# Comparative Study between Different Speed Controller Techniques Applied to the Indirect Field-Oriented Control of an Induction Machine-Performances and Limits

CHAYMAE LAOUFI, AHMED ABBOU and MOHAMMED AKHERRAZ
Electric Engineering Department,
The Mohammadia School's of Engineers
Mohammed V University Agdal
Avenue Ibn Sina, B.P 765, Agdal, Rabat
MOROCCO
laoufi.chaymae@gmail.com
abbou@emi.ac.ma
akherraz@emi.ac.ma
http://www.emi.ac.ma

*Abstract:* - This paper presents a comparative study between various control strategies. The design of different controllers, the sliding mode controller, the self tuning fuzzy logic controller, the fuzzy logic controller and the classical PI controller are proposed. The simulations results showed the performances and limits of the different cited controllers. In fact, the sliding mode controller is characterized by a high resistance to the perturbations of the machine parameters and the self tuning fuzzy logic controller is advantageous in terms of response time. Whiles fuzzy logic controller presents the better performances compared to the classical PI controller.

*Keywords:* - Indirect Field-Oriented Control; Sliding Mode Controller; Fuzzy Logic Controller; PI Controller; Self Tuning Fuzzy Logic Controller.

## Nomenclature

$i_{s\alpha}$, $i_{s\beta}$ : stator currents; α- and β- axis components
$V_{s\alpha}$,$V_{s\beta}$ : stator voltages; α- and β- axis components
$\Phi_{rd}$, $\Phi_{rq}$ : rotor flux; d- and q- axis components
$\Phi_r$ : rotor flux magnitude
$L_s$, $L_r$, M : stator, rotor and mutual inductances
$R_s$, $R_r$ : stator, rotor resistance
$C_{em}$ : electromagnetic torque
$T_s$, $T_r$ : stator, rotor time constant
$\theta_s$ : synchronous reference frame position
$\omega_s$ : angular speed
$\omega_r$ : mechanical rotor speed
$\sigma$ : total leakage factor
p : number of pole pairs
J : total inertia moment
f : total viscous friction coefficient

## 1 Introduction

The industrial applications of indirect field-oriented control drives have greatly increased.

However, the dynamic characteristics of this control drive are complex, nonlinear and coupled.

Also, it is sensitive to the disturbance of the induction machine parameters.

In the order to limit these drawbacks, several intelligent controllers such as sliding mode controller (SMC), self tuning fuzzy logic controller (PIST) and fuzzy logic controller (FLC) have received much attention in recent years to controlling this drive.

In fact, the sliding mode is an effective control strategy for nonlinear systems with uncertainties [1]. Its principle is based on the definition of a surface called sliding surface depending on system states so that it is attractive. The synthesized global control consists of two terms: the first allows the stat trajectory to approach this surface and the second maintaining and sliding along it towards the origin of the phase plane [2]. It is characterized by good robustness, fast response time and disturbance rejection. However, one of the drawbacks of this controller is the chattering phenomenon caused by the discontinue control action.

The fuzzy logic controller presents the high performances of speed tracking. However, this controller is insufficient to deal with systems subjected to server perturbation because its gains are fixed [3]-[6]. So, to improve the limited performances of the fuzzy logic controller, in case of the disturbance parameters, the self tuning fuzzy logic controller have been developed [7]-[9].

This paper presents a comparative study between different strategies of speed controllers. The design of the sliding mode and the self tuning fuzzy logic controllers are proposed. The comparison of the different controllers is established in case of two methods. In first method, the different controllers are applied to adapt the error between the actual rotor speed and the reference speed. The second method consists to force the systems to follow a reference model by comparing the rotor speed with the output of this reference model [10]-[11].

The simulation results show the performances and limits of the proposed controllers. The self tuning fuzzy logic controller is advantageous in term of response time while the sliding mode controller and fuzzy logic controller present a high capacity to reject the disturbance [11].

## 2 Model of induction machine

Modeling of the induction machine is based on a number of assumptions:

- perfect symmetry ;
- Assimilation to a rotating machine with three-phases in the stator and three-phases in the rotor;
- Sinusoidal distribution of the magnetic field along the air gap;
- Negligible saturation and losses in the magnetic circuit;
- Negligence of the influence of the skin effect and overheating of conductors.

The induction machine is controlled by current through an inverter whose the switching logic is provided by three hysteresis controllers.

In the case of the reference (α,β), equations of the machine are given in general as shown below [12]:

$$\frac{di_{s\alpha}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r}\right) i_{s\alpha} + w_s i_{s\beta}\ \frac{(1-\sigma)}{\sigma M T_r}\phi_{r\alpha} + \frac{(1-\sigma)}{\sigma M} w\phi_{r\beta} + \frac{1}{\sigma L_s} V_{s\alpha} \quad (1)$$

$$\frac{di_{s\beta}}{dt} = -w_s i_{s\alpha} + \left(\frac{1}{\sigma T_s} + \frac{(1-\sigma)}{\sigma T_r}\right) i_{s\beta} - \frac{(1-\sigma)}{\sigma M} w\phi_{r\alpha} + \frac{(1-\sigma)}{\sigma M T_r} w\, \phi_{r\beta} + \frac{1}{\sigma L_s} V_{s\beta} \quad (2)$$

$$\frac{d\phi_{r\alpha}}{dt} = \frac{M}{T_r} i_{s\alpha} - \frac{1}{T_r}\phi_{r\alpha} + (w_s - w)\phi_{r\beta} \quad (3)$$

$$\frac{d\phi_{r\beta}}{dt} = \frac{M}{T_r} i_{s\beta} - (w_s - w)\phi_{r\alpha} - \frac{1}{T_r}\phi_{r\beta} \quad (4)$$

$$C_{em} = \frac{pM}{L_r}\left(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}\right) \quad (5)$$

## 3 Indirect rotor field-oriented control

Indirect rotor field-oriented control was developed for the purpose of decoupling the torque and the flux. This decoupling allows for a very fast response of torque. The principle of field-oriented control is to represent the dynamic model of the induction machine in the rotating reference with the rotor flux (Figure 1).

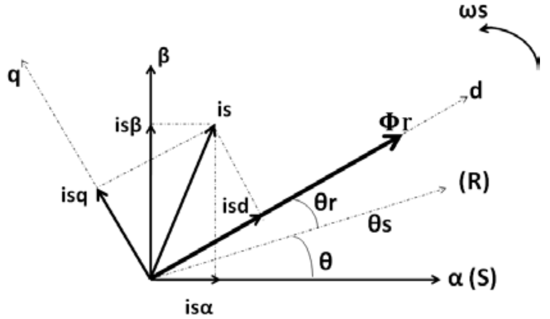


Fig. 1. Illustration of the rotor flux orientation

The alignment of the rotor flux $\Phi_r$ on the d-axis of the rotating reference implies the following:

$$\Phi_{rd} = \Phi_r \text{ and } \Phi_{rq} = 0 \quad (6)$$

This command consists to enforce the current of the induction machine to follow the reference currents $i_{sd\_ref}$ and $i_{sq\_ref}$ which are perfectly decoupled.

In the present work, the indirect rotor field-oriented command controlled by current (IRFOCC) is used. This technique is characterized by the absence of the rotor flux loop. So this flux is not measured and not estimated. Therefore, sensors and observers are not required [12].

### 3.1 Structure of the indirect rotor field oriented-control

In the case of this command, the rotor flux $\Phi_r$ is aligned with the d-axis of the rotating reference. This implies:

$$\Phi_{rd} = \Phi_r \ \text{ and } \ \Phi_{rq} = 0 \tag{7}$$

The equations of the induction machine with rotor flux oriented are given by the following:

If $\Phi_r$ is constant:

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

$$C_{em} = p \frac{M}{L_r} \Phi_r i_{sq} \tag{9}$$

The magnitude of the rotor flux $\Phi_r$ is determined only by the direct component of the stator current $i_{sd}$. And the electromagnetic torque $C_{em}$ is determined by the quadrature component of the stator current $i_{sq}$.

Since the flux is set at its reference value and maintained constant, the electromagnetic torque expression is given as follow:

$$C_{em} = K\phi_r \, i_{sq} \tag{10}$$

This equation is similar to the one of DC motor, where the torque depends only on the quadrature component of the stator current $i_{sq}$, if the flux $\Phi_r$ is kept constant.

So, finally we can see that the problem of coupling is removed between the two axes direct (d) and quadrature (q).

The structure of the speed drive (IRFOCC) comprises a conventional regulator of speed PI is shown by Figure 1:

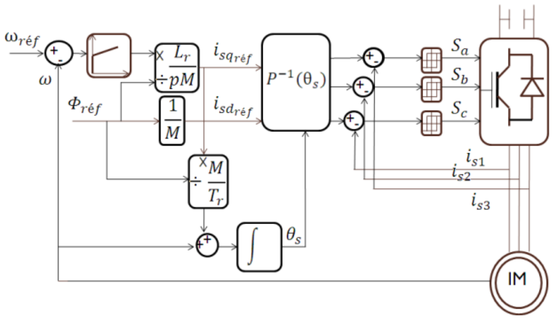


Fig. 2. Structure of the speed drive (IRFOCC)

In fact, the gains of the PI controller depend on machine parameters (rotor resistance $R_r$, inertia J) and external parameters (load torque $C_r$). Therefore any disturbance of these parameters directly influences these gains. The gains of the PI controller are given by the following equations:

$$K_\Omega = \frac{R_r}{4\sigma L_r} \tag{11}$$

$$\tau_\Omega = \frac{J}{f} \tag{12}$$

In fact, the machine parameters are variable and depend on the experimental conditions.

## 4 Sliding Mode Controller

The principle of this controller consists to control the system by forcing speed error ($e_\omega$) and its derivative ($\frac{de_\omega}{dt}$) to move towards a sliding surface. The sliding surface is a scalar function defined by the following equation:

$$S(e_\omega, \frac{de_\omega}{dt}, t) = 0 \tag{13}$$

Where the sliding variable is:

$$S(t) = \frac{de_\omega(t)}{dt} + \lambda e_\omega(t) \tag{14}$$

With λ is positive constant.

The object of the control is to maintain the surface to zero. This last equation is a linear differential equation whose unique solution is $e_\omega(t) = 0$.

In case of the speed controller design, the surface speed regulation is given by:

$$S(\omega) = \omega - \omega ref \tag{15}$$

$$\frac{dS(\omega)}{dt} = \frac{d\omega}{dt} - \frac{d\omega_{ref}}{dt} \tag{16}$$

By replacing the speed expression, we obtain:

$$\frac{dS(\omega)}{dt} = \frac{d\omega}{dt} - \frac{d}{dt}\left(\frac{Mp}{JL_r}\Phi_r i_{sq} - \frac{f}{J}\omega_{ref} - \frac{1}{J}C_r\right) \tag{17}$$

Now, we replace the current $i_{sq}$ by the control current $i_{sq\text{-}ref}$ . Such the structure of the sliding mode controller is constituted by two parts, one concerning the exact linearization ($i_{sqeq}$) and the other is stabilizing ($i_{sqn}$).So by replacing the current $i_{sq} = i_{sqeq} + i_{sqn}$, the equation (17) becomes:

$$\frac{dS(\omega)}{dt} = \frac{d\omega}{dt} - \frac{d}{dt}\left(\frac{Mp}{JL_r}\Phi_r i_{sqeq} + \frac{Mp}{JL_r}\Phi_r i_{sqn} - \frac{f}{J}\omega_{ref} - \frac{1}{J}C_r\right) \tag{18}$$

During the sliding mode and steady state, we have S(ω) = 0 and thereafter :

$$\begin{cases} \frac{dS(\omega)}{dt} = 0 \\ i_{sqn} = 0 \end{cases} \tag{19}$$

From where, we derive the formula of the equivalent command $i_{sqeq}$ :

$$i_{sqeq} = \frac{JL_r}{p\,M\Phi_r}\left(\frac{f}{J}\omega_{ref} + \frac{1}{J}C_r\right) \tag{20}$$

During the convergence mode, the following condition must be verified:

$$S(\omega).\frac{dS(\omega)}{dt} = 0 \tag{21}$$

By replacing the expression of the $i_{sqeq}$ in the equation (18), we obtain:

$$S(\omega) = -\frac{M\,p}{J\,L_r}\Phi_{r-ref}\,i_{sqn} \tag{22}$$

By choosing the form of the discontinuous command, so we pose:

$$i_{sqn} = K_\omega \mathrm{Sign}(S(\omega)) \tag{23}$$

So, the speed sliding mode controller is determined. The block diagram of this controller is showed in the Figure 3:

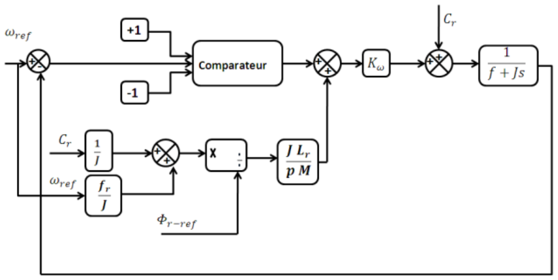


Fig. 3. Sliding mode controller for induction machine

## 5 Self Tuning Fuzzy Logic Controller

The block diagrams of the proposed methods are shown in the Figure 4 and Figure 6. The principle of the first method is to control the gains of a conventional PI in real time with the help of fuzzy logic and adjustment of these gains when a change is detected. In fact, the rotor speed is compared with the reference speed to generate the error $e_\omega$, this error and its derivative $\frac{de_\omega}{dt}$ are injected in the adaptation mechanism compound by a fuzzy logic adapter to generate the adaptation factors $\Delta K_p$ and $\Delta K_i$. These are also injected in the PI controller to correct the gains Kp and Ki.

The new parameters of the PI controller are obtained by:

$$Kp_f = Kp_i + \Delta Kp \tag{24}$$

$$Ki_f = Ki_i + \Delta Ki \tag{25}$$

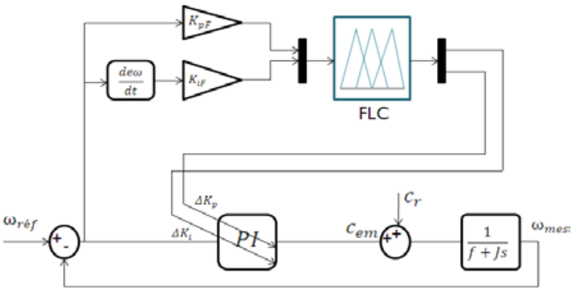


Fig. 4. Self-tuning fuzzy logic controller for induction machine

The principle of the second method is to force the system to follow a reference model. When a perturbation affects the parameters of the machine (rotor resistance, inertia) and external parameters (load torque) the adaptation mechanism corrects the gains of the PI controller to prevent the system to deviate from this reference model. In fact, the system composed by: the command IRFOCC, the inverter and the induction machine is equivalent to a low pass filter of the first order characterized by the following transfer function (Figure 5):

$$H_{BF} = \frac{1}{1+t_{r_{BF}}\,s} \tag{26}$$

Where:
s : The operator of Laplace.
$t_{rBF}$ : The closed loop response time determined by the response time of the response of the open-loop speed.

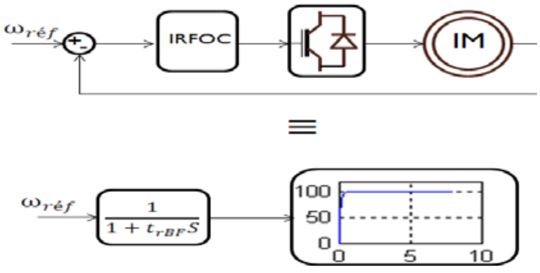


Fig. 5. Equivalence between the closed loop system and the low pass filter

The Figure 6 illustrates the principle of adaptation gains of the PI controller using the reference model. It is similar to the first method with the difference in the input of the adaptation mechanism. So the rotor speed is compared with the reference speed corresponding to the output of the reference model to generate the error $e_\omega$.

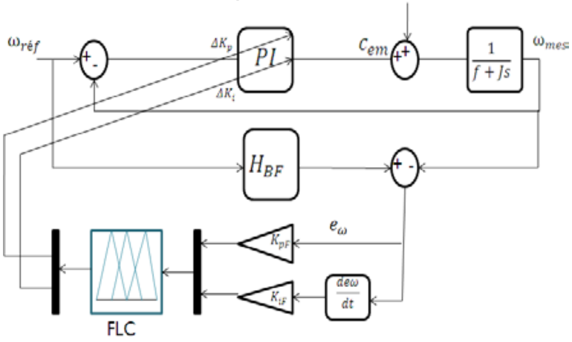


Fig. 6. Adaptation gains of the PI controller using the reference model

## 5.1 Description of the Fuzzy Logic Controller

The inputs of the fuzzy logic controller are the speed error ($e_\omega$) and its derivative ($\frac{de_\omega}{dt}$). The fuzzy logic controller observes the error and updates the outputs ($K_p$,$K_i$).

The fuzzy subsets of input variables are defined as follows:

- GN : Big negative
- MN : Average negative
- PN : Small negative
- Z : Zero
- PP : Small positive
- MP : average positive
- GP : Big positive

The fuzzy subsets of the output variables are defined as follows:

- G : Big
- P : Small

The membership functions for inputs and outputs are defined in the interval [-1 1] as follows [8]:

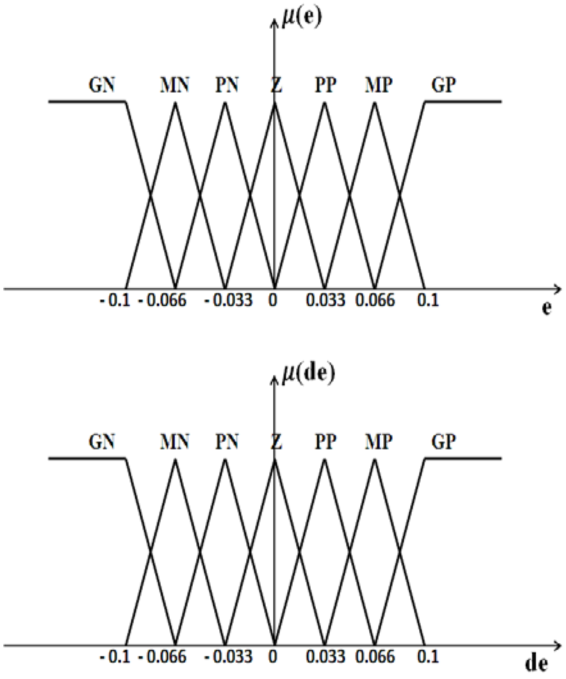


Fig. 7. Membership function for input variable

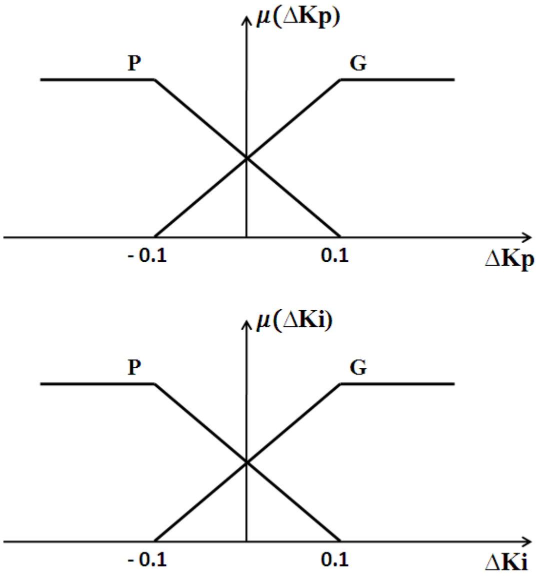


Fig. 8. Membership function for output variable

The bases rules used to calculate the output variables ΔKp and ΔKi are shown in the following tables 1 and 2.

Indeed, the fuzzy logic controllers used in this work is Mamdani type and the method of the defuzzification used is centroid method.

Table 1
Matrix inference to calculate ΔKp

|  | **GN** | **MN** | **PN** | **Z** | **PP** | **MP** | **GP** |
|---|---|---|---|---|---|---|---|
| **GN** | G | G | G | G | G | G | G |
| **MN** | P | G | G | G | G | G | G |
| **PN** | P | P | G | G | G | P | P |
| **Z** | P | P | P | G | P | P | P |
| **PP** | P | P | G | G | G | P | P |
| **MP** | P | G | G | G | G | G | P |
| **GP** | G | G | G | G | G | G | P |

Table 2
Matrix inference to calculate ΔKI

|  | GN | MN | PN | Z | PP | MP | GP |
|---|---|---|---|---|---|---|---|
| GN | G | G | G | G | G | G | G |
| MN | G | G | P | P | P | G | G |
| PN | G | G | G | P | G | G | G |
| Z | G | G | G | P | G | G | G |
| PP | G | G | G | P | G | G | G |
| MP | G | G | P | P | P | G | G |
| GP | G | G | G | G | G | G | P |

# 6 Results of Simulation and Interpretation

In order to define the performances and limits of the proposed controllers: the sliding mode controller (SMC), the self tuning fuzzy logic controller (PIST), the fuzzy logic controller (FLC) and the classical PI controller, some perturbations on some parameters of the induction machine (rotor resistance, inertia) and the external parameters (load torque, reference speed) have been generated. Two tests have been performed, the first test relates to the low speeds and the second test involves high speeds. The value of listed parameters has been increased by 100% at t = 2 s and the value of the reference speed has been changed respectively from 20 rad/s to 50 rad/s and from 50 rad/s to 100 rad/s at t = 3 s. We applied these test for the two methods.

## 6.1 First method simulations

The first test aims to evaluate the performances of the different controllers: sliding mode controller (SMC), self-tuning fuzzy logic controller (PIST), fuzzy logic controller and classical PI controller when the disturbance affects the rotor resistance. As shown in Figure 9 and Figure 10, the sliding mode controller and fuzzy logic controller reject perfectly the perturbations compared to a self tuning fuzzy logic controller which in turn presents a better capacity to reject the disturbances than a conventional PI controller. In fact, the effect of the perturbations observed for a conventional PI is reduced by more than the half for a self tuning fuzzy logic controller. In terms of the response time, the self tuning fuzzy logic controller is characterized by a very small response time at startup and during the change of the speed compared to the other controllers. Also, we note that the proposed controllers, especially sliding mode controller and self tuning fuzzy logic controller, present the best performances even at low speeds. More speed quantitative performances are summarized in tables 3 and 4.

Case of the low speeds:

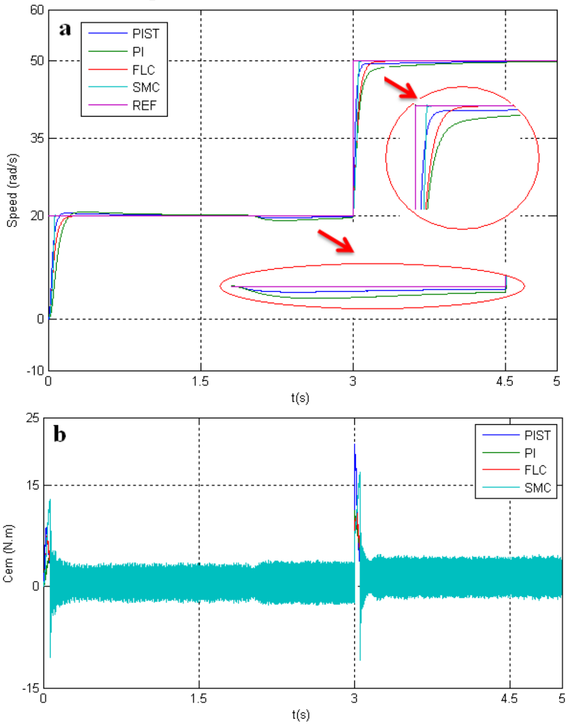
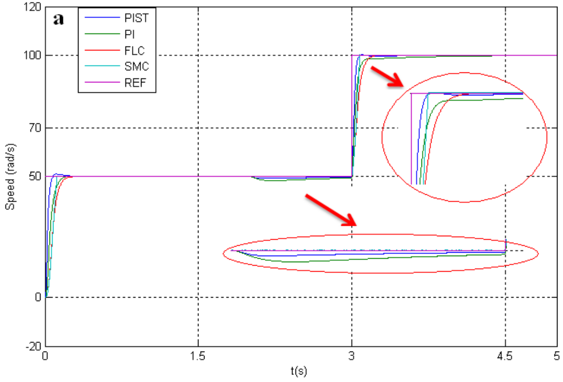


Fig. 9. High tracking responses of the speed (a), the electromagnetic torque (b) to change in rotor resistance (case of low speeds).

Case of the high speeds:



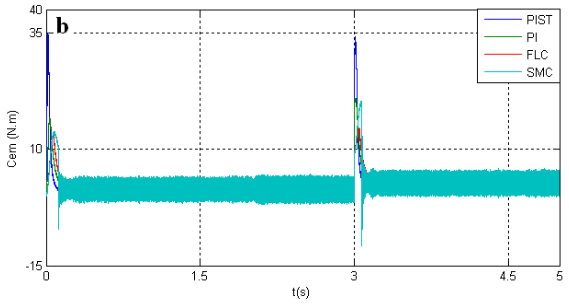


Fig. 10. High tracking responses of the speed (a), the electromagnetic torque (b) to change in rotor resistance (case of high speeds).

Table 3
Quantitative performances of speed tracking in case of disturbance of the rotor resistance (case of low speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 20 (rad/s) | 0.208 | 0.188 | 0.115 | 0.160 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 0 | 1 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.057 | 0.081 | 0.033 | 0.081 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 0 | 0 |

Table 4
Quantitative performances of speed tracking in case of disturbance of the rotor resistance (case of high speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.252 | 0.084 | 0.186 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 1.82 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.045 | 0.087 | 0.033 | 0.066 |
| Over shoot (%) In case of 100 (rad/s) | 0 | 0 | 0.3 | 0 |

The second test consists to appraise the robustness of the proposed controllers towards the variations of the load torque. As shown in Figure 11 and Figure 12, a variation in the load torque and an acceleration of the speed are respectively applied at t = 2 s and t = 3 s. The results simulations show that the dynamic tracking of speed and the electromagnetic torque are better when using SMC and PIST controller and the conventional PI rejects less rapidly the perturbation. More speed quantitative performances are summarized in tables 5 and 6.

Case of the low speeds:

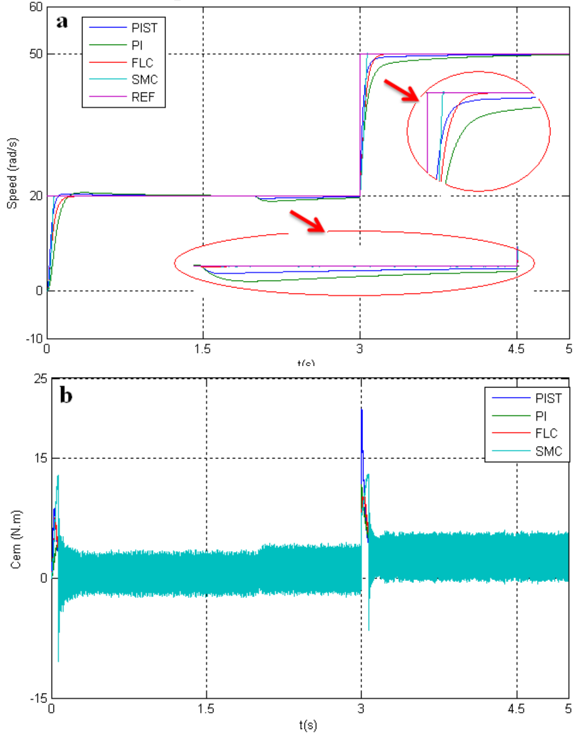
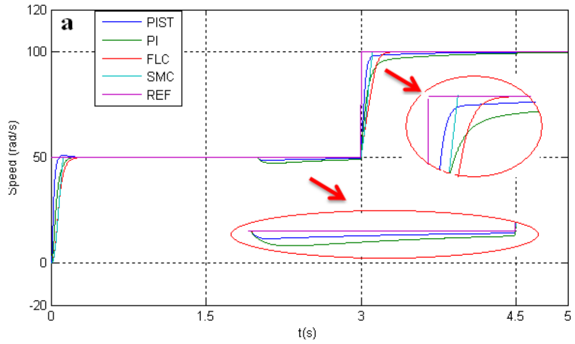


Fig. 11. High tracking responses of the speed (a), the electromagnetic torque (b) to change in load torque (case of low speeds).

Case of the high speeds:



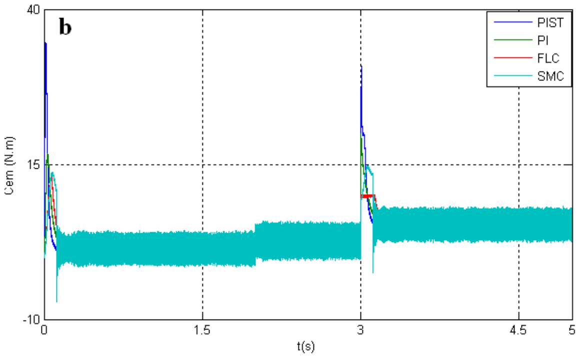


Fig. 12. High tracking responses of the speed (a), the electromagnetic torque (b) to change in load torque (case of high speeds).

Table 5
Quantitative performances of speed tracking in case of disturbance of the load torque (case of low speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 20 (rad/s) | 0.207 | 0.186 | 0.114 | 0.159 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 0 | 1 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.066 | 0.084 | 0.039 | 0.09 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 0 | 0 |

Table 6
Quantitative performances of speed tracking in case of disturbance of the load torque (case of high speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.252 | 0.084 | 0.186 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 0 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.057 | 0.105 | 0.039 | 0.084 |
| Over shoot (%) In case of 100 (rad/s) | 0 | 0 | 0 | 0 |

The aim of a third test is to compare the performances of the three controllers; SMC, PIST and FLC; in the case where a disturbance affects the inertia of the machine. As the previous cases, the PIST has the best performance in terms of response time with a small overshoot when changing the speed at second t=3 s. Also, it can be seen that the change of the operating point affects less a dynamic tracking of speed and the electromagnetic torque for a sliding mode controller compared to the other controllers.

Case of the low speeds:

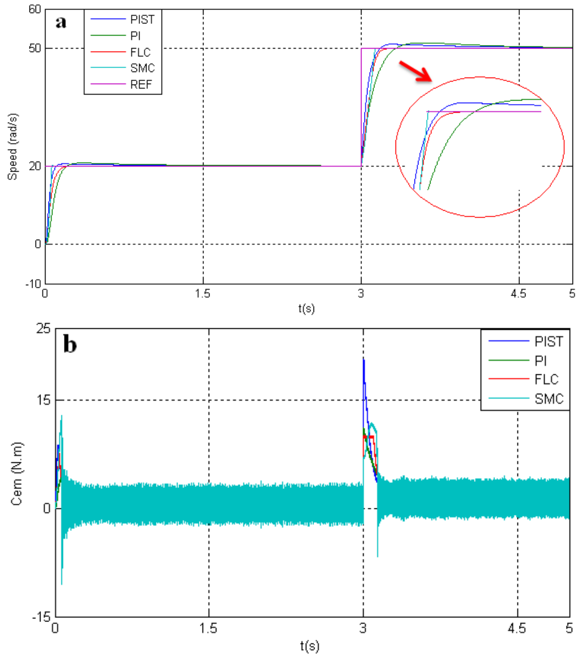
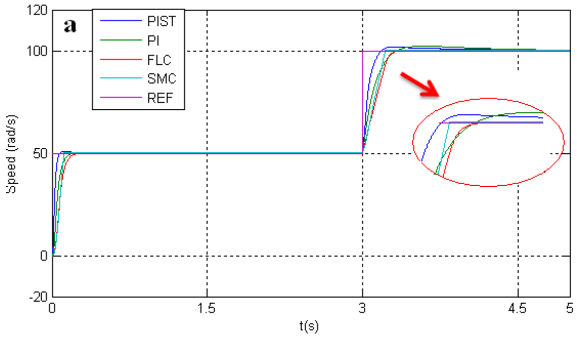


Fig. 13. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in inertia (case of low speeds).

Case of the high speeds:



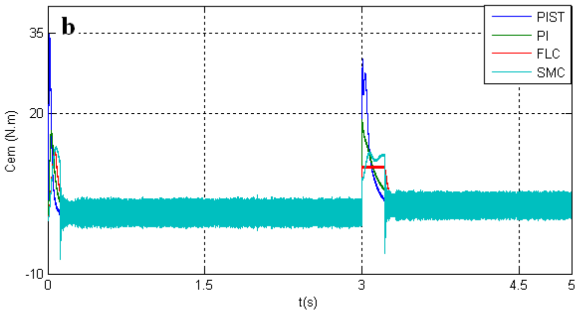


Fig. 14. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in inertia (case of high speeds).

Table 7
Quantitative performances of speed in case of disturbance of the inertia (case of low speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 20 (rad/s) | 0.207 | 0.186 | 0.114 | 0.159 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 0 | 1 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.12 | 0.153 | 0.075 | 0.171 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 1 | 0 |

Table 8
Quantitative performances of speed tracking in case of disturbance of the inertia (case of high speeds)

| | Controllers | | | |
|---|---|---|---|---|
| | PI | FLC | PIST | SMC |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.252 | 0.084 | 0.186 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 1.82 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.114 | 0.198 | 0.072 | 0.147 |
| Over shoot (%) In case of 100 (rad/s) | 2.3 | 0 | 1.8 | 0 |

## 6.2 Second Method Simulations

This test aims to evaluate the capacity of the system to follow the reference model as detailed in paragraph 5. As shown in Figure 15, Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20, the response corresponding to the sliding mode controller and fuzzy logic controller is similar to the response of the reference model but the sliding mode controller presents the poor performances to low speeds illustrated by the appearance of the chattering phenomenon. So the system became insensible to the variations of the parameters with this method. Also, it is observed that the performance of the self-tuning fuzzy logic controller is the best compared to that of the conventional PI controller and characterized by the small response time compared to the other controllers. The speed quantitative performances are summarized in tables 9, 10, 11, 12, 13 and 14.

Case of the low speeds:

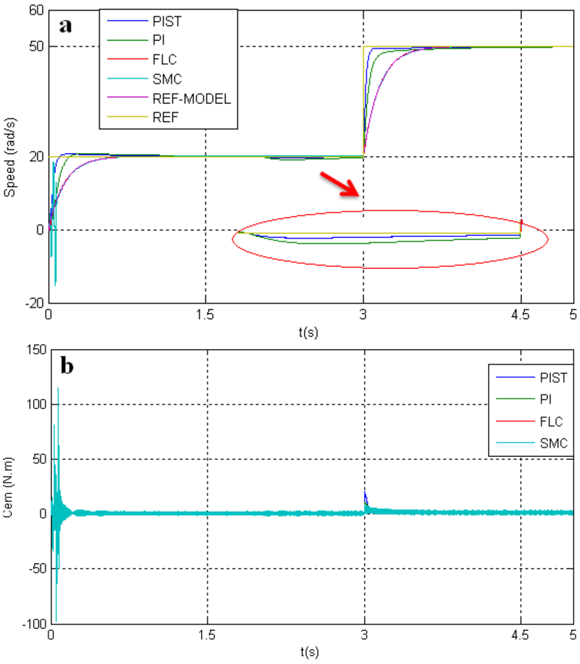


Fig. 15. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in rotor resistance (case of low speeds).

Case of the high speeds:

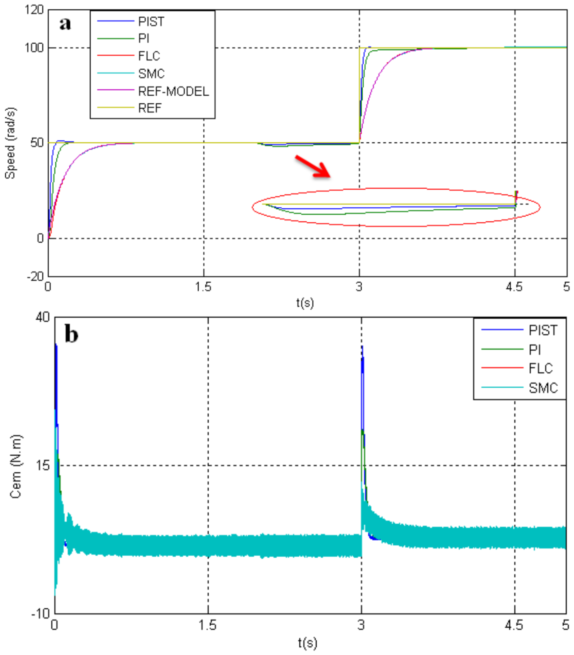


Fig. 16. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in rotor resistance (case of high speeds).

Table 9
Quantitative performances of speed in case of disturbance of the rotor resistance (case of low speeds)

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 20 (rad/s) | 0.297 | 0.144 | 0.453 | 0.459 | 0.459 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 2.15 | 0 | 0 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.042 | 0.087 | 0.225 | 0.225 | 0.225 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 0 | 0 | 0 |

Table 10
Quantitative performances of speed tracking in case of disturbance of the rotor resistance (case of high speeds)

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.084 | 0.465 | 0.465 | 0.459 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 1.96 | 0 | 0 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.045 | 0.03 | 0.141 | 0.138 | 0.138 |
| Over shoot (%) In case of 100 (rad/s) | 0 | 0 | 0 | 0 | 0 |

Case of the low speeds:

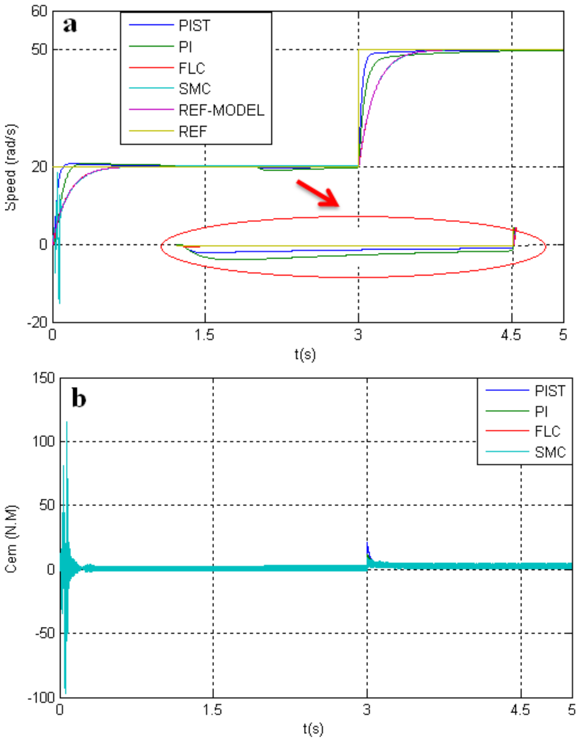


Fig. 17. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in load torque (case of low speeds).

## Case of the high speeds:

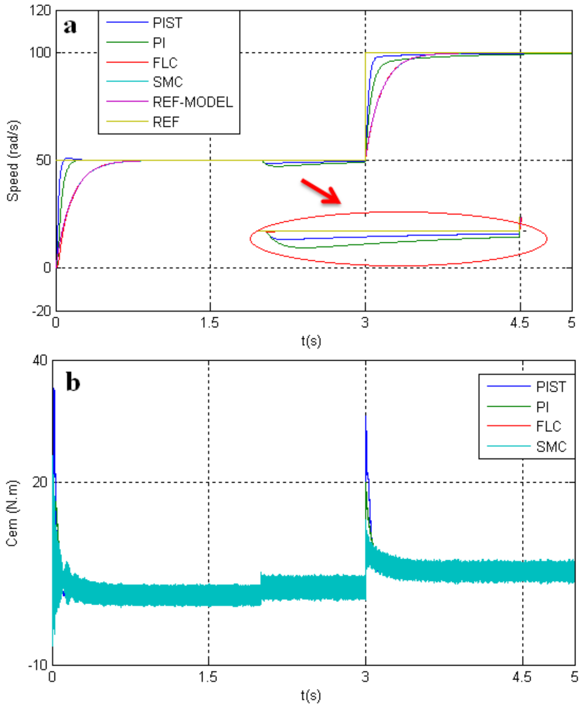


Fig. 18. High tracking responses of the speed (a) and of the electromagnetic torque (b) to change in load torque (case of high speeds).

Table 11
Quantitative performances of speed in case of disturbance of the load torque (case of low speeds)

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 20 (rad/s) | 0.297 | 0.144 | 0.453 | 0.459 | 0.459 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 2.15 | 0 | 0 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.042 | 0.084 | 0.213 | 0.213 | 0.213 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 0 | 0 | 0 | 0 |

Table 12
Quantitative performances of speed tracking in case of disturbance of the load torque (case of high speeds).

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.084 | 0.465 | 0.459 | 0.459 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 1.96 | 0 | 0 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.057 | 0.036 | 0.141 | 0.138 | 0.138 |
| Over shoot (%) In case of 100 (rad/s) | 0 | 0 | 0 | 0 | 0 |

## Case of the low speeds:

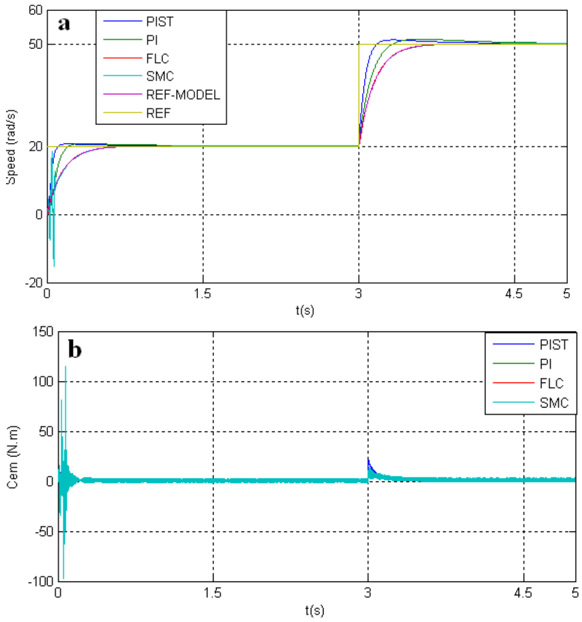


Fig. 19. High tracking responses of the speed (a) and the electromagnetic torque (b) to change in inertia (case of low speeds).

Case of the high speeds:

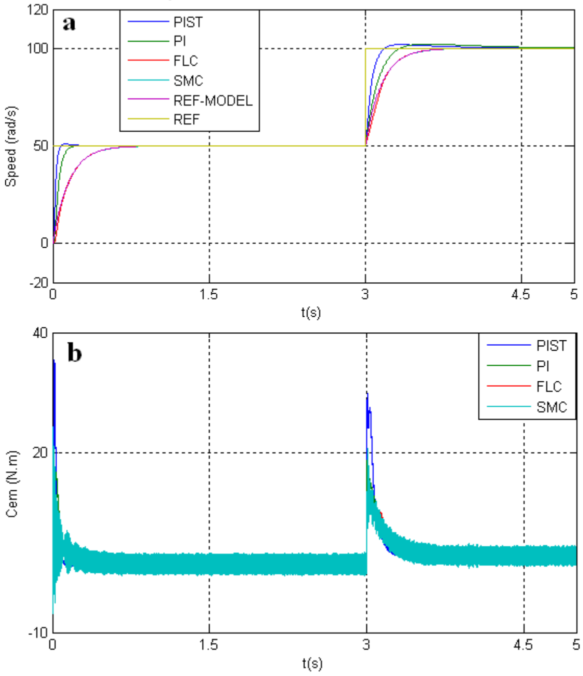


Fig. 20. High tracking responses of the speed (a) and the electromagnetic torque (b) to change in inertia (case of high speeds).

Table 13
Quantitative performances of speed in case of disturbance of the inertia (case of low speeds)

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 20 (rad/s) | 0.297 | 0.144 | 0.453 | 0.459 | 0.459 |
| Over shoot (%) In case of 20 (rad/s) | 0 | 2.15 | 0 | 0 | 0 |
| Response times (s) to attain 50 (rad/s) | 0.159 | 0.084 | 0.225 | 0.225 | 0.225 |
| Over shoot (%) In case of 50 (rad/s) | 0.62 | 1.68 | 0 | 0 | 0 |

Table 14
Quantitative performances of speed tracking in case of disturbance of the inertia (case of high speeds)

| | Controllers | | | | |
|---|---|---|---|---|---|
| | PI | PIST | FLC | SMC | REF-MODEL |
| Response times (s) to attain 50 (rad/s) | 0.174 | 0.084 | 0.465 | 0.459 | 0.459 |
| Over shoot (%) In case of 50 (rad/s) | 0 | 1.96 | 0 | 0 | 0 |
| Response times (s) to attain 100 (rad/s) | 0.108 | 0.066 | 0.195 | 0.141 | 0.141 |
| Over shoot (%) In case of 100 (rad/s) | 2.2 | 1.9 | 0 | 0 | 0 |

# 7 Conclusion

In this paper, the authors propose a comparative study between different control strategies by using different intelligent controllers: sliding mode controller, self tuning fuzzy logic controller and fuzzy logic controller. Also, two methods are proposed to improve the performances of the indirect rotor field-oriented control by replacing the conventional PI controller with sliding mode controller and self-tuning fuzzy logic controller and enforcing the system to follow a reference model. According the simulation results, the sliding mode controller is characterized by a high capacity to reject the disturbance of the machine parameters and the self tuning fuzzy logic controller is characterized by the small response time. Through a series of simulations tests, the sliding mode and the self tuning fuzzy logic controllers present the high performances of speed tracking and disturbance rejection.

## *Appendix*

The machine used in this work is the induction machine characterized by nominal values: 3 kW, 1400 tr/min, 220/380 V, 12.5/7.2 A, 3 phases, 50 Hz.

The parameters of the used induction machine are summarized in table 15, they were obtained by using the laboratory testing as described in [12].

Table 15
The used IM parameters

| Parameters | Values | Units |
|---|---|---|
| Rotor resistance Rr | 2.68 | Ω |
| Stator inductance Ls | 0.229 | H |
| Rotor inductance Lr | 0.229 | H |
| Mutual inductance M | 0.217 | H |
| Moment of inertia J | 0.046 | Kg.m2 |
| Coefficient of friction f | 0.001 | Kg.m2.s-1 |

## *References*

[1] Z. Zhang, J. Zhu, R. Tang, B. Bai, H. Zhang, Second order sliding mode control of flux and torque for induction motor, *Power and Energy Engineering Conference (APPEEC)*, 2010 Asia-Pacific, March 2010, pp. 1-4, 28-31.

[2] M. Moutchou, A. Abbou, and H. Mahmoudi, Induction machine speed and flux control using vector-sliding mode control with rotor resistance adaptation, *International Review of Automatic Control*, 2012, Vol. 5 Issue 6, pp. 804.

[3] MN. Uddin, TS. Radwan, and A. Rahman, Performances of fuzzy –based indirect vector control for induction motor drive, *IEEA Trans Industry Applications*, Sept/Oct 2002, Vol. 38 Issue5, pp. 1219-1225.

[4] CM. Liaw, and F.J. Lin, Position control with fuzzy adaptation for induction servomotor drive, *IEE Proceedings-Electric Power Applications*, Nov 1995, Vol. 142 Issue 6, pp. 397-404.

[5] K.H. Chao, and C.M. Liaw, Fuzzy robust speed controllers for detuned field-oriented induction motor drive, *IEE Proceedings-Electric Power Applications*, Jan 2000, Vol. 147 Issue1, pp. 27-36.

[6] L. Zhen, and L. Xu, Fuzzy learning enhanced speed control of an indirect field-oriented induction machine drive, *IEEE Trans Control Systems Technology*, March 2000, *Vol. 8 Issue2*, pp. 270-278.

[7] M. Masiala, and A. Knight, Self-tuning speed controller of indirect field-oriented induction machine drives, *Proceedings of the 17th International Conference on Electrical Machines*, Sept 2006, pp. 563568.

[8] M. Chebre, M. Zerikat, and Y. Bendaha, Adaptation des paramètres d’un contrôleur PI par un FLC appliqué à un moteur asynchrone, *Proceedings of the 4th International Conference on Computer Integrated Manufacturing CIP’2007*, November 2007, pp. 03-04.

[9] K. Laroussi, and M. Zelmat, Optimisation floue des parametres du régulateur PI appliqué à un moteur à induction, *Proceedings of the 3th International Conference on Sciences of Electronic, Technologies of Information and Telecommunications*, March 2005.

[10] C. Laoufi, A. Abbou, Y. Sayouti, and M. Akherraz, Self tuning fuzzy logic speed controller for performance improvement of an indirect field-oriented control of induction machine, *International Review of Automatic Control, Vol. 6 Issue 4,* July 2013, pp. 464-471.

[11] C. Laoufi, A Abbou and M. AKHERRAZ, Mohammed. Comparative study between several strategies speed controllers in an indirect field-oriented control of an induction machine, *Renewable and Sustainable Energy Conference (IRSEC) 2014 International. IEEE,* 2014, p. 866-872.

[12] A. Abbou, Contribution à l’étude et à la réalisation des stratégies de commande d’un moteur à induction sans capteur de vitesse-simulations et expérimentation, Ph.D. dissertation, Dept. Elect. Eng., Ecole Mohammadia d’Ingénieur, Rabat, Morocco, 2009.