A tuning proposal for direct fuzzy PID controllers oriented to industrial continuous processes

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Abstract: Conventional PID controllers have been a practical solution when controlling linear processes but its response is degraded considerably in strongly nonlinear processes. Fuzzy control presents an improvement in the response because its nonlinear nature. However, there is no absolute tuning methodology, with solutions ranging from trial and error to sophisticated computational methods. In this paper, we present a simple but effective systematic approach for the tuning of several direct fuzzy PID controllers, based on the calculation of static gains of linear sub-models and controller scaling factors. The proposed methodology was successfully tested in a nonlinear process model and a CSTR model.

Keywords: Fuzzy control, nonlinear control, tuning methods, scaling factors, PID control.

1. INTRODUCTION

In control of continuous processes, it is desired to impose a behaviour in the response of the system and maintain it in such behaviour despite the disturbances. The most popular controller used in the industry is the Proportional-Integral-Derivative (PID) because its performance in linear processes (Blevins, 2012), (Vilanova & Alfaro, 2011). For this controller different architectures and parameter adjustment methods (tuning) have been proposed (O'Dwyer, 2003), including empirical and analytical model-based approaches. In this case, tuning rules are proposed relating the controller parameters with the process model parameters, allowing a systematic adjustment. Historically, the well-known approach under this perspective was presented in (Ziegler and Nichols, 1942). During several decades a lot of tuning methods have been proposed. The extensive information in the literature and events worldwide about the evolution of the PID controller, for instance, the IFAC PID Workshop Present and Future of PID, indicates that it continues to be a trend in both the industrial and academic fields.

Although there are several methods of adjustment of the PID controllers and their extensive use, conventional PID controllers show performance degradation frequently, due to changes in operation points showing non-linear behaviour, even with an adequate tuning of the controller parameters at the point of operation of the process (Viljamaa and Koivo, 1995). Trying to solve these difficulties, the use of non-linear control systems that can provide a better performance compared with the conventional PID arises as an alternative.

Fuzzy control has been used in the industry with success in the last two decades (Guerra et al., 2015), (Precup and Hellendoorn, 2011) in control tasks of non-linear behaviours. As in conventional PID, the essential principle of operation is based on the calculation of the corrective action from the behaviour of the error. Many works show alternative ways to treat aspects of nonlinearity in the behaviour of processes (Diaz-Salgado et al., 2012). However the fuzzy approach can provide a simple strategy maintaining the classic PID structure through a soft switching of controller gains.

Several architectures for fuzzy logic control (FLC) have been proposed (Mann et al., 1999) such as direct, supervisory and hybrid. In the case of the direct fuzzy control, the fuzzy PID controller is within the feedback control loop, acting directly over the process. Another architecture is supervisory fuzzy PID, where the fuzzy controller acts as a gain scheduling supervisor of a conventional PID controller. Additionally, in the hybrid architecture the control actions are a parallel combination of a FLC and a conventional PID.

Regardless of the architecture used, the FLCs show advantages such as adaptation capacity to control non-linear processes, flexibility of implementation and no strict-mathematical model required (Babuska, 2009). One disadvantage of the FLCs design and tuning is that methods are not general enough, they have not been broadly detailed and there is still room for more systematic approaches. Therefore, trial and error procedures are frequently required through simulations by computational systems or process tests. This caused by the huge number of parameters or aspects to be modified in the FLC controller, including rule base and membership functions, among others (Hu et al., 2001), (Mann et al., 1999). In order to obtain a better performance to solve the tuning problem, techniques from computational intelligence like genetic algorithms (Lin and Xu, 2006) and artificial neural networks (Hímer et al., 2005) have been used. These methods employ objective functions to solve an optimization problem, which usually implies a complex mathematical treatment and in some cases convergence problems and a high computational cost.

In the industry and within the engineering practice is not typical the availability of a rigorous mathematical representation describing the behaviour of the process; hence simple models are more common, and developing of tuning methods with the minimum information of the process is desirable, in order to obtain the controller parameters in a simple way. In this work, a methodological approach of a family of direct FLC tuning is proposed, obtaining the appropriate input and output scaling factors of the fuzzy system. These gains influence the performance and stability of the system in the same way as the gains of a conventional PID. An inadequate choice leads to excessive oscillations, over-damping and instability. The appropriate calculation of the scale factors is obtained from the dynamic response of the process to be controlled, through expressions allowing the establishment of a simple and systematic procedure, reducing the necessary time in the tuning of the FLC.

This article is organized as follows: section 2 introduces different architectures of direct FLC PID controllers, section 3 presents the methodological approach for the tuning of the considered fuzzy PID controllers; section 4 reveals the analysis of results through simulations applied to two nonlinear systems, and finally section 5 presents conclusions and recommendations for future work.

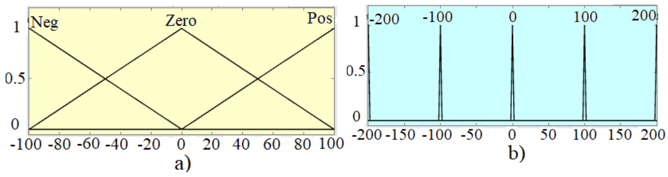
2. DIRECT FLC ARCHITECTURES

Direct architecture FLCs are used in many applications (Mann et al., 1999), for which the control surface can be modified by changes in the following elements: rule base, shape of membership functions (MFs), location in the discourse universes, selection of the fuzzy inference system and defuzzification method. As a consequence, the non-linear mapping of the inputs and the output is changed. Another way to modify the nonlinearity of the FLC is through the scaling factors, which allow the MFs both for inputs and output to be modified in the discourse universes, allowing the modification of the controller's time response.

2.1 FPD+I Architecture

The architecture *fuzzy proportional-derivative-plus-integral* (FPD+I) proposed in (Jantzen, 1998) uses the error (e) and the derivative of the error (Δe) as inputs to the FLC, and output control action (u). In the inputs, a dynamic pre-filtering is carried out to obtain Δe and/or ∫e by means of linear filters. In addition, the signals are normalized in an operating range [-1, 1]. In the output, a dynamic post-filtering is performed to normalize the signal to [0, 100].

By selecting the scale factors and the standard parameters defined in figure 1, a linear control surface is generated, allowing an equivalence with the response of a conventional PID controller of ideal architecture. In the construction of the rule base, the inputs *e* and *Δe* are considered, in order to correct the steady-state error in the response, and the integral of the error is added to the output of the fuzzy system by an escalation factor.



u		e		
		Neg	Zero	Pos
Δe	Neg	-200	-100	0
	Zero	-100	0	100
	Pos	0	100	200

c)

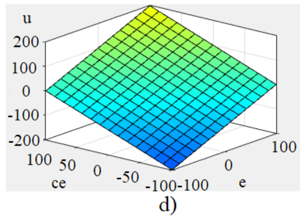


Fig. 1. a) MFs for the inputs e, Δe, b) MF for the output u, c) Rule base, d) Control surface.

Therefore, the architecture of the FLC is shown in figure 2:

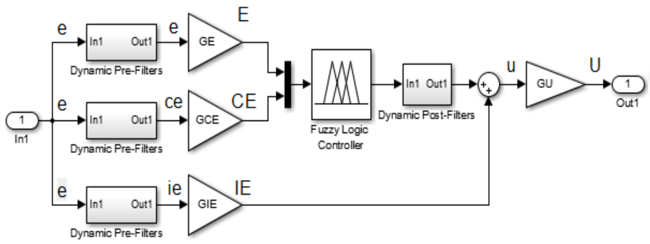


Fig. 2. Architecture of an FPD + I controller

The control action of an ideal PID is defined as:

$$U(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + Td\frac{de(t)}{dt}\right) \tag{1}$$

The control action produced by the FLC is:

$$U = GU\left[GE \cdot e + GCE \cdot ce + GIE \cdot ie\right] \tag{2}$$

By comparing the control actions (1) and (2), the expressions for the scaling factors are as follows:

$$GE = 100 \tag{3}$$

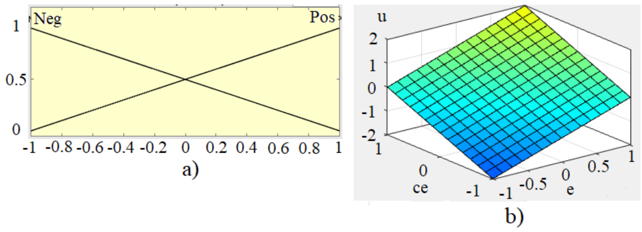
$$GU = k_p / GE \tag{4}$$

$$GCE = T_d \cdot GE \tag{5}$$

$$GIE = GE / T_i \tag{6}$$

2.2 MHPID Architecture

The architecture *modified hybrid proportional-integral-derivative* (MHPID) proposed in (Escamilla, 2002), uses as inputs of the FLC the e and Δe and as output u. It is also necessary a dynamical pre-filtering and dynamic post-filtering. To obtain a linear control surface that will allow finding the values of the scale factors, the following base of rules and membership functions for the inputs will be used:



R_1: If E is N and $\dot{E}$ is N then $u = p_1{*}E + q_1{*}\dot{E} + r_1$
R_2: If E is N and $\dot{E}$ is P then $u = p_2{*}E + q_2{*}\dot{E} + r_2$
R_3: If E is P and $\dot{E}$ is N then $u = p_3{*}E + q_3{*}\dot{E} + r_3$
R_4: If E is P and $\dot{E}$ is P then $u = p_4{*}E + q_4{*}\dot{E} + r_4$
c)

Fig. 3. a) MFs for the inputs e, Δe, b) Control surface, c) Rule base.

This architecture is constructed from the sum of the contributions of a FLC-PD and a FLC-PI. The same rule base is used for the two controllers, then the control action produced by the FLC is defined as:

$$U = GCU \cdot GE \int e(t)dt - GCU \cdot GCEy(t) + \\ + GU \cdot GEe(t) - GU \cdot GCE \frac{dy(t)}{dt} \tag{7}$$

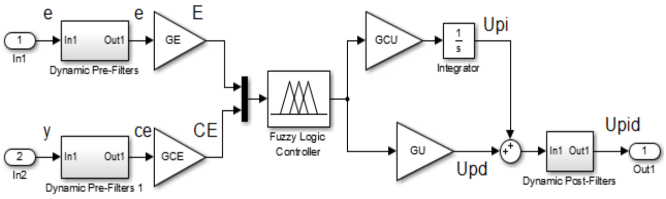


Fig. 4. Architecture of an MHPID controller

To obtain the equivalence with its linear counterpart, the comparison of the control action is made with a PID of 2 degrees of freedom with a weighting of the reference and derived on the output, as follows:

$$U = k_p\left(\beta \cdot y_r - y + \frac{1}{T_i}\int e(t) - T_d\frac{dy(t)}{dt}\right) \tag{8}$$

Comparing (7), (8) and establishing a relation Td/Ti = ¼, the scaling gains are obtained:

$$GE = 1 \tag{9}$$

$$GCE = 2 \cdot T_d \tag{10}$$

$$GU = K_p/2 \tag{11}$$

$$GCU = K_p/T_i \tag{12}$$

3. TUNING METHODOLOGY

The proposed tuning methodology for FPD+I and MHPID controllers consists of:

- Identification and modeling of the process
- Calculation of scale factors of FLC through conventional PID gains
- Fine-tuning of scale factors of the FLC through a *Kf* parameter, related to the static gains of the linear sub-models in the different points of operation.

3.1 Analyze the Behaviour of the Plant

For identification and modelling purposes, it consists in the understanding of the behaviour of the closed-loop system, especially the way it reacts to changes in the input. In particular, in this work two frequent cases of the presence of non-linearities in industrial applications of process have been considered, while varying the reference (increasing the set point) in different points of operation of the process:

i) The response of the system takes more time to reach the set point.

ii) The response of the system presents an overshoot that increases.

3.2 Obtain the approximate mathematical representation of the Plant

The adjustment of the fuzzy PID controller in the architectures considered requires a minimum knowledge of the system to be controlled. In the industrial environment, identification methods are used to approximate the behaviour of linear sub-models, commonly for first or second order models plus dead time. In this paper, we propose a simple but effective adjustment for the fuzzy PID controller, based on the calculation of a coefficient called K_f that is related to the static gains of the linear sub-models in the different points of operation. As the reference changes in the process and considering self-regulated processes such as those described in the previous step, the static gains are determined in the different points of operation and between these, the lower K_{lower} and upper K_{upper} values are chosen. K_f coefficient relating the static gains of the linear sub-models is determined as follows:

$$K_f = K_{lower}/K_{upper} \tag{13}$$

3.3 Obtaining Fuzzy Scale Gains

Transfer the gains of the linear PID controller (differentiating its architecture: ideal, series and parallel) that is in operation, to the Fuzzy PID controller by means of the conversion equations proposed in (Jantzen, 1998) and (Escamilla, 2002), through a linear control surface.

3.4 Tuning

Modify the scaling gains according to the K_f parameter. After defining the architecture of the fuzzy controller and obtaining an approximate performance with its linear counterpart, the new gains must be found by:

Jantzen´s FPD+I:

$$GU = GU_n \cdot K_f \tag{14}$$

$$GCE = GCE_n \cdot 0.5 \tag{15}$$

$$GIE = GIE_n \tag{16}$$

Escamilla´s MHPID:

$$GE = GE_n \quad (17)$$

$$GCE = GCE_n \quad (18)$$

$$GU = GU_n \cdot 4K_f \quad (19)$$

$$GCU = GCU_n \cdot K_f \quad (20)$$

For the equations from (14) to (20), the subscript n refers to the nominal value, that is to say, the value found with the conversion equations (3) to (6) for Jantzen and (9) to (12) for Escamilla. These sets of equations were obtained seeking to develop a practical but effective tuning method applicable to an industrial level, modifying the least amount of scaling factors. The determination of such values is supported by the performance of numerous computational tests taking into account measurements of performance indices and temporal response of the system.

The windup treatment in the fuzzy controller architectures is performed through a feedback gain to re-calculate the integral term (Astrom and Hagglund, 1995). In the following section, two case studies have been considered to validate the experimental results of the proposed methodology.

4. EXPERIMENTAL RESULTS

To evaluate the performance of the direct FLC controllers proposed in the previous section, simulations were implemented in the Matlab software, using tools such as Simulink and fuzzy logic toolbox. The tested processes are non-linear models, the first model was extracted from (Viljamaa and Koivo, 1995), for the second case the Matlab CSTR model was used. The objective is to perform tasks of reference tracking and rejection of disturbances. To analyze the behaviour of the controllers, the following measurement criteria were used: Integral of the absolute error (IAE) and Integral of the time by the absolute error (ITAE). For each process, a PID linear controller was tuned under the internal model control (IMC) technique (Morari, 1989) and its response was compared with the direct FLC, obtaining a better performance of the FLC in the presence of non-linearities This behaviour against changes in the reference can be seen later in figures 7 and 11.

1) Non-Linear Model

$$\dot{x}(t) = \begin{bmatrix} x_2(t) \\ -0.25\,x_1(t) - 0.70\,x_2(t) + (4.75 - 4.50\,x_1(t))u(t) \end{bmatrix} \quad (21)$$

$$y(t) = x_1(t)$$

The range of work for this system was chosen from 0 to 1 in incremental steps of reference of magnitude 0.1. The dynamic response of the process to step inputs allowed the characterization as second-order models. In the lower and upper operating points, the transfer functions obtained are:

$$G_l = \frac{4.737}{s^2 + 0.6992\ s + 0.6981} \quad (22)$$

$$G_u = \frac{0.2656}{s^2 + 0.879\ s + 4.58} \quad (23)$$

Therefore, the corresponding lower and upper static gains are K_l =6.786, Ku =0.0580. From these values and applying equation (13) for the case is obtained K_f= 117.

Figure 5 shows the reaction curve of the process due to step inputs.

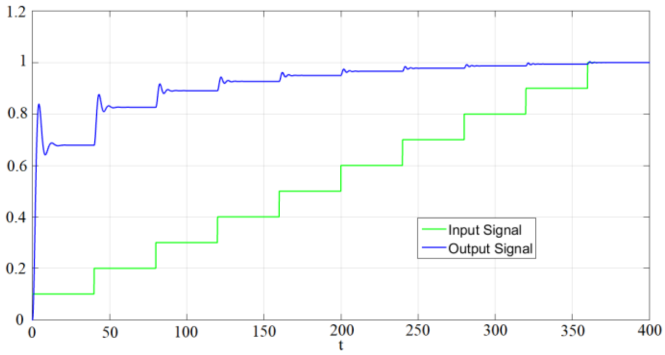


Fig. 5. System reaction curve.

Figure 6 shows the temporary response of controllers introducing a step type disturbance at t = 30 s and Gaussian noise 10 times higher the bandwidth of the plant. The numerical evaluation of the time response and performance indices is presented in table 1.

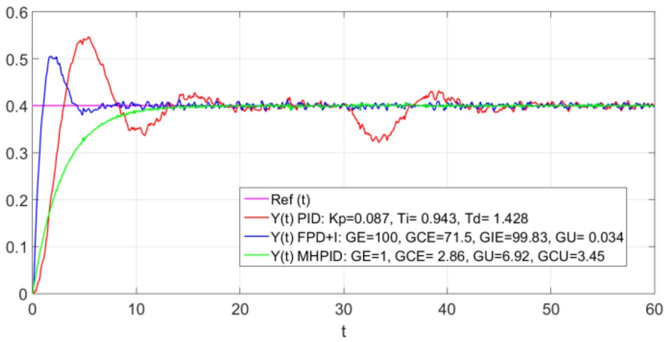


Fig. 6. Time response of controllers.

Table 1. Performance measurements.

	Without disturbance t = 60 s					Disturbance	
Controllers	Mp (%)	Tr (s)	Ts(s)	IAE	ITAE	IAE	ITAE
PID-IMC	36.6	3.01	20.19	1.56	12.24	1.88	23.48
FPD+I	22.85	1.19	8.9	0.55	5.96	0.55	6.04
MHPID	---	---	17.23	1.20	5.10	1.19	5

In Figure 7 the response of the PID IMC presents an impulse in the lower part and degradation in the upper part while the PID FLCs present a more consistent temporal performance. This is shown in Table 2, obtaining an improvement in the Integral of the Time-weighted Absolute value of the Error (ITAE) performance index for FPD+I of 90.9% and for MHPID of 74.3%.

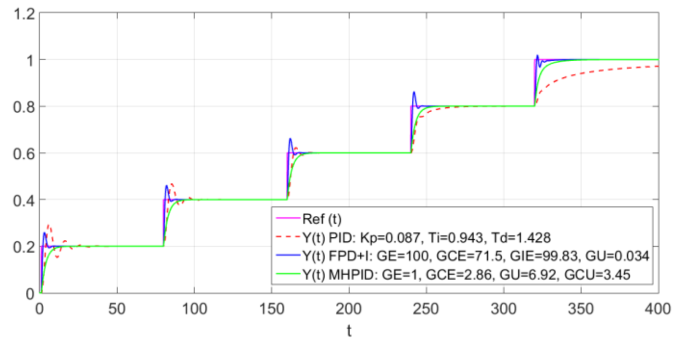


Fig. 7. Time response to variations of the reference.

Table 2. Measurement of performance indices

Controllers	PID IMC	FPD+I	MHPID
IAE	8.3	1.15	3.15
ITAE	2168	195.2	556.1

2) Non-Linear Plant

A model of a continuously stirred tank reactor (CSTR) was chosen. The reactor converts a chemical matter A to a chemical matter B through an irreversible exothermic reaction of first order A → B, the phenomenological model consists of 2 non-linear differential equations (Bequette, 1998). The reactor has three inputs: u1, u2, u3 and two outputs: y1, y2, as describes in figure 8. The control objective is maintaining the reactor temperature y2(t) in a desired reference point in a way that maximize the transformation of the chemical matter A, by regulating the temperature of the coolant in the jacket (u3), the manipulated variable.

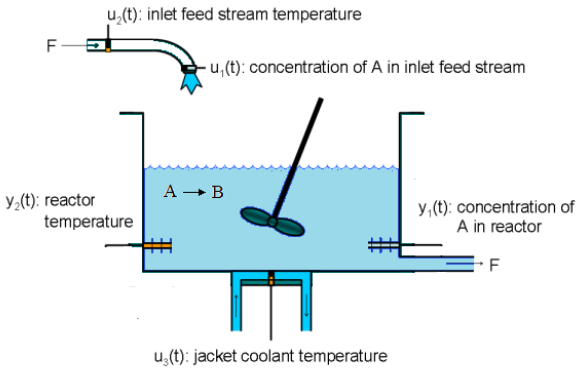


Fig. 8. CSTR reactor. Modified from (Bequette, 1998)

The working range for this system was chosen from 300 K to 350 K in incremental reference steps of magnitude 10 K. The dynamic response of the process to step input allowed the characterization as first order models plus dead time. In the lower and upper operating points, the transfer functions obtained are:

$$G_l = \frac{1.27\, e^{-0.245 s}}{2.484\, s + 1} \tag{24}$$

$$G_u = \frac{0.47\, e^{-0.005 s}}{1.65\, s + 1} \tag{25}$$

Therefore, the corresponding lower and upper static gains are K_l =1.27, Ku =0.47. From these values and applying equation (13) is obtained for the case K_f= 2.70

Figure 9 shows the reaction curve of the process due to step inputs.

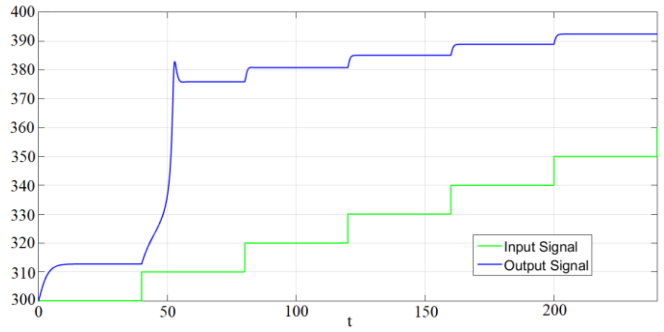


Fig. 9. System reaction curve.

Figure 10 shows the time response of controllers introducing a step type disturbance at t = 11 s and Gaussian noise 10 times higher the bandwidth of the plant. The numerical evaluation of the time response and performance indexes are presented in table 3.

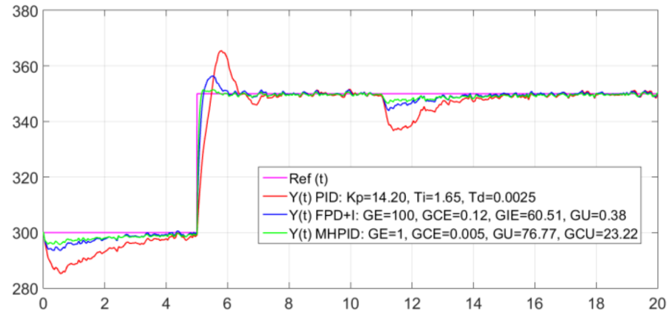


Fig. 10. Time response of controllers.

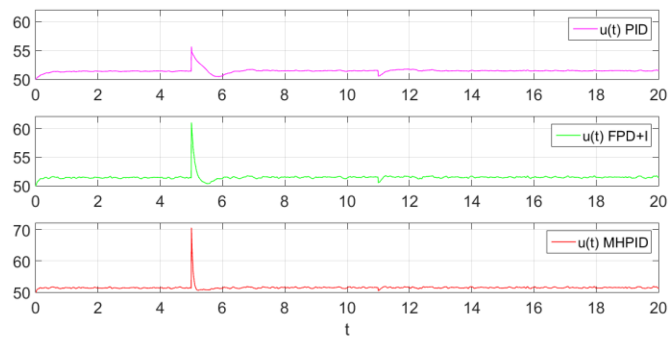


Fig. 11. Control action with the presence of noise

Table 3. Performance measurements

	Without disturbance t = 20 s					Disturbance	
Controllers	Mp %	Tr (s)	Ts (s)	IAE	ITAE	IAE	ITAE
PID-IMC	30.8	0.47	2.77	56.2	247.8	75.92	490.9
FPD+I	12.8	0.22	1.3	23.48	123.2	29.64	198.4
MHPID	2.4	0.15	0.95	16.82	87.13	22.93	168

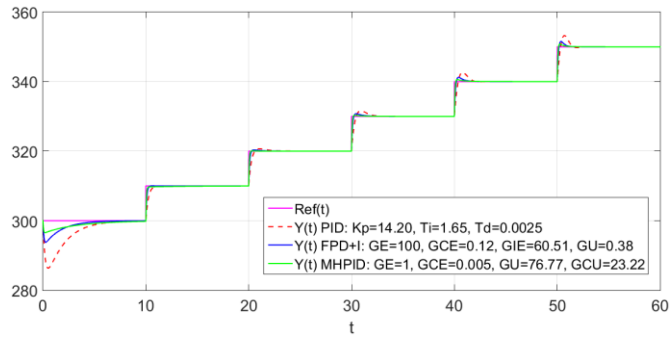


Fig. 12. Time response of controllers to variations of the reference.

In Figure 12, the response of the PID IMC shows an increase in the oscillations with the variation of the SP, while the FLC managed to reduce the overshoot and the oscillations of low amplitude. This is shown in Table 4, obtaining an improvement in the ITAE performance index for the FPD+I of 59.6% and for MHPID of 69.9%.

Table 4. Measurement of performance indices

Controllers	PID IMC	FPD+I	MHPID
IAE	48.75	18.74	16.29
ITAE	614	247.8	184.6

From tables 1 and 3 it can be seen that, when introducing disturbances to closed loop systems, FLCs correct the value of the process variable more quickly and smoothly than linear PIDs.

From Tables 2 and 4 it can be deduced that the FPLC FPD+I present better performance indexes in non-linear processes where the SP is increased, and the response of the system becomes slower, while the MHLC FLC presents better performance indexes for non-linear processes where the set point is increased, and the response of the system becomes oscillatory.

5. CONCLUSIONS

A new simple but effective methodology for tuning of direct fuzzy PID controllers based on the FPD+I and MHPID architectures was proposed. The tuning equations obtained are function of the scaling factors and the values of the static gains found in the upper and lower operating points in the process, obtaining a performance improvement, comparatively with the linear PID or fuzzy linear equivalents.

The proposed tuning methodology for direct fuzzy PIDs is effective, illustrated by the two specific cases of the processes considered, without having to adjust the parameters that modify the control surface in fuzzy systems. The proposal allows its practical application in industrial processes obtaining a considerable reduction in the tuning time and improving the performance for processes with multiple changes in operating points. As future work, it is considered the implementation in industrial platforms and the extension of the applicability to processes with more complex dynamics, as well as the study of stability and robustness.

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