A PID Controller Comparative Study of Tuning Methods for a Three-Phase Induction Motor Speed Control

Salvador Ramírez, Diego A. Zepeda, Jaime Cerda, Vicente Torres

Abstract— **This article presents the performance of different tuning methods of PID controllers applied to a three-phase induction motor using a commercial frequency inverter in a LabVieW™ programming environment on a personal computer. For the handling of the motor a Danfoss industrial type Frequency Variator is used. The reading and handling of data is done by means of a National Instruments data acquisition card. In the tuning of the PID controller, four tuning methods were used, the method based on the reaction curve, the Cohen and Coon method, the Poles method and the Lopez method. Finally, the answers obtained from all the tuning techniques are compared taking as a plant the induction motor.**

Index Terms — **induction motor, PID controller, tuning, time response.**

I. Introduction

Nowadays, in the control of current industrial processes, more than 90% of the controllers are Proportional, Integral, Derivative (PID) type. PID-type controllers are widely used to control different processes ranging from aerospace applications, regulatory applications and servo applications [1]. The PID controllers are chosen due to the simplicity in the adjustment of the performance / robustness requirements, in addition to their ability to achieve a zero steady-state error in the presence of constant disturbances [2]. If the process has a precise mathematical model, the PID controller can be used effectively to control the process. There are three parameters in the PID controller whose exact values need to be calculated to obtain the best control output. The main problem with PID controllers is the precise and efficient adjustment of the parameters that meet the performance specifications of the closed loop system.

PID controller adjustment has always been an area of active interest in the process control industry. The Ziegler Nichols (ZN) method is one of the best conventional tuning methods available now [3]. Although the ZN tuning method tunes the systems very optimally, better performance is needed for a very fine response and this is obtained using some other PID controller parameter tuning methodology

The incursion of the three-phase induction motors in the industry, have reached applications where it is interesting and advantageous to optimize the performance such as: paper machines, fans, centrifugal pumps; and many other applications. Also where the transitory regime is of equal duration and importance, such as rolling mills, elevators, cranes, electric vehicles, robots, and many more [4, 5]. Here, speed variators have come to solve the problem of being able to use the motors at variable speeds without diminishing their efficiency allowing full control and optimization of the engine in permanent and transitory regime, which saves money in the electricity bill in production companies where these have been installed [6]
Thus the objective of this work is to show the performance of a classic PID controller applied to a three-phase induction motor, starting from the gains obtained by the tuning methods based on the reaction curve, the Cohen and Coon, Poles and Lopez's. The objectives of the PID controller that must be minimized are: minimum rise time, less overshoot and minimum establishment time.

II. System Description

The representative diagram used for the control of the squirrel-cage induction motor is shown in figure 1. Where the elements that comprise it are: the squirrel-cage motor coupled to a DC generator to perform the load function of the squirrel cage motor. The tachometer that allows sensing the speed of the engine. A data acquisition card to transfer the information of the sensed signal of the motor to a personal computer (PC) and send the control signal from the PC to the frequency inverter, which activates the induction motor; and the personal computer which is in charge of controlling the motor. Following all these components are described:

- Squirrel Cage Motor: The motor used for this work is a 3-phase four-pole squirrel-cage induction motor with a power supply voltage of 120/280 to 60 hz, and a 2 kW capacity of the Lab-Volt brand. To simulate the operation of the induction motor in a work environment, a load was applied which is represented by a Direct Current Generator of the Lab-Volt brand. The generator consists of a 4-pole

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J. Cerda, S. Ramirez and D. Zepeda are with the Universidad Michoacana, Morelia, Mexico. phone: +52 443 3223500 ext. {1177, 4350}; e-mail: {jcerda@umich.mx, srzavala@umich.mx}
V. Torres is with the Tecnologico de Morelia, Morelia, Mexico. e-mail: vtg_1982@hotmail.com

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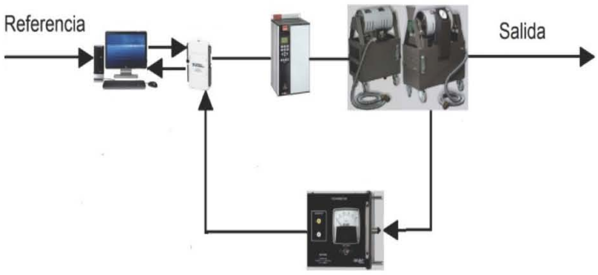

Figure 1. Control system diagram

machine with a capacity of 2 kW. With this motor a load of the resistive type with a value of 20 Ω is fed. When the resistive load is connected, the mechanical load in the induction motor will increase, as the resistive load increases, the mechanical load will be greater, allowing the motor to be subjected to different loads [7].

- Tachometer: is the sensor used to measure the speed of the engine. It consists of a permanent magnet generator connected to a calibrated meter. The output of the generator provides a voltage / speed ratio of 1 V of CD / 1000 rev / min. [7]
- Data Acquisition Card: The data acquisition card used is the NI-USB-6216 model from National Instruments, used to acquire the speed signal and transmit the control signal to the frequency inverter [8, 9].
- Computer: The computer is responsible for making the digital PID controller. The control system is implemented in the graphic programming environment of National Instruments LabVIEW. Figure 2 shows the panel designed to manage the PID controller; where it can be seen it is constituted by a graphic window that shows the response of the controller, an adjustment box to choose a value of the reference and finally other adjustment boxes to place the proportional, integral and derivative gains.
- Frequency Variator: Used to vary the frequency of the power supply of the induction motor. The frequency converter used is of the industrial type of the Danfoss brand model VLT 5000 [10]. The parameters of power, operating frequency, speed, voltage and motor supply current are programmed in the inverter to achieve a linear frequency output given by equation (1) that represents the voltage & frequency ratio.

$$\text{Frequency} = \text{Control Voltage} * 13.7254 \quad (1)$$

III. Classic PID Controller

These controllers have proven to be extremely beneficial in the control of many industrial applications. The structure of these controllers is formed by three basic actions such as Proportional, Integral and Derivative. The combination of these actions has the advantage of each of these individually. Equation (2) describes this type of controller in its analog form [1].

Figure. 2 PID controller frontal panel.

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right) \quad (2)$$

Where:

- e (t) = Error = vel_de_referencia - vel_actual
- K_p = Proportional gain.
- Ti = Integral gain.
- Td = Derivative gain.

For the conversion of the analogous equation (2) to a digital one, for this work it was carried out by the rectangular approximation method obtaining equation (3) [11].

$$u_n = K_p\left(e_n + \frac{1}{T_i}\sum_{n=0}^{n}\left(\frac{e_n+e_{n+1}}{2}\right)T_s + T_d\frac{e_n-e_{n-1}}{T_s}\right) \quad (3)$$

where T_s is the sampling period of the signal. One of the disadvantages of this type of controller is to find the values of their gains since there can be an infinity number of solutions of the same ones.

IV. SINTONIZATION METHODS

Transient Response Method: The method is based on the reaction curve of the process before a step-type input as shown in Figure 3 [1]. And it consists of approximating the input-output behavior of the plant, to a first order system with dead time given by 4.

$$G(s) = \frac{K}{\tau s+1}e^{-Ls} \quad (4)$$

Where: K is the static gain, τ is the apparent time constant, L is the dead time constant The delay operator e ^ (- Ls) can approximate a rational function given by equation 5.

$$e^{-Ls} \cong \frac{1-\frac{Ls}{2}}{1+\frac{Ls}{2}} \quad (5)$$

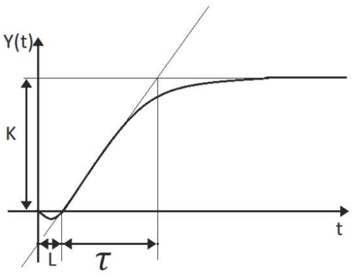

Figura 3. Respuesta de una planta a la entrada escalón

The parameters necessary to perform the tuning of the controller, is obtained from the rules shown in Table I.

TABLE I
RULES FOR TUNING CONTROLLLERS BY THE TRANSIENT RESPONSE METHOD

Controller	K_p	T_i	T_d
P	1/RL	∞	0
PI	0.9/RL	L/0.3	0
PID	1.2/RL	2L	L/2

Cohen and Coon method: The transient response method does not consider the process to be self-regulated. Cohen and Coon then introduced an index of self-regulation defined as $\mu = L / \tau$ and they proposed new tuning equations [2]. These are based on a better model given by equation 4 that can be obtained from control loops [1].
The parameters used for the transient response method are used and obtained in the same way. Equations 6 are used to reduce the space in Table II where the equations to obtain the gains K_p, T_i and T_d are appreciated.

$$a = \frac{KL}{\tau} \qquad T = \frac{L}{L+\tau} \tag{6}$$

TABLE II
COHEN AND COON METHOD TUNNING EQUATIONS

Control	K_c	T_I	T_D
P	$\frac{1}{a}\left(1+\frac{0.35T}{1-T}\right)$	∞	0
PI	$\frac{0.9}{a}\left(1+\frac{0.92T}{1-T}\right)$	$\frac{3.3-3T}{1+1.2T}L$	0
PID	$\frac{1.35}{a}\left(1+\frac{0.18T}{1-T}\right)$	$\frac{2.5-2T}{1-0.39T}L$	$\frac{0.37-0.37T}{1+0.81T}L$

Pole Method: This method is based on the location of poles, which says that if the poles are in the left half plane, the system is stable.This method is based on obtaining a second order transfer function that allows obtaining some parameters necessary for the calculation of the gains.

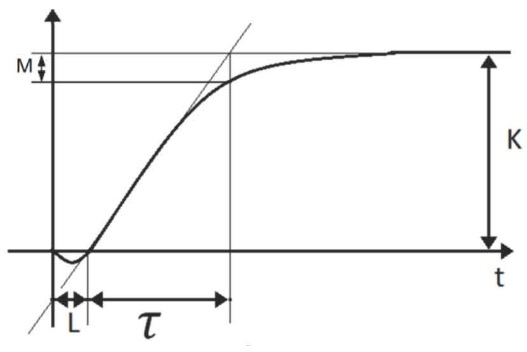

Figure 4. Transfer function parameter computation

In order to obtain the second order transfer function, it is necessary to draw several lines in the response curve of the open loop system [12]. Figure 4 shows how to draw the lines and obtain the necessary parameters to be able to obtain the transfer function. Subsequently, equations 7 are applied.

$$a = \frac{M}{K} \qquad T_1 = \tau\frac{3ae^1-1}{1+ae^1} \qquad T_2 = \tau\frac{1-ae^1}{1+ae^1} \tag{7}$$

With the results of 7 the approximate transfer function given by 8 is obtained.

$$G(S) = \frac{K}{(T_1S+1)(T_2S+1)} \tag{8}$$

The above equations will be correct only if they meet the given ratio by:

$$\frac{1}{3e^1} < a < \frac{1}{e^1}$$

After calculating the values of 8; the desired stabilization values are proposed, such as the maximum overshoot (M_p) and the stabilization time (T_s); from these values you can obtain the damping factor (ζ) and the natural frequency (ω_n) as mentioned in [13]. With the above values, a transfer function given by (9) is produced, which has two complex poles that will help to compensate and obtain the system stabilization.

$$\frac{w_n^2}{S^2+2\zeta w_n S+w_n^2} \tag{9}$$

When we obtain the poles of the transfer function, we will find two poles with an imaginary part of the form -a ± i * b. Taking a pole, the angle α is calculated with respect to the origin. After having obtained the parameters damping factor, natural frequency and angle, the values of the constants of the PID controller can be calculated by means of equations 10, 11 and 12.

$$K_c = \frac{T_1T_2w_n^2(1+2\alpha\zeta)-1}{K_p} \tag{10}$$

$$T_i = \frac{T_1T_2w_n^2(1+2\alpha\zeta)-1}{T_1T_2w_n^3} \tag{11}$$

$$T_d = \frac{T_1T_2w_n(\alpha+2\zeta)-T_1-T_2}{T_1T_2w_n^2(1+2\alpha\zeta)-1} \tag{12}$$

Lopez method: The performance criteria used by Lopez were: Integral of the absolute error (IAE), Integral of the absolute error along the time (IAET) and Integral of the squared error (ISE) [14]. The optimization of the integral performance criteria of López is based on the best model of 4 that can be obtained, for control loops that work with a PID-Ideal controller. Tuning equations are given by 13.

$$K_cK_p = a\left(\frac{L}{\tau}\right)^b \qquad \frac{T_i}{\tau} = \frac{1}{c}\left(\frac{L}{\tau}\right)^{-d} \qquad \frac{T_d}{\tau} = e\left(\frac{L}{\tau}\right)^f \tag{13}$$

Where K_p is equal to K and the values for the constants a, b, c, d, e, f for the different criteria are given in table III.

TABLE III
LOPEZ METHOD CONSTANTS TO COMPUTE THE PID GAINS

	a	b	c	d	e	f
IAE	1.435	-0.921	0.878	-0.749	0.482	1.137
IAET	1.357	-0.947	0.842	-0.738	0.381	0.995
ISE	1.495	-0.945	1.101	0.771	0.560	1.006

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Obtaining the induction motor transfer function: Firstly, the motor reaction curve was obtained by applying a step input with a value of 2100 rpm in open loop, to obtain the response of the system and to obtain the gains of the PID controller applying the different tuning methods described. Figure 5 shows the response curve of the open-loop system from which the dead time values (L = 1.9s.), Time constant (τ = 5 s.), The amplitude of the applied step (K) are obtained. = 33.98 rps.) And the value of M = 5.1 rps; with these values the model of the system can be approximated to a system of first order given by 4.

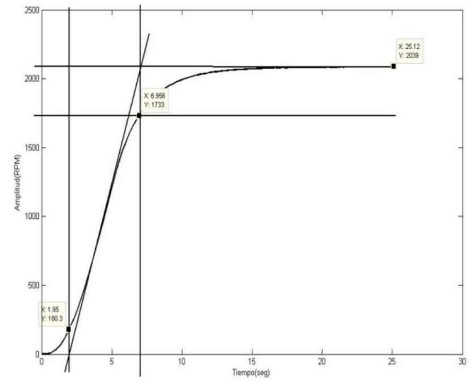

Figure 5 Open loop step response

V. Tests

First the gains of the PID controller were calculated for the described tuning methods and subsequently the tests of the behavior of the system in closed loop were carried out with a reference signal of speed of 1000 rpm. For the transient response method when applying the equations of table I, the gains Kc = 0.0929, Ti = 3.8 and Td = 0.95 are obtained; and the response of the closed loop system is shown in figure 6.

In the Cohen and Coon Method; applying equations 6, the necessary values are obtained in order to apply the equations presented in table II; which leads to the gains values Kc = 0.1091, Ti = 3.868 and Td = 0.6556; The response of the closed loop system is shown in figure 7.

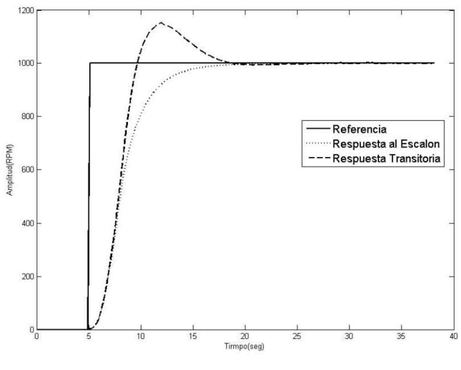

Figure 6. Transitory response step input method

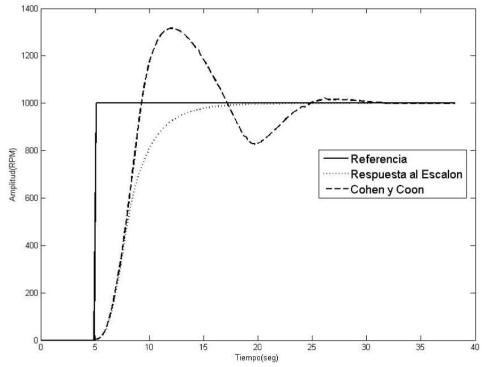

Figure 7. Cohen and Coon method step input response

For the Pole Method; applying equations 7, we can obtain the transfer function given by 8 and selecting the maximum overshoot of 4.3 and the stabilization time of 14 seconds that improve the open-loop response. With these values, the damping factor ζ and the natural frequency w_n of the system are obtained. Building the transfer function given by 7, where the location of the poles is -0.286 ± 0.285i, with an angle of 2.35 rad.

With the obtained values and using (8), (9) and (10) the controller's gains are calculated obtaining: K_d = 0.063996, T_i = 1.3854 and T_d = 0.1931. And the response of the closed loop system is shown in Figure 8.

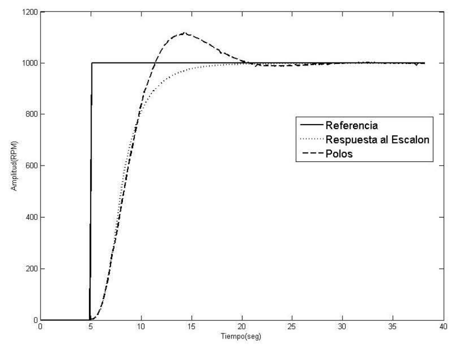

Figure 8. Poles method step input response

In the López Method; when applying the equations of 11 and taking into account the ISE constants (which are the ones that presented a better response) of table 3, the values of the gains K_c = 0.5469, T_i = 2.1537 and T_d = 1.0578 are obtained; and the response of the closed loop system is shown in Figure 9.

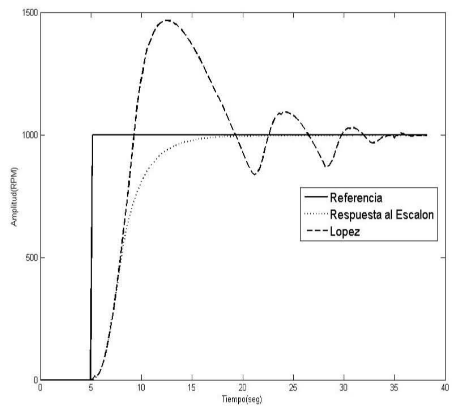

Figure 9. Lopez ISE method step input response

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Figure 10 shows the comparison in the step response of the different tuning methods applied to the system. All the methods present an overshoot but not all oscillate as in the case of the method of Lopez and Cohen and Coon. The Transient Response method has an overshoot greater than that of Poles, but both manage to stabilize at the same time. Thus it can be seen that the most outstanding method is that of poles.

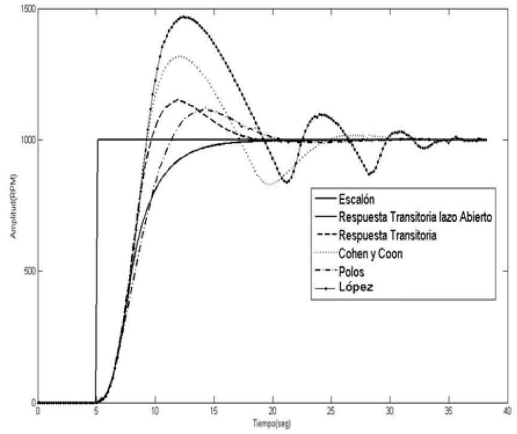

Figure 10. Comparing methods response

As it was mentioned, the proposed tuning methods only present approximate values of the gains. Now adjusting these values to have a better performance; taking the values of the starting pole method and readjusting them based on the behavior of the system, the new gain values $K_c = 0.05$, $T_i = 1.38$ and $T_d = 1.19$ are obtained; with which the stabilization time and the overshoots generated in the pole method are shortened. Figure 11 shows the response of the closed loop system for the pole method where it has an overshoot and for the new improved gains a smaller overshoot is observed than the one made by the pole method.

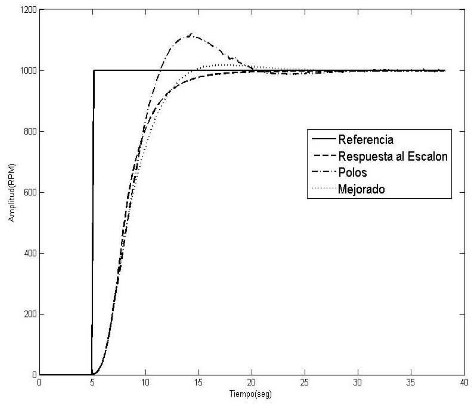

Figure 12. Poles and enhanced method step response

VI. Conclusions

In this work, the comparison between different tuning methodologies for PID controllers has been presented. The results of the tuning methods of the PID controller; were verified in real time when applied to a three-phase induction motor, using a commercial frequency inverter and using high-level programming languages; as is the case of LabVIEW™, which greatly facilitates the implementation of the driver. According to the results obtained, the PID controller adjusted by the pole method provides adequate control characteristics (minimum rise time, less overshoot and minimum establishment time), furthermore, it allows to have a starting point for the fine adjustment of theose characteristics.

The obtaining of the gains for the improvement of the performance of the controller was obtained after several tests, taking initially into account the gains of the PID from the poles method, which was of great utility to initiate the correct tuning of the controller.

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