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Performance Assessment and Retuning of PID Controllers for Load Disturbance Rejection

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Abstract: In this paper we propose an algorithm for the load disturbance rejection performance assessment of a PI(D) controller and for the retuning of the parameters in case the obtained response is not satisfactory. The technique can be applied simply by evaluating the load disturbance closed-loop response. The automatic tuning for a set-point filter is also proposed in order to address the set-point following task. Simulation results show the effectiveness of the methodology.

1. INTRODUCTION

Although Proportional-Integral-Derivative (PID) control is widely known and employed in industry (Åström and Hägglund, 2006; Leva et al., 2001; Visioli, 2006b), in many practical cases the controller is poorly tuned because the operator does not have a clear understanding of what a good performance could be. On the other hand, in large plants there are hundreds of control loops and it is almost impossible for operators to monitor each of them manually. Thus, automatic tools for performance evaluation and self tuning of PID controllers can be really desirable (Bobál et al., 2005) and in this context it would be much appreciated that the retuning is accomplished by using routine operating data, without the need of performing special experiments (as in the case of standard automatic tuning methodologies) that would lead to time and energy consumption and, in general, would affect the process operations.

In the wide scenario of the performance assessment techniques (see, for example, (Jelali, 2006; Huang and Shah, 1999; Qin, 1998; Harris, 1989; Eriksson and Isaksson, 1994; Patwardhan and Shah, 2002)), the stochastic performance (namely the capability of rejecting a stochastic disturbance) is typically evaluated by comparing the output variance with the minimum one achievable by PID controller (Ko and Edgar, 2004).

On the other side, the deterministic performance is mainly related to the set-point following or to the load disturbance rejection tasks. The set-point following task has been discussed in (Huang and Jeng, 2002; Swanda and Seborg, 1999; Yu et al., 2011) and in (Veronesi and Visioli, 2009) where an effective retuning technique has additionally been proposed. Regarding load disturbance rejection performance, the so-called Idle Index methodology to detect sluggish control loops has been presented in (Hägglund, 1999) and further discussed in (Kuehl and Horch, 2005). This has also been exploited in (Visioli, 2006a), where the proposed technique assesses the tuning of a PI controller and then gives guidelines on how to retune it, if necessary.

In this paper we propose a new method for assessing the performance of a PID controller applied to a self-regulating process (with dead time). In case the performance is not satisfactory, the technique provides a new tuning of the parameters. Basically, the methodology consists in evaluating a load disturbance step closed-loop response and, after having estimated the process parameters, an index (based on an appropriate tuning) is given to assess the controller performance. Then, in case the controller needs to be retuned, new values of the parameters are selected. Furthermore, the employment of a properly (automatically) designed set-point filter can help to improve also the set-point following response.

The paper is organised as follows. The problem is formulated in Section 2 where the Skogestad *half rule* (Skogestad, 2003) is also reviewed briefly. The method for the estimation of the process parameters is presented in Section 3. The performance assessment technique is described in Section 4 together with the algorithm for the retuning of the parameters. Simulation results are given in Section 5. Conclusions are drawn in Section 6.

2. PROBLEM FORMULATION

We consider the unity-feedback control system of Figure 1 where the self-regulating process P is controlled by a PID controller whose transfer function is in ideal ("non interacting") form:

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

where K_p is the proportional gain, T_i is the integral time constant and T_d is the derivative time constant. If the derivative action is employed, a filter on it is also applied for reducing the actuator wear caused by the unavoidable process variable measurement noise (which is amplified by the derivative action itself). The filter time constant is usually selected in order to filter the high-frequency noise

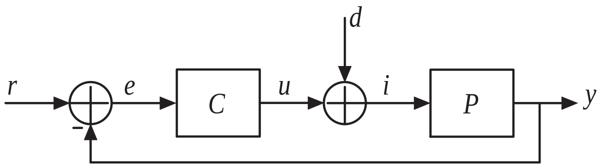

Fig. 1. The control scheme considered.

and, at the same time, in order for the cutoff frequency to be higher than the system bandwidth (Ang et al., 2005). For this reason, the filter will be neglected hereafter without loss of generality.

For the purpose of explaining clearly the method proposed in this paper, the controller transfer function can be rewritten as

$$C(s) = \frac{K_p}{T_i s}\tilde{c}(s) \tag{2}$$

where

$$\tilde{c}(s) := T_i T_d s^2 + T_i s + 1. \tag{3}$$

As estimated model of the process under control, the following first-order-plus-dead-time (FOPDT) transfer function is considered:

$$\hat{P}(s) = \frac{\mu}{\tau s + 1}e^{-\theta s}. \tag{4}$$

It is worth recalling that this simple model may come from a model reduction technique like the so called half-rule (Skogestad, 2003) which states that the largest neglected (denominator) time constant is distributed evenly to the effective dead time and the smallest retained time constant. In practice, it means that even a higher order transfer function

$$P(s) = \frac{\mu}{q(s)}e^{-\theta_0 s}, \qquad q(s) = \prod_i (\tau_i s + 1) \tag{5}$$

can be approximated by a FOPDT provided that

$$\tau = \tau_1 + \frac{\tau_2}{2}, \qquad \theta = \theta_0 + \frac{\tau_2}{2} + \sum_{i \geq 3} \tau_i. \tag{6}$$

It is therefore worth noting that the value of the sum of lags and delay of the model is the same one as the real process, *i.e.*,

$$T_0 := \sum_i \tau_i + \theta_0 = \tau + \theta. \tag{7}$$

Thus, T_0 is a relevant process parameter that is worth estimating for the purpose of the retuning of the PID controller, as it will be shown in the following sections. Finally, differently from (Skogestad, 2003), the presence of positive zeros is not considered in (5); however, the associated time constants can be simply added to the dead time of the process (Skogestad, 2003).

We consider that the PI(D) controller C has been already (roughly) tuned and that a load step disturbance d of (unknown) amplitude A_d occurs on the process at the time $t = 0$; this means that in a real application the instant at which it occurs has to be known in advance. The aim of the proposed methodology is to estimate a model of the process by evaluating the load disturbance step response and, based on that, to assess the performance of the PID controller. If the achieved performance, compared to a benchmark one, results to be unsatisfactory, then the PI(D) controller is conveniently retuned.

3. ESTIMATION OF THE PROCESS PARAMETERS

The aim of this section is to explain how the parameters of the simplified model can be easily determined after the occurrence (and the subsequent rejection) of a load disturbance. The method to be employed in case of set-point step change has been already proposed and discussed in (Veronesi and Visioli, 2009) and also applied in an industrial application as reported in (Veronesi and Visioli, 2010).

As already mentioned, we consider the closed-loop control scheme of Figure 1 where the PI(D) controller C has been already (roughly) tuned and with a load disturbance step d of (unknown) amplitude A_d entering into the process at the time $t = 0$. The disturbance amplitude A_d can be estimated by considering the final value of the integral of the control error. In fact, the expression of the Laplace transform of the control error is:

$$\begin{aligned} E(s) &= -\frac{P(s)}{1 + C(s)P(s)}D(s) \\ &= -\frac{T_i s \mu e^{-s\theta}}{T_i s q(s) + K_p \tilde{c}(s)\mu e^{-s\theta}}\frac{A_d}{s}, \end{aligned} \tag{8}$$

and therefore the final value of the integrated error (*IE*) is:

$$\begin{aligned} \lim_{t\to+\infty} \int_0^t e(v)dv &= \lim_{s\to 0} s\frac{1}{s}\frac{A_d}{s}\left(-\frac{T_i s \mu e^{-s\theta}}{T_i s q(s) + K_p \tilde{c}(s)\mu e^{-s\theta}}\right) \\ &= -\frac{A_d T_i}{K_p}. \end{aligned} \tag{9}$$

Thus, the amplitude of the step disturbance can be determined trivially as

$$A_d = -\frac{K_p}{T_i}\int_0^\infty e(t)dt. \tag{10}$$

Once the amplitude of the step disturbance has been determined, the process gain μ can be determined by considering the Laplace transform of the process input $i = u + d$ (see Figure 1), that is (note that, once the amplitude A_d of the constant disturbance has been determined, $i(t)$ can be easily obtained by postprocessing the data):

$$\begin{aligned} I(s) &= U(s) + D(s) \\ &= -\frac{C(s)P(s)}{1 + C(s)P(s)}D(s) + D(s) \\ &= \frac{1}{1 + C(s)P(s)}\frac{A_d}{s} \\ &= \frac{T_i s q(s)}{T_i s q(s) + K_p \tilde{c}(s)\mu e^{-s\theta}}\frac{A_d}{s}. \end{aligned} \tag{11}$$

Thus, by integrating $i(t)$ and by applying the final value theorem, the result is

$$\begin{aligned} \lim_{t\to+\infty} \int_0^t i(v)dv &= \lim_{s\to 0} s\frac{1}{s}\frac{T_i s q(s)}{T_i s q(s) + K_p \tilde{c}(s)\mu e^{-s\theta}}\frac{A_d}{s} \\ &= \frac{T_i A_d}{\mu K_p}. \end{aligned} \tag{12}$$

The process gain μ can be therefore found easily, once the value of A_d has been determined by using (10), as

$$\mu = A_d \frac{T_i}{K_p \int_0^\infty (u(t) + A_d)dt}. \tag{13}$$

Finally, the determination of the sum of the time constants of the process can be performed by initially considering the variable

$$v(t) := \mu(u(t) + d(t)) - y(t). \tag{14}$$

By applying the Laplace transform to (14) and by expressing u and y in terms of d, we can write

$$\begin{aligned} V(s) &= \frac{\mu - P(s)}{1 + C(s)P(s)} D(s) \\ &= \frac{\mu - P(s)}{1 + C(s)P(s)} \frac{A_d}{s} \\ &= \frac{\mu T_i A_d s}{T_i s q(s) + K_p \mu \tilde{c}(s) e^{-s\theta}} \frac{q(s) - e^{-s\theta}}{s}. \end{aligned} \tag{15}$$

By twice integrating $v(t)$ and by applying the final value theorem the result is (see (5))

$$\begin{aligned} &\lim_{t\to+\infty} \int_0^t \int_0^\xi v(\zeta) d\zeta d\xi \\ &= \lim_{s\to 0} s \frac{1}{s^2} \frac{\mu T_i A_d s}{T_i s q(s) + \mu K_p \tilde{c}(s) e^{-s\theta}} \frac{q(s) - e^{-s\theta}}{s} \\ &= \frac{T_i A_d}{K_p} \lim_{s\to 0} \left(\frac{q(s) - 1}{s} + \frac{1 - e^{-s\theta}}{s} \right) \\ &= \frac{T_i A_d}{K_p} \left(\sum_j \tau_j + \theta \right) = \frac{T_i A_d}{K_p} T_0. \end{aligned} \tag{16}$$

Thus, T_0 can be obtained as

$$T_0 = \frac{K_p}{T_i A_d} \int_0^\infty \int_0^t v(\xi) d\xi dt. \tag{17}$$

Note that the estimation of the process parameters is based on the integral of signals and therefore the method is inherently robust to the measurement noise. Further, the process parameters are obtained independently on the values of the PID parameters (provided that the closed-loop system is stable), because the estimation is based on steady-state values of the variables. Then, the apparent dead time θ of the system can be evaluated by considering the time interval from the occurrence of the load disturbance and the time instant when the condition $|y - \bar{y}| > 0.02\mu A_d$ occurs, where $\bar{y}$ is the current steady state value of the process variable. Actually, from a practical point of view, in order to cope with the measurement noise, a simple sensible solution is to define a noise band NB (Åström et al., 1993) (whose amplitude should be equal to the amplitude of the measurement noise) and to rewrite the condition as $|y - \bar{y}| > NB$. Finally, note that the step disturbance signal can be applied just for the purpose of (re)tuning the PID controller (in this case its amplitude should be as small as possible in order to perturb the process as less as possible) but also a step response during routine process operations can be employed.

In the proposed method, the occurrence of an abrupt (namely, step-like) load disturbance has been assumed. Indeed, this is the most relevant case for the control system, as the disturbance excites significantly the dynamics of the control system itself. Thus, the performance assessment technique has to be implemented together with a procedure for the detection of abrupt load disturbances, such as, for instance, the one proposed in (Veronesi and Visioli, 2008).

4. PERFORMANCE ASSESSMENT AND RETUNING

In the very wide field of PI(D) parameters tuning formulae (O'Dwyer, 2006), the load rejection performance can be assessed by comparing that obtained with a given controller with the one achievable by applying a tuning rule specifically designed for this control target. It is important to stress that, in addition to the minimisation of the control error, in practical cases the desired performance should also take into account the robustness of the control system and the control effort.

Thus, as a desired performance, we selected the integrated absolute error $IAE = \int_0^\infty e(t)dt$ obtained by the Chen-Seborg tuning rule proposed in (Chen and Seborg, 2002) which aims at achieving the following closed-loop transfer function (this can be easily ascertained by approximating the delay term as $e^{-s\theta} = (1 - \frac{s\theta}{2})/(1 + \frac{s\theta}{2})$)

$$\frac{Y(s)}{D(s)} = \frac{T_i}{K_p} \frac{(1 + s\theta/2)se^{-s\theta}}{(1 + s\tau_c)^3} \tag{18}$$

where τ_c is a design parameter. We choose $\tau_c = \theta$, which represents typically an effective trade-off between robustness and aggressiveness (Skogestad, 2003).

By modelling the process with a FOPDT transfer function in which the main lag is $\tau = T_0 - \theta$, and by choosing $\tau_c = \theta$, the tuning formulae proposed in (Chen and Seborg, 2002) for a PID controller become

$$\begin{aligned} K_p &= \frac{28T_0 - 41\theta}{27\mu\theta}, \\ T_i &= \frac{\theta}{4} \frac{28T_0 - 41\theta}{2T_0 - \theta}, \\ T_d &= \frac{\theta(11T_0 - 19\theta)}{28T_0 - 41\theta}. \end{aligned} \tag{19}$$

Since the desired closed-loop transfer function (18) has only real poles, its response exhibits no oscillations, provided that τ_c is chosen greater than $\theta/2$. Hence, in the ideal case, we have that the desired integrated absolute error IAE_d is equal to the integrated error, that is (see (9)):

$$IAE_d = \frac{A_d T_i}{K_p}. \tag{20}$$

By replacing K_p and T_i in (20) with the values suggested by the tuning formulae (19); for PID control we have therefore

$$IAE_d = \frac{27 A_d \mu \theta^2}{4(2T_0 - \theta)}. \tag{21}$$

Thus, a performance index for the load rejection task (called $LRPI$: Load disturbance Rejection Performance Index) can be easily defined by comparing the obtained integrated absolute error with the desired one, that is:

$$LRPI_{PID} = \frac{27 A_d \mu \theta^2}{4(2T_0 - \theta) \int_0^\infty |e(t)| dt}. \tag{22}$$

A similar reasoning is applied if a PI controller is selected. In this case, the target closed-loop transfer function between the process variable and the load disturbance is

$$\frac{Y(s)}{D(s)} = \frac{T_i}{K_p} \frac{se^{-s\theta}}{(1 + s\tau_c)^2} \tag{23}$$

Correspondingly, the tuning formulae are:

$$K_p = \frac{T_i T_0}{4\mu\theta^2}, \qquad T_i = \frac{\theta(3T_0 - 4\theta)}{T_0} \tag{24}$$

and the performance index is

$$LRPI_{PI} = \frac{4A_d\mu\theta^2}{T_0\int_0^\infty |e(t)|dt} \tag{25}$$

It turns out that the value of this $LRPI$ index should be equal to 1 for a well-tuned PI(D) controller and a lower value (that is, if $LRPI$ is less than a given threshold) indicates that the controller should be retuned. The value of the threshold can be selected by the user depending on how tight is the required performance in a given application, however, from a practical point of view the sensible default value of 0.6 can be imposed. It is worth noting, however, that a value greater than one may result. Indeed, the aim of the method is not to achieve the minimum value of the integrated absolute error, but the one resulting from the application of the tuning rules (19) and (24) which take into account also the robustness and control effort issues.

Considering then the set-point following task, we have that, for PID controllers, (see (18))

$$F(s) := \frac{Y(s)}{R(s)} = \frac{\left(T_iT_ds^2 + T_is + 1\right)\left(1+\frac{\theta}{2}s\right)}{(1+s\tau_c)^3}e^{-s\theta}. \tag{26}$$

Thus, by adopting a two-degree-of-freedom PID controller, it can be reduced to a simple FOPDT. In fact, by filtering the set-point with a transfer function

$$H(s) := \frac{aT_iT_ds^2 + bT_is + 1}{\left(T_iT_ds^2 + T_is + 1\right)\left(1+\frac{\theta}{2}s\right)} \tag{27}$$

two additional zeroes are available. By choosing to place both of them at $-1/\theta$, the following values of the parameters b and a can be obtained:

$$b = \frac{2\theta}{T_i}, \qquad a = \frac{T_ib^2}{4T_d} = -\frac{1}{\theta}. \tag{28}$$

The overall transfer function between the set-point and the controlled variable (26) results

$$\tilde{F}(s) = H(s)F(s) = \frac{e^{-s\theta}}{1+s\tau_c} \tag{29}$$

for which the step response integrated absolute error is

$$IAE = \int_0^\infty |e(t)|dt = 2A_s\theta. \tag{30}$$

where $e(t) = r(t) - y(t)$ and A_s is the amplitude of the set-point step. Therefore the set-point following performance can be evaluated by the following Set-point Following Performance Index ($SFPI$):

$$SFPI = \frac{2A_s\theta}{\int_0^{+\infty} |e(t)|dt} \tag{31}$$

for which the same reasoning done for the load disturbance rejection case can be applied. Note that this is the same performance evaluation criterion proposed in (Veronesi and Visioli, 2009).

Finally, in case of simple PI controller, the closed-loop transfer function for set-point step change results

$$F(s) = \frac{(T_is+1)}{(1+s\tau_c)^2}e^{-s\theta} \tag{32}$$

and therefore the set-point filter can be designed as

$$H(s) = \frac{\tau_cs+1}{1+sT_i} \tag{33}$$

in such a way the overall closed loop transfer function between a set-point step change and the process variable is still (29).

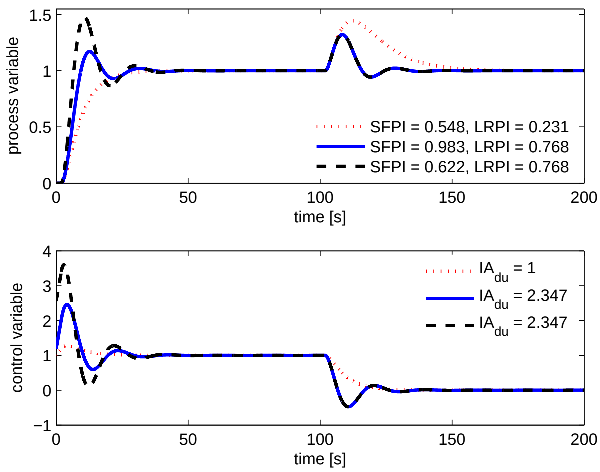

Fig. 2. Results of Example 1. Dotted-red line: initial tuning; dashed-black line: simple PI retuned; solid-blue line: retuned PI plus set-point filter.

5. SIMULATION RESULTS

In all the following simulation examples we set the amplitude of the set-point and load disturbance step signals as $A_s = A_d = 1$.

5.1 Example 1

As a first example the following second-order-plus-dead-time (SOPDT) model is considered:

$$P(s) = \frac{e^{-2s}}{(1+10s)(1+s)}. \tag{34}$$

A PI controller is employed and the initial PI parameters are $K_p = 1$ and $T_i = 10$. After the load disturbance occurs on the process, the gain K is correctly determined by means of (13), while the computation (17) gives exactly $T_0 = 13$; finally the dead time is estimated to be $\theta = 2.74$. The performance indices related to this initial manual tuning are $LRPI = 0.231$ and $SFPI = 0.548$, which indicates a quite poor behaviour of the controller. Hence, the PID parameters are retuned by using (24), resulting in $K_p = 5.910$, $T_i = 2.558$ (and $T_d = 0$). Figure 2 shows the performance improvement that results from the retuning; of course, when the set-point filter (33) is applied, the typical aggressiveness in load disturbance rejection task has not to be paid by an high overshoot in the set-point following, like it happens if the filter is not used. In fact, in both cases we have $LRPI = 0.768$ but by set-point filtering we have $SFPI = 0.983$ while with simple PI we have $SFPI = 0.662$. In the bottom part of the figure the control variables are shown, together with the values of the index

$$IA_{du} = \int_0^\infty \left|\frac{du}{dt}\right|dt \tag{35}$$

which is a measure of how much the actuator has been stressed by the control output trend. Note that, since the load disturbance rejection performance is addressed here, the value of the IA_{du} is the one related only to the load disturbance rejection transient response.

5.2 Example 2

The following third-order process is considered:

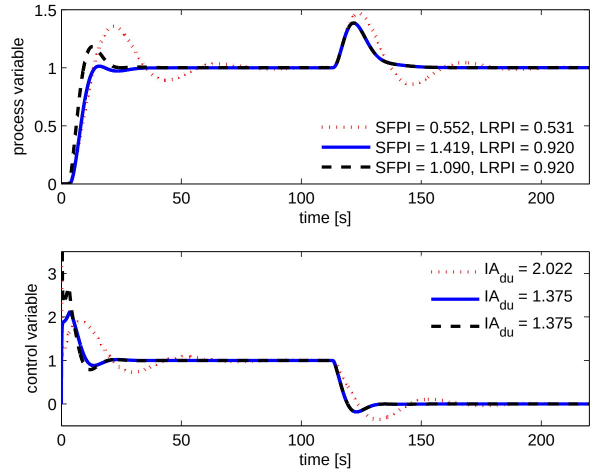

Fig. 3. Results of Example 2. Dotted-red line: initial tuning; dashed-black line: simple PID retuned; solid-blue line: retuned PID plus set-point filter.

$$P(s) = \frac{e^{-3s}}{(1+10s)(1+s)^2} \tag{36}$$

Initially, the following PID parameters have been selected $K_p = 1$, $T_i = 5$ and $T_d = 1$. After the load disturbance occurs on the process, the gain K is correctly determined by mean of (13), while the computation (17) gives exactly $T_0 = 16$. Finally, the dead time is estimated to be $\theta = 4.28$. The performance indices related to this initial manual tuning are $LRPI = 0.531$ and $SFPI = 0.552$, which indicate that the performance can be improved. Hence, the PID parameters are retuned by using (19), resulting in $K_p = 2.063$, $T_i = 10.083$ and $T_d = 1.459$. Figure 3 shows the performance improvement resulting from the retuning. Again, when the set-point filter (27), tuned as in (28), is applied, the typical aggressiveness in load disturbance rejection task has not to be paid by an high overshoot in the set-point step response, like it happens if the filter is not used. In fact, in both cases we have $LRPI = 0.920$ but by set-point filtering we have $SFPI = 1.419$ while with simple PID we have $SFPI = 1.090$. In the bottom part of the figure the control variables are shown, together with the values of the IA_{du} index.

5.3 Example 3

Another third-order process is considered, but in this case the apparent dead time is more significant:

$$P(s) = \frac{e^{-s}}{(1+s)^3}. \tag{37}$$

With the initial PID parameters $K_p = 1$, $T_i = 2$ and $T_d = 0.5$, when a load disturbance occurs, the process gain is correctly determined by means of (13), while the computation (17) gives exactly $T_0 = 4$. Finally, the dead time is estimated to be $\theta = 1.59$. The performance indices related to this initial manual tuning are $LRPI = 0.818$ and $SFPI = 0.720$, which indicate that the controller performance is satisfactory. However, the PID parameters have been retuned by using (19), resulting in $K_p = 1.090$, $T_i = 2.903$ and $T_d = 0.468$. Figure 4 shows the performance improvement resulting from the retuning. Again, the use of the set-point filter (27), tuned as in (28),

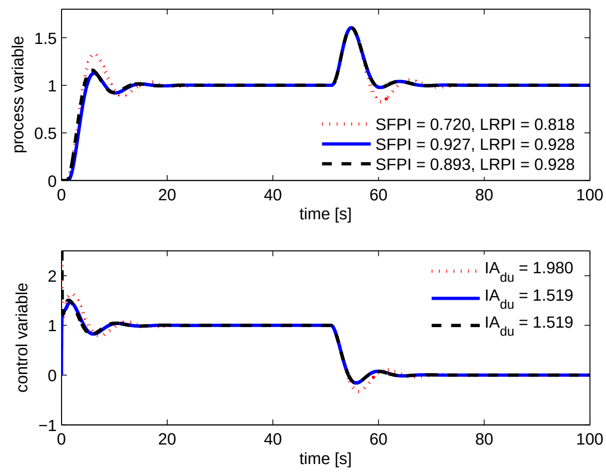

Fig. 4. Results of Example 3. Dotted-red line: initial tuning; dashed-black line: simple PID retuned; solid-blue line: retuned PID plus set-point filter.

allows the set-point following to improve slightly with the same load disturbance rejection response: in fact, in both cases we have $LRPI = 0.928$ but by set-point filtering we have $SFPI = 0.927$ while with simple PID we have $SFPI = 0.893$.

5.4 Example 4

In order to show the effectiveness of the proposed technique even when the process variable measurement is affected by noise, the following third-order model is considered:

$$P(s) = \frac{e^{-2s}}{(1+10s)(1+2s)^2}. \tag{38}$$

The PID parameters are initially set as $K_p = 1$, $T_i = 20$ and $T_d = 0.5$. A white noise with variance $\sigma_{wn} = 2 \cdot 10^{-5}$ is applied to the process output. After the load disturbance occurs on the process, the gain K is determined by means of (13) as $\mu = 1.001$, while the computation (17) gives $T_0 = 16.198$; finally the dead time is estimated to be $\theta = 3.77$. The performance indices related to the initial tuning are $LRPI = 0.167$ and $SFPI = 0.375$, which indicate that the controller needs to be retuned. By adopting (19), the new PID parameters result $K_p = 2.934$, $T_i = 9.844$ and $T_d = 1.344$. Figures 5 and 6 show the performance improvement resulting from the retuning. Again the usage of the set-point filter (27), tuned as in (28), allows to improve slightly the set-point following with the same load disturbance rejection response: in fact, in both cases we have $LRPI = 0.740$ but by set-point filtering we have $SFPI = 0.895$ while with simple PID we have $SFPI = 0.632$.

6. CONCLUSIONS

In this paper we have proposed a methodology for the performance assessment and retuning of PI(D) controllers for self-regulating processes. The main feature of this methodology is that the performance of the (pre-existing) controller is evaluated and the new PID controller parameters are selected without the need of special experiments, but just considering the (abrupt) load disturbances closed loop response (so that it can be implemented by using

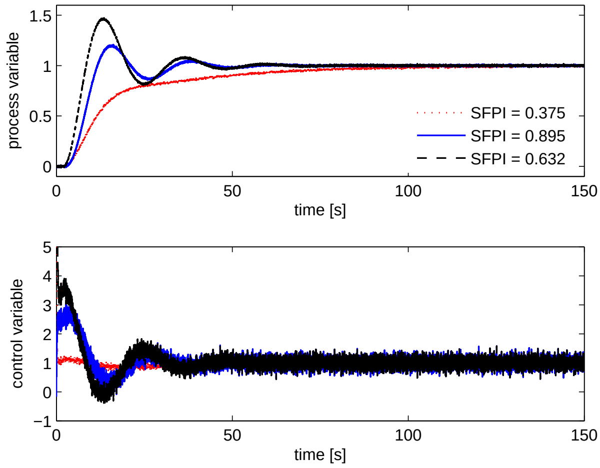

Fig. 5. Setpoint following response of Example 4. Dotted-red line: initial tuning; dashed-black line: simple PID retuned; solid-blue line: retuned PID + setpoint filter.

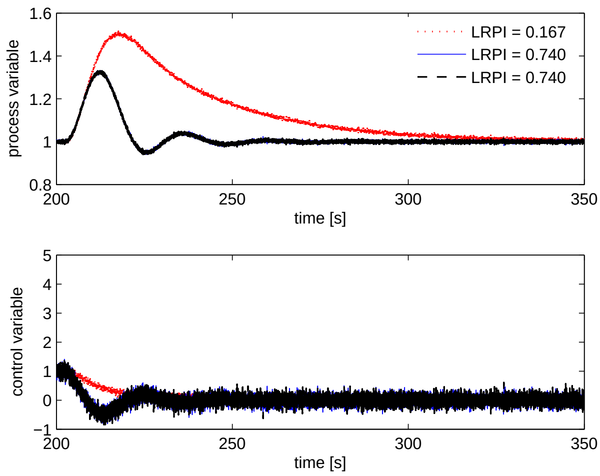

Fig. 6. Load rejection response for Example 4. Dotted-red line: initial tuning; dashed-black line: simple PID retuned; solid-blue line: retuned PID + setpoint filter.

normal data available during normal routine operations). The technique does not depend on the initial PID settings and uses integral computations, therefore it is quite robust with respect to the measurement noise. Performance indices are given both for PI and PID control together with PI(D) parameters retuning formulae; furthermore, a set-point filter is automatically tuned to improve the set-point following performance. The effectiveness of the technique has been demonstrated by simulation results.

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