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A Comparative Study of PI/PID Classical and Intelligent Tuning Methods

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Abstract. Proportional-plus-Integral-plus-Derivative (PID) controllers are widely used in the industrial world. Due to their popularity, a large number of methods have been suggested in the literature to tune them. This paper summarizes and compares seven different PID tuning techniques (in addition to some of their variations). The comparison includes some of the early approaches; namely, Ziegler-Nichols methods, minimum error, phase and gain margins, pole allocation, and LQR. Modern techniques (fuzzy logic and genetic algorithm) are also used and assessed. The seven tuning alternatives are evaluated in terms of their performance, complexity and flexibility.

Keywords: PID tuning, Ziegler-Nichols, Minimum integral error, Genetic algorithms, Fuzzy logic.

1. Introduction

Proportional-plus-Integral-plus-Derivative (PID) controllers are the most commonly used controllers in the industrial world. In fact, according to a 1993 study conducted by JEIMA (Japan Electric Instruments Manufacturers Association), it was found that 91.3% of the 2978 surveyed industrial applications use PID [1-3]. The success and longevity of PID controllers were characterized in a recent workshop, where over 90 papers dedicated to PID research including software packages, hardware modules and patented PID tuning rules were presented [2]. Such facts should not be too surprising because PID controllers are easier to understand than other techniques. In addition, due to their simple structure they are relatively easier to implement.

The most common form of the PID is represented by the transfer function:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

Other equivalent forms are often used such as:

(non-interacting)
$$G_c(s) = K_c[1 + \frac{1}{T_i s} + T_d s] \tag{2}$$

and

(interacting)
$$G_c(s) = K_c^{'}[T_d^{'} s + 1][1 + \frac{1}{T_i^{'} s}] \tag{3}$$

Transformation from one form to another is straightforward.

Owing to the popularity of this control method, a number of approaches have been developed to determine the PID parameters for single-input-single-output (SISO) systems. Among the more vastly used are Ziegler-Nichols method, minimum integral error, pole allocation, gain and phase margins, optimal control, genetic algorithms (GA), and fuzzy logic.

Basically, most patented identification and tuning methods are process-engineering oriented and appear ad hoc. In addition, it seems that the major difficulty appears in delivering an optimal transient response due to unexpected difficulties in setting optimal terms and, consequently, artificial intelligence is incorporated in software or onboard algorithms to augment simple PID structures [1]. In [4], a hybrid fuzzy-GA PID controller was proposed toward an optimal design. The salient feature of this approach is that it combines the fuzzy gain scheduling method and a fuzzy proportional–integral-derivative (PID) controller to solve the non-linear control problem.

In this paper, seven tuning techniques are compared and evaluated in terms of performance, ease of design and flexibility. The comparison is based on the application to a generic fourth order model with a reasonable complexity.

2. Ziegler-Nichols Tuning Methods

This tuning method is considered one of the early attempts to PID tuning and yet it is still widely used. There are few variations to this approach among which are: Ziegler-Nichols method based on ultimate gain and period, Ziegler-Nichols method based on reaction curve, and refined Ziegler method.

2.1. Ziegler-Nichols method using ultimate gain and period

This method was proposed by J. Ziegler and N. Nichols around 1940. The ultimate gain K_u and ultimate period T_u are used to tune the control parameters for the quarter-dacay ratio (QDR) response in which each oscillation has an amplitude that is one-fourth of the previous one. The ultimate gain K_u is the gain at which the loop oscillates with constant amplitude when the process is under closed-loop proportional control and the ultimate period T_u is the period of these oscillations.

For the PID in forms (2) and (3), the Ziegler-Nichols QDR tuning formulas based on K_u and T_u are [5]:

$$\begin{aligned} K_c &= 0.75K_u \qquad & T_i &= T_u/1.6 \qquad & T_d &= T_u/10 \\ K_c^{'} &= 0.6K_u \qquad & T_i^{'} &= T_u/2 \qquad & T_d^{'} &= T_u/8 \end{aligned} \tag{4}$$

In addition to its simplicity, this method can produce reasonably fast responses for most industrial loops (usually accompanied with excessive overshoot if not fine-tuned). However, many processes do not permit operation near marginal stability and, hence, experimental evaluation of K_u and T_u is not practical. Even in cases where operation in marginal stability is possible, some loops may not exhibit sustained oscillation with proportional control (first-order systems as an obvious example). An additional drawback of this method is that the ultimate gain and period do not give insight into which control factor could be modified to improve performance.

2.2. Ziegler-Nichols method using process reaction curve

This method alleviates the drawbacks of relying on the ultimate and gain period. It assumes that the process is represented by a first-order plus dead-time model, i.e.:

$$G(s) = \frac{Ke^{-Ls}}{\tau s + 1} \tag{5}$$

where

K : the process steady-state gain
L : the effective process dead-time, and
τ : the effective process time-constant.

Based on this model, the alternative tuning formulas for QDR response is given by:

$$K_c^{'} = \frac{1.2\tau}{KL} \qquad T_i^{'} = 2L \qquad T_d^{'} = 0.5L \tag{6}$$

This alternative method offers acceptable performance for many control loops while being fairly simple. However, it still can't overcome the excessive overshoot unless fine-tuned. In addition, it depends on modeling the plant as a first-order plus dead time which may not always be possible.

2.3. Refined Ziegler-Nichols method

This method is also developed for the first-order plus dead-time model of the form given by (5). The tuning formulas for PI control (form (2) with $T_d = 0$) are given by [6]:

$$K_c = \frac{5K_u}{6}\left[\frac{12 + K_u K}{15 + 14K_u K}\right] \tag{7}$$

$$T_i = \frac{T_u}{5}\left[\frac{4}{15}K_u K + 1\right] \tag{8}$$

This method gives an almost consistent phase margin of 50 degrees but a varying gain margin of about six for $(L/\tau) = 0.2$ decreasing to three for $(L/\tau) = 1.0$. The performance is consistent with about 10% overshoot [7].

3. PID Tuning for Minimum Error Integrals

This approach is based on minimizing either the integral of the absolute error (IAE) or the integral of the absolute of the product of time and error (IATE). This method uses first-order plus dead-time model parameters described by (5) and the PID takes the non-interactive form given by (2). It is suitable only for processes with (L/τ) in the range (0.1 to 1.0).

3.1. Tuning by minimum IAE

The minimum IAE tuning formulas for set-point changes are given by [8]:

$$K_c = \frac{1.086}{K}\left(\frac{L}{\tau}\right)^{-0.869} \tag{9}$$

$$T_i = \frac{\tau}{0.74 - 0.13(L/\tau)} \tag{10}$$

$$T_d = 0.348\tau\left(\frac{L}{\tau}\right)^{0.914} \tag{11}$$

3.2. Tuning using minimum IATE

For minimum IATE, the parameters are given by [8]:

$$K_c = \frac{0.965}{K}\left(\frac{L}{\tau}\right)^{-0.855} \tag{12}$$

$$T_i = \frac{\tau}{0.796 - 0.147(L/\tau)} \tag{13}$$

$$T_d = 0.308\tau\left(\frac{L}{\tau}\right)^{0.929} \tag{14}$$

4. PI Tuning Using Phase and Gain Margins

This method is based on the gain and phase margins to tune PI parameters (form (2) with $T_d = 0$). For plants that can be modeled by the first-order plus dead-time structure given by (5), the tuning formulas are [7]:

$$\omega_p = \frac{A_m \Phi_m + \frac{\pi}{2} A_m (A_m - 1)}{(A_m^2 - 1)L} \tag{15}$$

$$K_c = \frac{\omega_p \tau}{A_m K} \tag{16}$$

$$T_i = \frac{1}{\left(2\omega_p - \frac{4\omega_p^2 L}{\pi} + \frac{1}{\tau}\right)} \tag{17}$$

where (A_m, Φ_m) is a specified gain and phase margin pair and ω_p is the phase crossover frequency.

5. PID Tuning Based on Pole Allocation

This method assumes that the plant is described by a second-order plus dead time model in the form:

$$\hat{G}(s) = \frac{e^{-sL}}{as^2 + bs + c} \tag{18}$$

where a, b, c and L are unknowns to be determined. Unlike the first-order structure given by (5), the model can have real or complex poles. Therefore, it is suitable for representing monotonic or oscillatory processes while still being of sufficiently low order. To determine the four unknowns, it is sufficient to match the actual process, $G(s)$, to the model given by (18) at two non-zero frequencies, e.g. $s=j\omega_c$ and $s=j\omega_b$, where $\angle G(j\omega_c)=-\pi$ and $\angle G(j\omega_b)=-(\pi/2)$, such that $G(j\omega_c) = \hat{G}(j\omega_c)$ and $G(j\omega_b) = \hat{G}(j\omega_b)$. The a, b and c values can then be calculated using [9]:

$$a = \frac{1}{\omega_c^2 - \omega_b^2}\left[\frac{\sin(\omega_b L)}{|G(j\omega_b)|} + \frac{\cos(\omega_c L)}{|G(j\omega_c)|}\right] \tag{19a}$$

$$b = \frac{\sin(\omega_c L)}{\omega_c |G(j\omega_c)|} \tag{19b}$$

$$c = \frac{1}{\omega_c^2 - \omega_b^2}\left[\frac{\omega_c^2 \sin(\omega_b L)}{|G(j\omega_b)|} + \frac{\omega_b^2 \cos(\omega_c L)}{|G(j\omega_c)|}\right] \tag{19c}$$

A good approximation for L is the smaller absolute root of the following quadratic equation:

$$p(\omega_c^2 - \theta\omega_b^2)L^2 + (q\omega_c - \theta r\omega_b)L - \theta = 0 \tag{20a}$$

where

$$\begin{aligned} p &= \left(8/\pi^2\right)\left(1-\sqrt{2}\right) & q &= \left(2/\pi\right)\left(2\sqrt{2}-1\right) \\ r &= \left(2/\pi\right)\left(2\sqrt{2}-3\right) & \theta &= \left(\omega_c\,|G(j\omega_c)|\right)/\left(\omega_b\,|G(j\omega_b)|\right) \end{aligned} \tag{20b}$$

According to the equivalent time constant principle, we have:

$$\frac{1}{\tau_0} = \begin{cases} \dfrac{c}{\sqrt{b^2 - 2ac}} & b^2 - 4ac \ge 0 \\ \dfrac{b}{2a} & b^2 - 4ac < 0 \end{cases} \tag{21}$$

The damping ratio ξ_0 of the open-loop plant is defined as:

$$\xi_0 = \begin{cases} \dfrac{b}{2\sqrt{ac}} & b^2 - 4ac < 0 \\ 1 & b^2 - 4ac \geq 0 \end{cases} \tag{22}$$

For the PID controller of form (1), using pole-allocation method, the controller parameters are found to be [9]:

$$\begin{bmatrix} K_p \\ K_i \\ K_d \end{bmatrix} = k \begin{bmatrix} b \\ c \\ a \end{bmatrix} \tag{23}$$

where k is a gain chosen so that the controller zeros cancel the model poles. For $\xi_0 > 0.7071$ or $L/\tau_0 < 0.15$ or $L/\tau_0 > 1$,

$$k = \frac{0.5}{L} \tag{24a}$$

For $\xi_0 \leq 0.7071$ or $0.15 \leq L/\tau_0 \leq 1$,

$$k = \min\left\{ \frac{1}{\tau_0} e^{-(L/\tau_0)}, \frac{1}{eL} \right\} \tag{24b}$$

6. PI/PID Tuning on the Basis of LQR Approach

In this method [10], the PI parameters are tuned on-line according to the LQR method (optimal control). A criterion for selecting the state and control weighting matrices (Q and R) that will lead to a specified natural frequency (ω_n) and damping ratio (ξ) of the closed-loop system is given. For the first-order plus delay model given in (5) and a PI controller model G_c given by Eq. (1) with $K_d = 0$, the algorithm starts by choosing the closed loop ω_n and ξ, and setting R=1. Then, the PI parameters are tuned according to the time-varying formulas [10]:

- For $0 \leq t < L$

$$K_i(t) = R^{-1}\bar{b}\left[p_{12} f_{11}(t) + p_{22} f_{21}(t)\right] \tag{25a}$$

$$K_p(t) = R^{-1}\bar{b}\left\{ \frac{1}{a} p_{12} f_{11}(t) + \frac{1}{a} p_{22} f_{21}(t) + \left[p_{12} f_{12}(t) - \frac{1}{a} p_{12} f_{11}(t) + p_{22} f_{22}(t) - \frac{1}{a} p_{22} f_{21}(t) \right] e^{-a(L-t)} \right\} \tag{25b}$$

- For $t \geq L$

$$K_i(t) = R^{-1}\bar{b}\left[p_{12} f_{11}(L) + p_{22} f_{21}(L)\right] \tag{26a}$$

$$K_p(t) = R^{-1}\bar{b}\left[p_{12} f_{12}(L) + p_{22} f_{22}(L)\right] \tag{26b}$$

where p_{12} and p_{22} are elements of the solution P of the Riccati equation, $\bar{a} = 1/\tau$, $\bar{b} = K/\tau$, and f_{ij} are some time-varying functions related to both the open-loop and closed-loop state-transition matrices [10]. In some cases, this method can be extended to second-order models simply by choosing one zero of the PID so that it cancels one real pole of the plant. By doing so, the problem is reformulated into designing a PI controller for a first order plus delay model as described above. It is apparent that this method is critical to the choice of ω_n and ξ or $\omega_n L$.

7. PID Tuning Using Genetic Algorithms

Genetic Algorithms (GA) are powerful derivative-free optimization tools that require no specific details about the optimized system or function. The only link between the GA and the problem being solved is the fitness function, which is chosen by the designer to reflect how good the solution is. The candidate solution is coded in a binary string called chromosome. The algorithm performs the three classical operators: reproduction, crossover, and mutation in search of the best chromosome (the fittest one) [11-14].

A binary number of *6n* bits is used to code any given candidate solution (*2n* bits to represent K_p, *2n* bits to represent K_i, and *2n* bits to represent K_d). For each of the three gains, *n* bits are used to code the decimal part and the other *n* bits are used to code the fraction part. The number of bits (*n*) is chosen according to the expected magnitude of the gains and the desired resolution. For cases where the PID gains are not expected to be of magnitudes much higher than 100, a resolution of seven bits is enough with reference to the derivative time constant, i.e. $T_i = \alpha T_d$. To obtain the PID in the standard form given by (1), the following simple conversion is made:

$$K_p = K_c, \qquad K_d = K_c T_d, \qquad K_i = K_p^2 \big/ (\alpha K_d) \tag{27}$$

8. PID Tuning Using Fuzzy Logic

This approach is also known as fuzzy gain scheduling of PID controllers. In this scheme, the controller parameters are determined based on the current error *e(t)* and its first derivative $\dot{e}(t)$. The basic structure of the PID is the same as the form given by (2). The integral time constant is determined.

For convenience, K_p and K_d are normalized into the range between zero and one using the following linear transformation:

$$\begin{aligned} K_p' &= (K_p - K_{p,\min}) \big/ (K_{p,\max} - K_{p,\min}) \\ K_d' &= (K_d - K_{d,\min}) \big/ (K_{d,\max} - K_{d,\min}) \end{aligned} \tag{28a}$$

The ranges of the gains are: $K_{p,min}$=0.32K_u, $K_{p,max}$=0.6K_u, $K_{d,min}$=0.08K_uT_u, and $K_{d,max}$=0.15K_uT_u where K_u and T_u are the gain and period of oscillation at the stability limit under proportional control [15, 16].

The parameters K_p', K_d', and α are determined by a set of fuzzy rules taking the error and its derivative as inputs. The actual gains are then obtained using:

$$\begin{aligned} K_p &= (K_{p,\max} - K_{p,\min}) K_p' + K_{p,\min} \\ K_d &= (K_{d,\max} - K_{d,\min}) K_d' + K_{d,\min} \\ K_i &= K_p^2 \big/ (\alpha K_d) \end{aligned} \tag{28b}$$

9. Illustrative Example

To compare the seven aforementioned PID tuning methods, a fourth-order plant is considered. The plant has sufficient complexity for the purpose of evaluation. The transfer function of the process to be controlled is given by:

$$G(s) = \frac{1}{(s^2 + s + 1)(s + 2)^2} e^{-0.1s} \tag{29a}$$

Approximating (29a) by a first-order plus delay, by matching the responses at two points in the region of high rate of change in the reaction curve, yields:

$$G(s) = \frac{0.25}{1.2s + 1} e^{-1.45s} \tag{29b}$$

From this first-order model, it can be easily deduced that the gain K=0.25, the time constant τ =1.2, and delay L = 1.45 sec. At marginal stability (under proportional control), the ultimate gain and ultimate period are K_u=7.056 and T_u = 5.185 sec., respectively. The PID gains for the three variants of Ziegler method and the two variants of the minimum error method are readily calculated from the equations presented in Sections 1 and 2. It is noted here that $L/\tau > 1$. This "violation" may deteriorate the performance of the PI/PID controllers designed based on the first-order model.

To obtain the PI gains using the method based on phase and gain margins, the values of these margins (A_m and Φ_m) need to be specified. Such choice is critical to the performance of the PI controller. This method replaces the problem of finding the proper controller gains by the problem of finding the proper margins. For this example, A_m is set to 3dB and Φ_m to 60 degrees. These values are judged as typical, albeit other values are likely to produce better results.

For the pole-allocation method, the approximate model given by (18) is found using (19) and (20). The model parameters are determined to be: a = 5.6504, b = 4.9513, c = 4.5006 and L = 0.8355. From (24), the value of k was found to be 0.3034. The PID parameters are easily calculated using (23).

To find the PID gains using the LQR method and as recommended in Section 5, one zero of the PID is chosen to be at -2 to cancel one real pole of the plant so that the transfer function becomes:

$$\overline{G}(s) = \frac{1}{(s^2 + s + 1)(s + 2)} e^{-0.1s} \tag{30}$$

The design process becomes of PI (instead of PID). $\overline{G}(s)$ is further reduced to:

$$\hat{\overline{G}}(s) = \frac{0.443}{(s + 0.8865)} e^{-0.968s} \tag{31}$$

Comparing to (5), we deduce that $\tau = 1/0.8865$, $K = 0.443/0.8865$, and L = 0.968. Choosing $\omega_n = 0.5$, and $\eta = 0.71$, $K_i(t)$ and $K_p(t)$ can be readily evaluated using (25) and (26).

The classic genetic algorithm is designed to optimize the PID parameters so that the response of the process is as close as possible to a chosen target. The response of a prototype second-order system with $\xi = 0.7071$ and $\omega_n = a\cos(\xi) / \left(L\sqrt{1-\xi^2}\right)$ is chosen as such a target. For the GA, the knowledge of the model is not needed. However, a fitness function reflecting the performance of the system is crucial. A common fitness function can be expressed in terms of IATE, i.e.:

$$f(t) = \frac{1}{\int |te(t)| dt} \tag{32}$$

The population size, number of generations, mutation rate, and cross-over rate are, respectively, 20, 30, 0.05 and 0.5 the results can be obtained after just 30 iterations.

To tune the PID control using fuzzy gain scheduling, the fuzzy inputs (the error and its first derivative) are partitioned into five triangular fuzzy membership functions (MF's): Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). Only two fuzzy MF's are needed for the normalized output gains (K_p' and K_d'). They are named Small (S) and Big (B). For the third fuzzy output (α), three triangular MF's representing the value of the output (2, 3 or 4) are chosen. The membership functions are shown in Fig. 1, and the rule base for the fuzzy gain scheduling is given in Tables 1, 2 and 3.

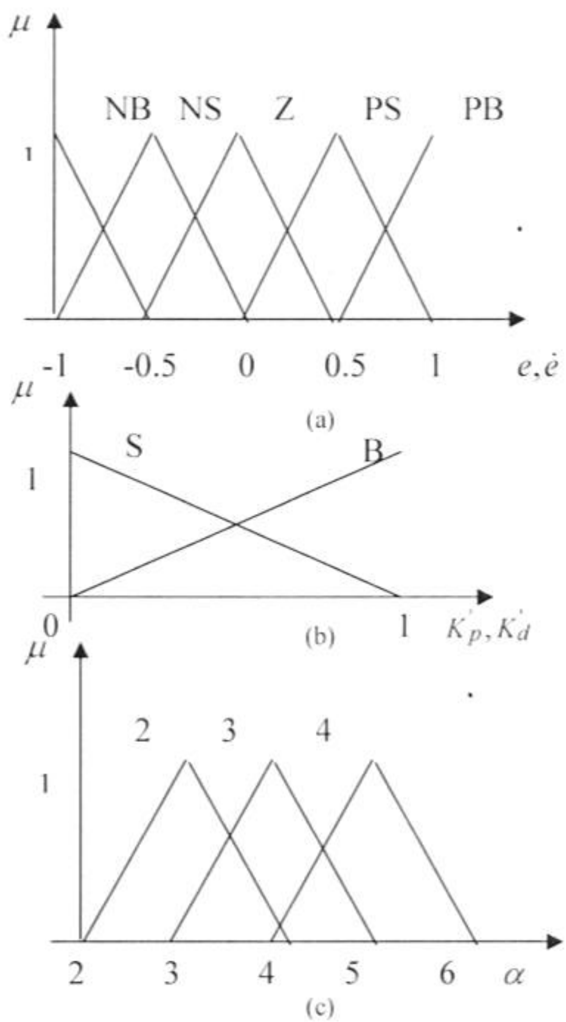

Fig. (1). Fuzzy membership functions.

Table (1). Fuzzy tuning rules for Kp'.

$e(t)$ \ $\dot{e}(t)$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	B	B	B	B	B
NS	S	B	B	B	S
Z	S	S	B	S	S
PS	S	B	B	B	S
PB	B	B	B	B	B

Table (2). Fuzzy tuning rules for K_d'.

$e(t)$ \ $\dot{e}(t)$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	B	S	S	S	B
NS	B	B	S	B	B
Z	B	B	B	B	B
PS	B	B	S	B	B
PB	B	S	S	S	B

Table (3). Fuzzy tuning rules for α.

$e(t)$ \ $\dot{e}(t)$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	3	2	2	2	3
NS	3	3	2	3	3
Z	4	3	3	3	4
PS	3	3	2	3	3
PB	3	2	2	2	3

The PID gains for all approaches presented in this paper are summarized in Table 4. An evaluation in terms of percent maximum overshoot (% O.S.) and the settling time (T_s) based on the 5% criterion is summarized in Table 5. A step response comparison is illustrated in Figs. 2, 3 and 4.

Table (4). Summary of the PID gains.

	Z-N Ultim. gain	Z-N React. curve	Refined Ziegler	IAT	ITAE	Phase and gain margins	Pole allocation	LQR	GA	Fuzzy
K_p	5.292	4.965	2.039	3.685	3.284	1.733	1.504	N/A*	3.140	N/A*
K_I	1.633	1.370	1.377	1.790	1.692	1.440	1.367	N/A*	1.800	N/A*
K_d	2.744	2.880	N/A+	1.830	1.447	N/A+	1.717	N/A*	3.950	N/A*

+ Only PI is considered here
* Time varying gains

Table (5). Evaluation in terms of overshoot and 5% settling time.

	Z-N Ultimate gain	Z-N Reaction curve	Refined Ziegler	IAT	ITAE	Phase and gain margins	Pole allocation	LQR	GA	Fuzzy
% O.S.	18.0	8.6	10.6	18.3	16.2	14.7	4.9	4.6	3.7	0.0
T_s (sec)	12.3	12.3	12.5	10.6	10.9	13.2	4.8	10.5	3.6	9.4

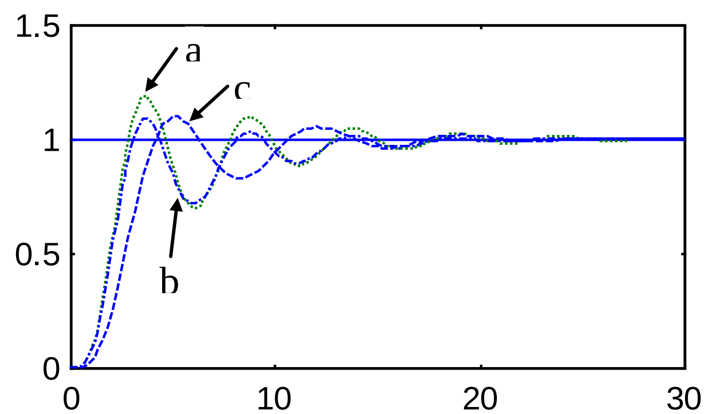

Fig. (2). Step response: a) Zigler-Nichols ultimate gain. b) Zigeler-Nichols (reaction curve). c) Refined Ziegler.

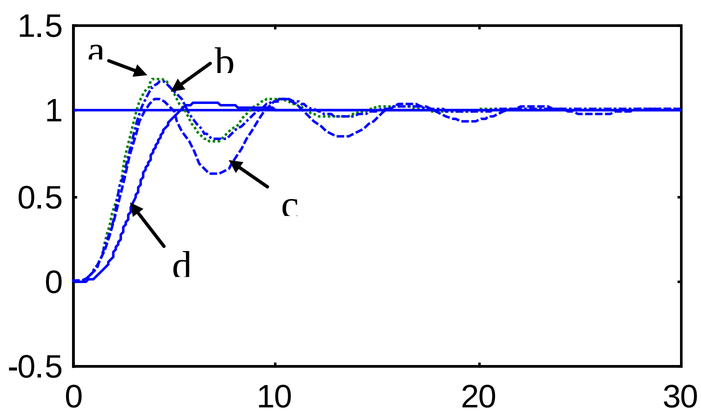

Fig. (3). Step response: a) IAE. b) ITAE. c) Phase and gain margins. d) Pole allocation.

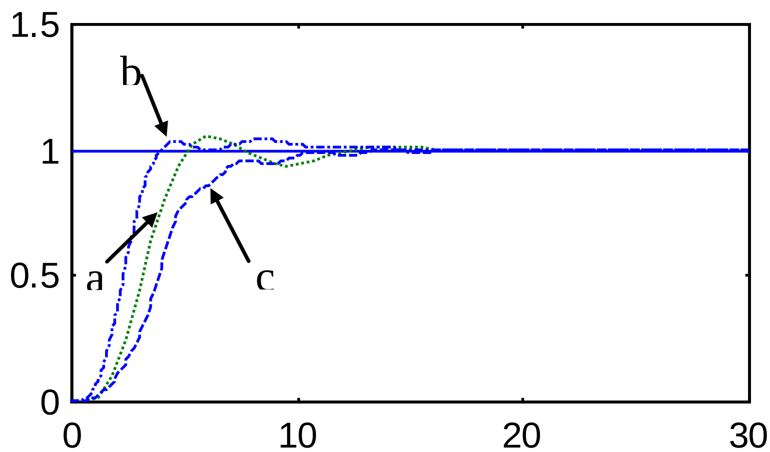

Fig. (4). Step response: a) LQR. b) GA. c) Fuzzy logic.

10. Conclusions

A comparative study of a number of PI/D tuning methods has been conducted. Seven different techniques were presented and evaluated. A fourth-order system was used to evaluate the performance of the different techniques. It was observed that the earlier techniques (e.g. Ziegler-Nichols, minimum error, phase and gain margins) are the easiest in terms of design. However, they share the drawback of excessive overshoot. In addition, they require a first-order model of the system which may not always be possible. Moreover, these techniques are not flexible. The design has to be repeated for any variations in the model.

The optimal control approach and fuzzy logic produce time-varying gains, which should offer better performance in comparison to fixed gains. However, the additional complexity of the design is not compensated by any exceptional improvement in the performance.

The pole allocation method provides a good response (in terms of speed and overshoot) while being straightforward. Nevertheless, its design process is little lengthier and less flexible than most of the other alternatives.

Out of the different approaches presented in this work, the genetic algorithm stands out as the one that offers the best PID gains with no specific knowledge of the plant and no additional complexity in the design process. More importantly, the algorithm can be used for any model as long as the fitness function reflects the desired performance.

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دراسة مقارنة لطرق التوليف التقليدية والذكية للمتحكمات النسبية والتكاملية أو النسبية والتكاملية والتفاضلية

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ملخص البحث. تعتبر المتحكمات النسبية والتكاملية والاشتقاقية (PID) من أكثر طرق التحكم استعمالاً في الصناعة، ولشهرتها فقد تعددت وبشكل كبير الطرق المقترحة لضبطها. غرض هذه الورقة العلمية تقديم ملخص تفصيلي لسبع طرق مختلفة ومقارنة أدائها. تشمل المقارنة بعضاً من الطرق التي اقترحت في مراحل سابقة مثل: طرق زقلر-نيكولز، وأقل الخطأ، وهوامش الكسب والطور، وتوطين الأقطاب، والمنظم الخطي التربيعي. كما تضمن ذلك استخدام طرق حديثة كمنطق الغموض والطرق الجينية ودراسة أدائها. ولقد قوّمت هذه الطرق السبعة المختلفة بناء على أدائها ودرجة تعقيدها ومرونتها.