IMC PI Control Loops Frequency and Time Domains Performance Assessment and Retuning ⋆

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Abstract: This paper is about a performance assessment strategy for IMC PI control systems using collected data from a specific closed-loop experiment. It is used time and frequency indexes to analyze how close or far the closed-loop is from the desired performance. A data-driven PI retuning method is applied to improve the control system for IMC PI specifications and the chosen indexes.

Keywords: PID control, Performance Assessment, Data-driven Retuning, IMC, Gain Margin, Phase Margin, IAE

1. INTRODUCTION

The most common controller is Proportional-Integrative-Derivative (PID) type. Some authors estimate about more than 90% of the control systems have them implemented in many forms as Proportional-Integrative (PI) (Jelali, 2012). However, the majority of those controllers does not operate as they were projected. In many study cases, it is verified that most of the control loops suffer from poor performance (Torres et al., 2006).

In this context, researches have developed many techniques for control performance assessment (CPA). They aim at automatically detect poor control using collected data from closed-loop experiments or routine operations (Gao et al., 2017). If a bad performance is detected, the CPA technique will suggest a solution to improve the control loop as new tuning parameters. An overview of control performance assessment techiques can be found in Jelali (2012). According to a recent survey, the most common problem addressed by CPA techniques is wrong tuning settings (Bauer et al., 2016). Hence, the information obtained in the CPA can be used to retune the PI/PID controller.

Usually, the performance assessment is done by indexes comparison between a benchmark and the current control-loop (Jelali, 2006). Hence, a large deviation indicates that the performance can be improved. The integrated absolute error (IAE) have been used to detect oscillations and load disturbance capability for a closed-loop time response (Jelali, 2012). However, to analyze only this index could not be conclusive for the closed-loop performance (Barroso et al., 2015).

Robustness characteristics as gain and phase margins can be employed as frequency domain performance indexes (Jeng et al., 2006). In Barroso et al. (2015), the closed-loop performance is assessed in the frequency domain using relations between margins and Internal Model Control (IMC) PI characteristics (Rivera et al., 1986), based on the results obtained in Ho et al. (2001). That analysis results in a curve for gain and phase margins that can be used as a benchmark for a IMC PI tuning comparison. In order to estimate gain and phase margins properly, Barroso et al. (2015) uses an excitation signal that combines the standard relay (Åström and Hägglund, 1984) and the phase margin experiment (de Arruda and Barros, 2003).

Most of tuning techniques use low order identified models, as first or second order process plus time delay (FOPTD or SOPTD). However, this can result in a conservative tuning or slow loops. In Gao et al. (2017), it is proposed a data-driven optimal tuning using closed-loop step response data directly based on a reference model, avoiding a parametric closed-loop identification.

In this paper, a methodology for performance assessment and retuning of PI control-loops is proposed. This methodology assess the control-loop performance compared to an IMC PI benchmarking. The frequency and time domain performance indexes are estimated using the data from a closed-loop experiment with the reference signal from Barroso et al. (2015). The PI controllers are retuned using the data-driven optimization approach from Gao et al. (2017) improved with a equality constraint and an IMC PI as the reference model. The aim is to match the defined time and frequency specifications, as gain and phase margins.

This paper is organized as follows: The problem statement is defined in in Section 2. The proposed experiment design is described in Section 3. The frequency and time domain

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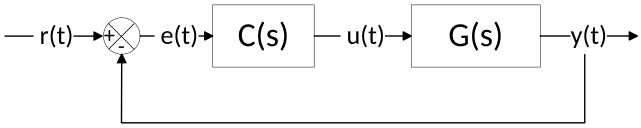

Fig. 1. Closed-Loop System

performance assessment are explained in Sections 4 and 5 respectively. The simulation results for processes are presented and evaluated in Section 6. The conclusions are discussed in Section 7.

2. PROBLEM STATEMENT

Consider a single-input single-output (SISO) closed-loop system as shown in Figure 1. As $G(s)$ is the process and the initial PI controller $C(s)$ with the following expression:

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

The K_p and K_i are the controller Proportional and Integral gains respectively. It is assumed that the controller $C(s)$ is tuned according to the IMC PI design (Rivera et al., 1986). Hence, the closed-loop model is:

$$T(s) = \frac{Y(s)}{R(s)} = \frac{G(s)C(s)}{1 + G(s)C(s)} = \frac{1}{\tau_c s + 1} e^{-\tau_d s} \tag{2}$$

with τ_c the tuning parameter and τ_d the process delay.

From classical control, gain margin (A_m) and phase margins (ϕ_m) are defined according the following equations:

$$A_m = \frac{1}{|G(j\omega_c)C(j\omega_c)|} = \frac{1}{|L(j\omega_c)|} \tag{3}$$

$$\phi_m = \pi + \angle G(j\omega_g)C(j\omega_g) = \angle L(j\omega_g) + \pi \tag{4}$$

where $L(j\omega)$ is the loop gain transfer function, ω_c and ω_g are the critical and crossover frequencies, respectively. These are obtained in the conditions $\angle G(j\omega_c)C(j\omega_c) = -\pi$ and $|G(j\omega_g)C(j\omega_g)| = 1$.

The problem can be stated as: Assess experimentally an arbitrary closed-loop system with a PI controller using frequency and time domain indexes and compare with a desired closed-loop IMC PI benchmarking. Then, use a data-driven approach to retune the PI controller parameter in order to obtain the desired specifications and improve the performance indexes.

3. EXPERIMENT DESIGN

In Barroso et al. (2015), it is proposed a reference excitation signal to excite the system at both the critical and crossover frequencies. This is done by applying a reference composed as the sequence of three different signals: a step, a standard relay test (Åström and Hägglund, 1984) and a phase margin experiment (de Arruda and Barros, 2003).

Initially, a step is applied until the output reaches 63% of the reference value (at $t = T_1$). Then, the phase margin experiment is done for a certain number of periods (ending at $t = T_2$). After, the standard relay experiment is executed, also for a defined number of periods (until $t = T_3$). Finally, the reference signal is set to the initial operation condition. A simple example of this excitation signal applied in a plant is shown in Figure 2.

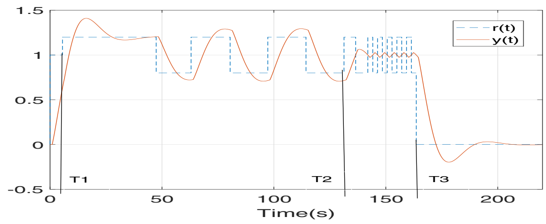

Fig. 2. Proposed Excitation Signal

3.1 Gain and Phase Margins Estimation

Based on the collected data, it is possible to compute the oscillations frequencies ω_g and ω_c. Initially, it is necessary to measure a stable limit cycle period during the time intervals $[T_1; T_2]$ and $[T_2; T_3]$ to obtain the estimates $\widehat{\omega}_g$ and $\widehat{\omega}_c$ respectively. Hence, each loop gain frequency response ($L(j\widehat{\omega}_g)$ and $L(j\widehat{\omega}_c)$) can be estimated using the Discrete Fourier Transform (DFT) data from the chosen stable limit cycles. Then, it is possible to obtain the gain $\widehat{A}_m$ and phase margins $\widehat{\phi}_m$:

$$\widehat{A}_m = \frac{1}{|L(j\widehat{\omega}_c)|} \tag{5}$$

$$\widehat{\phi}_m = \pi + \angle L(j\widehat{\omega}_g) \tag{6}$$

3.2 Delay Estimation

The cross-correlation method is chosen to be used in this paper. According to Jelali (2006), it obtains a good time delay estimation. This technique is done by analyzing the output $y(t)$ and reference $r(t)$ signals in the time interval from $t = 0$ and $t = T_1$. Hence, the process delay τ_d can be estimated by the following equation:

$$\widehat{\tau}_d = \max_{\tau_d} E\{y(k)r(k-\tau_d)\} \approx \max_{\tau_d} \sum_k y(k)r(k-\tau_d) \tag{7}$$

4. FREQUENCY DOMAIN PERFORMANCE ASSESSMENT

From the gain and phase margins definitions, it is possible to obtain analytic relations for an IMC-PI control-loop.

Lemma 1. Considering $\tau_c = \beta\tau_d$, in the analytic relations between τ_c, A_m, ϕ_m and ω_g presented Acioli Júnior and Barros (2011), it is possible to relate A_m, ϕ_m and β directly by the following equations:

$$\phi_m = \frac{\pi}{2}\left(1 - \frac{1}{A_m}\right) \tag{8}$$

$$\beta = \frac{2A_m}{\pi} - 1 \tag{9}$$

Proof. Further details and complete development can be found in Barroso et al. (2015). Q.E.D.

From Equation (8), it is possible to plot an IMC PI benchmark curve $\phi_m(A_m)$ that shows the gain and phase margins behavior for a IMC PI closed-loop. Hence, estimating the margins of a closed-loop, the monitored controller performance can be assessed as good or poor, in an IMC PI sense, if the point is close or far from the curve as shown in Figure 3.

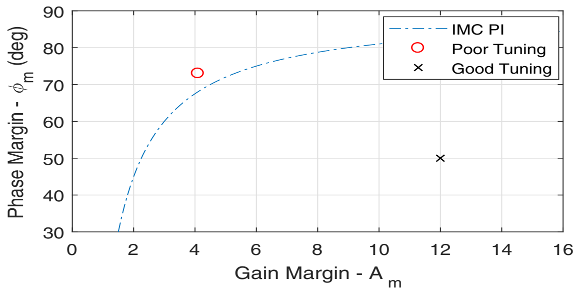

Fig. 3. An example of the frequency performance assessment of PID controllers

Moreover, it is possible to project an IMC PI closed-loop by defining only one of those three parameters: β, A_m or ϕ_m, as the other two are computed from Equations (9) to (8). In this paper, the reference model is specified using a delay estimation and defining a reference gain margin.

5. TIME DOMAIN PERFORMANCE ASSESSMENT

The IAE is widely applied as time domain performance index. It can be used to detect oscillations in the closed-loop response and load disturbance capability. The experimental IAE (IAE_{exp}) can be calculated by $IAE_{exp} = \int_0^\infty |e(t)|dt$.

For specific reference signals, analytic expressions can be obtained. In Barroso et al. (2015), it proposed an analytic formula to calculate IAE index (IAE_{Comp}) for IMC PI closed-loop to a step sequence reference signal:

$$IAE_{Comp} = \sum_{i=0}^{N-1}\left[R_i(\tau_d+\tau_c)+(-1)^i R_i\tau_c e^{-\frac{(T_{Ni}-\tau_d)}{\tau_c}}\right] + \sum_{i=0}^{N-2}\left[\sum_{j=i+1}^{N-1} 2\alpha_j R_i \tau_c e^{\frac{(T_{Ni}-\tau_d)}{\tau_c}}\right] \quad (10)$$

as N is the number of transactions of the reference signal, R_i is the setpoint amplitude variation between two transactions, T_{ab} is time interval between a and b, and α_j is an index defined by:

$$\alpha_j = \begin{cases} 1 & \text{if}|i-j|\text{is odd} \\ -1 & \text{if}|i-j|\text{is even} \end{cases} \quad (11)$$

For a single step particular case, the equation (10) is simplified to:

$$IAE_{Comp} = R_0(\tau_d+\tau_c) \quad (12)$$

that corresponds exactly to the equation shown in Veronesi and Visioli (2010)

6. PI RETUNE

In Gao et al. (2017), it is presented how to calculate optimal increments for the PID controller parameters to approximate the closed-loop to a specified reference model. This is done by a time domain data-driven retuning approach that does not require a complete parametric process identification, only a delay τ_d estimation.

The retuned PI controller is described by the following equations:

$$\overline{C}(s) = (K_p + K_p^\Delta) + \frac{K_i + K_i^\Delta}{s} \quad (13)$$

$$\overline{C}(s) = \left(1 + \frac{K_p^\Delta + \frac{K_i^\Delta}{s}}{C(s)}\right) C(s) \quad (14)$$

where K_p^Δ and K_i^Δ are the Proportional and Integrative gains increments respectively.

Lemma 2. The retuning optimization problem presented by Gao et al. (2017) can be modified by adding a frequency domain equally constraint function:

$$\min_\theta J = ||\Omega - \Phi\theta||_2^2 \quad \text{subject to } \mathbf{A}\theta - \mathbf{b} = \mathbf{0} \quad (15)$$

This ensures that the tuning gains are adjusted for the closed-loop has a time and frequency response close as possible to the specifications.

Proof. The complete development to obtain matrices Ω and Φ can be found in Gao et al. (2017).

The matrices $\mathbf{A}$ and $\mathbf{b}$ in the equally constraint function are obtained from comparing the resulted $\overline{L}(s)$ and reference $L_r(s)$ loop gains:

$$\overline{L}(s) = L_r(s) = \overline{C}(s)G(s) \quad (16)$$

$$\overline{C}(s) = \frac{L_r(s)}{G(s)} \quad (17)$$

Using the equation (14) at (17):

$$\left(1 + \frac{K_p^\Delta + \frac{K_i^\Delta}{s}}{C(s)}\right) C(s) = \frac{L_r(s)}{G(s)} \quad (18)$$

$$C(s) + K_p^\Delta + \frac{K_i^\Delta}{s} = \frac{L_r(s)}{G(s)} \quad (19)$$

$$K_p^\Delta + \frac{K_i^\Delta}{s} = \frac{L_r(s) - L(s)}{G(s)} \quad (20)$$

Changing the Laplace domain to frequency, using $s \to j\omega$:

$$K_p^\Delta + j\left(-\frac{K_i^\Delta}{\omega}\right) = \frac{L_r(j\omega) - L(j\omega)}{G(j\omega)} \quad (21)$$

Organizing the equation (21) in matrices, it is obtained:

$$\begin{bmatrix} 1 & 0 \\ 0 & -\frac{1}{\omega} \end{bmatrix} \begin{bmatrix} K_p^\Delta \\ K_i^\Delta \end{bmatrix} = \begin{bmatrix} \Re\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \\ \Im\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \end{bmatrix} \quad (22)$$

Hence:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & -\frac{1}{\omega} \end{bmatrix} \quad (23)$$

$$\mathbf{b} = \left[\Re\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right) \ \Im\left(\frac{L_r(j\omega) - L(j\omega)}{G(j\omega)}\right)\right]^T \quad (24)$$

As optimization problem (15) is convex and the matrices are constant, the solution vector θ is obtained using the constrained least square estimator analytic formula:

$$\theta = \theta_0 - (\Phi^T\Phi)^{-1}\mathbf{A}^T[\mathbf{A}(\Phi^T\Phi)^{-1}\mathbf{A}^T]^{-1}[\mathbf{A}\theta_0 - \mathbf{b}] \quad (25)$$

Table 1. Initial Tuning Parameters - $G_1(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
K_p	0.4593	0.3439	0.7059	0.2118
K_i	0.0712	0.0887	0.1307	0.0392

Table 2. Initial Margins and Delays - $G_1(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
$\widehat{\tau_d}$	6.2100	6.3200	6.2400	6.2600
$\widehat{A_m}$	2.5087	2.6830	1.6123	4.5985
$\widehat{\phi_m}$	84.1041	73.5938	73.0638	85.2209

where θ_0 is the solution of the unconstrained least square problem.

$$\theta_0 = (\Phi^T \Phi)^{-1} \Phi^T \Omega \tag{26}$$

Q.E.D.

7. SIMULATION RESULTS

To evaluate the proposed assessment and retuning strategies, two high order process were chosen. Each of them was tuned using four different PI rules applied in FOPTD reduced systems: IAE-PI Rovira, ITAE-PI Rovira (Rovira et al., 1970), IMC Fast ($\tau_c = 1.5\tau_d$) and IMC Slow ($\tau_c = 5\tau_d$). In all closed-loop projects, the selected reference margins are $A_{ref} = 3$ and, consequently by equation (8), $\phi_{ref} = 60°$.

According to the IMC PI design equations (8 and 9), the reference closed-loop transfer functions ($T_r(s)$) are different for various delays estimations. To simplify the procedure, the reference models are defined using delay estimation average.

The controllers are retuned by equation (25), using in the constraint function the estimated data at crossover frequency $\widehat{\omega}_g$. As the proposed excitation signal has a different behavior according to the controller applied, a single step reference signal was chosen to estimate indexes IAE_{Comp} and IAE_{exp}. A Gaussian noise with zero mean and variance of 0.0001 is added in system outputs signals in all simulations.

7.1 Process 1

This first analyzed process is given by the following equation:

$$G_1(s) = \frac{-1.5s + 1}{(2s + 1)(s + 1)^3} e^{-1.5s} \tag{27}$$

The FOPTD reduced model is:

$$G_{FOPTD1}(s) = \frac{1}{2.85s + 1} e^{-5.1s} \tag{28}$$

The initial tuning parameters are listed in Table 1. Each delay, gain and phase margins for the different controller projects are estimated using the methods discussed in previous sections by applying the proposed signal as listed in Table 2. The respective time outputs are shown in Figure 4.

The frequency performance assessment plot for the estimated data in Table 2, equation (8) and the reference margins is shown in Figure 5. It is noticed that the margins points are spread and any of them do not match neither the both references nor the benchmark curve.

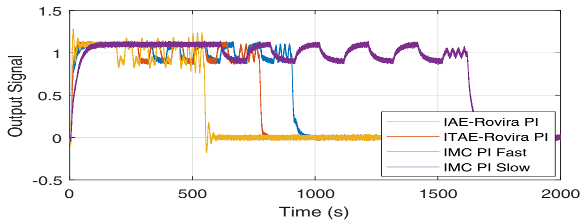

Fig. 4. Output Response for the excitation signal - $G_1(s)$

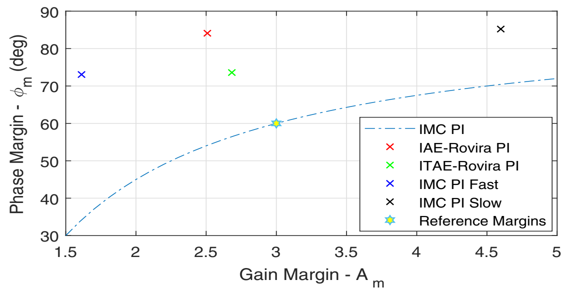

Fig. 5. Initial Margins Plot - $G_1(s)$

Table 3. IAE - $G_1(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
Initial	14.0444	11.2851	11.1139	25.5050
Retuned	11.9879	11.9907	12.0799	11.9822

The time domain performance is assessed by comparing the IAE indexes with a defined reference model. Using the delay average (6.2575), equations (9) and (8), it is obtained:

$$T_{r1}(s) = \frac{1}{5.693s + 1} e^{-6.2575s} \tag{29}$$

For $T_{r1}(s)$, the IAE_{Comp} is 11.9509 by equation (12). The experimental results (IAE_{exp}) for each closed-loop are listed in the Table 3. The respective outputs behaviors are shown in Figure 6.

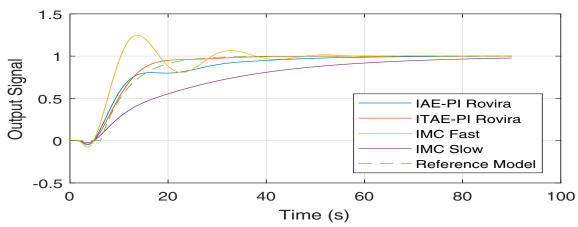

Fig. 6. Step response for initials tuning - $G_1(s)$

Comparing the results listed in Tables 2 and 3, it is possible to notice that most of the estimated time and frequency indexes are different from the defined references. Although some of them have values close to one specification, the others indexes have deviations from the references. Moreover, the output responses have different time behavior even with similar IAE_{exp} values. Hence, all of the controllers parameters must be retuned to obtain a behavior as the reference model and better performance indexes. Using the constrained optimal PI retuning, it is possible to obtain new parameters as listed in Table 4.

From those retuned controllers, the proposed excitation signal was applied again in each closed-loop to obtain the

Table 4. Parameters Retuned - $G_1(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
K_p	0.2837	0.2837	0.2877	0.2834
K_i	0.0835	0.0834	0.0828	0.0835

Table 5. Margins for the retuned controllers - $G_1(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
$\widehat{A}_m$	2.7936	2.9117	2.8363	2.7943
$\widehat{\phi}_m$	72.7643	72.7694	73.1441	72.7359

new margins estimations. The results, listed in Table 5, show that they have converged to similar values, however they are not exactly equal to the reference model because of the processes complexity. This can be verified in the frequency performance assessment plot, shown in Figure 7, that the margins points are concentrated in a small region.

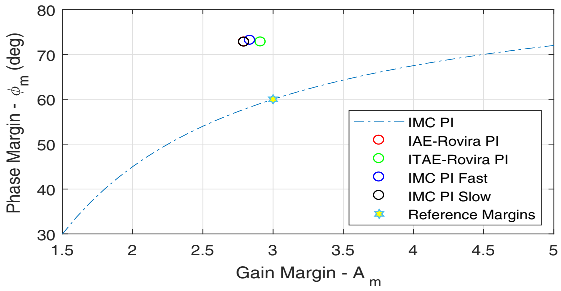

Fig. 7. Margins Plot after Retuning - $G_1(s)$

Applying a step signal in each new closed-loop as shown in Figure 8, it is possible to calculate each IAE_{exp} for the retuned closed-loops, as listed in Table 3. The indexes have converged to a value similar to the IAE_{Comp} (11.9509) and it was obtained a smoother output time response.

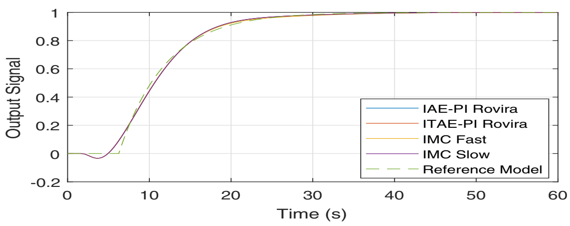

Fig. 8. Step response after retuning - $G_1(s)$

Based on the new indexes, it is possible to verify that all performance indexes were improved compared with the results for the initial controllers listed in Tables 2 and 3. The output systems behaviors became closer to the desired specifications as it is shown with the frequency and time performance indexes, listed in Tables 3 and 5. Even, for initial tunings that have better performance indexes, the retuning strategy was capable to have a smoother response with a small deviation on them.

7.2 Process 2

This process is given by the following equation:

$$G_2(s) = \frac{1.5s + 1}{(2s + 1)(s + 1)^3} e^{-1.5s} \qquad (30)$$

Table 6. Initial Tuning Parameters - $G_2(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
K_p	0.7188	0.5542	0.9578	0.2874
K_i	0.1933	0.1876	0.2481	0.0744

Table 7. Initial Margins and Delays - $G_2(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
$\widehat{\tau}_d$	2.1800	2.2100	2.1200	2.3900
$\widehat{A}_m$	2.2596	2.4577	1.7672	4.7246
$\widehat{\phi}_m$	76.5988	72.4882	73.9522	85.9808

Table 8. IAE - $G_2(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
Initial	5.3417	5.4808	5.8114	13.4380
Retuned	5.3072	5.3169	5.2954	5.3889

The respective FOPTD reduced model is given by the following equation and the initial controller parameters are listed in Table 6.

$$G_{FOPTD2}(s) = \frac{1}{2.53s + 1} e^{-2.66s} \qquad (31)$$

From the proposed experiment, the delay and margins are estimated and listed in Table 7. In the frequency performance assessment plot, Figure 9, it is shown the margins points are distributed across all the plot and any of them do not match neither the both references nor the benchmark curve.

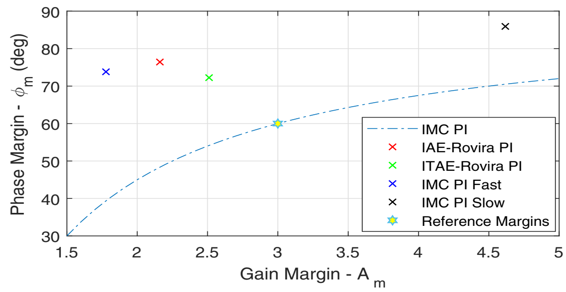

Fig. 9. Initial Margins Plot - $G_2(s)$

The reference model is defined for the time delay average (2.3175) using the equations (9) and (8):

$$T_{r2}(s) = \frac{1}{2.109s + 1} e^{-2.3175s} \qquad (32)$$

The time performance indexes are estimated and listed in Table 8. For the reference model $T_{r2}(s)$, the IAE_{Comp} is 4.4261, by equation (12). The outputs behavior are shown in Figure 10. The IAE_{exp} have divergent values for each tuning and the time behaviors are different from the reference. Hence, it is necessary to retune all the controllers to have the output shape closer to the desired model and better performance indexes.

Based on the new obtained controllers gains, listed in Table 9, the frequency and time performance are assessed again. Those respective results are listed in Tables 10 and 8, they have converged to values near to the reference but not exactly due the process limitations, as shown in margins plot and in the step time response Figures 11 and 12 respectively. Because of the pole in the process transfer

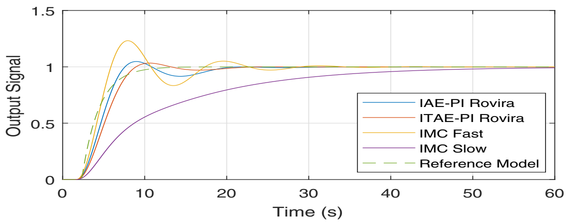

Fig. 10. Step response for initials tuning - $G_2(s)$

Table 9. Parameters Retuned - $G_2(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
K_p	0.7460	0.7399	0.7482	0.7399
K_i	0.2110	0.2133	0.2049	0.2238

Table 10. Margins for the retuned controllers - $G_2(s)$

	IAE Rovira	ITAE Rovira	IMC Fast	IMC Slow
$\widehat{A}_m$	2.1263	2.1291	2.1316	2.0747
$\widehat{\phi}_m$	74.2767	73.8419	75.2945	71.9707

function, it is not possible to obtain a closed-loop without an overshoot, as it is shown in Figure 12.

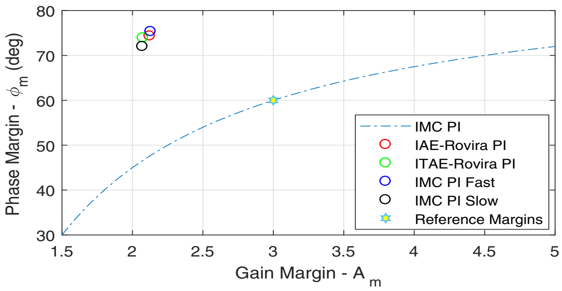

Fig. 11. Margins Plot after Retuning - $G_2(s)$

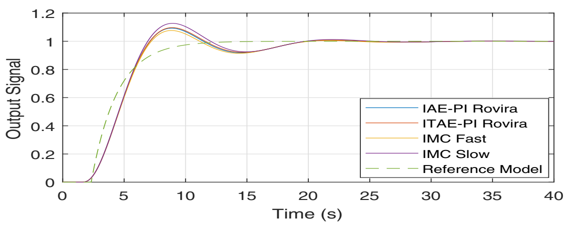

Fig. 12. Step response after retuning - $G_2(s)$

8. CONCLUSION

A performance assessment strategy for frequency and time domain characteristics is defined for IMC PI closed-loops. The selected indexes are chosen from the system characterization that allows to define a reference model from A_m, ϕ_m or β. Then, the closed-loop experiment is designed to estimate the delay, gain and phase margins. The frequency performance is assessed by comparing the estimated margins with a IMC PI benchmark curve and the reference model. The time performance is assessed by the IAE index for single step signals. If the system does not satisfy those chosen specifications, the closed-loop can be retuned using a constraint optimization rule to obtain new controller gains that improve the performance indexes.

Analyzing the results from the simulations, it is verified that is possible to assess the performance for arbitrary PI closed-loops with different characteristics and behaviors. Moreover, the retuning strategy applied obtains similar gains for different tunings and it is able to improve the performance indexes closer to the reference values and generate a smoother output time response due the process limitations.

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