applications that need high precision in speed and torque control [3] while induction motors are used in closed-loop for adjustable speed applications [4]. With recent advances of powerful microprocessors, such as the Digital Signal Processors (DSP), the implementation of complex techniques for induction motors control becomes possible [5].

The Indirect Field Oriented Control strategy (IFOC) is widely used for high performance drive system, and has been adopted as a standard solution for industrial problems related to induction motor drive [6]-[7]. This strategy of vector control made the drive equivalent to DC motor, driven by using the slip frequency to achieve the orientation [8]. In [9], many vector control schemes have been developed. However, in all these schemes both the torque and rotor flux are controlled by the stator current which is decomposed into two components.

Indirect Field Oriented Control (IFOC) uses the slip frequency for producing the field orientation and aligns the stator current component with the rotor flux [10]. The drive based on this strategy is designed using IM parameters, which change with temperature and frequency, resulting in a poor transient response and low efficiency. We know that the variation of the rotor resistance affects the value of the rotor time constant, which means that this latter would have a dominant effect on the control performance. Therefore, it is mandatory to guarantee the similarity between the motor model parameters and the ones of the real motor in order to preserve the drive performance [11]. Some solutions based on Neural Networks are proposed to increase the robustness and efficiency of the drive. Other solutions propose to add an estimator of the rotor resistance to the drive system to ensure high performance [12]-[13].

Among the recent methods used for online rotor resistance identification, the High Gain Observer is one of the most adequate solutions for nonlinear and observable systems, where we can classify the induction motor [14]-[15]-[16], it needs less computational time compared with other nonlinear, extended state observers or Kalman filters, in addition to that, it is easier in implementation.

Other techniques use the principle of Fuzzy Logic approach for online rotor time constant tuning through a Fuzzy Controller which changes adaptively, the step size of the ratio between the motor and the control reference. The problem related to this parameter variation has been investigated by many authors and several works have been published in this regard [18]-[19]-[20]-[21]-[22].

The most important contribution of this paper is to present comparative study between the High Gain Observer approach and the Fuzzy Compensator approach, that are both used for online rotor time constant identification, in order to present a possible exploitation in the fault detection issue. The Results obtained will be helpful to improve induction motor drive and lead developers towards the most powerful method. The influence of the rotor time constant on the Indirect Filed Oriented Control induction motor drive performance is first proved by simulation. The obtained results will be improved by adding the two approaches to the drive, and the investigation on the performance of the drive under online rotor time constant updating will be carried. The complete indirect vector control scheme of induction motor, incorporating the two approaches for rotor time constant updating, has been successfully implemented in simulation, using MATLAB/SIMULINK® software and experimented in real time using the dSPACE 1104 controller board from TMS320F240.

This paper is organized as follows: The equations of IM model and the Indirect Field Oriented Control are developed in Section 2, while Section 3 describes both the High Gain Observer and the Fuzzy Compensator for rotor time constant identification. In Section 4, simulation results of the proposed study described in this work are discussed. In Section 5, after describing the hardware platform developed around the dSPACE 1104 board, the different experimental results are presented, discussed and many conclusions are drawn. For future development and research in this area, we present, in section 6 another hardware platform developed, using dsPIC board for further comparison. The most important contributions of this work are presented in the conclusion in Section 7.

2 Model Description and Control Design

2.1 Dynamic Model of Induction Motor

The induction motor model, described by using a space vector notation and written in (d, q) reference frame, rotating on the synchronous speed ω_s, is presented in the following equations [23]-[24]:

$$\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq} \\ v_{sq} &= R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd} \end{aligned} \quad (1)$$

$$\begin{aligned} v_{rd} &= 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \\ v_{rq} &= 0 = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \end{aligned} \tag{2}$$

where v_{sd} and v_{sq} are the (*d, q*) axis stator voltages, (i_{sd}, i_{sq}) and (i_{rd}, i_{rq}) are respectively the *(d, q)* axis stator and rotor currents, ω_s and ω_r are respectively the reference frame and the slip speed. ($\varphi_{sd}, \varphi_{sq}$) and ($\varphi_{rd}, \varphi_{rq}$) represent the (*d, q*) axis stator and rotor fluxes. They can be described by the following equations:

$$\begin{aligned} \varphi_{sd} &= L_s i_{sd} + M i_{rd} \\ \varphi_{sq} &= L_s i_{sq} + M i_{rq} \end{aligned} \tag{3}$$

$$\begin{aligned} \varphi_{rd} &= M i_{sd} + L_r i_{rd} \\ \varphi_{rq} &= M i_{sq} + L_r i_{rq} \end{aligned} \tag{4}$$

where L_s and L_r are stator and rotor inductance, M is the mutual inductance.

The mechanical and the electromagnetic torque equations are given by:

$$T_e - T_l = J_\Delta \frac{d\omega}{dt} + f_r \omega \tag{5}$$

$$T_e = p \frac{M}{L_r} (\varphi_{rd} i_{sq} - \varphi_{rq} i_{sd}) \tag{6}$$

where T_e is the electromagnetic torque, T_l describes the load torque, ω is the rotor speed, f_r is the friction coefficient, J_Δ represents the total inertia and p is the number of pole pairs.

The induction motor can be also described by a state model. In the electrical drive literature, many models are proposed. They can be chosen according to the adopted drive theory. We present, by the following system, the state model used to design the drive:

$$\begin{aligned} \dot{X} &= [A].X + [B].U \\ Y &= [C].X \end{aligned} \tag{7}$$

where [*A*], [*B*] and [*C*] are the evolution, the control and the observation matrices. They are respectively given by:

$$X^T = (i_{sd}\ i_{sq}\ \varphi_{rd}\ \varphi_{rq}) \ ; \ U = \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} \ ; \ Y = \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix}$$

$$A = \begin{bmatrix} -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) & \omega_s & \frac{1-\sigma}{\sigma M T_r} & \frac{1-\sigma}{\sigma M}\omega \\ -\omega_s & -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) & -\frac{1-\sigma}{\sigma M}\omega & \frac{1-\sigma}{\sigma M T_r} \\ \frac{M}{T_r} & 0 & -\frac{1}{T_r} & \omega_s - \omega \\ 0 & \frac{M}{T_r} & -(\omega_s - \omega) & -\frac{1}{T_r} \end{bmatrix}$$

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

with σ is the total leakage factor, it is given by the following expression:

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

T_s and T_r represent, respectively, the stator and the rotor time constants. They are given by the expressions below:

$$T_s = \frac{L_s}{R_s} \text{ and } T_r = \frac{L_r}{R_r}. \tag{8}$$

2.2 The Indirect Field Oriented Control

According to the rotor field oriented control theory [25]-[26], the stator current of the induction motor can be decomposed into two orthogonal components in the synchronous rotating reference frame, which are named respectively the torque current and the magnetizing current. The purpose is to independently control the torque and the flux such as a DC motor. Fig. 1 shows this orientation:

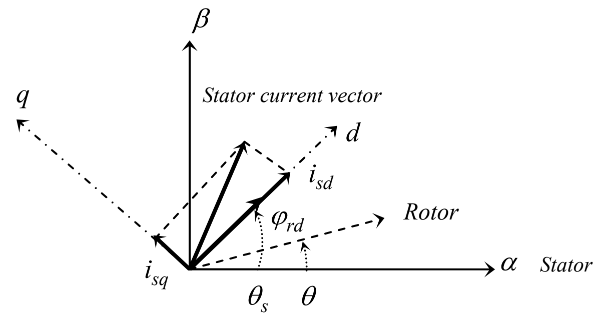


Fig. 1 Reference frames and space vector representation.

θ_s and θ are respectively *(d, q)* the reference frame and the rotor position.

Considering the orientation in Fig. 1 we have:

$$\varphi_{rd} = \varphi_r \text{ and } \varphi_{rq} = 0 \tag{9}$$

where φ_r is the total flux according to the axis d. From the induction motor model that we've developed in the first section and considering the result of the orientation given by (9) we have:

$$\frac{d\varphi_r}{dt} = \frac{M}{T_r} i_{sd} - \frac{1}{T_r}\varphi_r \qquad (10)$$

$$0 = \frac{M}{T_r} i_{sq} - (\omega_s - \omega)\varphi_r \qquad (11)$$

From equation (10), the modulus of the rotor flux can be kept at a desired level by controlling the direct-axis stator current, also in steady state, (10) can be written as:

$$\frac{M}{T_r} i_{sd} = \frac{1}{T_r}\varphi_r \Rightarrow i_{sd}^{\ *} = \frac{1}{M}\varphi_r^{\ *} \qquad (12)$$

* Denotes reference value.

In (11) the term $\frac{M}{T_r\varphi_r} i_{sq}$ represents the slip speed of the rotor flux ω_r, considering that the synchronous speed is equal to the sum of the rotor speed and the slip speed of the rotor flux we obtain:

$$\theta_s = \int \omega_s = \int(\omega + \omega_r) = \theta + \int \frac{M}{T_r\varphi_r^{\ *}} i_{sq}^{\ *} \qquad (13)$$

According to equation (13), the division of the direct and quadrature-axis stator currents (i_{sd}, i_{sq}) is controlled by the slip speed ω_r, and the two reference currents are used to determine the required slip speed. When the rotor position and the reference value of the slip speed angle are added, the rotor flux position is obtained.

We have shown in equation (6) that the electromagnetic torque expression in the dynamic regime presents a coupling between the rotor flux and the stator current.

In the case of the indirect field oriented control, the electromagnetic torque can be expressed as:

$$T_e = p\frac{M}{L_r}\varphi_r i_{sq} \qquad (14)$$

Then we can write:

$$i_{sq}^{\ *} = \frac{L_r}{pM\varphi_r^{\ *}} T_e^{\ *} \qquad (15)$$

We can notice that if the rotor flux is kept constant by the direct axis stator current, the torque can be controlled by the q-axis current.

Always from the state model, we have:

$$\frac{di_{sd}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{sd} + \omega_s i_{sq} + \frac{1-\sigma}{\sigma M T_r}\varphi_r + \frac{1}{\sigma L_s} v_{sd}$$

$$\frac{di_{sq}}{dt} = -\omega_s i_{sd} - \left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{sq} - \frac{1-\sigma}{\sigma M}\omega\varphi_r + \frac{1}{\sigma L_s} v_{sq}$$

This can be written as:

$$\begin{aligned} v_{sd} &= \sigma L_s \frac{di_{sd}}{dt} + R_{sr} i_{sd} - \sigma L_s \omega_s i_{sq} - \frac{M}{L_r^{\ 2}} R_r \varphi_r \\ v_{sq} &= \sigma L_s \frac{di_{sq}}{dt} + R_{sr} i_{sq} + \sigma L_s \omega_s i_{sd} + \frac{M}{L_r}\omega\varphi_r \end{aligned} \qquad (16)$$

It seems that the d-axis and q-axis voltage equations are coupled by the terms $-\sigma L_s \omega_s i_{sq} - M/L_r^{\ 2} R_r \varphi_r$ and $\sigma L_s \omega_s i_{sd} + M/L_r\, \omega\varphi_r$. We can conclude that these terms represent disturbances for the drive, and they can be cancelled if the decoupling method which uses feedback of coupling voltage is employed. In this case, the voltage equations become:

$$\begin{aligned} v_{sd} &= v_{sd}^{\ *} - e_{sd} = \sigma L_s \frac{di_{sd}}{dt} + R_{sr} i_{sd} \\ v_{sq} &= v_{sq}^{\ *} - e_{sq} = \sigma L_s \frac{di_{sq}}{dt} + R_{sr} i_{sq} \end{aligned} \qquad (17)$$

where:

$$R_{sr} = R_s + \left(\frac{M}{L_r}\right)^2 R_r\,; \quad e_{sd} = \sigma L_s \omega_s i_{sq} + \frac{M}{L_r^{\ 2}} R_r \varphi_r$$

$$e_{sq} = -\sigma L_s \omega_s i_{sd} - \frac{M}{L_r}\omega\varphi_r$$

e_{sd} and e_{sq} represent the compensation terms.

Taking into account these terms, dynamics of the stator currents is represented by simple linear first order differential equations. That means that a simple PI controller can be used to ensure currents components control. Fig. 2 shows the decoupling system with the compensation terms. $\mathrm{H}(s)_{sd}$ and $\mathrm{H}(s)_{sq}$ represent the d and q axis transfer functions of the induction motor if the compensation is considered. They are given by:

$$\mathrm{H}(s)_{sd} = \mathrm{H}(s)_{sq} = \frac{1}{R_{sr} + \sigma L_s s} \qquad (18)$$

where s denotes Laplace variable.

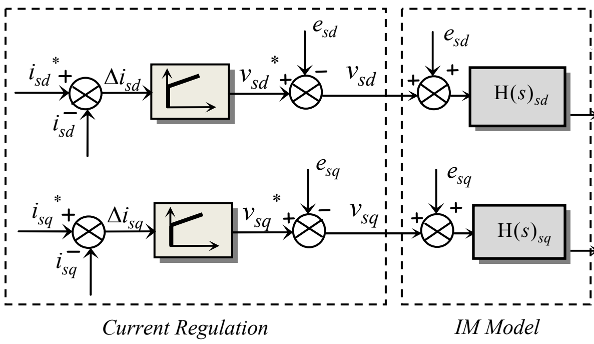


Fig. 2 Compensation and decoupling system

3 Design of High Gain Observer and Fuzzy Compensator for Online Rotor Time Constant identification

3.1 Design of the High Gain Observer

The High Gain Observer is one of the suitable solutions for non linear systems. Considering the induction motor as nonlinear, multivariable and highly coupled, this observer is more preferable for continuous adaptation to the rotor resistance as discussed in [14]-[15]-[16].

This observer will be used to obtain the rotor resistance, and then we will extract the rotor time constant since these two parameters are related by (8). Considering the following system given by:

$$\begin{aligned} \dot{x} &= f(x) + g(x).u \\ y &= h(x) \end{aligned} \tag{19}$$

The observer which can be proposed for the above system is given by the following system, as developed in [14]:

$$\begin{aligned} \dot{\hat{x}} &= f(\hat{x}) + g(\hat{x}).u - \left(\frac{\partial \Gamma}{\partial \hat{x}}(\hat{x}(t))\right)^{-1} S_\theta^{-1}(h(\hat{x}) - y) \\ \hat{y} &= h(\hat{x}) \end{aligned} \tag{20}$$

where:

$\hat{x}$ is the observer value of which dynamic is adjusted trough the gain θ

Γ : is an application $R^n \rightarrow R^n$

With

$$\Gamma = \left[h_1, L_f h_1 ..., L_f^{\delta_1} h_1, h_2, L_f h_2, ..., L_f^{\delta_2} h_2 ..., h_m, L_f h_m, ..., L_f^{\delta_m} h_m\right]^T$$

$L_f^{\delta_k}$ is the δ_k^i Lie derivative, m is the number of outputs and S_θ satisfies the Lyapounov relation given by the following equation, developed in [17]:

$$\dot{S}_\theta = -\theta S_\theta - A^T S_\theta - S_\theta A + C^T C = 0$$

The observation of $\hat{x}$ is made in two steps:

- 1st step for prediction; it is characterized by the term $f(\hat{x}) + g(\hat{x}).u$.
- 2nd step for correction, its appropriate term is $\left(\frac{\partial \Gamma}{\partial \hat{x}}(\hat{x}(t))\right)^{-1} S_\theta^{-1}(h(\hat{x}) - y)$.

What makes the difference between this observer and the other non linear observers, is the use of minimum gains θ_k, that allow high dynamic for the observer and require less computational time [14]-[15]-[16].

In the case of Indirect Filed Oriented Control, the design of the High Gain Observer consists of identifying the terms S_θ^{-1} and $\left(\frac{\partial \Gamma}{\partial \hat{x}}(\hat{x}(t))\right)^{-1}$.

The following system allows the estimation of both components of rotor fluxes φ_{rd} and φ_{rq} :

$$\begin{aligned} \frac{d\varphi_{rd}}{dt} &= \frac{L_r}{M}\left(v_{sd} - R_s i_{sd}\right) + \omega_s \varphi_{rq} - \frac{\sigma L_r L_s}{M}\left(i_{sd} - \omega_s i_{sq}\right) \\ \frac{d\varphi_{rq}}{dt} &= \frac{L_r}{M}\left(v_{sq} - R_s i_{sq}\right) + \omega_s \varphi_{rd} - \frac{\sigma L_r L_s}{M}\left(i_{sq} - \omega_s i_{sd}\right) \end{aligned} \tag{21}$$

Thus, the High Gain Observer will be designed according to the following model as developed in [15]:

$$\begin{aligned} \dot{x}_1 &= \left(\omega_s - \omega\right) x_2 + \frac{M}{L_r} i_{sd} x_3 - \frac{x_3}{L_r} x_1 \\ \dot{x}_2 &= -\left(\omega_s - \omega\right) x_1 + \frac{M}{L_r} i_{sq} x_3 - \frac{x_3}{L_r} x_2 \\ \dot{x}_3 &= 0 \end{aligned} \tag{22}$$

where: $\left[x_1\ x_2\ x_3\right]^T = \left[\varphi_{rd}\ \varphi_{rq}\ R_r\right]^T$

The observer design is done by choosing:

$$\dot{\hat{x}}^T = \left[\dot{\hat{\varphi}}_{rd}\ \dot{\hat{\varphi}}_{rq}\ \dot{\hat{R}}_r\right]^T; \quad h(\hat{x}) = \begin{bmatrix} \hat{\varphi}_{rd} \\ \hat{\varphi}_{rq} \end{bmatrix}; \quad y = \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \end{bmatrix}$$

$$\text{and} \qquad S_\theta^{-1} = \begin{bmatrix} 2\theta_1 & \theta_1^2 & 0 \\ \theta_1^2 & \theta_1^3 & 0 \\ 0 & 0 & 2\theta_2 \end{bmatrix}$$

$\left(\frac{\partial \Gamma}{\partial \hat{x}}(\hat{x}(t))\right)^{-1}$ can be given by the following expression as developed in [14]:

$$\left(\frac{\partial \Gamma}{\partial \hat{x}}(\hat{x}(t))\right)^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ -\frac{\hat{R}_r}{\hat{\varphi}_{rd}} & -\frac{L_r}{\hat{\varphi}_{rd}} & \frac{\left(\omega - \omega_s\right).L_r}{\hat{\varphi}_{rd}} \end{bmatrix}$$

And then, $\dot{\hat{x}}$ will be given as proved in [14] by:

$$\begin{bmatrix} \dot{\hat{\varphi}}_{rd} \\ \dot{\hat{\varphi}}_{rq} \\ \dot{\hat{R}}_r \end{bmatrix} = \begin{bmatrix} \frac{M\hat{R}_r}{L_r} i_{sd} - \frac{\hat{R}_r}{L_r}\hat{\varphi}_{rd} + (\omega_s - \omega_r)\varphi_{rq} \\ \frac{M\hat{R}_r}{L_r} i_{sd} - (\omega_s - \omega_r)\varphi_{rd} + \frac{\hat{R}_r}{L_r}\hat{\varphi}_{rq} \\ 0 \end{bmatrix} - \left(\frac{\partial T}{\partial x}(\hat{x}(t))\right)^{-1} \begin{bmatrix} 2\theta_1 & \theta_1^2 & 0 \\ \theta_1^2 & \theta_1^3 & 0 \\ 0 & 0 & 2\theta_2 \end{bmatrix} \left(\begin{bmatrix} \hat{\varphi}_{rd} \\ \hat{\varphi}_{rq} \\ 0 \end{bmatrix} - \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \\ 0 \end{bmatrix} \right)$$

Fig. 3 shows the structure of the High Gain observer for rotor resistance estimation:

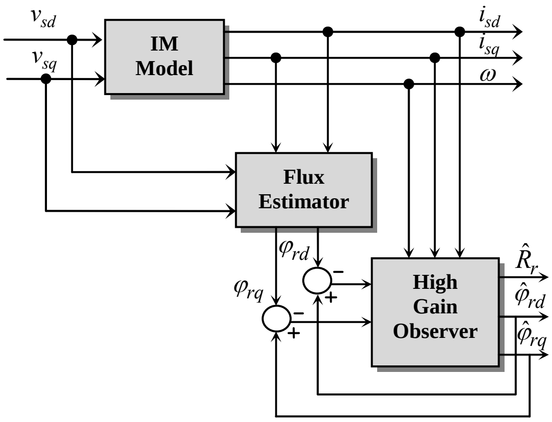


Fig. 3 High Gain Observer Structure

3.2 Design of Fuzzy Compensator

Recently, because of the problems related to nonlinear control, and to the difficulties of the determination of a good model, Fuzzy Logic has been adopted as a very useful solution, and now it has found a particular attention. [27]-[28]. In the case of induction motor, Fuzzy Logic techniques have been proposed in different error minimization for instance: Speed control, switching table in the case of Direct Torque Control, Online tuning of parameter variation and other problems.

For the rotor time constant, Fuzzy Logic can be introduced as a compensator to generate the estimated value of this parameter as discussed in many works [18]-[19]-[20]-[21]-[22]. The fuzzy controller compensator generates the incremental control signal error $\Delta\hat{T}_r$ from two errors ε_{rd} and ε_{rq} as depicted in Fig. 4. These errors are given by:

$$\begin{aligned} \varepsilon_{rd} &= \varphi_{rd}^{*} - \varphi_{rd} \\ \varepsilon_{rq} &= \varphi_{rq}^{*} - \varphi_{rq} \end{aligned} \tag{23}$$

Two gains $k_{\varepsilon rd}$ and $k_{\varepsilon rq}$ are used to adjust each error. The output of the controller $\Delta\hat{T}_r$ is added to the rotor time constant reference T_{rref} to generate the estimated value $\hat{T}_r$ [18] which is given by:

$$\hat{T}_r = T_{rref} + \Delta\hat{T}_r \tag{24}$$

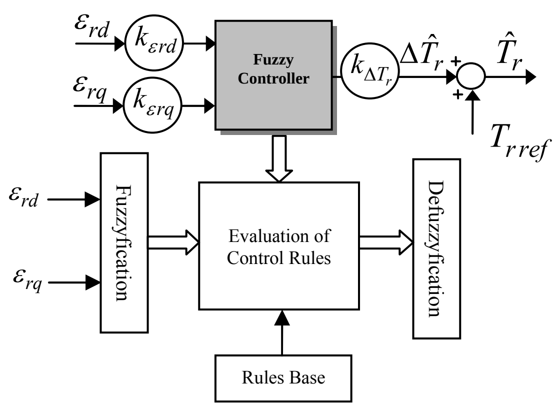


Fig. 4 Fuzzy Compensator schem for online rotor time constant updating

Three blocks are used to describe the constitution of the fuzzy controller: Fuzzyfication, rules base, and Defuzzyfication [29]. Fig. 5 shows the membership functions of each input signal ε_{rd}, ε_{rq} and the output $\Delta\hat{T}_r$. Seven triangular membership functions traditionally were used to describe both the input and output of the Fuzzy Controller. The corresponding fuzzy sets are:

NB= Negative Big, NM = Negative Medium, NS = Negative Small, ZE = Zero, PS= Positive Small, PM= Positive Medium, PB= Positive Big.

Defuzzyfication is done by centroid method based on the inference method Mamdani.

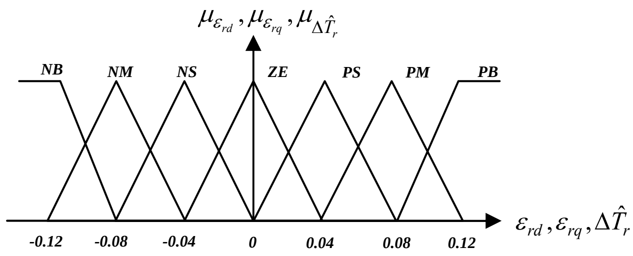


Fig. 5 Fuzzy controller input and output membership functions

In this case, the fuzzy controller has 49 rules as illustrated in Table 1:

Table. 1 Rules base of the fuzzy Compensator

ε_{rd} \ ε_{rq}	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
PB	*ZE*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*
PM	*NS*	*ZE*	*PS*	*PM*	*PB*	*PB*	*PB*
PS	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*	*PB*
ZE	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*
NS	*NB*	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*
NM	*NB*	*NB*	*NB*	*NM*	*NS*	*ZE*	*PS*
NB	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*ZE*

Table. 2 Induction Motor Data

Components	Name	Values
P	Rated Power	1kW
N	Rated Speed	1425 rpm
V	Rated Voltage	220 V
R_s	Stator Resistance	6.8 Ω
R_r	Rotor Resistance	5.43 Ω
L_s	Stator Inductance	0.3973 H
L_r	Rotor Inductance	0.3973 H
M	Mutual Inductance	0.3973 H
J	Motor Load-Inertia	0.02 Kg.m^2
p	Number of pole pairs	2

4 Simulation Results and Discussion

Simulation studies were performed by Matlab/Simulink® for an Induction Motor with parameters as shown in Tables 2. The dynamic performance of the drive system for different operating conditions has been studied using the High Gain Observer and the Fuzzy Compensator for Online Rotor time constant identification.

The scheme of the proposed studies presented in this work is illustrated in Fig. 6.

In order to analyze the drive system performance for their flux and torque responses, simulations are carried out for the induction motor drive taking into account the variation of the rotor time constant. The drive was the subject to step reference of the electromagnetic torque of 5N.m and 0.8 Wb for the rotor flux. Figures below show the performance degradation.

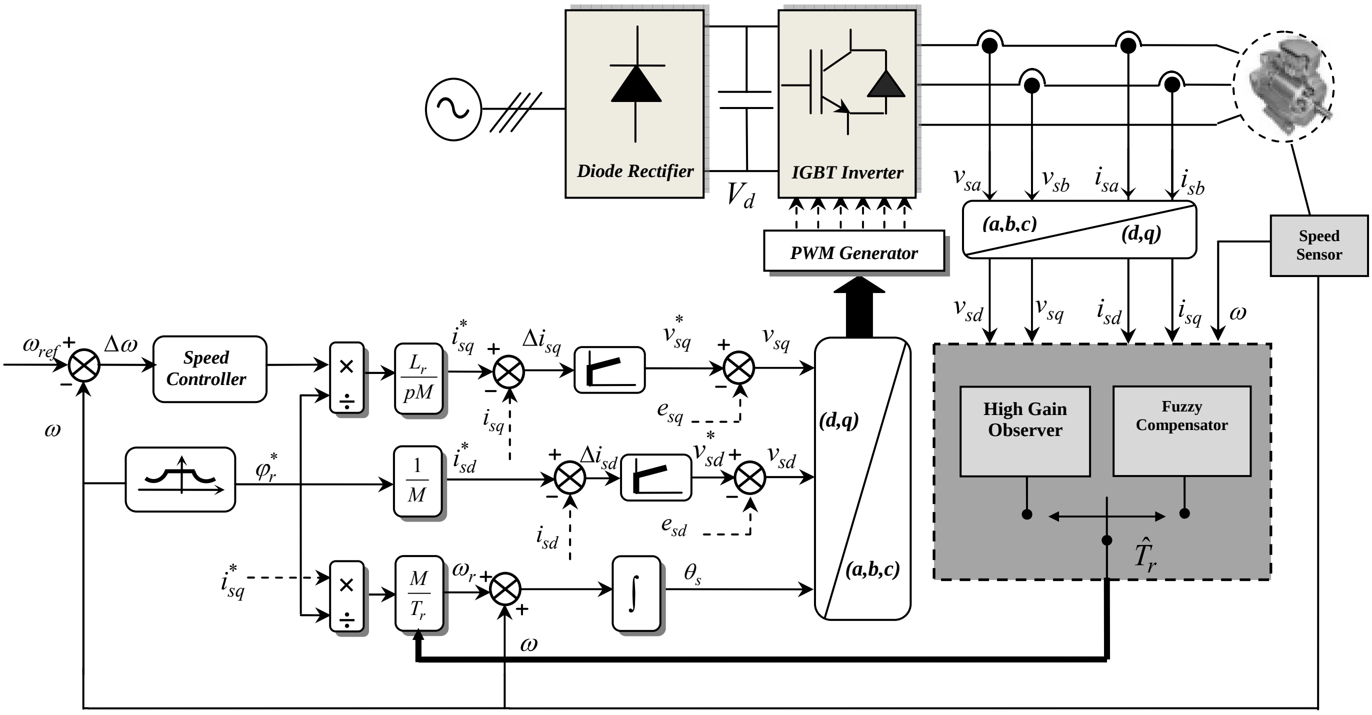


Fig. 6 IFOC Scheme with OnLine Rotor Time Constant identification

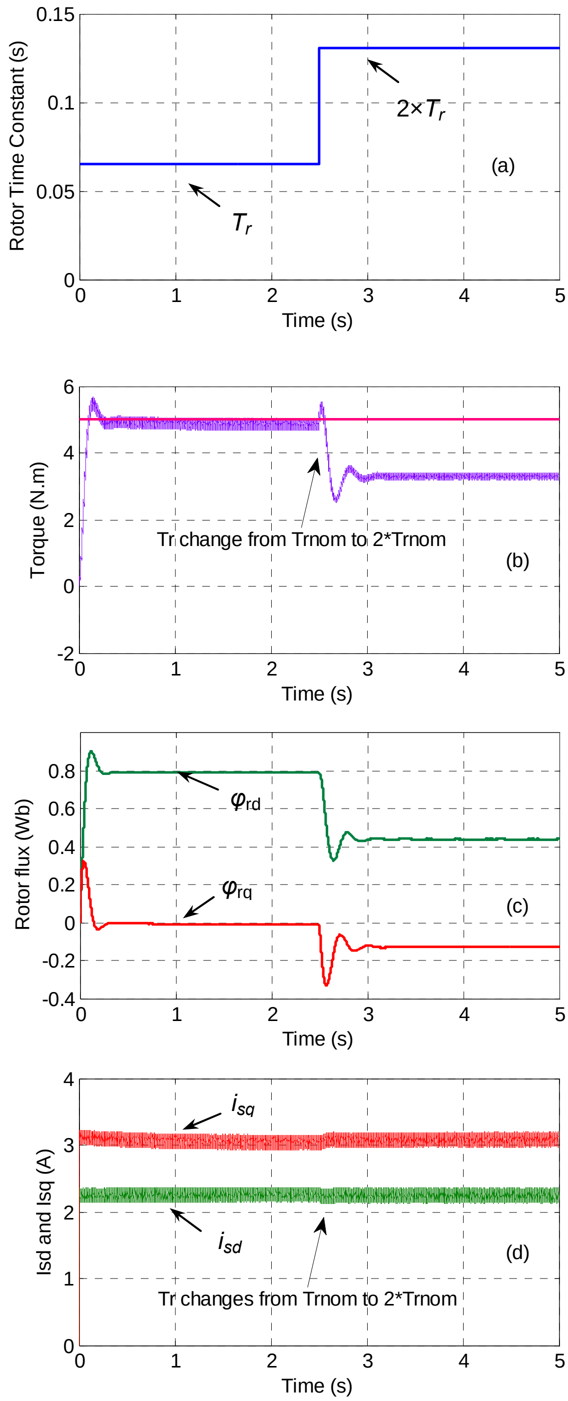


Fig. 7 IFOC performance with increased rotor time constant (a) The rotor time constant variation (b) Electromagnetic Torque, (c) Rotor flux, (d) i_{sd} and i_{sq} Components

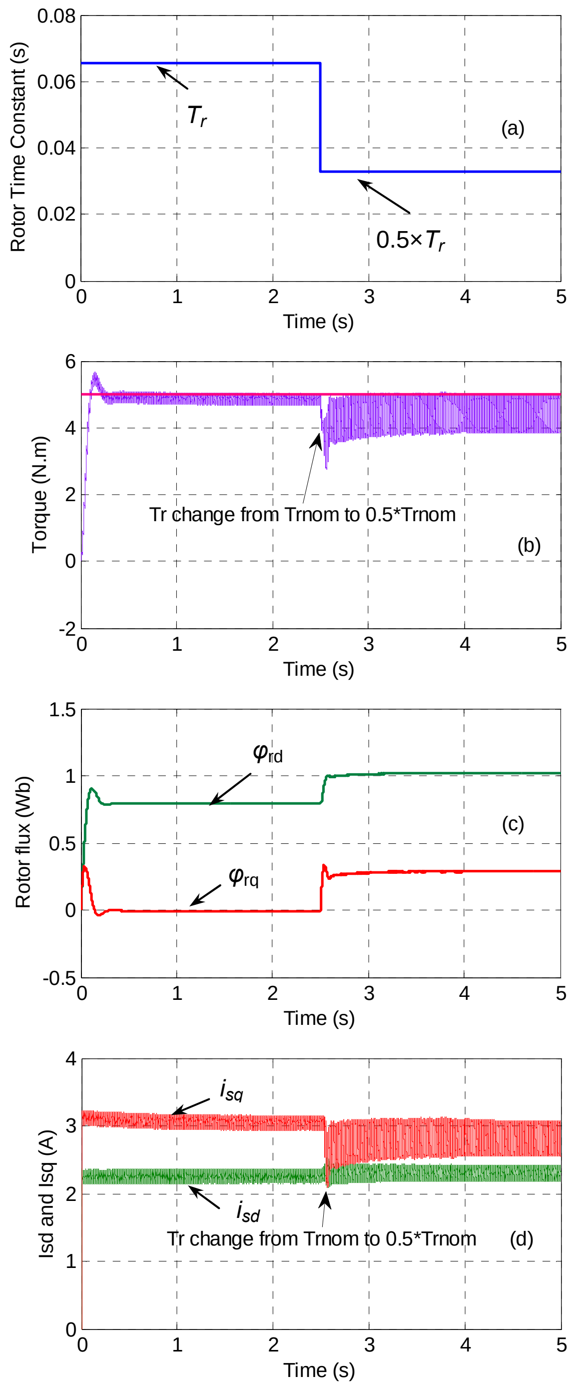


Fig. 8 IFOC performance with decreased rotor time constant (a) The rotor time constant variation (b) Electromagnetic Torque, (c) Rotor flux, (d) i_{sd} and i_{sq} Components

Fig 7 and 8 show the effect of a step change in the rotor time constant on the electromagnetic torque and the axis stator currents i_{sd} and i_{sq} in the rotating reference frame.

The estimated rotor flux of the induction motor increases and decreases according to the rotor time constant variation due to the change in the electromagnetic torque in steady state.

4.1 Open Loop Control with Online rotor time constant identification

The tests achieved in open loop control were performed with the electromagnetic torque as reference. The drive has a reference step of 5N.m for the electromagnetic torque and 0.8 Wb for rotor flux. Both the High Gain Observer and the Fuzzy Compensator will be used for the online rotor time constant identification in the drive to allow comparative studies. The resolution of the equation (20) proves that it doesn't need the θ_2 in the construction of the observer because it disappears while developing the equations. The determination of the gain θ_1 can be done using the trial error method to obtain an optimized operating mode as discussed and illustrated in [15]-[16]-[17]. For our case, the choice has been done to respect the stability of the observer and also to obtain high dynamic for the estimation. Studies have been developed for $\theta_1 = 3$, and to illustrate the limit of stability tests have been made for $\theta_1 = 4$ then for $\theta_1 = 5$. Figures below have been obtained for increased variation of rotor time constant where θ_1=3:

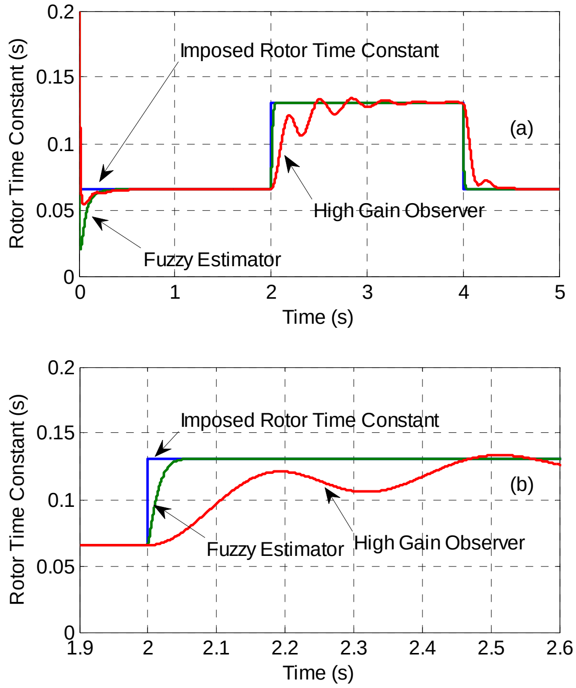


Fig. 9 (a) Online Rotor time constant identification (a) using the High Gain Observer for θ_1=3 and Fuzzy Compensator, (b) Zoom on the estimated rotor time constant

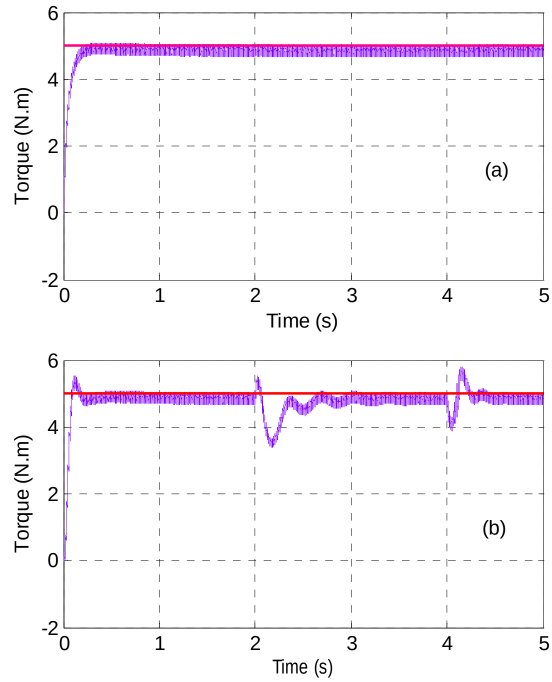


Fig. 10 Electromagnetic Torque response with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

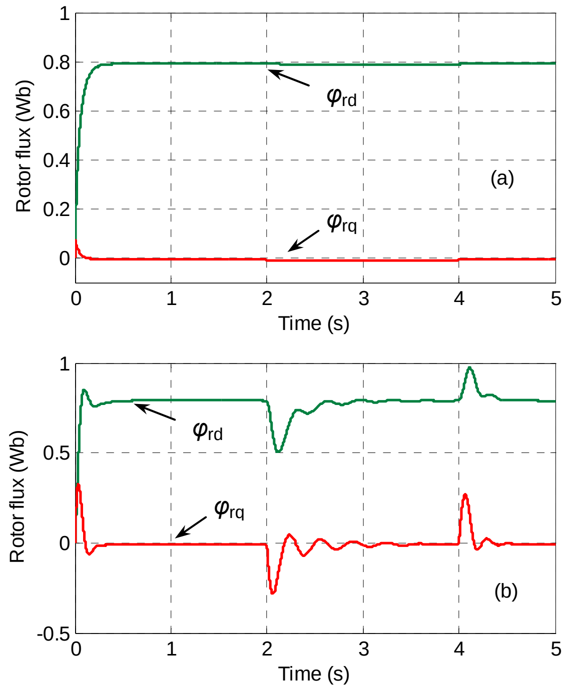


Fig. 11 Rotor flux components with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

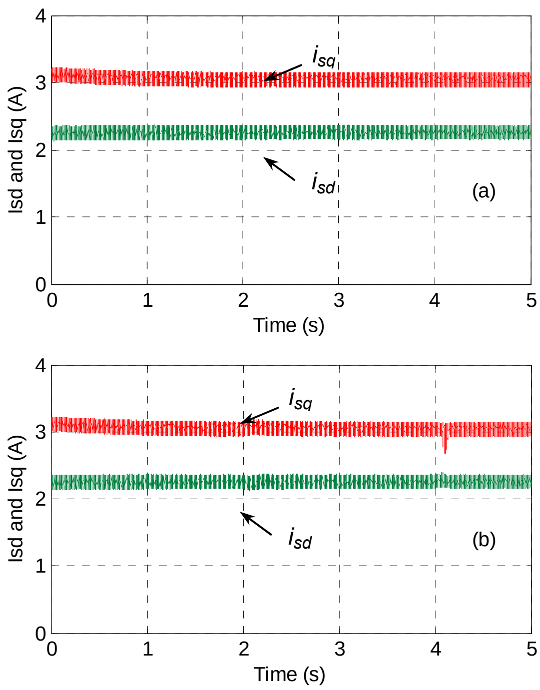


Fig. 12 Stator current components with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for $\theta_1=3$

Fig. 9 illustrates the results of the online rotor time constant identification, and shows that the Fuzzy Compensator ensures a good tracking to the imposed rotor time constant, in comparison with the High Gain Observer, which presents some undulations and a slow response in the transient state. The high performances obtained are clearly shown in the electromagnetic torque and rotor flux as illustrated in Fig 10 and 11, the Fuzzy Compensator reduces the effect of the variation and ensures a good tracking to the reference values without excess and preserves the dynamic of the drive.

In order to show the limit of stability of the High Gain Observer, several tests have been accomplished with different gains θ_1. This limit of stability was obtained for $\theta_1 = 4$ and $\theta_1 = 5$ as shown in figures below.

As remarked in Fig 13, the limit of the stability was obtained for $\theta_1 = 5$. The result with $\theta_1 = 4$ presents high ripple compared to estimation with $\theta_1 = 3$. Results obtained prove the optimal choice for the gains θ_1.

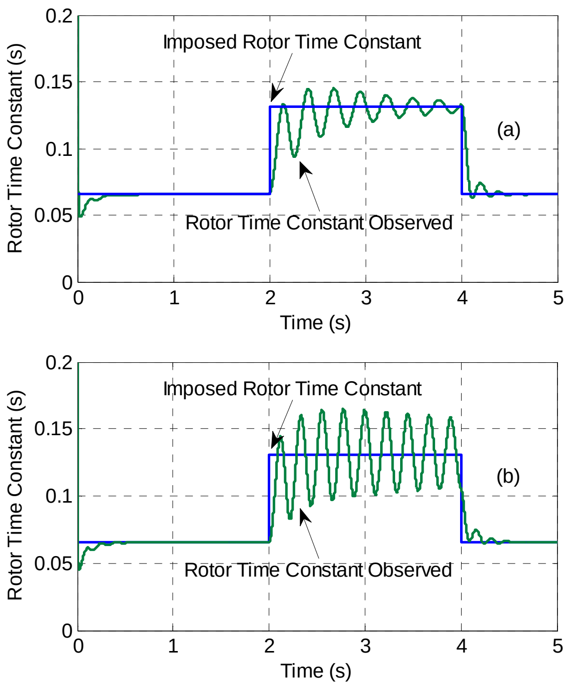


Fig. 13 Online Rotor time constan identification using the High Gain Observer (a) for $\theta_1=4$ (b) for $\theta_1=5$

In order to allow to the proposed study possible exploitation in the fault detection issue, the case of decreased variation of the rotor time constant is also discussed through the figures below.

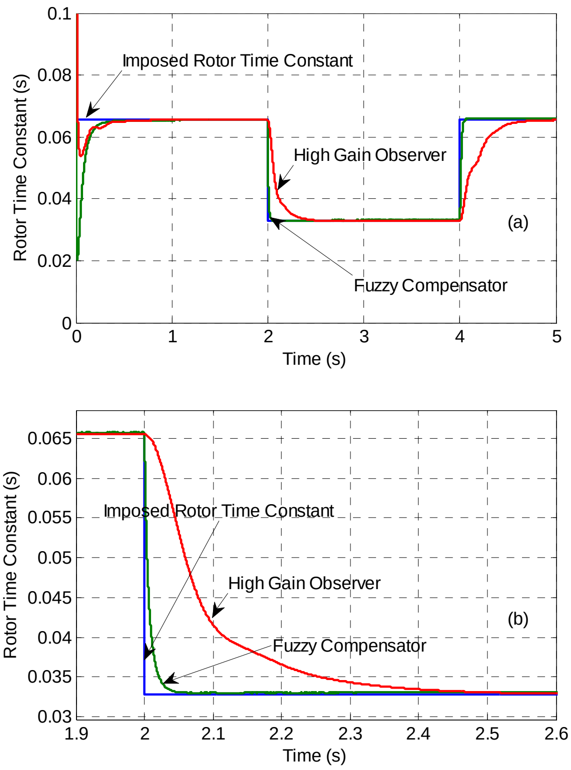


Fig. 14 Online Rotor time constant identification (a) using the High Gain Observer for $\theta_1=3$ and Fuzzy Compensator, (b) Zoom on the estimated rotor time constant

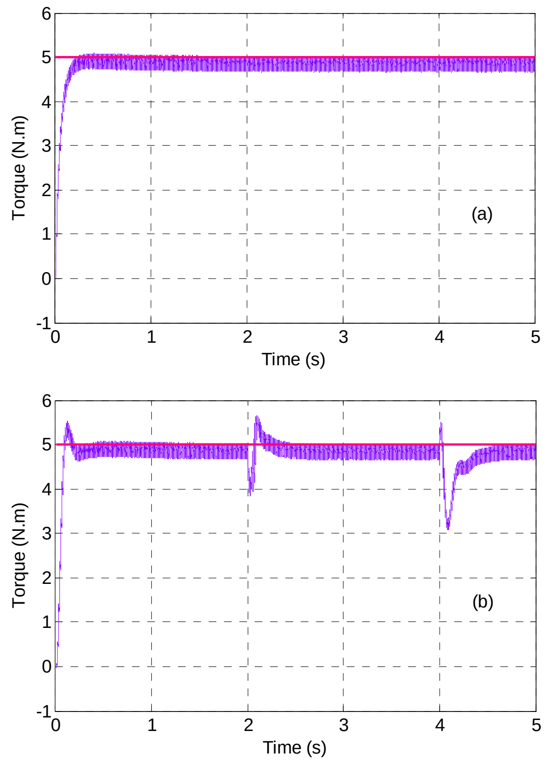


Fig. 15 Electromagnetic Torque response with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

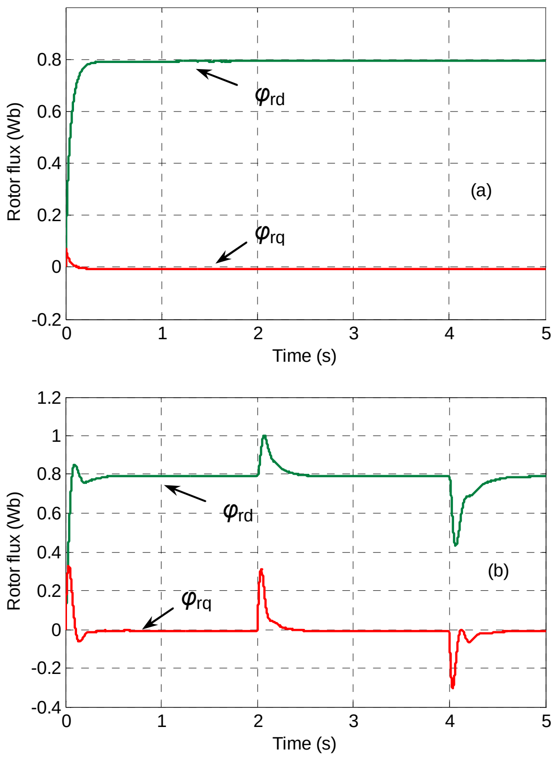


Fig. 16 Rotor flux components with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

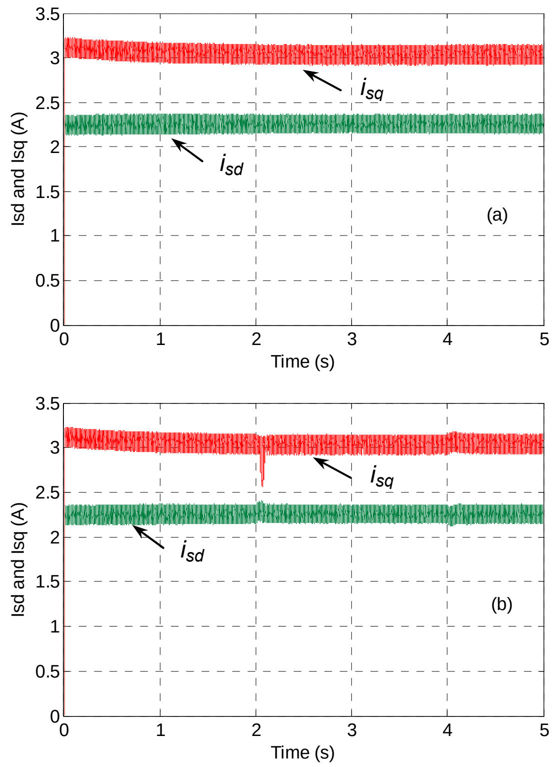


Fig. 17 Stator current components with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

As shown above, even for a decreased variation of the rotor time constant, the Fuzzy Compensator ensures a good tracking and preserves the performances of the drive. This is illustrated by Fig 14 and 15. In the case of the Fuzzy Compensator, the rotor time constant, the electromagnetic torque and the rotor flux follow very closely their references without excess. Fig 16 and 17 illustrate the field oriented control characteristics that were preserved. As show, the dynamic of the rotor flux components.

4.2 Closed Loop Control with Online rotor time constant identification

In the closed loop control with an online rotor time constant identification, the drive is subject to a step reference of 80 rd/s of the speed and 0.8Wb of the rotor flux. The gain of the observer is θ_1= 3. Figures below illustrate the results of this investigation. In this case, we use a ramp for the rotor time constant variation.

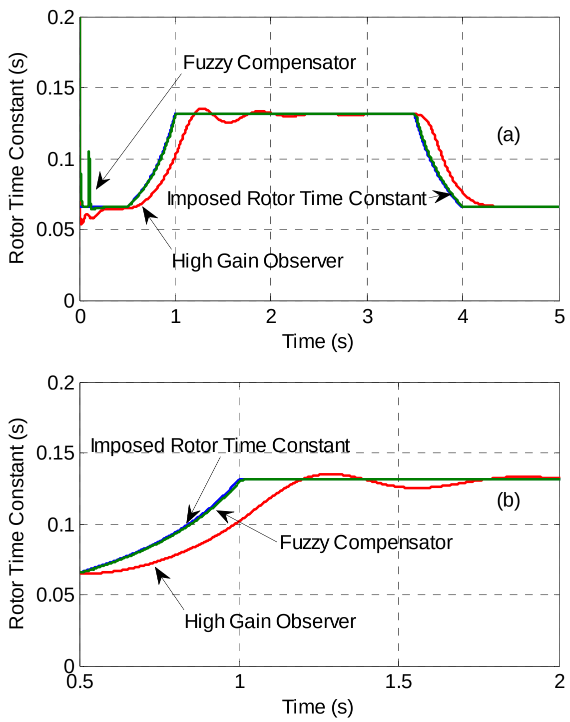


Fig. 18 Online Rotor time constant identification in the case of speed control using the High Gain Observer for θ_l=3 and Fuzzy Compensator (b) Zoom on the estimated rotor time constant

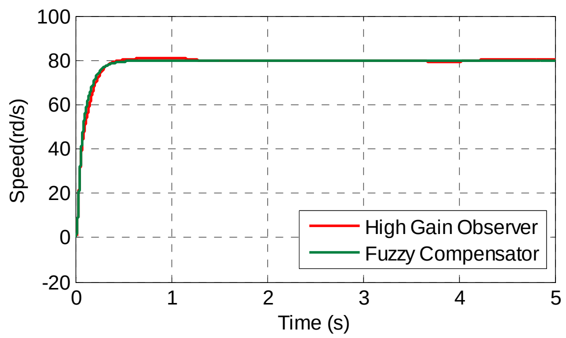


Fig. 19 Speed response with Online Rotor time constant identification

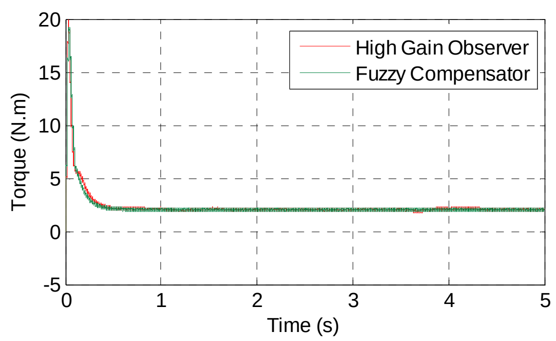


Fig. 20 Electromagnetic torque response with Online Rotor time constant identification

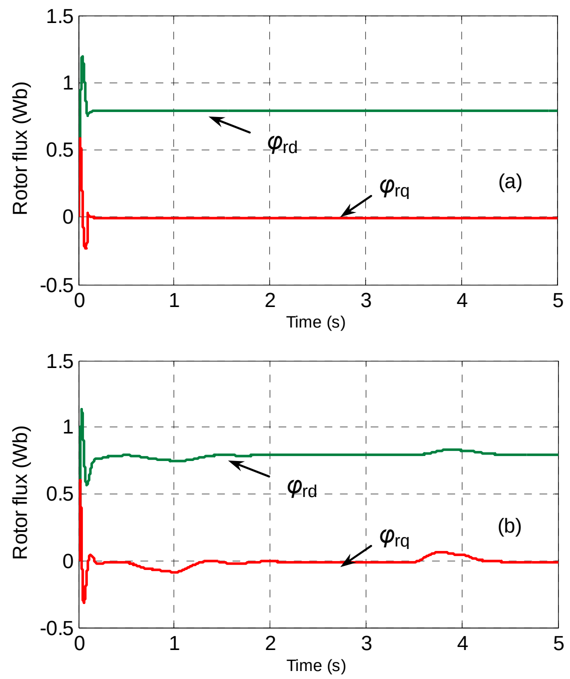


Fig. 21 Rotor flux components with Online Rotor time constant identification in Closed loop control (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_l=3

Figures above show the results in the case where the rotor time constant variation has a practical ramp change profile. As depicted in Fig. 18, the estimated rotor time constant using the Fuzzy Compensator is stabilized very closely to the current value and the error between the imposed value and the estimated value of the rotor time constant can be considered as negligible in comparison with the High Gain Observer which allows a slow transient state. The IFOC drive with the Fuzzy Compensator has been stabilized when the disturbance is applied to the drive. This is illustrated much more in Fig 19 and 20. Also, as shown in Fig 21, the IFOC drive with the Fuzzy Compensator preserves the high performances of field oriented strategy.

5 The experimental Setup and Results

5.1 Experimental Setup

The proposed study has been implemented using a dSPACE 1104 board with TMS320F240 DSP. The dSPACE works on Matlab/Simulink® platform which is a common engineering software.

dSPACE boards are associated with Control Desk software, which makes the record of the results easy. Control Desk also helps by making the development of controllers effective and automates the experiments. With the dSPACE 1104, the user can design the drive in MATLAB/Simulink® and with the help of Real-Time Workshop (RTW) of MATLAB/Simulink® and Real Time Interface (RTI), he can convert them into real-time codes. This is illustrated in Fig 24.

The experimental setup shown in Fig. 22 consists of an induction motor delta coupled with the parameters as shown in Table 2. The induction motor is driven under load with the help of DC generator mechanically coupled to the motor and having the following characteristics: 1KW, 220V, 6.5A, 2520 rpm.

Power circuit for the drive consists of an industrial inverter SEMIKRON IGBT with opto-isolation and gate driver circuit SKHI20opA. The inverter switching frequency is 4.2 kHz, with a dead time period of 1 μs, and the sampling time vector control execution is 0.0001s.

LEM current sensors were used to measure the motor line currents then transformed to be a voltage ranging from 0 to ±10 volts which will be the inputs of the A/D bloc.

For the stator voltage, we use the stator voltages references which are available on the control algorithm to avoid the use of the real stator voltages for the voltage model flux. Fig. 22 shows the photograph of the experimental setup and Fig. 24 shows the experimental platform.

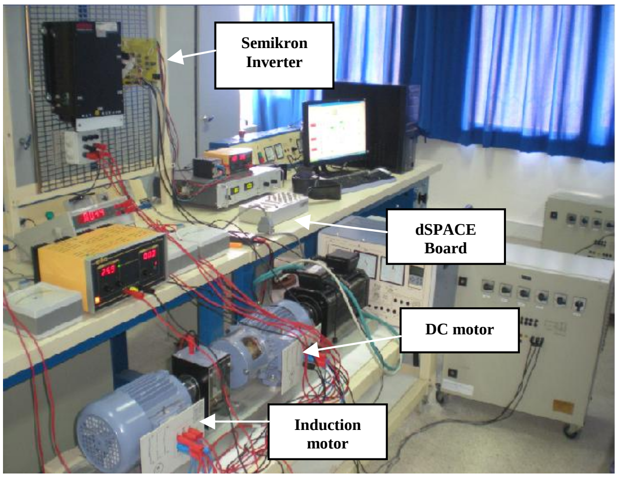


Fig. 22 Photograph of the experimental setup

The fuzzy compensation method has been implemented in real time, using an embedded function which allows a real time compilation of the fuzzy logic code developed in MATLAB-Code. The implementation of the fuzzy compensator using the embedded function is shown in Fig. 23.

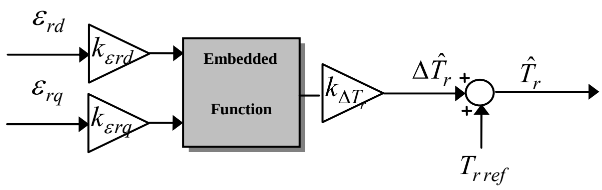


Fig. 23 Fuzzy Logic Implementation using Embedded Function

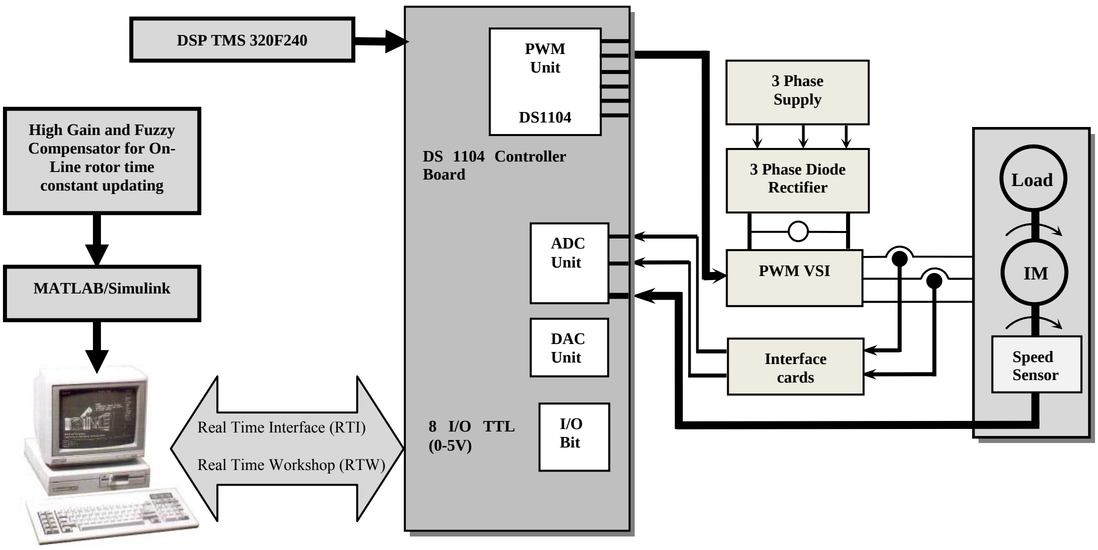


Fig. 24 Experimental Platform

5.2 Open Loop Control with Online rotor time constant identification

The tests achieved in the open loop control were performed with the electromagnetic torque as reference. The drive was under control of 2N.m reference step of the electromagnetic torque and 0.6Wb of the rotor flux. Both the High Gain Observer and Fuzzy Compensator will be used for online rotor time constant identification in the drive. Experimental investigations are presented in figures below.

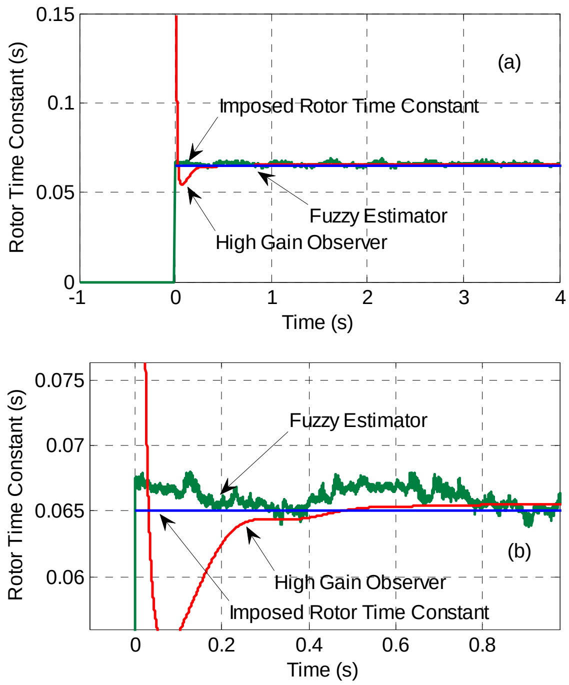


Fig. 25 Online Rotor time constant identification (a) using the High Gain Observer for θ_l=3 and Fuzzy Compensator, (b) Zoom on the estimated rotor time constant

As shown in Fig 25, 26 and 27, the high performance of the Fuzzy Compensator is illustrated with fast convergence to the exact value of the rotor time constant which is illustrated in Fig 25 in spite of some undulation. Also, High performance in the electromagnetic torque and rotor flux was obtained through the updating of the rotor time constant with less transient time as depicted in Fig 27.

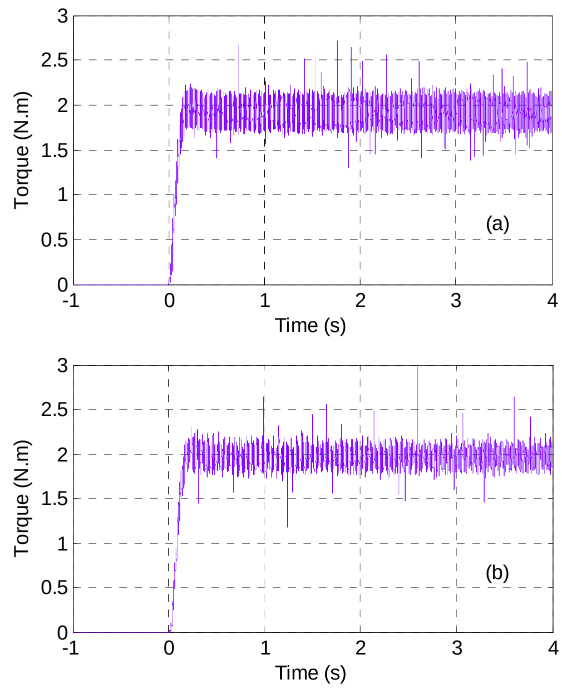


Fig. 26 Electromagnetic Torque response with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_l=3

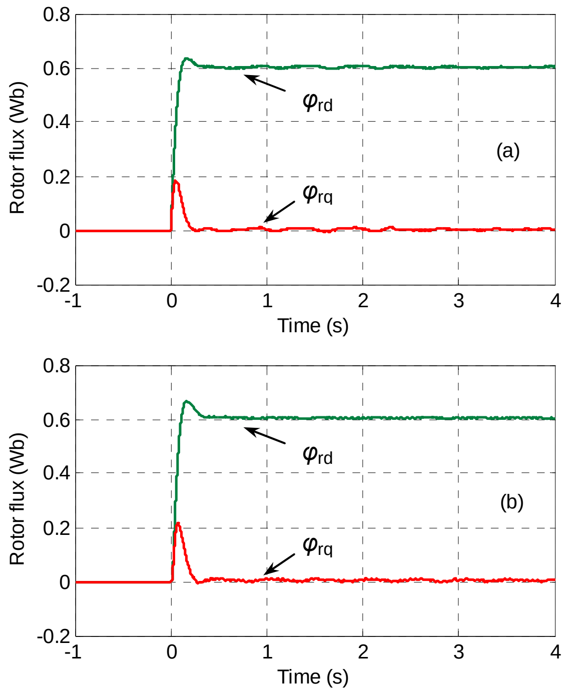


Fig. 27 Rotor flux components with Online Rotor time constant identification in open loop control (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_l=3

5.2 Closed Loop Control with Online rotor time constant identification

In order to evaluate the proposed study further, a closed loop speed control with a simple PI controller is applied to the drive which was subject to 80rd/s of reference step of the mechanical speed and 0.6Wb of the rotor flux. The results obtained in real time implementation are shown in figures below

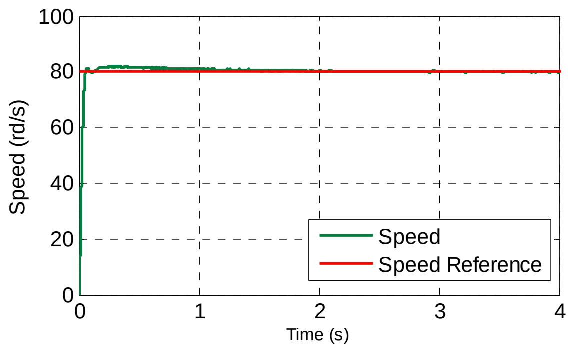


Fig. 28 Speed response with Online Rotor time constant identification

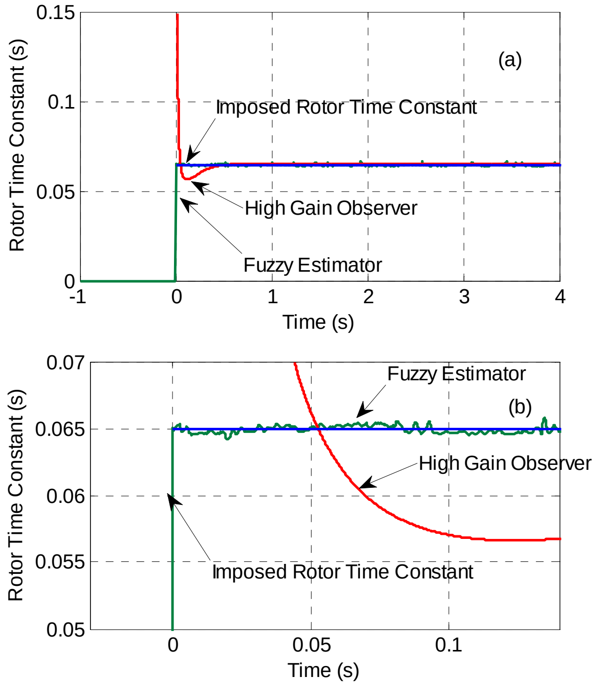


Fig. 29 Online Rotor time constant identification (a) using the High Gain Observer for θ_1=3 and Fuzzy Compensator, (b) Zoom on the estimated rotor time constant

Fig. 29, 30 and 31 illustrate the experimental results of Indirect Vector Control with online rotor time constant identification using the High Gain Observer and Fuzzy Compensator in the case of closed loop control. The results show high dynamics and a good tracking obtained with Fuzzy Compensator. The high gain observer also gives good tracking despite the overshoot obtained in the estimated rotor time constant during the transient state.

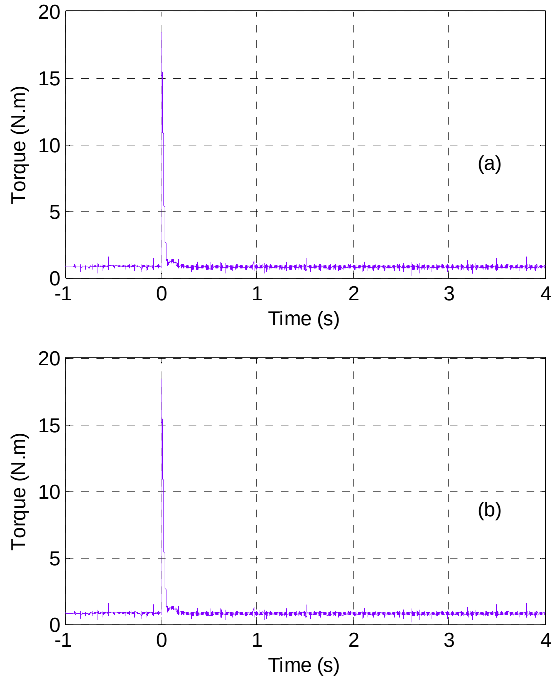


Fig. 30 Electromagnetic Torque response with Online Rotor time constant identification (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

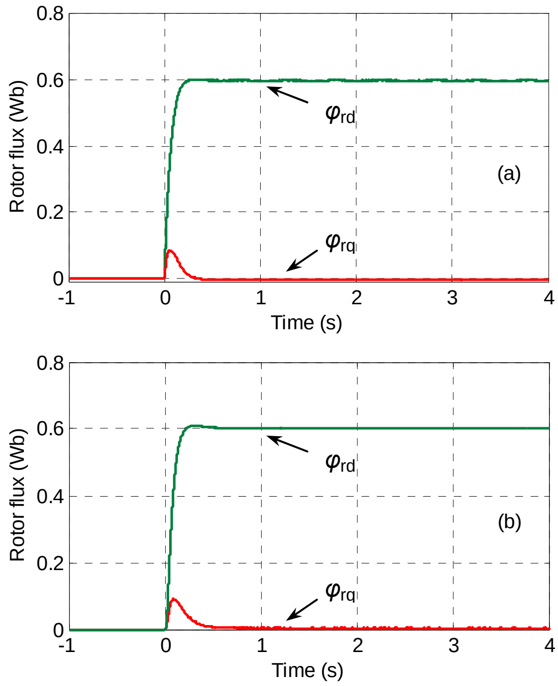
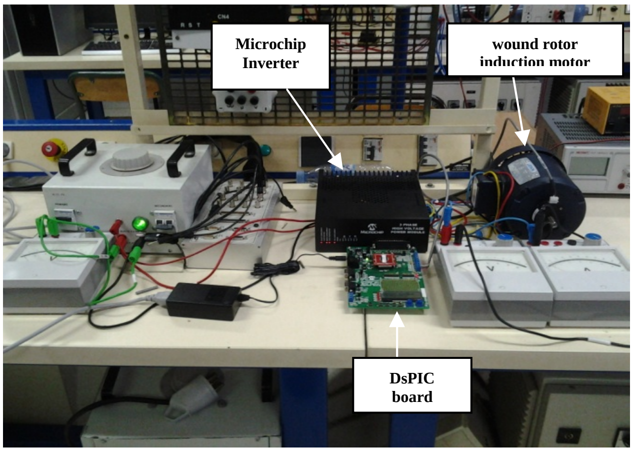


Fig. 31 Rotor flux components with Online Rotor time constant identification in open loop control (a) using Fuzzy Compensator (b) using the High Gain Observer for θ_1=3

6 Current and future developments

For the future researches, a second hardware platform has been developed for comparative studies with the dSPACE board, and to have opportunity to extend the proposed research. The new hardware platform is currently being developed for the implementation of the proposed studies as shown in Fig. 32. A dsPIC system with DSP (dsPIC30F4011) used with microchip inverter (Microchip dsPICDEM MC1H 3-Phase High Voltage Power Module), the switching frequency of this inverter can reach 20 kHz. This experimental setup is developed for a wound rotor induction motor with power of 0,55kW.



7 Conclusion

This paper describes online rotor time constant identification in Indirect Vector Control of Induction Motor using two approaches, the High Gain Observer and the Fuzzy Compensator. The first part of this study has been proved through simulation results that confirm a good improvement made with the online identification and the high superiority of the Fuzzy Compensator under several tests of rotor time constant variation and different operating conditions. The real time implementation has been also discussed through experimental results obtained using dSPACE board using the two approaches. From the experimental results, the improvement in the drive performance obtained with the Fuzzy Compensator is more appreciated. In transient state or steady state conditions, when the fuzzy updating scheme is connected, it provides excellent tracking performance.

Acknowledgements

This work was supported by The National School of Applied Sciences (ENSA Marrakesh – Morocco), Faculty of Sciences and Technologies (FST Marrakesh – Morocco) and Cadi Ayyad University Marrakesh – Morocco.

References:

[1] Leonhard. W, *Control of electrical drives* Berlin, Germany: Springer-Verlag, 1990.

[2] Bose B.K, *Power electronics and Ac drives* New-Jersey, USA, Prentice Hall, Englewood Cliffs, 1986; 122-152.

[3] Guillemin. P, Fuzzy logic applied to motor control, *IEEE Transactions on Industry Applications*, vol 32, Jan/Feb 1996, pp .51-56.

[4] Cheng F.F, Yeh. SN, Application of fuzzy logic in the speed control of AC servo system and an intelligent inverter, *IEEE Transactions on Energy Conversion*, vol 8 n.2, June 1993, pp. 312-318.

[5] de Santana. E.S, Bim. E, do Amaral. W.C, A Predictive Algorithm for Controlling Speed and Rotor Flux of Induction Motor, *IEEE Transactions on Industrial Electronics*, vol 55 n.12 Decembre 2008, pp. 4398 – 4407.

[6] F. Blaschke, *The Principles of Field Orientation as applied to the New Transvector Closed Loop control System for Rotating Field Machines*, Siemens Review, vol.34, May 1972, pp. 217-220.

[7] Wang Z.S, Ho S.L, Indirect Rotor Field Orientation Vector Control for Induction Motor Drives in the Absence of Current Sensors, *The 5th International Power Electronics and Motion Control Conference ~ IPEMC 2006* ~, August 14-16, 2006, Shanghai, China.

[8] Mohamed Boussak, Kamel Jarray, A High-Performance Sensorless Indirect Stator Flux Orientation Control of Induction Motor Drive, *IEEE Transactions on Industrial Electronics*, vol. 53 n. 1, February 2006, pp. 41 – 49.

[9] Profumo. F, DeDoncker. R, Ferraris. P, Pastorelli. M, Comparison of universal field oriented (UFO) controllers in different reference frames, *IEEE Transactions on Power Electronics*, vol.10 n.2, March 1995, pp. 205–213.

[10] Z. Boulghasoul, A. Elbacha, E. Elwarraki, D. Yousfi, Robustness of fuzzy controller based adaptation mechanism for MRAS sensorless IM drives, *The 19 IEEE International Conference on Electrical Machines ~ ICEM 2010* ~, September 6-8, 2011, Rome, Italy.

[11] R. D. Lorenz, Tuning of field oriented induction motor controllers for high-performance applications, *IEEE Trans. Ind. Applicat*, vol. IA-22, pp. 293–297, Mar. /Apr. 1986.

[12] Baburaj Karanayil, Muhammed Fazlur Rahman, Colin Grantham, Stator and rotor resistance observers for induction motor drive using fuzzy logic and artificial neural networks, *IEEE Transactions on Energy Conversion*, vol. 20 n. 4, December 2005, pp. 771 – 780.

[13] Baburaj Karanayil, Muhammed Fazlur Rahman, Colin Grantham, Online Stator and Rotor Resistance Estimation Scheme Using Artificial Neural Networks for Vector Controlled Speed Sensorless Induction Motor Drive, *IEEE Transactions on Industrial Electronics*, vol. 54 n. 1, February 2007, pp. 167 – 176.

[14] T. Boumegoura, Recherche de signature électromagnétiques des défauts dans une machine asynchrone et synthèse d'observateurs en vue du diagnostic. *Ph.D. dissertation, L'Ecole Centrale de Lyon*, pp. 92-102,Lyon 2001.

[15] BOUMEGOURA Tarek, CLERC Guy, YAHOUI Hamed, GRELLET Guy, SALLES Gaël , Rotor resistance estimation by non-linear observer for diagnostic and control systems, *Journal european des systèmes automatisés*, 2000, vol. 34, no8, pp. 1011-1024.

[16] Abbou. A, Mahmoudi. H, Elbacha. A, High-Gain Observer Compensator for Rotor Resistance Variation On Induction Motor RFOC, *14th IEEE International Conference on Electronics, Circuits and Systems, 2007. ICECS 2007*, 11-14 Dec, Marrakech, Morocco.

[17] G.Bornard, H.Hamrnouri, A high gain observer for a class of uniformily obserable Systems, *IEEE, Brignton*, Great Britain, 1991

[18] BENAICHA Samira, CONTRIBUTION A LA COMMANDE TOLERANTE AUX DEFAUTS D'UN SYSTEME A MOTORISATION ASYNCHRONE : "Apport de l'Intelligence Artificielle pour l'aide à la Supervision et à la Décision ", *Ph.D. dissertation,* University of Batna, 2010Algeria.

[19] F. Zidani, M. Nait-Said, M. Benbouzid, D. Diallo, and R. Abdessemed, A Fuzzy Rotor Resistance Updating Scheme for an IFOC Induction Motor Drive, *IEEE Power Engineering Review*, vol. 21, no. 11, pp. 47-50, November 2001.

[20] E. Bim, Fuzzy optimization for rotor constant identification of an indirect FOC induction motor drive*, IEEE Transactions on Industrial Electronics*, vol. 48, no. 6, pp. 1293-1295, December 2001.

[21] M. Ta-Cao and H. Le-Huy, Rotor resistance estimation using fuzzy logic for high performance induction motor drives, *in Proc. The 24th Annual Conference of the IEEE Industrial Electronics Society*, 1998, pp. 303 - 308.

[22] B. Karanayil, M. F. Rahman, and C. Grantham, PI and fuzzy estimators for on-line tracking of rotor resistance of indirect vector controlled induction motor drive, *in Proc. IEEE International Electric Machines and Drives Conference*, 2001, pp. 820-825.

[23] Jean-Pierre CARON, Jean Paul HAUTIER, *Modélisation et commande de la machine asynchrone*, Editions Technip -Paris 1995.

[24] I. I. Siller-Alcalá, M. Abderrahim, J. Jaimes-Ponce, and R. Alcántara-Ramírez, Speed-Sensorless Nonlinear Predictive Control of a Squirrel Cage Motor, *WSEAS TRANSACTIONS on SYSTEMS and CONTROL*, Issue 2, Volume 3, February 2008.

[25] Andrzej M. Trzynadlowski, *The Field Orientation Principle in Control of Induction Motors* , Kluwer Academic Publishers, U.S.A.

[26] Aimin Yang, Junping Wu, Wenxiang Zhang, Xianhong Kan, Research on asynchronous motor vector control system based on rotor parameters time-varying, *WSEAS TRANSACTIONS on SYSTEMS and CONTROL,* Issue 4, Volume 7, April 2008

[27] L. A. Zadeh, *Fuzzy Sets*, Information and Control, vol. 8, 1965, pp.338-353.

[28] CONSTANTIN VOLOSENCU, Control of Electrical Drives Based on Fuzzy Logic, *WSEAS TRANSACTIONS on SYSTEMS and CONTROL*, Issue 9, Volume 3, September 2008

[29] Y. Sayouti, A. Abbou. M. Akherraz H. Mahmoudi, MRAS-ANN Based Sensorless Speed Control For Direct Torque Controlled Induction Motor Drive, *International Conference on Power Engineering, Energy and Electrical Drives ~ POWERENG* 2009 ~, March 18-20, 2009, Lisbon, Portugal.