Performance/Robustness Trade-off Design Framework for 2DoF PI Controllers

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Abstract: The aim of the paper is to present a design framework for two-degree-of-freedom (2DoF) proportional integral (PI) controllers that allows to deal with the control system *performance/robustness trade-off*. It is based on the use of a model reference optimization procedure with target servo-control and regulatory control closed-loop transfer functions for first- and second-order-plus-dead-time (FOPDT, SOPDT) models. A *smooth servo/regulatory combined performance* is obtained by forcing both closed-loop transfer functions to perform as close as possible to target non-oscillatory dynamics. A comparison with other methods shows the effectiveness of the proposed design methodology.

Keywords: PI controllers, two-degree-of-freedom controllers, model reference control, performance/robustness trade-off.

1. Introduction

Since their introduction in 1940 [1,2] commercial *proportional integral derivative* (PID) controllers have with no doubt become the best option in industrial control applications. The success is mainly due to its simple structure and the meaning of the corresponding three parameters. This fact makes PID control easier to be understood by more control engineers than advanced control techniques. In addition, the performance of a PI or PID controller is satisfactory in most of industrial applications. See [3,4] as an example.

Since Ziegler and Nichols [5] presented the PID controller tuning rules, a great number of procedures have been developed, from the classic methods of Cohen and Coon [6], López et al. [7], and Rovira et al. [8], and modifications of the original tuning rules [9-11], to a variety of new techniques such as: analytical tuning [12,13]; optimization methods [14,15]; gain and phase margin optimization [14,16].

O'Dwyer [17] presents a collection of tuning rules for PI and PID controllers, which shows their abundance.

Among different approaches, the direct or analytical synthesis constitutes a quite straightforward approach to PI/PID controller design. The controller synthesis presented by Martin [18] made use of zero-pole cancellation techniques. Similar relations were obtained by Rivera et al. [19], applying the IMC concepts [20] to tune PI and PID controllers for low-order process models. A combination of analytical procedures and the IMC tuning can be found in [13, 21-24].

A common characteristic of the analytically deducted tuning methods is that they include a *design parameter* usually related with the closed-loop control system speed of response. The selection of such design parameter will not only affect the system performance but also its relative stability.

In industrial process control applications, the set-point remains normally constant and a good load-disturbance rejection is required; regulatory control. In addition, due to process operation conditions, the set-point may eventually need to be changed and then a good transient response to this change is required; the so called servo-control. However, because these two demands can not be simultaneously satisfied with a one-degree-of-freedom (1DoF) controller, the use of a two-degree-of-freedom (2DoF) controller allows to tune the controller considering the regulatory control-loop performance and the robustness while using the extra parameter that is provided to improve the servo-control behaviour.

The control system design procedure is usually based on the use of low-order linear models identified at the closed-loop normal operation point. Due to the non-linear characteristics in most of the industrial processes, it is necessary to consider the expected changes in the process characteristics assuming certain relative stability margins, or robustness requirements for the control system. Therefore the design of the closed-loop control system with 2DoF PI controllers must take into account the trade-off between the system *performance* to load-disturbance and set-point changes and the *robustness* to variation of the controlled process characteristics [25].

If only the system performance is taken into account, using an integrated error criterion (integrated absolute error (IAE), integrated time-weighted absolute error (ITAE), or integrated squared error (ISE)) or a time response characteristic (overshoot, rise time, or settling time), as in [26,27], the resulting closed-loop control system will probably have very low robustness. On the other hand, if the system is designed to have high robustness, as in [10], and if the performance of the resulting system is not evaluated, the designer would have no idea of the *cost* involved in operating such a highly robust system. In some previous studies [28,29], the performance and robustness of the system were taken into account for optimizing the IAE or ITAE performance, but only the usual minimum level of robustness could be guaranteed.

Without considering the exception of [13,21,22] the analytically deducted and the IMC-PID tuning rules normally do not take into account the performance/robustness trade-off or provide a recommendation for the design parameter selection.

An alternative way for designing 2DoF PI controllers is presented in this case. What is presented in this paper is a *design framework* that allows considering all the previously commented aspects at once. The design is build up on a constrained model matching model reference optimization that allows resolving the performance/robustness trade-off with the selection of an appropriate design parameter for first- and second-order-plus-dead-time controlled process models.

As additional contribution the approach also provides a framework where different tuning rules can be evaluated and compared. An original way of establishing such comparison is addressed.

This paper is organized in the following way: the transfer functions of the controlled process model, the controller, and the control system are presented in Section 2; the proposed optimization procedure is described in Section 3; the optimization procedure is summarized in Section 4 and a comparison with other tuning methods is shown in Section 5. The paper ends with some conclusions.

2. Problem Formulation

Consider the closed-loop control system in Figure 1 where $P(s)$ and $C(s)$ are the controlled process model and the controller transfer functions respectively. In the system, $r(s)$ is the set-point, $u(s)$ is the controller output signal, $d(s)$ is the load-disturbance and $y(s)$ is the process controlled variable.

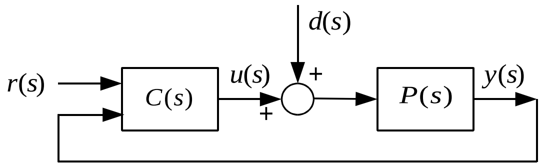

Figure 1. Closed-Loop Control System

The closed-loop control system output, $y(s)$, to a change in its inputs, $r(s)$ and $d(s)$, is given by

$$y(s) = M_{yr}(s)r(s) + M_{yd}(s)d(s), \qquad (1)$$

where $M_{yr}(s)$ is the *servo-control* closed-loop transfer function, and $M_{yd}(s)$ is the *regulatory control* closed-loop transfer function.

The regulatory control main objective is the *load disturbance rejection*; this is, to return the controlled variable to its set-point if a disturbance enters to the control system. For the servo-control, it is intended to *follow a set-point change*; this is, to bring the controlled variable to its new set-point. These two different responses will depend on the closed-loop transfer functions in (1) and may not be independently selected if a 1DoF controller is used but may be selected with a constrained independence if a 2DoF controller is used.

The development of the proposed design approach for 2DoF PI controllers will take into account the closed-loop control system performance stating target responses for both the set-point and the load-disturbances step changes and measuring the control system performance with the integrated absolute error and the control effort total variation, and its robustness with maximum sensitivity.

2.1 2DoF proportional integral controller

The process will be controlled with a two-degree-of-freedom proportional integral (PI_2) controller [30] whose output is

$$u(s) = K_p \left\{ \beta r(s) - y(s) + \frac{1}{T_i s}\left[r(s) - y(s) \right] \right\} \quad (2)$$

where K_p is the controller *proportional gain*, T_i *integral time constant* and β the *set-point proportional weight*. The controller block diagram is shown in Figure 2.

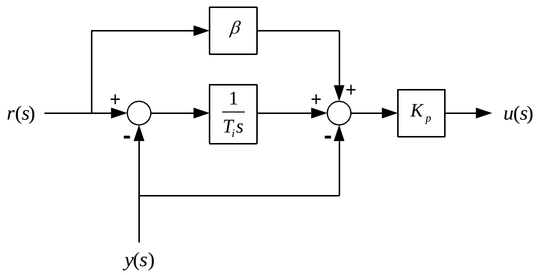

Figure 2. Two-Degree-of-Freedom PI Controller

Controller output (2) will be rewritten for the analysis (not for the implementation) as

$$u(s) = C_r(s) r(s) - C_y(s) y(s), \quad (3)$$

where

$$C_r(s) = K_p \left(\beta + \frac{1}{T_i s} \right), \quad (4)$$

is the PI_2 controller part applied to the set-point *r*, the *set-point controller* transfer function, and

$$C_y(s) = K_p \left(1 + \frac{1}{T_i s} \right), \quad (5)$$

is the PI_2 controller part applied to the feedback signal *y*, the *feedback controller* transfer function.

The servo-control and the regulatory control closed-loop transfer functions in (1) are now

$$M_{yr}(s) = \frac{C_r(s) P(s)}{1 + C_y(s) P(s)}, \quad (6)$$

and

$$M_{yd}(s) = \frac{P(s)}{1 + C_y(s) P(s)}, \quad (7)$$

which are related by

$$M_{yr}(s) = C_r(s) M_{yd}(s). \quad (8)$$

2.2 Over damped controlled process models

The over damped controlled processes will be represented by a linear model given by the transfer function

$$P(s) = \frac{K e^{-Ls}}{(Ts+1)(aTs+1)}, \quad \tau_o = \frac{L}{T}, \quad (9)$$

where K is the model gain, T its main time constant, a the ratio of its two time constants $(0 \le a \le 1)$, L the dead-time, and τ_o the model *normalized dead-time* $(0.1 \le \tau_o \le 2.0)$.

Model transfer function (9) allows to represent first-order-plus-dead-time (FOPDT) processes $(a = 0)$, over damped second-order-plus-dead-time (SOPDT) processes $(0 < a < 1)$, and dual-pole-plus-dead-time (DPPDT) processes $(a = 1)$.

The parameters of the controlled process model (9), $\theta = \{K, T, a, L, \tau_o\}$, may be identified from the process reaction curve [29].

2.3 Closed-loop target transfer functions

For the development of the proposed design method, it is important to have the lowest possible number of design parameters. The control system response target to a load-disturbance step change will have only one design parameter T_c (the closed-loop time constant). It is selected as non-oscillatory; for a smooth response; and with no steady-state error, by the following target transfer function

$$M_{yd}^t(s) = \frac{K_o s e^{-Ls}}{(T_c s+1)^2 (aT_c s+1)}, \quad (10)$$

where K_o and T_c are the regulatory control closed-loop transfer function static gain and time-constant respectively. In a PI regulatory control system the closed-loop transfer function gain K_o in (10) is given by $K_o = T_i / K_p$, then

$$M_{yd}^t(s) = \frac{(T_i / K_p) s e^{-Ls}}{(T_c s+1)^2 (aT_c s+1)}. \quad (11)$$

Using (11) and (4) in (6) the servo-control closed-loop transfer function results in:

$$M_{yr}(s) = \frac{(\beta T_i s+1)e^{-Ls}}{(T_c s+1)^2(aT_c s+1)}. \tag{12}$$

Then, to have a response to a set-point step change without oscillation and no overshoot, and with no steady-state error, the servo-control closed-loop target transfer function is selected as

$$M^t_{yr}(s) = \frac{e^{-Ls}}{(T_c s+1)(aT_c s+1)}. \tag{13}$$

If T_c is expressed as a function of the controlled process model (9) main time constant $(T_c = \tau_c T)$, then $\tau_c = T_c / T$ may be used as the dimensionless design parameter. The closed-loop performance specification will require only one parameter, τ_c, that the ratio of the closed-loop system response speed to the controlled process speed.

Using (13) and (11) in (1) the global target control system output $y^t(s)$ is computed as

$$y^t(s) = \frac{e^{-Ls}}{(\tau_c Ts+1)(a\tau_c Ts+1)}r(s) + \frac{(T_i/K_p)se^{-Ls}}{(\tau_c Ts+1)^2(a\tau_c Ts+1)}d(s) \tag{14}$$

In the particular case of the FOPDT models $(a=0)$ the control system target output is then

$$y^t(s) = \frac{e^{-Ls}}{\tau_c Ts+1}r(s) + \frac{(T_i/K_p)se^{-Ls}}{(\tau_c Ts+1)^2}d(s) \tag{15}$$

3. Controller Design

Usually, the design of 2DoF PI controllers is made in two stages [10,29,32-34]. First, the parameters (K_p, T_i) of the feedback controller (5) required to obtain the desired regulatory control performance and/or a closed-loop control system with a specific robustness level are determined for a set of parameters of the controlled process model θ_p. After that and on a second step, the set-point controller (4) free parameter (β) is used to improve the servo-control performance.

Then a different approach is followed. The complete set of PI_2 controller parameters $\theta_c = \{K_p, T_i, \beta\}$ will be obtained when considering, the regulatory control and the servo-control performance at once, to obtain a controller with a target *servo/regulatory combined performance* that will also produce a closed-loop control system with a specific *robustness* level.

The closed-loop control system target response (14) can be rewritten in the time domain as

$$y^t(t) = y^t_r(t) + y^t_d(t), \tag{16}$$

where y^t_r is the servo-control target step response and y^t_d the regulatory control target step response.

3.1 Regulatory control cost functional

For the regulatory control response the cost functional is defined as

$$J_d \equiv \int_0^\infty \left[y^t_d(t) - y_d(t)\right]^2 dt, \tag{17}$$

where $y^t_d(t)$ is the step response of the regulatory control target closed-loop transfer function (11) and $y_d(t)$ the corresponding one of the regulatory control system (7) with the controlled process (9) and the controller (5).

3.2 Servo-control cost functional

In a similar way the servo-control cost functional is defined as

$$J_r \equiv \int_0^\infty \left[y^t_r(t) - y_r(t)\right]^2 dt, \tag{18}$$

where $y^t_r(t)$ is the step response of the servo-control target closed-loop transfer function (13) and $y_r(t)$ the corresponding one of the servo-control system (6) with the controlled process (9) and the controller (4).

3.3 Controller optimization

For the 2DoF PI controller design an overall cost functional given by

$$J_T = J_r + J_d, \tag{19}$$

is optimized to obtain the controller optimum parameters $\theta^o_c = \{K^o_p, T^o_i, \beta^o\}$ such as

$$J^o_T \equiv J_T(\theta^o_c) = \min_{\theta_c} J_T. \tag{20}$$

Note that $\theta^o_c = \theta_c(\theta_p, \tau_c)$.

3.4 Performance and robustness evaluation

To allow the designer to select the appropriate design parameter τ_c both the control system performance and robustness must be evaluated.

Performance

The control system output performance will be evaluated using the integrated-absolute-error cost functional given by

$$J_e \equiv \int_0^\infty |e(t)|dt = \int_0^\infty |r(t) - y(t)|dt\,. \qquad (21)$$

This cost functional will be evaluated by regulatory (J_{ed}) and servo-control (J_{er}) operation.

On the other hand the *control effort total variation* will be evaluated by

$$TV_u \equiv \sum_{k=1}^{\infty} |u_{k+1} - u_k|\,, \qquad (22)$$

that also will be evaluated by load-disturbances (TV_{ud}) and set-point (TV_{ur}) changes.

Robustness

The closed-loop control system robustness will be computed using the maximum sensitivity M_S, defined as

$$M_S \equiv \max_\omega |S(j\omega)| = \max_\omega \left| \frac{1}{1 + C_y(j\omega)P(j\omega)} \right| \qquad (23)$$

3.5 Robust tuning of 2DoF PI controllers

Consider as a controlled process the four-order model proposed as benchmark in [35] and given by the transfer function

$$P(s) = \frac{1}{\prod_{i=0}^{3} (\alpha^i s + 1)}, \quad \alpha = 0.5\,. \qquad (24)$$

Using the three-point identification procedure *123c* [21] FOPDT and SOPDT models were obtained whose parameters are listed in Table 1.

Table 1. Controlled Process Models

K	T	a	L	τ_o
1	1.247	-	0.691	0.554
1	0.876	0.821	0.277	0.316

For the SOPDT model and following the proposed design procedure the parameters obtained for robust tuned 2DoF PI controllers are listed in Table 2.

Table 2. 2DoF PI Parameters

τ_c	K_p	T_i	β	M_S
0.7	1.709	1.449	0.519	2.03
0.9	1.183	1.487	0.601	1.626
1.1	0.805	1.405	0.735	1.412

Table 2. shows the existing performance/robustness trade-off. To increase the control system robustness M_S, its performance (speed) needs to be reduced, increasing τ_c.

4. 2DoF PI Controller Tuning

From the sections above the whole design procedure can be summarized as follows:

1. Obtain the model (9) from the controlled process reaction-curve or critical information.
2. Select a *design parameter* τ_c.
3. Optimize the cost functional J_T (19) to obtain the controller parameters $\theta_c = \{K_p, T_i, \beta\}$.
4. Evaluate the control system output performances, J_{er} and J_{ed} (21).
5. Evaluate the control effort total variations, TV_{ur} and TV_{ud} (22).
6. Evaluate the control system robustness, M_S (23).
7. Analyze the performance, control effort and robustness indicators and select a new design parameter (τ_c in step 2.) if required.

5. Comparison with other Tuning Methods

For comparison purposes the following PI tuning methods that include a design parameter to deal with the performance/robustness trade-off were selected: the IMC based IMC-PID in [36] and the *Simple Control* (SIMC) [11] for 1DoF PI/PID controllers, and the *Analytical Robust Tuning* (ART_2) [21,22] for 2DoF PI/PID controllers.

The same four-order controlled process (24) and models listed in Table 1, will bee used for the comparison.

In the particular process model used in this example, the IMC and SIMC tuning result in the same PI parameters.

Although the design parameter τ_c has the same meaning in all the compared methods its influence over the control system performance and robustness is different because the closed-loop transfer functions used in the deduction of the methods were not necessarily the same. Considering this and to obtain a comparison on the same base, the design parameter used with each of the methods compared was selected to obtain a specific robustness level $M_S \in \{2.0, 1.8, 1.6, 1.4\}$. Therefore, some iterations where needed when applying the selected tuning methods and the design method outlined in Section 4.

In this approach however all methods will provide the same robustness level, allowing to concentrate the analysis to the performance indicators.

The normalized (respect to the best one) performances, J_{ed}, J_{er}, obtained from the above methods are shown in Figure 3 and the normalized control effort total variation in Figure 4.

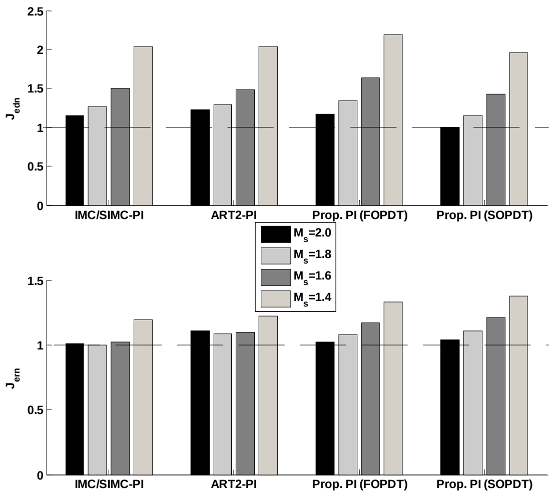

Figure 3. Example - Normalized Regulatory and Servo-control Performance

From the performance results it is noted the performance/robustness trade-off. If the control systems robustness is increased, its performance decreases. It is also noted that for the same robustness level the PI controller obtained from the SOPDT model has better regulatory control performance without a reduction of its servo-control performance.

The control effort total variation has an inverse relation to the control system robustness. An increase in the control system robustness produces a *smoother* controller output.

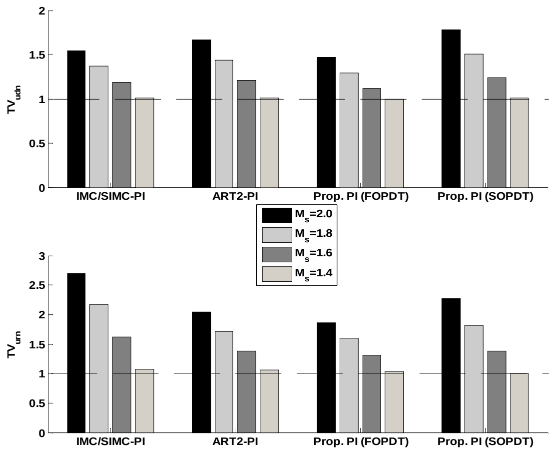

Figure 4. Example - Normalized Regulatory and Servo-control Total Variation

The quantitative indicators used (J_e, TV_u) must be complemented with some qualitative indicators obtained from the control system responses to step changes in the set-point and load-disturbance.

The obtained closed-loop responses to a 20% set-point step change followed by a 10% disturbance step change are shown in Figure 5 for $M_S = 2.0$ and in Figure 6 for $M_S = 1.4$.

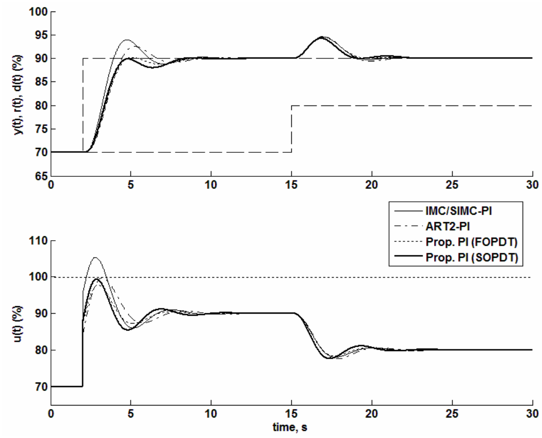

Figure 5. Example - Control Systems Responses, $M_S = 2.0$

Given the results it is evident that the 1DoF PI controller (IMC/SIMC tuning) produces high changes in the controller output to a set-point step change that produces higher overshoots and more oscillating responses when a fast response low robust system; is specified. The set-point weight factor of the 2DoF controllers allows a smooth controller output for all robustness levels.

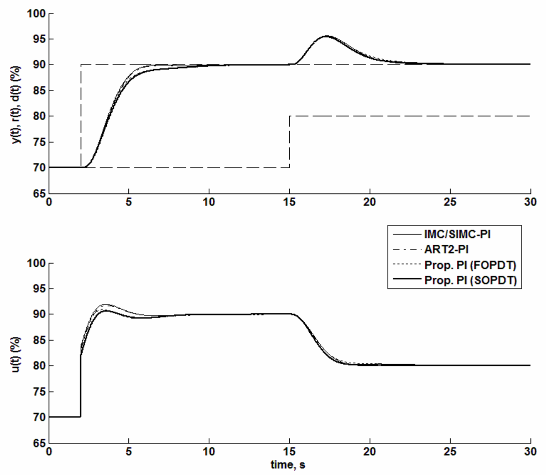

Figure 6. Example - Control Systems Responses, $M_S = 1.4$

An overall evaluation of the control system characteristics; performance and control effort versus robustness; shows that the proposed PI controller design procedure provides the required flexibility to take into account several of the conflicting control system design criteria.

6. Conclusions

The proposed design framework for two-degree-of-freedom (2DoF) proportional integral (PI) controllers allows to deal with the control system performance/robustness trade-off selecting the design parameter τ_c to produce fast and nearly non-oscillating responses to a set-point or load-disturbance step change, non requiring excessive control effort variations.

From the comparison made with other tuning methods it is evident that the same robustness levels may be obtained with different sets of controller parameters, then some other quantitative and qualitative indicators are needed to evaluate the control system behaviour.

The use of the proposed design methodology may be used to obtain tuning rules that will produce robust control systems.

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REFERENCES

1. BABB, M., **Pneumatic Instruments Gave Birth to Automatic Control**, Ctrl. Eng., vol. 37, no. 12, 1990, pp. 20-22.
2. BENNETT, S., **The Past of PID Controllers**, in IFAC Dig. Ctrl., Past, Present and Future of PID Ctrl, Terrassa, Spain, 2000
3. ABDEL-HADY, F, S. ABUELENIM, **Design and Simulation of a Fuzzy-Supervised PID Controller for a Magnetic Levitation System**, Studies in Informatics and Control, vol. 17(3), 2008, pp. 315-328.
4. MARABA, V. A., A. E. KUZUCUOGLU, **Speed Control of an Asynchronous Motor Using PID Neural Network**, Studies in Informatics and Control, vol. 20(3), 2011, pp.199-208.
5. ZIEGLER, J. G., N. B. NICHOLS, **Optimum settings for Automatic Controllers**, ASME Trans., vol. 64, 1942, pp. 759–768.
6. COHEN, G. H., G. A. COON, **Theoretical Considerations of Retarded Control**, ASME Trans., vol. 75, July, 1953.
7. LÓPEZ, A. M., J. A. MILLER, C. L. SMITH, P. W. MURRILL, **Tuning Controllers with Error-Integral Criteria**, Instr. Tech., vol. 14, 1967, pp. 57-62.
8. ROVIRA, A., P. W. MURRILL, C. L. SMITH, **Tuning Controllers for Setpoint Changes**, Instr. & Ctrl. Sys., vol. 42, 1969, pp. 67-69
9. CHIEN, I., J. HRONES, J. RESWICK, **On the Automatic Control of Generalized Passive Systems**, Trans. ASME, 1952, pp. 175-185.
10. HÄGGLUND, T., K. J. ÅSTRÖM, **Revisiting the Ziegler-Nichols Tuning Rules for PI Control**, Asian J. of Ctrl, vol. 4, 2002, pp. 354-380.
11. HANG, C., K. J. ÅSTRÖM, W. HO, **Refinement of the Ziegler-Nichols formula**, IEE Proc., (D), 138, 1991, pp. 111-118.
12. HWANG, S. H., H. C. CHANG, H.C., **Theoretical Examination of Closed-loop Properties and Tuning Methods of**

Single Loop PI Controllers, Chem. Eng. Sci, vol. 42, 1987, pp. 2395–2415.

13. SKOGESTAD, S., **Simple Analytic Rules for Model Reduction and PID Controller Tuning**, J. of Proc. Ctrl, vol. 13, 2003, pp. 291-309.
14. ÅSTRÖM, K. J., T. HÄGGLUND, **Advanced PID Control**, ISA – The Instr., Sys., & Aut. Soc., Research. Triangle Park, NC, 2006.
15. ÅSTRÖM, K. J., H. PANAGOPOULOS, T. HÄGGLUND, **Design of PI Controllers Based on Non-convex Optimization**, Automatica, vol. 34, 1998, pp. 585–601.
16. FUNG, H., Q. WANG, Q., T. LEE, T., **PI tuning in Terms of Gain and Phase Margins**, Automatica, vol. 34, 1998, pp. 1145–1149.
17. O'DWYER, A., **Handbook of PI and PID Controller Tuning Rules**, Imperial College Press, London, UK, 2nd ed., 2006.
18. MARTIN, J., C. L. SMITH, A. B. CORRIPIO, **Controller Tuning from Simple Process Models**, Instr. Tech., vol. 22, no. 12, 1975, pp. 39-44.
19. RIVERA, D. E., M. MORARI, S. SKOGESTAD, **Internal Model Control. 4. PID Controller Design**, Ind. & Eng. Ch. Proc. Des. & Dev., vol. 25, 1986, pp. 252-265.
20. GARCÍA, C. E., M. MORARI, **Internal Model Control. 1. a unifying review and some new results**, Ind. & Eng. Ch. Proc. Des. & Dev., vol. 21, 1982, pp. 308-323.
21. ALFARO, V. M., R. VILANOVA, O. ARRIETA, **Analytical Robust Tuning of PI Controllers for First-Order-Plus-Dead-Time Processes**, In 13th IEEE Intl. Conf. on Emerg. Tech. & Factory Aut. (ETFA2008). 15-18 September, 2008, Hamburg, Germany.
22. ALFARO, V. M., R. VILANOVA, O. ARRIETA, **A Single-Parameter Robust Tuning Approach for Two-Degree-of-Freedom PID Controllers**, In European Ctrl Conf., 2009, Budapest, Hungary.
23. ISAKSSON, A. J., S. F. GRAEBE, **Analytical PID Parameter Expressions for Higher Order Systems**, Automatica, vol. 35, 1999, pp. 1121-1130.
24. KAYA, I., **Tuning PI Controllers for Stable Process with Specifications on Gain and Phase Margings**, ISA Trans., vol. 43, 2004, pp. 297-304.
25. ALFARO, V. M., R. VILANOVA, **Sintonización de los controladores PID de 2GdL: desempeño, robustez y fragilidad**, XIV Cong. Lat-am. de Ctrl. Aut., Santiago, Chile, 2010, pp. 267-272 (in Spanish).
26. HUANG, H. P., J. C. JENG, **Monitoring and Assessment of Control Performance for Single Loop Analysis**, Ind. & Eng. Ch. Res., vol. 41, 2002, pp. 1297-1309.
27. TAVAKOLI, S., M. TAVAKOLI, **Optimal Tuning of PID Controllers for First Order Plus Time Delay Models using Dimensional Analysis**, in The 4th Intl. Conf. on Ctrl & Aut. (ICCA'03), Montreal, Toronto, Canada, (2003).
28. SHEN, J. C., **New Tuning Method for PID Controller**, ISA Trans., vol. 41, 2002, pp. 473-484.
29. TAVAKOLI, S., I. GRIFFIN, P. J. FLEMING, **Robust PI Controller for Load Disturbance Rejection and Set-point Regulation**, In IEEE Conf. on Ctrl. App. 2005, Toronto, Canada.
30. ÅSTRÖM, K. J., T. HÄGGLUND, **PID Controllers: Theory, Design and Tuning**, Instr. Soc. of America, Research Triangle Park, NC, USA, 1995.
31. ALFARO, V. M., **Low-Order Models Identification from the Process Reaction Curve**, Ciencia y Tecnología (Costa Rica), vol. 24, no. 2, pp. 197-216 (in Spanish), at http://revista-ciencia-tecnologia.ucr.ac.cr/index.php/ciencia-tecnologia/article/view/ 35.
32. ALFARO, V. M., R. VILANOVA, O. ARRIETA, **NORT: a Non-Oscillatory Robust Tuning Approach for 2-DoF PI Controllers**, 18th IEEE Intl. Conf. on Ctrl. App., S.-Petersburg, Russia, 2009, pp. 1003-1008.
33. ÅSTRÖM, K. J., T. HÄGGLUND, **Revisiting the Ziegler-Nichols Step Response Method for PID Control**, J. of Proc. Ctrl, vol. 14, 2004, pp. 635-650.

34. TAGUCHI, H., M. ARAKI, **Two-Degree-of-Freedom PID controllers - Their Functions and Optimal Tuning**, In IFAC Dig. Ctrl: Past, Present and Future of PID Ctrl. 2000, Terrassa, Spain.

35. ÅSTRÖM, K. J., T. HÄGGLUND, **Benchmark Systems for PID Control**, In IFAC Dig. Ctrl: Past, Present and Future of PID Ctrl. (PID'00). 5-7 April, 2000, Terrasa, Spain.

36. CHIEN, I. L., P. S. FRUEHAUF, **Consider IMC Tuning to Improve Controller Performance**, Ch. Eng. Prog., 1990, pp. 22-41.