

TecnoLógicas

Tecno Lógicas

ISSN: 0123-7799

tecnologicas@itm.edu.co

Instituto Tecnológico Metropolitano  
Colombia

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Tecno Lógicas, núm. 21, diciembre, 2008, pp. 99-111

Instituto Tecnológico Metropolitano

Medellín, Colombia

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# **SPEED CONTROL OF INDUCTION MOTOR USING FUZZY RECURSIVE LEAST SQUARES TECHNIQUE**

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## **Resumen**

Este artículo presenta el diseño de un controlador adaptativo, el sistema de control emplea lógica difusa adaptativa, modos deslizantes y es entrenado con la técnica de mínimos cuadrados recursivos. El problema de la variación de parámetros es resuelto con el controlador adaptativo; se utiliza un regulador interno PI con el cual se produce que el control de velocidad del motor de inducción sea realizado por medio de las corrientes de estator en vez de los voltajes. Se usa el modelo del motor en el sistema de coordenadas de flujo orientado del rotor para el desarrollo y prueba del sistema de control.

## **Palabras clave**

Control adaptativo, lógica difusa, motor de inducción.

## **Abstract**

A simple adaptive controller design is presented in this paper, the control system uses the adaptive fuzzy logic, sliding modes and is trained with the recursive least squares technique. The problem

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of parameter variation is solved with the adaptive controller; the use of an internal PI regulator produces that the speed control of the induction motor be achieved by the stator currents instead the input voltage. The rotor-flux oriented coordinated system model is used to develop and test the control system.

**Key words**

Adaptive control, fuzzy logic, induction motor.

## 1. INTRODUCTION

The induction motor (IM) has great variety of applications in industrial process when is used as fans or pumps, heating and air conditioning (Spiegel *et al.*, 2003). The low cost and reliability makes preferable the use of the IM front other type of motor (Leonhard, 2001). The control of IM has a wide variety of techniques, actually the researchers focus their works in the method of vector control or field oriented control, in order to estimate the parameters of the machine Chiasson (2005) describes a polynomial method, Alogne *et al.* (2001) present a methodology with least squares and genetic algorithms by means off-line identification, alternative methods of identification use stochastic optimization (Ursem *et al.*, 2004), Koubaa (2004) uses the identification procedure with the simple recursive least squares technique, the method is based on the steady state equations of the IM. A standstill on-line parameter estimation is proposed by Fang *et al.* (2005). The IM dynamic system is highly nonlinear, and has a coupling between flux and torque which makes difficult apply the conventional control. Chiasson (1998, 2005) employs the input-output linearization to control the speed and works with the model of field oriented coordinate system to design the controller system, the nonlinear control has the property to consider the whole dynamic of the system (Sasthy, 1999). Bose (2002) presents the methods of scalar control, sensorless, vector control and an advanced scalar control technique, known as direct torque control but has a disadvantage at low speed. These and other methods are affected by the parameter variations and to solve this problem, adaptive nonlinear methods such as adaptive fuzzy control, adaptive input-output feedback linearization technique and adaptive sliding mode (Mezouar *et al.* 2007) have been used over the IM. The adaptive fuzzy control uses the recursive least square training (Wang, 1992) and is developed under consideration of vector control method, Juang *et al.* (2007) design a PID fuzzy improved and Chiang *et al.* (2005) increase the perform of the controller with the addition of heuristic

optimization to tune the fuzzy system, Kim *et al.* (2006) made an identification and tune by the combination of fuzzy and genetic algorithm, an online neuro-fuzzy tuning procedure to adjust the PID gains is describe in (Kim *et al.* 2006) In (Rehman *et al.*, 2007) an adaptive fuzzy controller is designed but a disadvantage of this system is the training based on the gradient rule to update the approximator parameters, this technique is computationally more expensive than the fuzzy adaptive recursive least squares training system proposed. The principal reason to apply the adaptive fuzzy technique is due that the IM model is a nonlinear system and traditional linear controllers fail at the moment to be used in a entire range of speed operation, linear methods require a linearization around an operating point, additionally the linear controllers need a previous knowledge of parameters of the system to regulate appropriately the plant, a reason to avoid the artificial neural network is the difficult train and modeling.

The aim of this work is the design of a speed controller for the induction motor using an adaptive fuzzy tuning. The sections describe the induction motor model, the controller design and the results.

## 2. INDUCTION MOTOR MODEL

The model of the electric machine uses the rotor-flux field oriented coordinate system described in (Chiasson 2005), in which is clear and simple to design a speed controller. This model reduces the task of work with two axis of the rotor flux and uses a polar coordinate representation. The system in state space representation is presented in equations (1-6), with  $\theta$  the angular position in rad,  $\omega$  the angular speed in rad/s,  $i_d$  and  $i_q$  represents stator currents in the direct and quadrature axis respectively,  $\varphi_d$  the magnitude of the rotor field flux, while  $\rho$  is the angle of the rotor field flux.

The electrical and mechanical parameters are  $R_r$ ,  $R_s$  rotor and stator resistances respectively,  $L_s$ ,  $L_r$  y  $L_m$  are the stator, rotor and coupled inductances,  $J$  is the moment of inertia,  $f$  is the

viscous damping constant and  $T_L$  is the load torque. For simplicity is usually used  $\sigma=1-L_m/(L_s L_R)$  the linkage factor,  $\eta=R_R/L_R$  the inverse of time constant,  $n_p$  number of poles pair,  $\mu=n_p L_m/(J L_R)$  and  $\gamma=L_m^2 R_R/(\sigma L_s^2 L_R)+R_s/(\sigma L_s)$ .

$$\frac{d\theta}{dt} = \omega \quad (1)$$

$$\frac{d\omega}{dt} = \mu \varphi_d i_q - \frac{f}{J} \omega - \frac{T_L}{J} \quad (2)$$

$$\frac{d\varphi_d}{dt} = -\eta \varphi_d + \eta L_m i_d \quad (3)$$

$$\frac{di_d}{dt} = -\gamma i_d - \left( \frac{\eta L_m}{\sigma L_s L_r} \right) \varphi_d + n_p \omega i_q + \eta L_m \frac{i_q^2}{\varphi_d} + \frac{u_d}{\sigma L_s} \quad (4)$$

$$\frac{di_q}{dt} = -\gamma i_q + \left( \frac{L_m}{\sigma L_s L_r} \right) n_p \omega \varphi_d - n_p \omega i_d - \eta L_m \frac{i_q i_d}{\varphi_d} + \frac{u_q}{\sigma L_s} \quad (5)$$

$$\frac{d\rho}{dt} = n_p \omega + \eta L_m \frac{i_q}{\varphi_d} \quad (6)$$

### 3. CONTROLLER DESIGN

This section presents the technique of nonlinear adaptive control and the sliding modes control. The main idea is to design a field oriented vector control scheme, the method lets control the torque of the induction motor with a decoupling between the torque and flux. Note that the electromagnetic torque  $T_e = J \mu \varphi_d i_q$  is the product of two state variables and at the same time depends of the magnitude of the rotor flux. In field oriented control the flux along of the  $q$ -axis should be zero and in this way the flux is aligned along the  $d$ -axis. If the condition mentioned before agree and the flux is kept constant then the current  $i_q$  will control the speed and now the control system looks like a dc machine controller (Chiasson 1998), (Bose 2002).

The developed method in this work is the direct adaptive fuzzy control, which uses an adaptive fuzzy approximator to approximate the controller, and guarantee that the output error decreases.

The control law  $u$  is approximated through a training of fuzzy logic systems using recursive least squares (FRLS) and sliding mode (SM), the system is given by (7).

$$\dot{y} = f(x) + g(x)u \quad (7)$$

Where  $y$  is the output of the system,  $f(x)$  and  $g(x)$  are smooth vector fields. There exist  $g_0$  and  $g_1$  such that  $0 < g_0 \leq g(x) < g_1 < \infty$ , and exist  $G(x) \geq 0$  such that  $|\dot{g}(x)| = \left| \frac{\partial g}{\partial x} \dot{x} \right| \leq G(x)$  for all  $x \in S_x$ .

where  $S_x \subseteq \mathbb{R}^n$  is the space of the state trajectory. Using feed-back linearization we have an ideal control law in (8).

$$u = \frac{1}{g(x)}(-f(x) + \dot{y}_m) \quad (8)$$

where  $u(t) = \dot{y}_m + \delta e_s + \bar{e}_s$ ,  $\bar{e}_s = \dot{e}_s - \dot{e}_0$  and  $\delta > 0$ .  $y_m$  is the desired output trajectory, the tracking error is defined by  $e_s$  and  $e_0 = y_m - y$ , thus  $\bar{e}_s = \dot{e}_s - \dot{e}_0$ , such that  $e_s = e_0$ .

The goal of the adaptive controller is to learn how to control the plant to carry the tracking error close to zero. The control law  $u$  could be expressed like the equation (9).

$$u = \hat{u}_d + d_u(x) \quad (9)$$

Where  $\hat{u}_d$  is the controller approximated by FRLS (Wang, 1992, 1994),  $d_u(x)$  is the bounded approximation error. Then consider the direct adaptive controller (Rehman *et al.*, 2007):

$$u_d = \hat{u}_d + u_{sd} \quad (10)$$

In (10)  $u_{sd} = k \operatorname{sgn}(e_s)$  is a term of control by sliding modes, where  $k$  is the constant that ensures that  $y$ ,  $\hat{u}_d$  and  $u_{sd}$  are bounded, and the error magnitude goes to zero or near to zero.

#### 4. RESULTS

Induction motor parameters used in simulations are  $R_s = 0,19 \, \Omega$ ,  $R_r = 0,39 \, \Omega$ ,  $L_r = 4,6 \, \text{mH}$ ,  $L_s = 4,20 \, \text{mH}$ ,  $L_m = 4,00 \, \text{mH}$ ,  $n_p = 2$ ,  $J = 0,0226 \, \text{Kg m}^2$ ,  $f = 0,00014 \, \text{Nm/rad/s}$ . Simulation results are shown in Fig. 2, 3 and 4, the load torque is set constant in 5 Nm, the initialization values of the FRLS to adaptive training are set in the same way like the values of the linear recursive least squares algorithm. An internal PI is used such that the stator currents are the control variables. The current by the d axis is kept constant and then the current  $i_q$  is employed to control the IM and is the other reference of the PI regulator, this can be seen in the resulting system of Fig. 1, we can appreciate the full control system implemented; where the FRLS controller uses the tracking error and produce a part of the current reference, the other part is produced by the sliding controller.

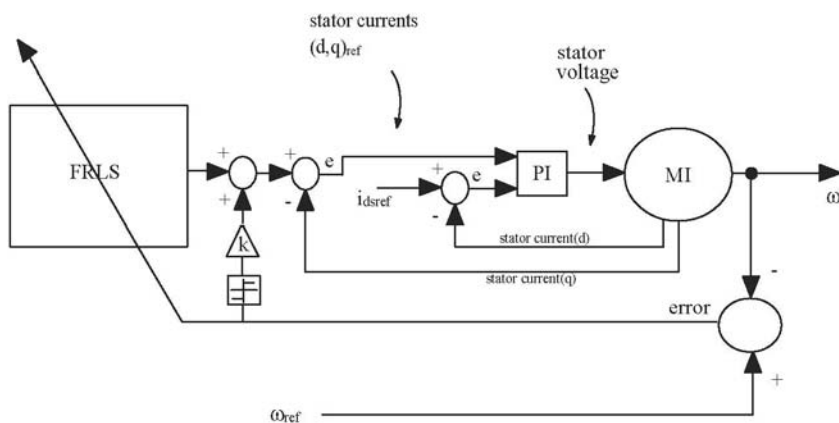
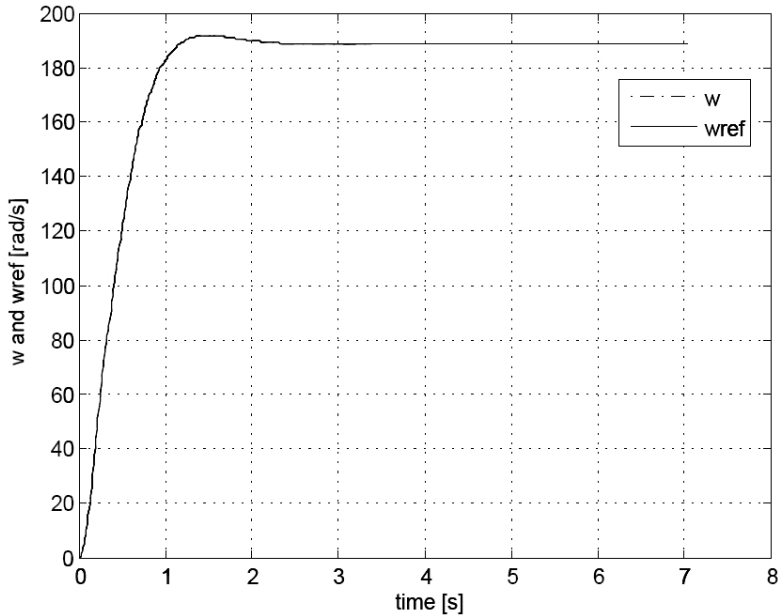


FIG. 1. SYSTEM MODEL

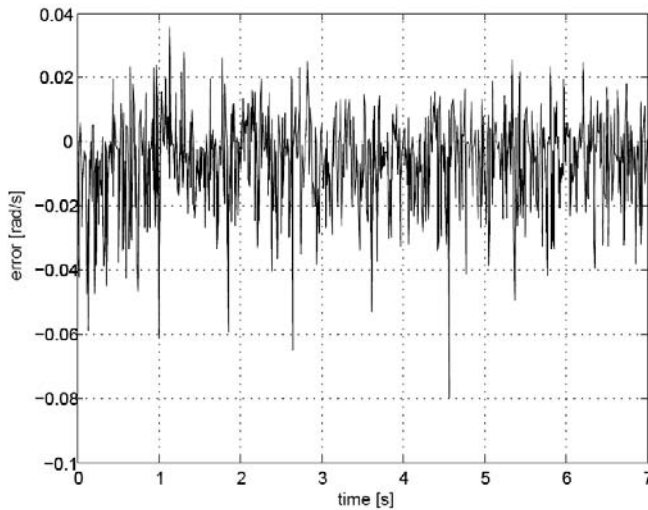
Fig. 2 presents the speed variation in closed loop, at the beginning the system output has an error respect to the speed reference which is reduced around 0.1s, this can be also observed in the plot of the tracking error (Fig. 3); due to the parameter

initialization of the adaptive system, the pull up of the motor is lead to final speed ( $188\text{rad/s}$ ) in a smooth way. Fig. 4 shows the stator current variation with a speed change and we can see the rotor flux performance. The stator currents and the rotor flux stand inside the limits of the motor.



**Fig. 2.** MOTOR SPEED AND REFERENCE SPEED

Fig. 5 shows the behavior of a conventional PID and the hybrid fuzzy recursive method is in Fig. 2. The start of the motor is made with the fuzzy controller and the PID, a lower mean square error (MSE) is achieved by the adaptive controller. Table 1 shows this comparison, where performance of the hybrid controller (Fuzzy RLS and SM) is higher than the others controllers. The MSE is computed like (11) with  $T=7\text{s}$  and  $T=5\text{s}$  respectively.

**FIG. 3.** TRACKING ERROR

$$MSE = \frac{1}{T} \int_{t=0}^{t=T} e^2 dt \quad (11)$$

**TABLE 1.** MSE SUMMARY FOR THE CONTROLLERS

CONTROLLER	MSE ( $T_L=5\text{Nm}$ )
PID	0,7980
Fuzzy RLS and SM	0,0026

In order to make a comparison of the performance shown in Rehman *et al.* (2007), when the  $T_L=0\text{ Nm}$  and highlighting that they did not give information of the used induction motor parameters, from the table 2 we can observe that the MSE obtained with the training FRLS algorithm is lower, and the tracking error of Fig. 6 shows a similar behavior to the error of Fig. 3, but has the peak around 3 rad/s. To make comparisons we convert the error from rad/s to rpm and later calculate the MSE. The speed and reference speed in Fig. 7 reach the 188 rad/s.

TABLE 2. MSE SUMMARY

CONTROLLER	MSE ( $T_L=0\text{NM}$ )
Direct adaptive fuzzy	5,0749
Indirect adaptive fuzzy	8,798
Fuzzy RLS and SM	0,7768

5. CONCLUSION AND DISCUSSION

It has been shown a speed controller of the induction motor through a combined technique that employs the fuzzy logic and sliding modes. The intelligent controller implemented in this work gives an advantage over the classical nonlinear and linear control techniques because it considers the parameter variation and therefore controller parameters are estimated in an adaptive form. The adaptive technique makes unnecessary the use of a flux estimator that makes computationally heavy the system. Fig. 3 shows that tracking error tends to zero at the beginning of the implementation controller, which shows the performance of the controller implemented. The fuzzy adaptive controller uses the heuristic and the mathematical model to be implemented; this gives the advantage over other controllers.

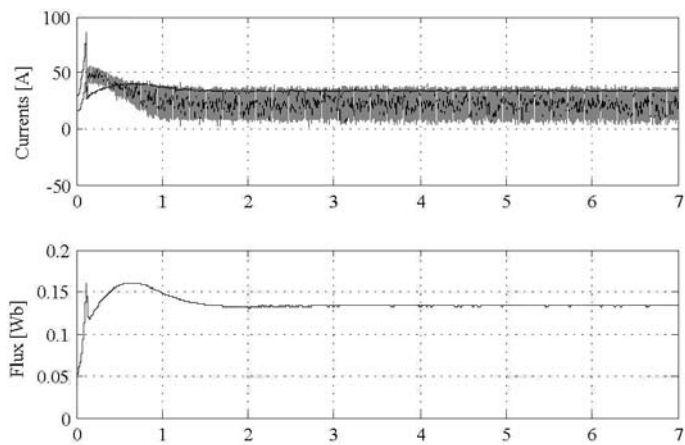
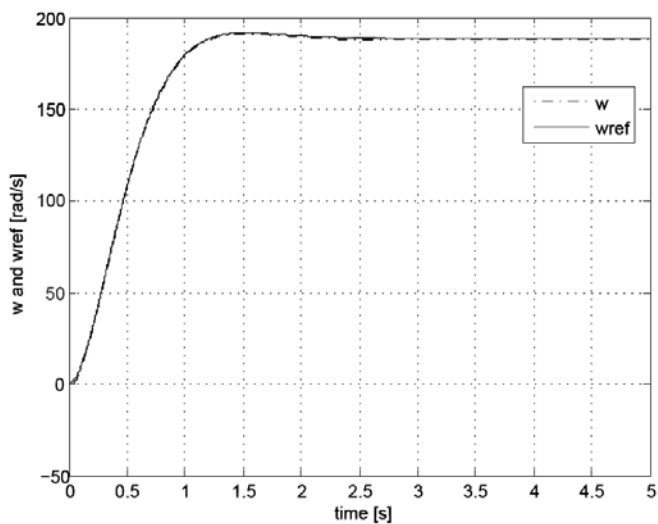
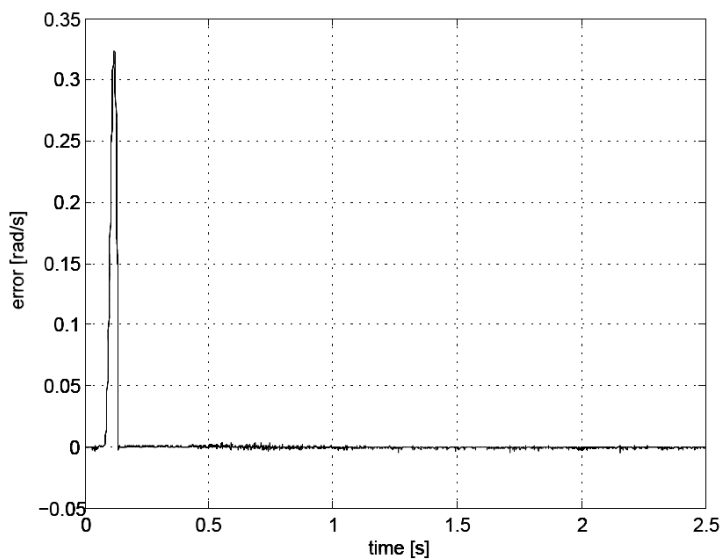


FIG. 4. STATOR CURRENTS AND ROTOR FLUX

**Fig. 5.** PID SPEED CONTROL**Fig. 6.** TRACKING ERROR  $T_L=0$  NM

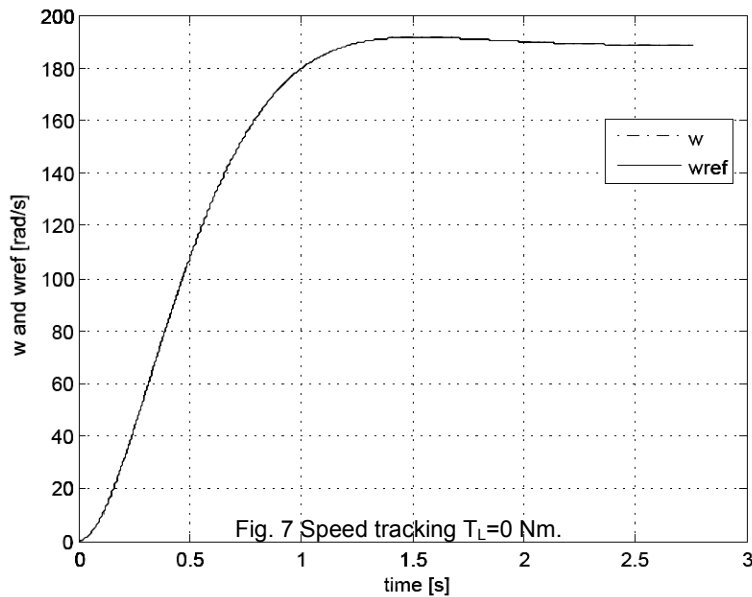


FIG. 7. SPEED TRACKING  $T_L = 0$  NM

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