SENSORLESS SPEED ROTOR FLUX ORIENTED CONTROL OF THREE PHASE INDUCTION MOTOR

Alfred Pjetri, MsC
Ymer Luga, Prof. Dr
Astrit Bardhi, Prof. Ass
Automation Department, Electrical Engineering Faculty, PUT, Albania

Abstract

Sensorless speed rotor flux oriented control of induction motor drives it is known to produce high performance because of decoupling rotor flux and torque producing current components of stator currents. This paper describes a simple and robust sensorles speed rotor flux oriented control system for three phase induction motor drives that it is adequate for high dynamic applications. To control the rotor speed of the induction motor drives, a PI controller is included in the speed control system. A hysteresis current controllers are applied for changing the magnitude and the frequency of the output voltage of the PWM voltage source inverter which fed the induction motor. In order to verify the proposed sensorlees speed control system, the model of the system is implemented in MATLAB Simulink software, which is suitable for testing the dynamic simulation. Simulation results shows that the reference and rotor speed of induction motor are very closed to each-other under step load torque changes.

Keywords: Sensorless speed control of induction motor

Introduction:

It is well known, from the market industry that more than half of the electric energy produced in developed countries is converted into mechanical energy by induction motors. Between different types of induction motors, three phase squirrel cage induction motors are most popular ones. More than 90% of industrial electrical drives using squirrel cage three phase induction motors. This is because the induction motors compare to other electric motors have low cost, are very robust and have low maintenance cost (Pjetri, 2011), (Marwali, 1997). In most cases the induction motor loads (mechanisms) needs motor speed control.

Depending how the induction motor speed is monitored, two are the speed control systems; with or without mechanical sensor speed (sensorlees).

It is clear that the control systems with mechanical speed sensor have a higher cost, reduce the reliability and require constant maintenance. Induction motor control systems without speed sensor eliminate above disadvantages. This is the reason that nowadays the sensorlees speed control of induction motors industry is in focus of many researchers (Kubota, 2002), (Kwon, 2004), (Jemli, 1998), (Salem, 2005). Nowadays field oriented control is the most common way for sensorlees speed control of induction motors. Independence torque and flux control is the main advantage of this method (Quang, 2008).

In order to implement the sensorlees speed control, the dynamic model of induction motor must be able to allow independent torque and flux control (Trzynadlowski, 2000). Independent torque and flux control of induction motor provides high accuracy and fast dynamic speed response even in transient regimes. Rotor flux oriented control of three phase induction motors is one of the most effective method for sensorlees speed control between the various methods of field oriented control, because it is simple to implement and very robust method.

This paper presents a simple and very effective sensorlees speed rotor flux oriented control system of three phase induction motors. The validity of the proposed method it is shown through simulations in Matlab Simulink software.

Rotor flux oriented dynamic model of three phase induction motor

For obtaining dynamic model of induction motor it is assumed symmetrical three phase stator winding with insulated neutral point, linear magnetic circuit and constant active resistance of the motor windings.

From space vector theory, the dynamic model of three phase squirrel cage induction motor can be expressed in orthogonal arbitrary reference frame (Quang, 2008), (Trzynadlowski, 2000). The dynamic model in orthogonal arbitrary reference frame ($u,v,0$) which rotates counterclockwise with arbitrary speed ω_a can be expressed as follow:

$$u_{su} = \frac{d\psi_{su}}{dt} - \omega_a \psi_{sv} + R_s i_{su} \qquad o = \frac{d\psi_{ru}}{dt} - (\omega_a - \omega) \cdot \psi_{rv} + R_r i_{ru}$$
$$u_{sv} = \frac{d\psi_{sv}}{dt} + \omega_a \psi_{su} + R_s i_{sv} \qquad o = \frac{d\psi_{rv}}{dt} + (\omega_a - \omega) \cdot \psi_{ru} + R_r i_{rv}$$

$$\psi_{su} = L_s i_{su} + L_m i_{ru} \qquad \psi_{ru} = L_r i_{ru} + L_m i_{su}$$
$$\psi_{sv} = L_s i_{sv} + L_m i_{rv} \qquad \psi_{rv} = L_r i_{rv} + L_m i_{sv} \qquad (1)$$

$$T = \frac{3}{2} p \frac{L_m}{L_r} (\Psi_{ru} i_{sv} - \Psi_{rv} i_{su}) \qquad T - T_l = \frac{J}{p}\frac{d\omega}{dt} = \frac{J}{p}\frac{d^2\theta}{dt^2}$$

The dynamic model given in Eq. 1, by considering a orthogonal synchronous reference frame (*d,q,0*) which rotates with synchronous speed ω_1 ($\omega_1 = \omega_a$) with d axis aligned with rotor flux vector can be expressed:

$$u_{sd} = \frac{d\psi_{sd}}{dt} - \omega_1 \psi_{sq} + R_s i_{sd} \qquad 0 = \frac{d\psi_{rd}}{dt} + R_r i_{rd}$$
$$u_{sq} = \frac{d\psi_{sq}}{dt} + \omega_1 \psi_{sd} + R_s i_{sq} \qquad 0 = (\omega_1 - \omega) \cdot \psi_{rd} + R_r i_{rq}$$
$$\psi_{sd} = L_s i_{sd} + L_m i_{rd} \qquad \psi_{rd} = L_r i_{rd} + L_m i_{sd}$$
$$\psi_{sq} = L_s i_{sq} + L_m i_{rq} \qquad 0 = L_r i_{rq} + L_m i_{sq} \qquad (2)$$
$$T = \frac{3}{2} p \frac{L_m}{L_r} \Psi_{rd} i_{sq} = C_m \Psi_{rd} i_{sq} \qquad T - T_l = J\frac{d\Omega}{dt} = \frac{J}{p}\frac{d\omega}{dt} = \frac{J}{p}\frac{d^2\theta}{dt^2}$$

Where u_{sd}, u_{sq}; i_{sd}, i_{sq}, i_{rd}, i_{rq}; ψ_{sd}, ψ_{sq}, ψ_{rd}, ψ_{rq} are orthogonal components of stator voltages, stator and rotor currents and stator and rotor fluxes. Meanwhile T, T_l, Ω and ω are electromagnetic torque, load torque, mechanical rotor speed and electrical rotor speed. The above model it is suitable for sensorlees speed control algorithm implementation in induction motor electrical drives (Quang, 2008), (Trzynadlowski, 2000).

Rotor speed estimation based in dynamic model of induction motor

Speed monitoring at any instant time is an essential requirement for speed control systems of induction motor electrical drives. Monitoring of speed in induction motors can be realized by measuring it through mechanical sensors placed on the motor shaft or by estimated it through dynamic model of induction motor.

Using of mechanical sensor for measuring the speed of the motor has a high cost, reduce reliability during operating and also requires periodic maintenance.

For overcoming the disadvantages of mechanical sensor speed monitoring, we propose monitoring the motor speed based in dynamic model (Kubota, 2002), (Jemli, 1998). It is clear that the speed estimate based on steady state model of induction motor doesn't assure accuracy in dynamic regimes and therefore it is used in low performance electrical drives. In order to guarantee speed estimation accuracy during dynamic regimes it is needed dynamic model of induction motor. This is the main reason that the method is used to estimate the speed in high performance electrical drives such are the position ones (Kubota, 2002), (Kwon, 2004).

Since the currents and the stator voltages are measured directly in stationary reference frame it is convenient to express the dynamic model of induction motor in stationary reference frame (*D*, *Q*, *0*) fixed in the stator. This it is can be easy done by replacing in Eq. 1, $\omega_a = 0$.

$$u_{sD} = \frac{d\psi_{sD}}{dt} + R_s i_{sD} \qquad o = \frac{d\psi_{rD}}{dt} + \omega \cdot \psi_{rQ} + R_r i_{rD}$$

$$u_{sQ} = \frac{d\psi_{sQ}}{dt} + R_s i_{sQ} \qquad o = \frac{d\psi_{rQ}}{dt} - \omega \cdot \psi_{rD} + R_r i_{rQ}$$

$$\begin{aligned} \psi_{sD} &= L_s i_{sD} + L_m i_{rD} \\ \psi_{sQ} &= L_s i_{sQ} + L_m i_{rQ} \end{aligned} \qquad \begin{aligned} \psi_{rD} &= L_r i_{rD} + L_m i_{sD} \\ \psi_{rQ} &= L_r i_{rQ} + L_m i_{sQ} \end{aligned} \tag{3}$$

$$T = \frac{3}{2} p \frac{L_m}{L_r} \left(\Psi_{rD} i_{sQ} - \Psi_{rQ} i_{sD} \right) \qquad T - T_l = \frac{J}{p} \frac{d\omega}{dt} = \frac{J}{p} \frac{d^2\theta}{dt^2}$$

Based on dynamic model in stationary reference frame given in Eq. 3 , after some simple mathematical calculation we can take the equations which allow us to estimate the orthogonal *D*, *Q* rotor flux components and motor speed.

The orthogonal rotor flux components are:

$$\begin{aligned} \Psi_{rD} &= \frac{1}{s} \frac{L_r}{L_m} \left[u_{sD} - (R_s + s\,\sigma L_s) i_{sD} \right] \\ \Psi_{rQ} &= \frac{1}{s} \frac{L_r}{L_m} \left[u_{sQ} - (R_s + s\,\sigma L_s) i_{sQ} \right] \end{aligned} \tag{4}$$

Motor speed:

$$\omega = \frac{\Psi_{rD}(s\Psi_{rQ}) - \Psi_{rQ}(s\Psi_{rD}) - \dfrac{L_m}{\tau_r}(i_{sQ}\Psi_{rD} - i_{sD}\Psi_{rQ})}{\Psi_{rD}^2 + \Psi_{rQ}^2} \tag{5}$$

Where $\sigma = (1-(L_m^2 / L_r L_s))$ is the leakage coefficient and $\tau_r = L_r / R_r$ is the rotor time constant

From Eq. 4 and Eq. 5 it can be seen that by measuring the currents and the stator voltages we can estimate the orthogonal rotor flux components and then motor speed.

Sensorlees speed rotor flux oriented control system of induction motor

Knowledge of the rotor flux vector position (angle) at any instant time it is a necessary requirement for field oriented control (Quang, 2008), (Trzynadlowski, 2000). Accuracy of recognition of the rotor flux angle is crucial in control, because the calculation of stator current orthogonal components i_{sd}, i_{sq} depends directly from this angle (Lee, 1994), (Raj, 2010). Angular position of the rotor flux vector estimation Θ_r it is based on the relative difference between synchronous and rotor speed $\omega_s = \omega_1 - \omega$ as follow:

$$\Theta_r = \int_0^t \omega_1 dt = \int_0^t \omega_s dt + \int_0^t \omega dt = \int_0^t \omega_s dt + \theta \qquad (6)$$

Where θ is electrical angular of rotor displacement and ω_1 is electrical synchronous speed.

The required value of slip speed, ω_s can be calculated from dynamic model of the motor under rotor field orientation conditions (Eq. 2). Since $\Psi_r = \Psi_{rd}$ ($\Psi_{rq} = 0$), we can get the expression of slip speed as follow:

$$\omega_s = \frac{L_m i_{sq}}{\tau_r \Psi_{rd}} \qquad (7)$$

While the rotor flux can be determined by the equation:

$$\Psi_{rd} = \frac{L_m i_{sd}}{1+\tau_r s} \qquad (8)$$

where $s = d/dt$ is the diferential operator.

Reference current value i_{sd}^{ref} for a given reference rotor flux Ψ_{rd}^{ref} can be calculated from Eq.8 as follow:

$$i_{sd}^{ref} = \frac{(1+\tau_r s)}{L_m} \Psi_{rd}^{ref} \qquad (9)$$

Meanwhile reference current value i_{sq}^{ref} for a given reference torque T_{ref} can be calculated from torque motion expression of Eq.2.

$$i_{sq}^{ref} = \frac{T_{ref}}{C_m \Psi_{rd}} \tag{10}$$

Based on the above algorithm of rotor flux oriented control, in Fig. 1 it is shown the proposed sensorless speed control system for three phase squirrel cage induction motor. As a reference rotor flux it is accepted its rated value.

As it can be seen from Fig. 1, the inverter output phase currents (motor currents) are controlled through so-called Hysteresis Controller (HC) (Trzynadlowski, 2000).

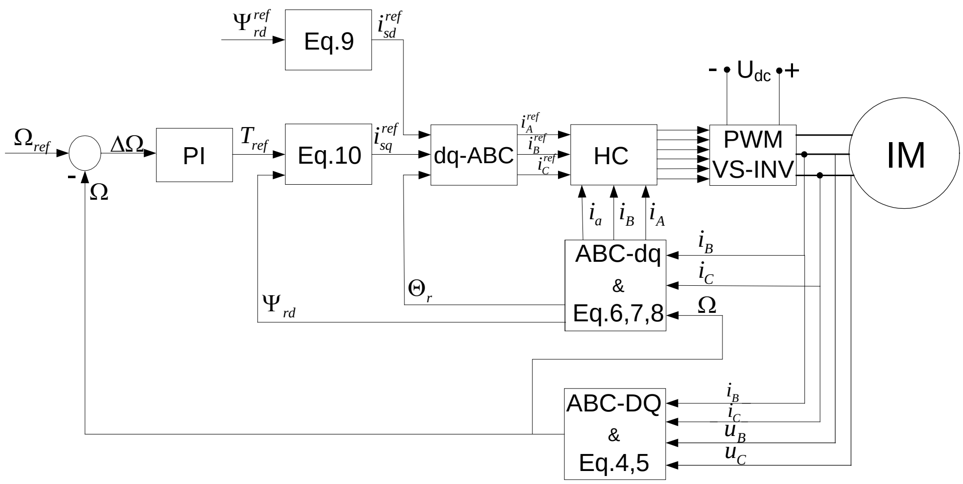

Figure 1. Sensorlees speed rotor flux oriented control system of induction motor

Using of HC controllers overcomes the difficulties encountered of linear controller tuning as it is in traditional field oriented speed control systems (Perez, 1998), (Bazanella, 2001).

The HC controllers generate impulses for controlling the IGBT gates, making in this manner the inverter output magnitude and frequency voltage changing.

The verification of the algorithm proposed in this paper, for sensorlees speed control system shown in Fig. 1 is done by implementing in MATLAB Simulink software.

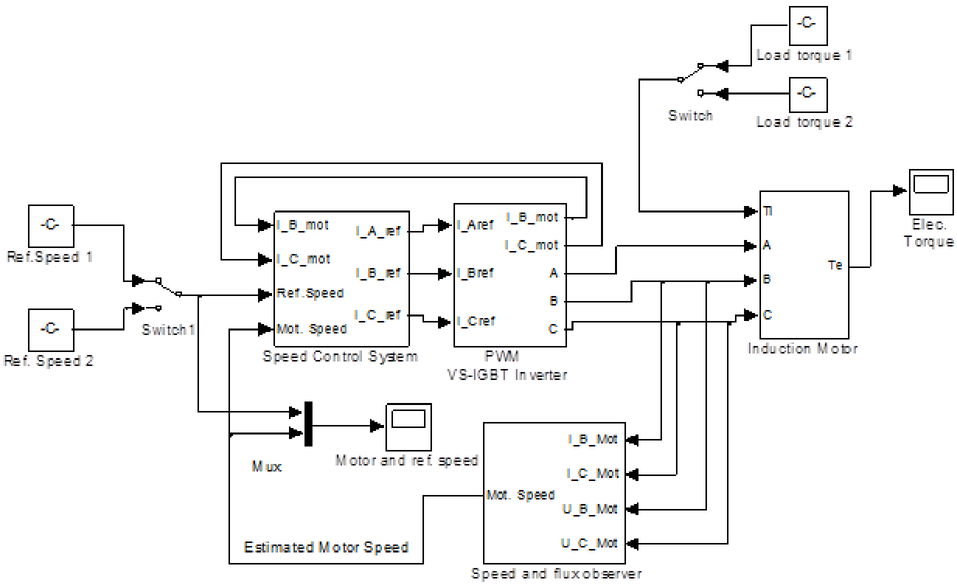

Figure 2. Simulink model of sensorlees speed control system of induction motor

The way how it is implemented the sensorlees speed control system of induction motor in Simulink it is shown in Fig. 2 and Fig. 3.

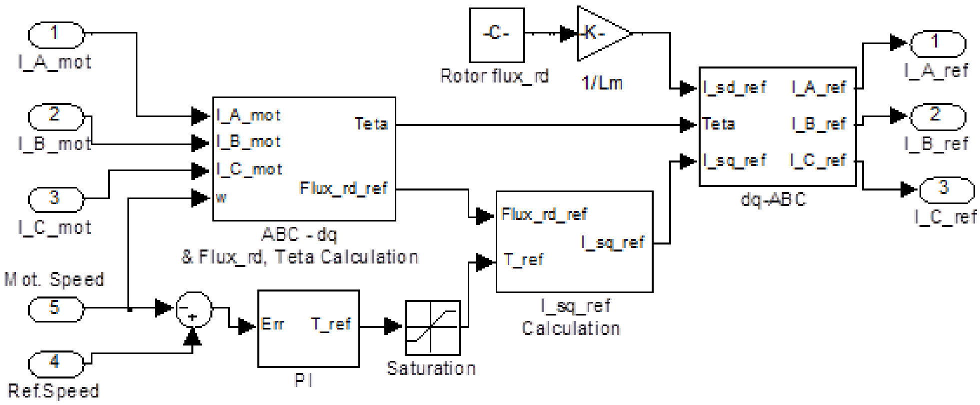

Figure 3. Simulink speed control system

Simulation results

The simulation results are taken for two reference speed values under step load torque changes. The three phase squirrel cage induction motor data used in this paper are shown in table 1.

From the calculation the PI controller coefficient are $Kp=12$ and $Ki=2$, meanwhile the hysteresis controller band is chosen *0.8*, (Elwer, 2006), (Chang, 2000).

Table 1

Pn [kW]	nn [rpm]	Un [V]	fn [Hz]	Rs [Ω]	Rr [Ω]	Ls [H]	Lr [H]	Lm [H]	J [kgm^2]	Udc [V]
1.47	*1430*	*380*	*4.2*	*4.2*	*3.9*	*0.39365*	*0.39365*	*0.375*	*0.009*	*620*

In Fig. 4 and Fig. 5 are shown the response of motor speed and electromagnetic torque of induction motor.

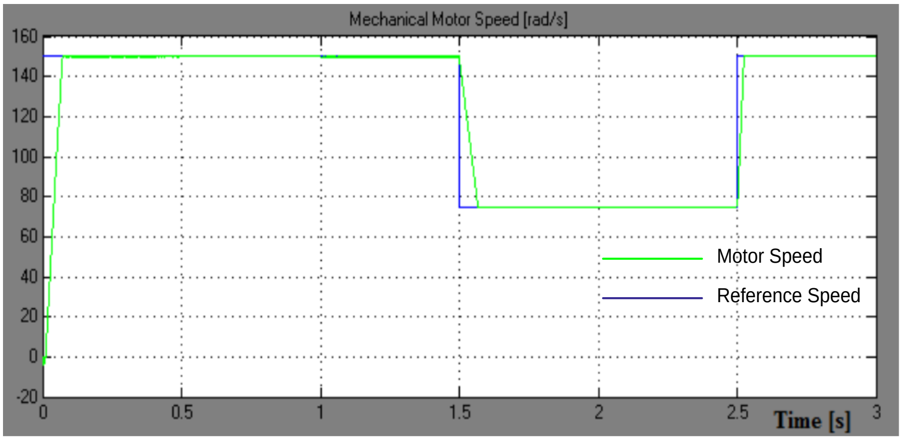

Figure 4. Dynamic speed response

As a reference speed value are taken rated value 150 rad/s and 75 rad/s, which is half of rated speed value. For booth reference speeds it is step changed load torque from rated value to half of rated torque value and vise versa, as it can be clearly seen from Fig. 4 and Fig. 5.

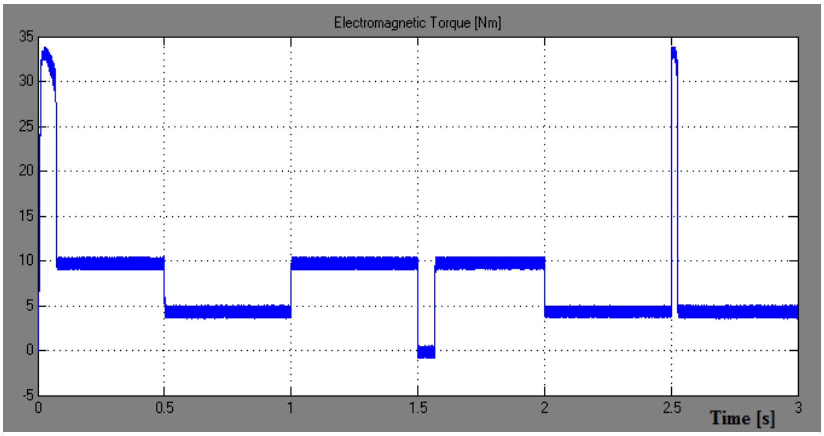

Figure 5. Dynamic electromagnetic torque response

It is well known that the performance of every control system it is realized through quality indicators such as overshoot, settling time and steady state error By analyzing the speed response of Fig. 4 for all disturbance of control system (step load changes) the maximum values of quality indicators for this case are; overshoot 0.87 %, settling time 0.11 s and steady state error 0.67%. As it can be understand the value of quality indicators are optimal.

A result obtained by simulations clearly shows that the sensorlees speed rotor flux oriented control system proposed in this paper, it is suitable for high performance drives.

Conclusion

By analysis of the results obtained from the simulation of control system in Simulink, we conclude that the proposed sensorlees speed rotor flux oriented control system gives very good results in terms of quality indicators not only in steady state regime but also in dynamic regimes.

As it is shown from the simulation results the quality indicators have optimal values. This is the reason that the sensorlees speed control method is adequate for high performance electrical drive such us positions ones. .

It is very important to notice that in rotor field oriented control systems, the accuracy estimation of rotor flux vector is crucial.

References:

A. Pjetri, Y. Luga, A. Bardhi, Kontrolli skalar i shpejtësisë së motorëve asinkronë pa sensor, Konferenca Kombëtare, Teknologjitë të Avancuara - Rruga Jonë e Zhvillimit, Tetor 2011, Tiranë.

H. Kubota, I. Sato, Y. Tamura, K. Matsuse, Hisayoshi Ohta, and Y. Hori, "Regenerating Mode Low-Speed operation of Sensorless Induction Motor Drive With Adaptive Observer," IEEE-IA, Vol. 38, No. 4, July/August 2002, PP. 1081-1086.

Young Ahn Kwon, and Sung Hwan Kim, "A New Scheme for Speed Sensorless Control of Induction Motor," IEEE-IA, Vol. 51, No. 3, June 2004, PP. 545-550.

M. Jemli, M. Boussak, M. Godda and M. B. A. Kamoun, "MRAS Identification Schemes for Sensorless Indirect Field Oriented Control of Induction Motor Drives with Rotor Resistance Tuning," Proc. of ICEM, Turkey 1998, PP. 1572-1577.

M.N. Marwali, and A. Keyhani, "A comparative study of rotor flux based MRAS and back EMF based MRAS speed estimators for speed sensorless vector control of induction machines," IEEE-IAS Annual Meeting, 1997, PP. 160– 166.

Z. M. Salem, M. M. Khater, S. A. Kalilah and S. A. Mahmoud, "Four Quadrant Speed Estimation Based on Model Reference Adaptive System," Engineering Research Journal, Vol.28, No.2, April 2005, PP. 169–177

N. P. Quang, J. A. Dittrich, “Vector Control of Three-Phase AC Machines: System Development in the Practice”, Springer, 2008.

A.M.Trzynadlowski: “The field orientation principle in control of induction motors”, Kluver Academic Publisher, 2000.

D. C. Lee, S. K. Sul, M. H. Park, “High Performance Current Regulator for a Field-Oriented Controlled Induction Motor Drive”, IEEE Trans. on Industry Application, vol. 30, no. 5, pp. 1247-1257, 1994.

G. C. Raj, D. P. Renuga, M. A. Prasana, “Improved Indirect Rotor Flux Oriented Control of PWM Inverter fed Induction Motor Drives” ACEEE Int. J. on Electrical and Power Engineering, Vol. 01, No. 03, Dec 2010.

G. E. Perez, “On field-oriented control of induction motors: tuning of the PI gains for performance enhancement”. IEEE, pp.971 - 976 vol.1, 1998.

A. S. Bazanella, R. Reginatto, “Brief Robust tuning of the speed loop in indirect field oriented control of induction motors” IFAC, pp. 1811-1818 vol. 37, 2001.

A. S. Elwer, “A Novel Technique for Tuning PI-Controllers in Induction Motor Drive Systems for Electric Vehicle Applications”, Journal of Power Electronics, Vol. 6, No. 4, Oct 2006.

G. W. Chang, G. P. Espinoza, E. Mendes, R. Ortega, “Tuning rules for the PI gains of field-oriented controllers of induction motors”, IEEE Transactions on Industrial Electronics, vol: 47, pp. 592-602, 2000.