International Journal of Emerging Engineering Research and Technology
Volume 4, Issue 1, January 2016, PP 82-89
ISSN 2349-4395 (Print) & ISSN 2349-4409 (Online)

PID Controller with Adjustable Parameters via Fuzzy Logic

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ABSTRACT

The automatic tuning gains into a PID (Proportional-Integral-Derivative) controller, based on the error properties generated between the output system and the reference signal, permit a greater adaptation between the system and its environment when an intelligent controller and an adequate fuzzy logic model are used. Contemplating Mamdani properties to reach a desired response through the regulation of the PID gains, here is presented an adaptive strategy which allows the tuning of PID gains instead of having them static, as with traditional methods given for steady states conditions and smooth movements. To avoid overshooting, new coefficients are required and the controller must adjusts the conditions so that the system does not lose stability; this is achieved if the membership functions and associated inferences are bounded by the distribution function error. The method considers an electric motor separately excited, simulated in Matlab®, and an illustrative comparison between the intelligent control and the traditional Ziegler-Nichols method.

Keywords: Automatic Tuning, Fuzzy Logic, Ziegler-Nichols Method, PID Controller.

INTRODUCTION

The discrete PID controller, based on the functional error, is commonly used in academic and industrial fields because its structure is simple, reliable, practical and easy to execute, adjusting its three internal gains in agreement to Ziegler-Nichols method [1]. However, it is not possible to estimate these gains in cases where the dynamic system changes losing the stationary conditions and requiring an expert hand to adjusts them, seeking to minimize the convergence error without knowing in precise manner how to determine the frontiers.

Minav (2012) [2] commented that Astöm- Panagolopoulos [3], Cohen-Coon [4] and Tyreus-Luyben [5] developed different strategies to assign gains using modal control, neural networks and fuzzy logic, among others; generating adaptive forms to tune the controller and in consequence modifying the system response. These facts represent opportunities to improve the system performance using auxiliary techniques or hybrid models as, for example, the use of statistical inferences to extract the PID gains, minimizing the settling time and overshoot magnitude.

The error is an innovation process defined as a function of the difference between the desired signal and the controlled system response, bounded by a distribution with statistical properties, changing the stationary conditions when an overshoot appears in the system. The distribution function suffers a little alteration, and the two first probability moments change too.

In the fuzzy sense, taking into account that the convergence error has a distribution function and its borders contain the membership functions, it is possible to create inferences based on experienced experts and is recommendable for applications where there is no precise model of the system behaviour. These characteristics permit improve the PID controller performance.

This paper compares the discrete classic PID, using the Ziegler-Nichols method, with fuzzy logic strategies; highlighting, that the membership functions, inferences mechanisms and the centroid concept are adapted with the innovation process.

STATE OF THE ART

The aim of PID controllers is to reduce the output system disturbances, and for the reference approaches, improve the tuning process. For example, according to Leva (1993) [6], the offline

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control system increase the integral gain, this leads to a bad efficiency because of the PID gain calculation; optimization has time and energy restrictions, complicating even more the particular solution and making difficult the implementation with limited resources in architectures, such as embedded platforms, where control algorithms usually have restrictions. Zhuang (1993) [7] described a partial solution obtaining formulas for the required gains calculation, focused on reducing the integral gain and defining a frequency and proportional gain into feedback; resulting in a method used for first order models characterized by lack of accuracy and a deficient performance.

Romero (2011) [8] proposed an automatic tuning algorithm for PI and PID controllers depending on feedback and minimizing the integral error due to load disturbances. This increases the controller integral gain value according to a phase margin and minimum gains restrictions. Due to the tuning procedure requires data from the frequency of the system response, Tan (2005) [9] suggested an empirical way to obtain the frequency of the feedback system response.

Mudi (2008) [10] proposed the load disturbances reduction and the convergence between the output and the reference signals when a change is detected, indicating that the Ziegler-Nichols tuning method tends to fail when it is applied in higher order systems, either linear or nonlinear, especially when changes in the reference exist because of excessive oscillations associated to an overshoot value. Instead of it developed the Augmented Ziegler-Nichols PI Controller (AZNPIC); tuning involved a weak control action when the process moves towards the set point, but in contrast, there is an aggressive control action when the process moves away from the set point. It also achieves the adjustment by modifying the proportional and integral gains, depending on error and rate of change at the last moment. AZNPIC operation is based on the response of a typical underdamped second order system (Figure 1). For example, if the error is high and the controlled variable is close to the reference, then the proportional gain must be high to reach the reference (cases A and C); on the other hand, the integral gain must be negative and small enough to avoid an overshoot.

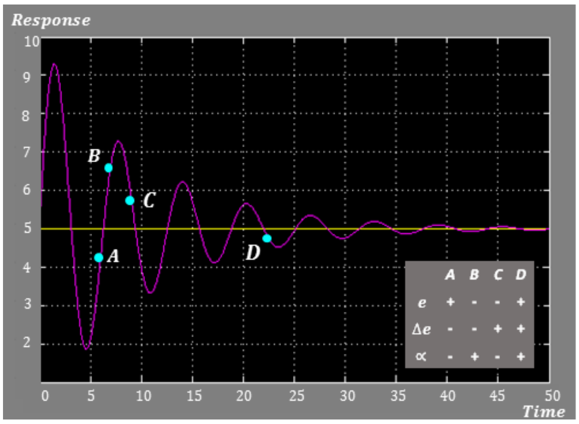

Fig1. *Typical response of an underdamped second order system. The reference is in yellow, and the response is in magenta. (Information taken from Mudi (2008)).*

The system performance needs not only the analytical tuning PID methods, but also different control techniques and their combinations, for example, Fuzzy Logic (FL), Neural Networks (NN) and Genetic Algorithms (GA). These hybrid-tuning systems do not modify the PID simplicity. Sun (2013) [11] proposed an example of automatic Fuzzy logic tuning, where error and its change rate are the base to obtain k_p, k_d and k_i gains from a conventional PID. Wang (2009) [12] implemented one similar solution focusing on the complexity when the controlled variable is nonlinear.

In academic and industrial scopes, the motor separately excited is one of the most used systems due to its starting and stopping performances. The PID controller applied to the system is affected by static and dynamic friction obtaining a nonlinear behaviour, requiring an additional tuning technique. The one Rui (2009) [13] proposed has a classic PID controller scheme and a fuzzy inference module for new parameter tuning values.

PERMANENT MAGNET MOTOR MODEL

Guevara (1999) [14] proposed the model of a monophasic permanent magnet motor whose equivalent circuit is shown in Figure 2, describing its variables in Table 1. The magnetic field associated to the stator is not included in the circuit because a magnet generates it. In (1) it is given the relationship between the motor torque and the electrical current and in (2) the angular velocity and Counter Electro Motive Force (CEMF), respectively.

$$T(t) = K_p\, i(t) \tag{1}$$

$$\varepsilon(t) = K_b \frac{d\theta}{dt} = K_b\, \omega(t) \tag{2}$$

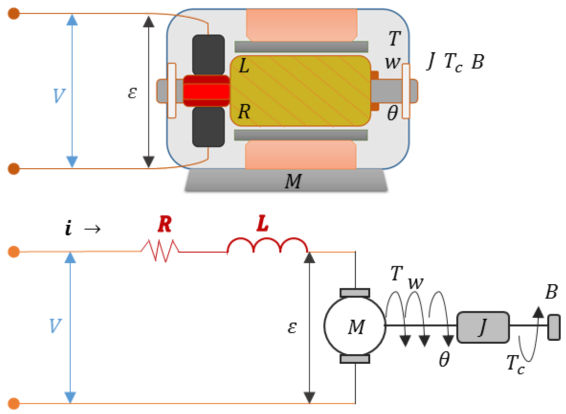

Fig2. *Equivalent circuit of a permanent magnet motor.*

Table1. *Variables of the Circuit Included in Figure 2.*

Magnitude	Variable	Units Variable
Rotor’s electrical current	*i*	[A]
Voltage of the rotor’s power supply	*V*	[V]
Rotor resistance	*R*	[Ω]
Rotor coil inductance	*L*	[H]
Counter Electromotive Force (CEMF)	ε	[V]
Motor torque	*T*	[N m]
Angular velocity	ω	[rad/s]
Angular position	ϴ	[rad]
Inertia moment	*J*	[Kg m^2]
Viscous friction coefficient	*B*	[(N m) / (rad s^{-1})]
Load torque	T_c	[N m]

Having K_p and K_b, as torque and CEMF constants, (3) and (4) are the approximated descriptions of the permanent magnet motor behaviour based on Kirchhoff voltage law, the torque and the inertia moment.

$$K_p\, i(t) = J \frac{d\omega(t)}{dt} + B\omega(t) + T_c \tag{3}$$

$$V(t) = L \frac{di(t)}{dt} + Ri(t) + K_b\omega(t) \tag{4}$$

The transfer function in Laplace domain, (5), is obtained by (3) and (4), clearing the angular velocity and considering a null torque at the beginning, but not in the following operations.

$$\frac{\omega(s)}{V(s)} = \frac{K_p}{s^2 JL + s(RJ + BL) + (RB + K_p K_b)} \tag{5}$$

Table2. *Magnet Motor Permanent Values, by Crouzet (2015) [15].*

Magnitude	Variable	Units Variable	Value
Rotor coil inductance	*L*	[H]	0.0416
Inertia moment	*J*	[Kg m^2]	1.9 $x10^{-6}$
Viscous friction coefficient	*B*	[(N m) / (rad s^{-1})]	5.277 x 10^{-5}
Rotor resistance	*R*	[Ω]	32
Torque constant	K_p	[N m/A]	0.0448
CEMF Constant	K_b	[V s]	0.0448

Equation (6), in time domain, gives the angular velocity according to (5) by using the inverse Laplace transform, a step input and the values of Table 2. Figure 3 shows its time response.

$$\omega(t) = 12.1296 - 13.2842 e^{-63.7293 t} + 1.1546 e^{-733.2383 t} \tag{6}$$

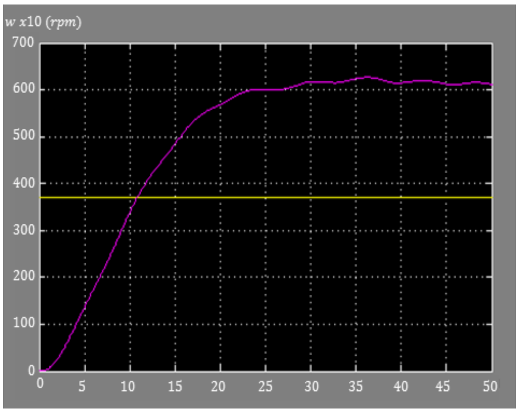

Fig3. *Permanent magnet motor response to a step input without control building mathematically into Simulink®. The reference is in yellow, and the response is in magenta.*

PID CONTROLLER APPLYING ZIEGLER-NICHOLS METHOD

The Ziegler-Nichols method tunes the PID system gain parameters in transient state responses, for an input step and follows the rules established in Table 3.

Table3. *Tuning Rules for Ziegler-Nichols Method by González (2013)[16].*

Controller	Kp	Ti	Td
P	T/L	∞	0
PI	0.9 T/L	L/0.3	0
PID	1.2 T/L	2 L	0.5 L

The parameters for the motor modelled with transient response are $L=0.0466x10^{-4}$ and $T=0.0198$; replacing these values in Table 3 and applying the PID model shown in Figure 4, the controlled motor time response is obtained as in Figure 5.

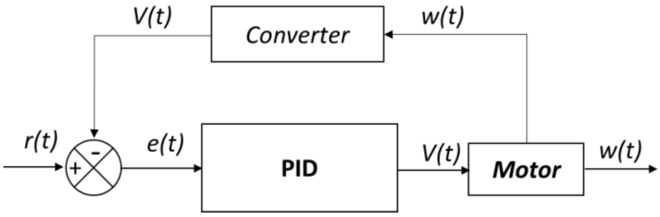

Fig4. *Control block diagram for a motor separately excited.*

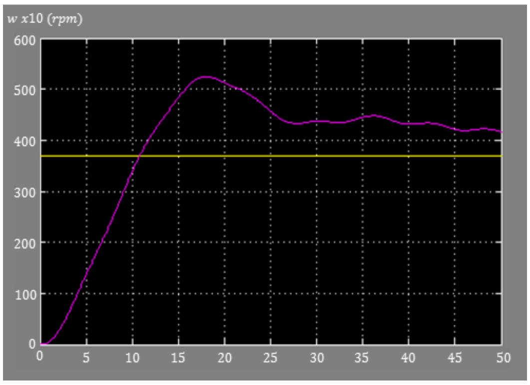

Fig5. *PID controller motor with separately excited response to a step input developed into Simulink®. The reference is in red, and the response is in blue.*

FUZZY LOGIC CONTROL DEPENDING ON MAMDANI'S CONCEPTS

From logic rule set: if A, and B then C, a methodology creates the control motor velocity. The block corresponding to the PID in Figure 4 is now replaced by one, including the four principal parts of a Fuzzy controller (Figure 6).

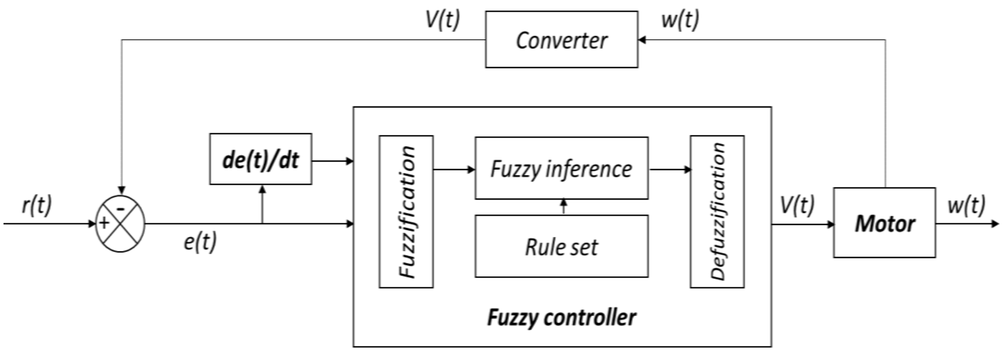

Fig6. *Fuzzy controller main block.*

The linguistic variables introduce the error and the differential error (D_Error) values: NN (much greater negative), MN (greater negative), LN (slightly negative), C (zero), LP (slightly less positive), MP (less positive), PP (much less positive) and the voltage (Voltage).

The set rule used is the one exhibited in Table 4, where the first row and column are the input variables for the conjunction operation and the content is the consequence between the velocity control and voltage variation. The membership functions to develop the fuzzification are triangular normalized values due to their geometric characteristics (Figure 7).

Table4. *Fuzzy Logic Rules for Velocity Motor Control.*

Velocity	"Error"			
		NN	MN	LN
"D_Error"	NN	MBV	MBV	MBV
	MN	BV	BV	MBV
	LN	BV	BV	BV
	C	BV	BV	BV
	LP	BBV	BV	BV
	MP	BBV	BBV	BV
	PP	BBV	BBV	BV

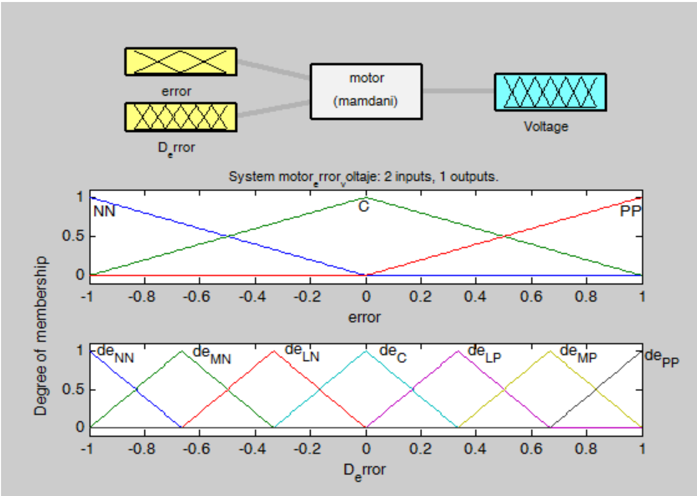

Fig7. *Fuzzification based on fis module using Matlab® with Error membership functions normalized.*

Every element from a Fuzzy set relates a linguistic and numerical value inside the interval [0, 1], named membership value or degree of membership used to evaluate rules from Table 4 to obtain a conclusion to defuzzificate by using the centroid method. Figure 8 shows the response of the controlled motor model.

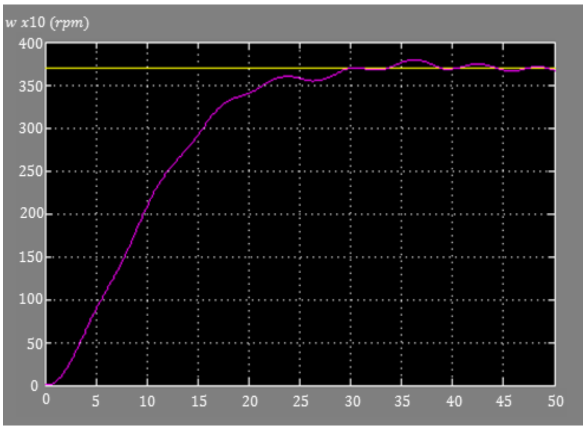

Fig8. *Response of electric motor separately excited adapting the parameters into a PID controller based on fuzzy logic depending on mathematical models applied in Simulink®. The reference is in yellow, and the response is in magenta.*

FUZZY LOGIC APPLIED IN PID TUNING

The automatic tuning method applied to a PID controller for the motor velocity, includes the load effect (Tc) as a random variable leading to the convergence error. At the beginning, the PID gains are calculated by the Ziegler-Nichols method (Figure 9).

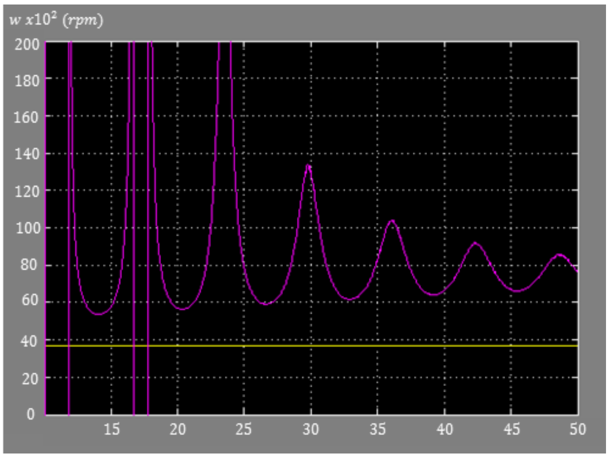

Fig9. *Tc effect into classic PID Motor response adjusting its parameters with Simulink® results. The reference is in yellow, and the response is in magenta.*

The criteria to assign the gains values hinges on the central membership function error and its change ratio wherein 35 normalized values are considered in order to estimate the means and calculated a degree of confidence for each central tendency estimation as shown in Figure 10. If the degree of confidence is bigger or equal to 80% then the Fuzzy tuning block obtains the new PID gains, in other cases, more samples are requested. The response to this tuning method is shown in Figure 11.

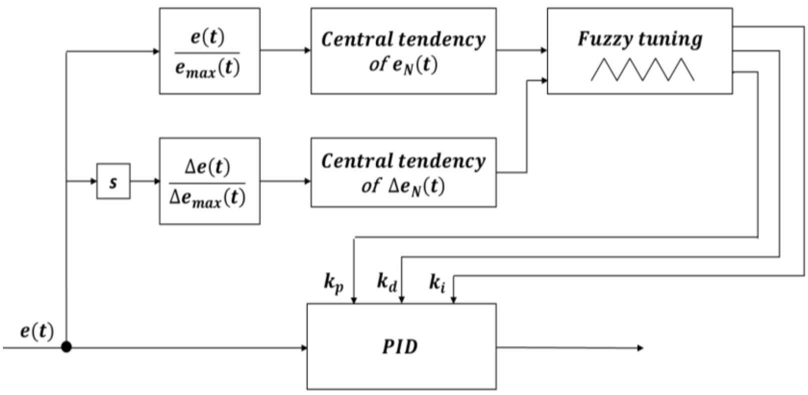

Fig10. *Fuzzy logic PID parameters tuning block diagram.*

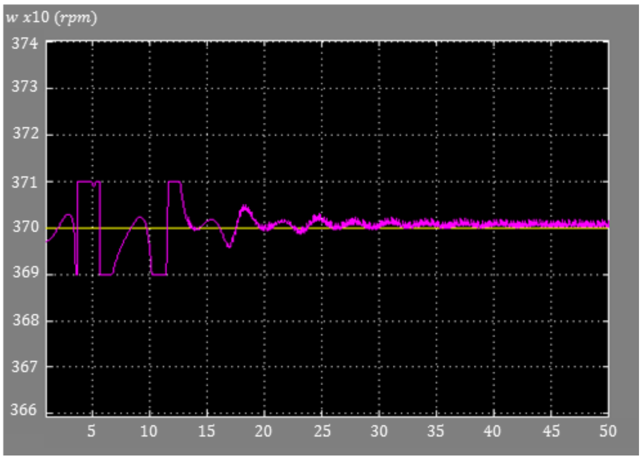

Fig11. *Automatic PID tuning applied on Simulink® as a fuzzy logic adaptation function influenced by Tc. The reference is in yellow, and the response is in magenta.*

CONCLUSIONS

Comparing angular velocity response when the system does not include noise effects (Tc=0), the PID static gains models have good response. When the system has an overshot, a Fuzzy model helps to minimize its effects into an output response. Nevertheless, if the operation conditions have been changed it is necessary to obtain new parameters because the considered error increases its complexity, and the PID controller suffers a new dynamic adjustment. How to solve the PID selection parameters problem? The answer in the fuzzy logic sense because it considers the random error and the distribution properties, bounding many membership functions and adapting to evolution forms. The fuzzy logic considerations into the PID controller have better results. For steady error properties, the control has not an aggressive action because it considers the historical error, predicting not only the possible error, but also the behaviour of the complete output system.

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