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Performance assessment and redesign of PI controllers with pulse excitations

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Abstract:
In this paper a methodology is presented to assess the performance of PI controllers from closed-loop response data for pulse setpoint signal. Here a previously published technique is extended to evaluate and redesign single-input single-output (SISO) control loops for single and double pulses. The paper describes a system identification procedure for continuous-time transfer function models and demonstrates how it can be used for control performance assessment and controller redesign.

Keywords: Control performance assessment, System identification, PID control, Tuning, Set-point following, IAE, IMC.

1. INTRODUCTION

The industrial importance of individual controller benchmarking is sustained by the fact that there are often thousands of loops in a typical process plant and many of these will not have been tuned adequately.

The Proportional-Integral-Derivative (PID) controllers are the most widely used in industrial process industries owing to their simplicity and robustness to the modeling error. Due to changes in the process and its operation, and mostly to the lack of skill of the operator, many control loops are found to perform poorly. Given the importance of the problem, there has been increasing interest in the control loop performance assessment and automatic tuning fields. The problem of determining the controller parameters, then, is of great importance in the professional control domain.

When the loop assessment and the controller tuning is performed, the control loop should behave well. It is therefore important to supervise the control loops. Since there are hundreds of controllers in most complex processes, it is virtually impossible to monitor their performance manually. This has motivated a significant research effort in automatic supervision for process control.

Many different approaches have been proposed in the literature to assess performance of control loops. The minimum-variance (MV) concept originally proposed by Harris (1989) has been widely used as a reference benchmark for performance assessment. Therefore, methodologies for the performance assessment have been reported in a variety of control applications. Desborough and Harris (1992) considered the assessment of control loop performance for both feedback and feedforward control using minimum variance as the benchmark cost measure. Reviews of related work can be found in Qin (1998), Huang and Shah (1999), Harris et al. (1999), and Jelali (2006).

Recently, Veronesi and Visioli (2009) proposed a procedure for the setpoint-following performance assessment of a PID controller and for the retuning of the parameters, based on the SIMC tuning rules and evaluating a setpoint step response. However, the setpoint step change response for some processes may be too long and the procedure is limited to the closed loop time constant equal to the dead time.

In this paper pulse excitations were considered in addition to the traditional closed-loop step response, and the choice of the desired closed loop time constant was generalized.

The approach adopted in this paper uses setpoint changes for plant identification and then makes use of the identified model for performance assessment. The paper is organized as follows. In section 2, the PI performance assessment problem is formulated. Then in section 3, the performance assessment methodology is explained. In section 4 the procedure for the process identification is presented. In section 5 the retuning methodology is explained. Simulations results are presented in section 6. Conclusions are drawn in section 7.

2. PROBLEM FORMULATION

Consider the unity-feedback control system shown in Figure 1 where $C(s)$ is a PI controller described by the following transfer function:

$$C(s) = K_c \left(\frac{T_i s + 1}{T_i s} \right) \tag{1}$$

where K_c is the proportional gain and T_i is the integral time.

The process $P(s)$ is assumed to be a first-order-plus-dead-time (FOPDT) transfer function:

$$P(s) = \frac{\mu}{\tau s + 1} e^{-\theta s} \tag{2}$$

where $\mu \neq 0$ is the process gain, $\theta \geq 0$ is the time-delay and $\tau > 0$ is the time constant.

The method of Direct Synthesis aims at achieving a closed-loop transfer function on the form

$$T(s) := \frac{C(s)P(s)}{1 + C(s)P(s)} = \frac{1}{\tau_c s + 1} e^{-\theta s} \tag{3}$$

where τ_c is the desired closed-loop time constant. The value of τ_c can be chosen freely, and depends on the control objective (see Swanda and Seborg (1999)). It should be larger than the time delay θ. Choosing small values of τ_c, close to θ, leads to fast closed-loop responses and good disturbance rejection. On the other hand, large values of τ_c favor stability and robustness and reduces the control efforts. The choice of an appropriate value of τ_c should be guided by a trade-off between these factors.

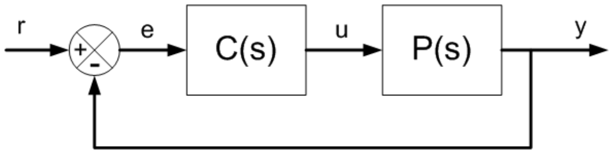

Fig. 1. The control scheme considered.

Considering the standard first-order-plus-time-delay model in (2), one can derive the following PI controller parameters:

$$K_c = \frac{\tau}{\mu(\theta + \tau_c)}$$
$$T_i = \tau \tag{4}$$

The aim of the proposed methodology is to verify if the tuning of the PI controller is satisfactory and, in the case that performance can be improved, to determine the new appropriate values of controller parameters.

3. PERFORMANCE ASSESSMENT

In order to quantify how far a PI controller is from the best achievable performance, it is therefore necessary to determine a suitable performance index. This section will focus on the use of the integrated absolute error (IAE) as a benchmark.

3.1 Integrated Absolute Error - IAE

To evaluate the output control performance often it is important to characterize the entire response curve. One such characterization is the integral of the absolute value of the control error (IAE) $e(t) := r(t) - y(t)$.

Proposition 1. The IAE for a step reference signal for the closed-loop in (3) is

$$IAE_{Step} = \int_0^\infty |e(t)|dt = A(\theta + \tau_c) \tag{5}$$

where A is the amplitude of the step change.

Proof.

$$\begin{aligned} IAE_{Step} &= \int_0^\infty |e(t)|dt \\ &= \int_0^\theta |A|dt + \int_\theta^\infty |Ae^{-(t-\theta)/\tau_c}|dt \\ &= A\theta + A\tau_c\left[1 - e^{-(T-\theta)/\tau_c}\right] \end{aligned} \tag{6}$$

then for $T \to +\infty$

$$IAE_{Step} = A(\theta + \tau_c). \tag{7}$$

The IAE for a step reference presented in (5) was already proposed in Yu et al. (2011).

Although the step is the most frequently type of excitation used to analyze the response of the closed-loop, for some processes it's application often demands a considerable long time. In the following case will be analyzed the application of a pulse reference signal.

Proposition 2. The IAE for a pulse reference signal for the closed-loop in (3) is

$$IAE_{Pulse} = 2A\left[\theta + \tau_c - \tau_c e^{-(T-\theta)/\tau_c}\right] \tag{8}$$

where T is the pulse width.

Proof.

The setpoint is a pulse signal given by

$$r(t) = \begin{cases} A, & 0 \leq t < T, \\ 0, & T \leq t < \infty. \end{cases} \tag{9}$$

The IAE resulting for a pulse reference signal can be decomposed into four parts, i.e.,

$$\begin{aligned} IAE_{Pulse} = & \; IAE_{(0 \leq t < \theta)} + IAE_{(\theta \leq t < T)} + IAE_{(T \leq t < T+\theta)} \\ & + IAE_{(T+\theta \leq t < \infty)} \end{aligned} \tag{10}$$

The closed-loop response $y(t)$ for each part is,

$$y(t) = \begin{cases} 0, & 0 \leq t < \theta, \\ A[1 - e^{-(t-\theta)/\tau_c}], & \theta \leq t < T, \\ A[1 - e^{-(t-\theta)/\tau_c}], & T \leq t < \theta + T, \\ A[1 - e^{-T/\tau_c}]e^{-(t-T-\theta)/\tau c}, & \theta + T \leq t < \infty. \end{cases} \tag{11}$$

Thus the error signal $e(t)$ for each part can be obtained as follows.

$$e(t) = \begin{cases} A, & 0 \leq t < \theta, \\ Ae^{-(t-\theta)/\tau_c}, & \theta \leq t < T, \\ -A[1 - e^{-(t-\theta)/\tau_c}], & T \leq t < \theta + T, \\ -A[1 - e^{-T/\tau_c}]e^{-(t-T-\theta)/\tau c}, & \theta + T \leq t < \infty. \end{cases} \tag{12}$$

Then, the corresponding IAE for a pulse reference signal is given by

$$IAE_{Pulse} = \int_0^\infty | \; e(t) \; | \; dt$$

$$
\begin{aligned}
&= \int_0^{\theta} A dt + \int_{\theta}^{T} A e^{-(t-\theta)/\tau_c} dt + \\
&+ \int_{T}^{T+\theta} A[1 - e^{-(t-\theta)/\tau_c}] dt \qquad (13)\\
&+ \int_{T+\theta}^{\infty} A[1 - e^{-T/\tau_c}] e^{-(t-T-\theta)/\tau_c} dt \\
&= A\theta + A\tau_c(1 - e^{-(T-\theta)/\tau_c}) + A\theta + \\
&+ A\tau_c[e^{-T/\tau_c} - e^{-(T-\theta)/\tau_c}] + \\
&+ A\tau_c[1 - e^{-T/\tau_c}] \\
&= 2A\theta + 2A\tau_c - 2A\tau_c e^{-(T-\theta)/\tau_c} \\
&= 2A\left[\theta + \tau_c - \tau_c e^{-(T-\theta)/\tau_c}\right].
\end{aligned}
$$

Despite the application of a faster setpoint change, the need to wait for the response of the closed loop to stabilize yet causes the experiment to be very slow. If the experiment is stopped after a certain time, before the response of the closed loop stabilizes, one obtains the following situation.

Consider the pulse transitions to occur at times t_i ($i = 0, 1, ...$) with t_0 the initial pulse transition. Assume also that the experiments stops at time t_n. Consider also the time interval $T_{ij} = t_i - t_j$, with $i > j$.

Proposition 3. For the case with a limited experiment time, the IAE for a pulse reference signal ($n = 2$), and step transitions at t_0 and t_1, for the closed-loop in (3) is

$$
\begin{aligned}
IAE_1 &= 2A\theta + 2A\tau_c - 2A\tau_c e^{-(T_{10}-\theta)/\tau_c} - \qquad (14)\\
&- A\tau_c e^{-(T_{21}-\theta)} + A\tau_c e^{-(T_{20}-\theta)/\tau_c}
\end{aligned}
$$

Proof. The setpoint is a pulse signal given by

$$
r(t) = \begin{cases} A, & 0 \le t < t_1, \\ 0, & t_1 \le t < t_2. \end{cases} \qquad (15)
$$

The IAE resulting for a pulse reference signal can be decomposed into four parts, i.e.,

$$
\begin{aligned}
IAE_1 &= IAE_{(0 \le t < \theta)} + IAE_{(\theta \le t < t_1)} + \qquad (16)\\
&+ IAE_{(t_1 \le t < t_1+\theta)} + IAE_{(t_1+\theta \le t < t_2)}
\end{aligned}
$$

The closed-loop response $y(t)$ for each part is,

$$
y(t) = \begin{cases} 0, & 0 \le t < \theta, \\ A[1 - e^{-(t-\theta)/\tau_c}], & \theta \le t < t_1 + \theta, \\ A[1 - e^{-T_{10}/\tau_c}] e^{-(t-T_{10}-\theta)/\tau_c}, & t_1 + \theta \le t < t_2. \end{cases} \qquad (17)
$$

Thus the error signal $e(t)$ for each part can be obtained as follows.

$$
e(t) = \begin{cases} A, & 0 \le t < \theta, \\ A e^{-(t-\theta)/\tau_c}, & \theta \le t < t_1, \\ -A[1 - e^{-(t-\theta)/\tau_c}], & t_1 \le t < t_1 + \theta, \\ -A[1 - e^{-T_{10}/\tau_c}] e^{-(t-T_{10}-\theta)/\tau_c}, & t_1 + \theta \le t < t_2. \end{cases} \qquad (18)
$$

Then, the corresponding IAE for a pulse reference signal is given by

$$
\begin{aligned}
IAE_1 &= \int_0^{t_2} |\, e(t) \,|\, dt \\
&= \int_0^{\theta} A dt + \int_{\theta}^{t_1} A e^{-(t-\theta)/\tau_c} dt + \int_{t_1}^{t_1+\theta} A[1 - e^{-(t-\theta)/\tau_c}] dt \\
&+ \int_{t_1+\theta}^{t_2} A[1 - e^{-T_{10}/\tau_c}] e^{-(t-T_{10}-\theta)/\tau_c} dt \\
&= A\theta + A\tau_c \left[1 - e^{-(T_{10}-\theta)/\tau_c}\right] + A\theta \\
&+ A\tau_c \left[e^{-T_{10}/\tau_c} - e^{-(T_{10}-\theta)/\tau_c}\right] + \\
&+ A\tau_c \left[1 - e^{-T_{10}/\tau_c}\right] \left[1 - e^{-(T_{21}-\theta)/\tau_c}\right] \qquad (19)
\end{aligned}
$$

$$
\begin{aligned}
IAE_1 &= 2A\theta + 2A\tau_c - 2A\tau_c e^{-(T_{10}-\theta)/\tau_c} - A\tau_c e^{-(T_{21}-\theta)} + \\
&+ A\tau_c e^{-(T_{20}-\theta)/\tau_c} \qquad (20)
\end{aligned}
$$

Proposition 4. The IAE for a double pulse reference signal for the closed-loop in (3) is

$$
\begin{aligned}
IAE &= 4A\theta + 3A\tau_c + A\tau_c \left[1 - e^{-T_{10}/\tau_c}\right] - 2A\tau_c \left[e^{-(T_{10}-\theta)/\tau_c}\right] - \\
&- 2A\tau_c \left[1 - e^{-T_{10}/\tau_c}\right] \left[e^{-(T_{21}-\theta)/\tau_c}\right] - \qquad (21)\\
&- 2A\tau_c \left[e^{-(T_{32}-\theta)/\tau_c}\right] + A\tau_c \left[e^{-T_{32}/\tau_c}\right] + \\
&+ A\tau_c \left[1 - e^{-T_{10}/\tau_c}\right] \left[e^{-T_{31}/\tau_c} - e^{-(T_{31}+T_{41}-\theta)/\tau_c}\right] + \\
&+ A\tau_c \left[1 - e^{-T_{32}/\tau_c}\right] \left[e^{-T_{31}/\tau_c} - e^{-(T_{41}-\theta)/\tau_c}\right].
\end{aligned}
$$

Proof. The proof follows as in the case of a single pulse considering the setpoint is a pulse signal given by

$$
r(t) = \begin{cases} A, & 0 \le t < t_1, \\ 0, & t_1 \le t < t_2, \\ A, & t_2 \le t < t_3, \\ 0, & t_3 \le t < t_4. \end{cases} \qquad (22)
$$

and the IAE resulting for a double pulse reference signal can be decomposed into eight parts, i.e.,

$$
IAE_2 = \sum_{i=1}^{8} IAE_i \qquad (23)
$$

4. PROCESS IDENTIFICATION

In order to tune the IMC controller it is necessary to have a process model. The excitation signal, the pulse, is applied at the setpoint and the manipulated variable $u(t)$ and the process variable $y(t)$ are recorded (see Acioli et al. (2009))

The model to be identified is a First-Order-Plus-Time-Delay (FOPTD) characterized by Equation (2).

4.1 Process Gain μ

The process gain is computed as the ratio between the integral of the deviations of the process variable and the manipulated variable. This is equivalent to compute the Fourier Transform at the zero frequency of the signals:

$$\mu = \int_0^t y(s)ds / \int_0^t u(s)ds \tag{24}$$

4.2 Time Delay θ

The time delay θ is estimated by a search. The search is based on the fact that the (no noise) process variable is zero up to the time delay θ so that:

$$\int_0^{t_f \geq T} y(s)ds = \int_\theta^{t_f \geq T} y(s)ds.$$

where t_f is the upper time limit for the search procedure.

The procedure is to compute the left term of the equation and perform a backward-in-time search to obtain the largest value of time for which the integral falls below a user defined relative threshold α. For instance, make $\hat{\theta} = T$, where T is the pulse width and decrease $\hat{\theta}$ until

$$\int_0^{t_f=T} y(s)ds - \int_{\hat{\theta}}^{t_f=T} y(s)ds < \alpha \int_0^{t_f=T} y(s)ds. \tag{25}$$

Threshold α is chosen, for instance, observing the standard deviation of the output signal around a fixed operating point.

4.3 Time Constant τ

As the identified model is a FOPTD model, the model is represented in the time domain as the differential equation

$$\tau \dot{y}(t) + y(t) = \mu u(t-\theta). \tag{26}$$

Integrating both sides and considering zero initial conditions

$$\tau y(t) + \int_0^t y(s)ds = \mu \int_0^t u(s-\theta)ds, \tag{27}$$

Changing the variable and using the fact that $u(t) = 0$ for $t < 0$

$$\tau y(t) + \int_0^t y(s)ds = \mu \int_0^{t-\theta} u(s)ds, \tag{28}$$

the only unknown is the time constant T.

Rearranging Equation (28) as

$$\int_0^t y(s)ds - \mu \int_0^{t-\theta} u(s)ds = -\tau y(t). \tag{29}$$

This problem can be solved using the least square and the solution is

$$\hat{\Theta} = \left(\Phi^T \Phi\right)^{-1} \Phi^T Y \tag{30}$$

where

$$\Phi = [\phi(0) \quad \phi(1) \quad ... \quad \phi((N-1)h)]^T \tag{31}$$

$$Y = [z(0) \quad z(1) \quad ... \quad z((N-1)h)]^T \tag{32}$$

$$\Theta = \tau \tag{33}$$

with h the sampling period. and

$$\phi(t) = -y(t) \tag{34}$$

$$z(t) = \int_0^t y(s)ds - \hat{\mu} \int_0^{t-\hat{\theta}} u(s)ds \tag{35}$$

where $\hat{\mu}$ and $\hat{\theta}$ are the estimated values for the process gain and process time delay, respectively.

5. RETUNING

If the performance provided by the controller turns out to be unsatisfactory, the PI controller has to be retuned. This can be done easily by considering the tuning rule (4) and the parameters that have been estimated, namely, by setting $\tau = \hat{\tau}$, $\mu = \hat{\mu}$ and $\theta = \hat{\theta}$.

6. SIMULATIONS EXAMPLES

In all the following simulation examples different setpoint changes were adopted as reference signal for the identification process. Initial values of the PID parameters were selected arbitrarily in order to present different situations.

This section uses a ϵ_2 index to assess the performance of the different setpoint changes presented. The ϵ_2 index compares the response of the closed-loop with the desired IMC response, and is defined by

$$\epsilon_2 = \int (y - y_{IMC})^2 dt \tag{36}$$

6.1 Example 1:

As a first example, consider the process

$$P_1(s) = \frac{1.5}{1.05s + 1} e^{-0.15s} \tag{37}$$

Initially the PI controller parameters were set as follows: $K_c = 3$ and $T_i = 0.7$.

According to (3) and considering $\tau_c = \theta$, a IMC desired model for this example would be given by

$$T_1(s) = \frac{1}{\tau_c s + 1} e^{-\theta s} = \frac{1}{0.15s + 1} e^{-0.15s} \tag{38}$$

and the IMC tuning parameters for the PI controller are $K_c = 2.33$ and $T_i = 1.05$. A setpoint step change for the IMC controller is shown in Figure 2.

For a setpoint step change given by

$$r(t) = \begin{cases} 0, & 0 \leq t < 1, \\ 1, & 1 \leq t < \infty. \end{cases} \tag{39}$$

the response with the initial values of the PI controller parameters is shown in Figure 2.

By applying the identification algorithm the following values of the process parameters were estimated: $\hat{\mu} = 1.5$,

$\hat{\tau} = 1$ and $\hat{\theta} = 0.2$. Then, using the IMC tuning rule in (4), the new values of the PI controller parameters were determined: $K_c = 1.67$ and $T_i = 1$. The response with the new values of the PI controller parameters is shown in Figure 2.

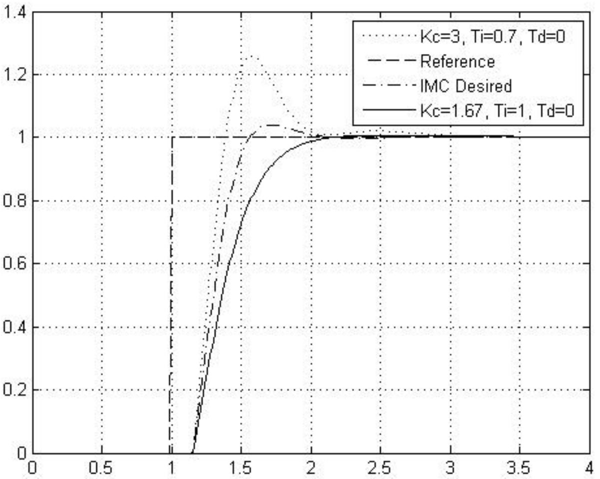

Fig. 2. Set-point step response for initial and retuned PI controller by step excitation of Example 1

For a setpoint pulse change given by

$$r(t) = \begin{cases} 0, & 0 \le t < 1, \\ 1, & 1 \le t < 1.29, \\ 0, & 1.29 \le t < 4. \end{cases} \quad (40)$$

In this case the following process parameters were estimated: $\hat{\mu} = 1.34$, $\hat{\tau} = 0.86$ and $\hat{\theta} = 0.17$. Again, using the IMC tuning rule in (4), the new values of the PI controller parameters were determined: $K_c = 1.89$ and $T_i = 0.86$. The response with the new values of the PI controller parameters is shown in Figure 3.

For a setpoint double pulse change given by

$$r(t) = \begin{cases} 0, & 0 \le t < 1, \\ 1, & 1 \le t < 1.29, \\ 0, & 1.29 \le t < 1.58, \\ 1, & 1.58 \le t < 1.93, \\ 0, & 1.93 \le t < 4. \end{cases} \quad (41)$$

For the double pulse setpoint change the following values of the process parameters were estimated: $\hat{\mu} = 1.5$, $\hat{\tau} = 1$ and $\hat{\theta} = 0.17$. The values of the IMC PI controller parameters were determined as in (4): $K_c = 1.96$ and $T_i = 1$. The response with the new values of the PI controller parameters is shown in Figure 3.

The IAE values for the different setpoint signals are presented in Table 1. The $IAE_{Theoretical}$ values were obtained by considering the equations (5), (14) e (21).

Table 1. IAE values for example 1.

Reference	IAE_{Exp}	$IAE_{Retuned}$	$IAE_{Theoretical}$
Step	0.372	0.418	0.3
Pulse	0.631	0.554	0.6
Double Pulse	1.131	0.956	1.019

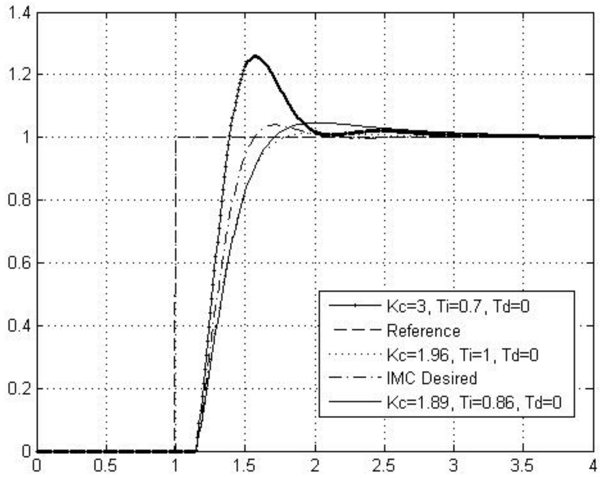

Fig. 3. Set-point step response for initial and retuned PI controller by different excitations of Example 1

The resulting ϵ_2 indices for the different tunings are presented in Table 2.

Table 2. Indexes values for example 1.

Reference	ϵ_2
Initial Controller	0.0265
Step	0.01769
Pulse	0.00584
Double Pulse	0.00462

6.2 Example 2:

As a second example, the following process has been considered:

$$P_2(s) = \frac{1}{(1.5s + 1)} e^{-2.5s} \quad (42)$$

The initial PI controller parameters adopted were $K_c = 0.6$ and $T_i = 1.8$.

For a setpoint step change given by

$$r(t) = \begin{cases} 0, & 0 \le t < 1, \\ 1, & 1 \le t < \infty. \end{cases} \quad (43)$$

the response with the initial values of the PI controller parameters is shown in Figure 4.

By applying the identification algorithm the following values of the process parameters were estimated: $\hat{\mu} = 0.99$, $\hat{\tau} = 1.07$ and $\hat{\theta} = 2.83$.

The response with the new values of the PI controller parameters is shown in Figure 4.

For a setpoint pulse change given by

$$r(t) = \begin{cases} 0, & 0 \le t < 1, \\ 1, & 1 \le t < 5.5 \\ 0, & 5.5 \le t < 50. \end{cases} \quad (44)$$

The values of the process parameters were estimated: $\hat{\mu} = 1$, $\hat{\tau} = 1.41$ and $\hat{\theta} = 2.57$, and the response with

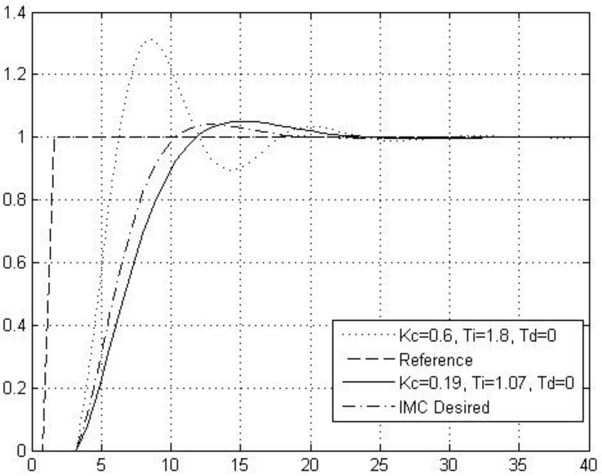

Fig. 4. Set-point step response for initial and retuned PI controller by step excitation of Example 2

the new values of the PI controller parameters is shown in Figure 5.

And for a setpoint double pulse change given by

$$r(t) = \begin{cases} 0, & 0 \le t < 1, \\ 1, & 1 \le t < 5.5, \\ 0, & 5.5 \le t < 9.05, \\ 1, & 9.05 \le t < 13.7, \\ 0, & 13.7 \le t < 50. \end{cases} \quad (45)$$

The following values of the process parameters were estimated: $\hat{\mu} = 1$, $\hat{\tau} = 1.42$ and $\hat{\theta} = 2.57$. The response with the new values of the PI controller parameters is shown in Figure 5.

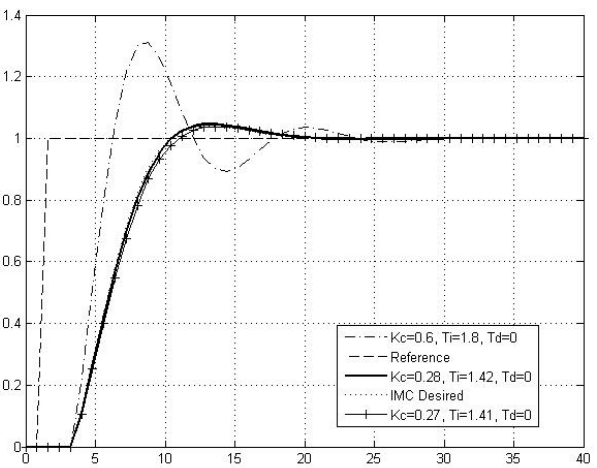

Fig. 5. Set-point step response for initial and retuned PI controller by different excitations of Example 2

The IAE values for the different setpoint signals are presented in Table 1.

The resulting ϵ_2 indices for the different tunings are presented in Table 4.

Table 3. IAE values for example 2.

Reference	IAE_{Exp}	$IAE_{Retuned}$	$IAE_{Theoretical}$
Step	4.011	5.981	5
Pulse	11.44	7.937	7.926
Double Pulse	22.01	12.66	13.262

Table 4. Indexes values for example 2.

Reference	ϵ_2
Initial Controller	1.001
Step	0.08768
Pulse	0.00838
Double Pulse	0.002021

7. CONCLUSION

This paper presented a methodology to assess the performance of PI controllers from closed-loop responses data for pulse setpoint signal. The tuning procedure was realized by following the IMC tuning principle, and a performance index was presented to validate the results.

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