

PI Controller Design for Actuator Preservation¹

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Abstract: *New explicit design relations for setting the controller parameters in PI control of industrial processes are proposed. The objective is to obtain proper transient responses with smooth control actions minimizing the variations of the controller output, hence preserving actuators from untimely attrition. The use of the proposed relations is illustrated by tests on real processes. Copyright ©2008 IFAC*

Keywords: PI Control; Tuning methods; Actuator preservation; Balanced control relations.

1. INTRODUCTION

Experience acquired through control practice show that the performance of a control system may be claimed to be good if all the following objectives are met:

- (1) Control quality or performance : minimization of some performance index, for example the IAE (Integral Absolute Error) criterion.
- (2) Robustness involving acceptable performance even if the process parameters undergo $\pm 20\%$ percentage changes from their nominal values.
- (3) Control action with limited number and size of the motions of mechanical parts in the actuators.

The latter point may be very important in some applications, for example in nuclear power plants where actuators include mechanical parts which may be very sensitive to wear. Therefore a properly defined statement of the control performance and robustness should include some specification of the acceptable controller output behavior with a view to the actuator preservation.

Generally, actuators will be preserved if the number of the control motions as also their size are reduced. An appropriate mathematical index for characterizing the controller output behavior is the so-called *total variation* of the control variable proposed in (Skogestad, 2003). So long as this total variation is minimized throughout the control system activity the actuator attrition is reduced.

In this paper a relation between this reduction of the controller output total variation and the PI controller settings is derived, and analytical relations for tuning PI

controllers are proposed with a view to the minimization of the control variable total variation. This results into a reduction of the actuator motions, therefore into a decrease of the actuator wear as well as of its energy consumption. Moreover, the control quality is kept good with transients close to the natural response of the controlled process.

The concept of actuator preservation will be dealt with a first-order plus dead time (FOPDT) process model since the latter provides an adequate characterization of the dynamics of many industrial processes,

$$G(s) = \frac{K_P}{1 + Ts} \exp(-Ls), \quad (1)$$

where L and T are the apparent dead time and the apparent time constant of the process, and K_P is the process gain. As pointed in (Åström and Hägglund, 1995), the difficulty of controlling a given process can be characterized by the *normalized dead time* $\tau = L/(L + T)$.

The paper is organized as follows. Section 2 introduces the concept of actuator preservation for PI control. Section 3 proposes simple tuning rules for tuning PI controllers in order to preserve the actuator. Section 4 gives a comparative study between PI controller tunings preserving actuators and other tuning rules which are derived without taking the preservation of the actuators into account. Section 5 shows some experimental results obtained with a laboratory water tank and from an application in the paper industry. Conclusions are given in Section 6.

2. ON ACTUATOR PRESERVATION

There are varying ways for characterizing the control system activity after a disturbance or after a step change

¹ This research is supported by the Ministry of Education, Youth and Sports of the Czech rep. via project 1N/04/0002, the Institutional Research Plan AV0Z10300504 and the Grant Agency of AS CR IAA200750802.

of the controller set point. The controller–output variation is large during the initial part of the transients and then, in general, the controller output should be able to overshoot its final value ; afterwards it will be smaller (Marlin, 2000). In fact, even after a long time, the control variable cannot be required to be absolutely constant, because feedback control has to respond to continuous changes in the controlled variable due to process disturbances and measurement noise.

The performance of the controller can be associated with the motions of the actuator. The number of the latter and their size are mathematically reflected in the so-called *total variation* of the control variable (Skogestad, 2003) given by the sum

$$\Delta_{TV} = \sum_{i=1}^{\infty} |u_{i+1} - u_i|, \quad (2)$$

where u is the control variable and the subscript i refers to sampled values. This quantity provides a proper concept for measuring the *smoothness* of the control variable, and this is a good potential candidate for quantizing the actuator preservation. Therefore the controllers should be designed to generate control actions with Δ_{TV} as small as possible.

For stable processes, in other words, for processes which have some capabilities of self-regulation, minimization of Δ_{TV} after a step change in the controller setpoint can be achieved by means of a single actuator motion with the control variable remaining constant after the initial part of the transients. This involves that the final value of the control variable has been reached immediately after the step change.

Let assume a step in the set point at the time $t = 0$ with the controlled process being in steady state before. In the ideal controller behavior $u(t)$ should be equal to $u(\infty)$ for all $t > 0$, hence

$$\dot{u}(t) = 0 \quad (3)$$

for all $t > 0$. For PI controllers represented in the velocity form

$$\dot{u}(t) = K \left[\dot{e}(t) + \frac{1}{T_I} e(t) \right]$$

where K and T_I are the proportional gain and the integral time of the controller, respectively, it leads to the constraint

$$T_I \dot{e}(t) = -e(t), \quad (4)$$

where $e(t)$ is the error signal. This constraint would result into a single exponential response in the case of the simplest first–order process ($L = 0$) provided that

T_I has been set equal to T . Except for this case, the above constraint cannot be satisfied at any time, due to additional lags and delays in the control loop.

However, one can design the controller in order to fulfil this constraint *in the average*. For that purpose one may integrate both sides in (4) and design the controller for equalizing these two integrals. In order to avoid the possibility that such an integral constraint be satisfied with oscillatory responses, the absolute values of the error signal and its time derivative should be used. Furthermore, since large initial values of the error signal can not be avoided, the error signal and its derivative should be weighted by time. This leads to the following weighted integral constraint

$$\int_0^{\infty} t|e(t)| dt = T_I \int_0^{\infty} t|\dot{e}(t)| dt. \quad (5)$$

It turns out that the left-hand side of (5) is the well-known *ITAE* (Integral Time Absolute Error) performance index (Åström and Hägglund, 1995). Similarly, the right-hand side of (5) has been called *ITAD* (Integral Time Absolute Derivative) in (Klán and Gorez, 2000).

In current control situations, there exists a close interplay between *ITAE* and *ITAD* with the three following cases:

- (1) *ITAE* < *ITAD*: control is nervous or even aggressive since the error signal variations are greater in the average than the actual values of the signal itself.
- (2) *ITAE* > *ITAD*: control is slow or too conservative since the signal changes are smaller in the average than the signal itself.
- (3) *ITAE* = *ITAD*: *balanced control* providing an intermediary ideal behavior between the two above behaviors, nervous and slow respectively.

In (Klán and Gorez, 2000) it was shown, that with balanced control the control variable would be kept, at least approximately, at a constant value equal to the required steady–state value. It is confirmed by experiments with different controller tunings that PI controllers tuned via (5) have a Δ_{TV} which is substantially reduced in comparison with other tunings, e.g. Ziegler–Nichols tuning. This will result into some preservation of the actuators with the quality of control still remaining quite good.

3. PI CONTROLLERS PRESERVING THE ACTUATORS

For the three-parameter model (1) the balance condition (5) leads to an explicit design relation for setting the controller integral time constant

$$T_I = (L + T) \frac{1 + (1 - \tau)^2}{2}, \quad (6)$$

where $L + T = T_{ar}$ is the average residence time of the process. In (Shinsky, 1990) it is noted that introducing

the process dead time and time lag in the controller tuning results in closed-loop responses matching the natural process step response. This condition will be met if the average residence time of the closed-loop system is equal to that of the controlled process. It gives the following explicit design relation for setting the controller gain

$$K = \frac{1}{K_P} \frac{1 + (1 - \tau)^2}{2}. \quad (7)$$

These tuning relations are valid at least for $\tau \leq 0.8$ and they are the simplest analytical relations that were derived for balanced tuning.

Actually, ideal design of controllers with a view to the actuator preservation involves that a step change of the controller set point should result into a control variable reaching immediately its steady-state value and keeping it thereafter. In other words, the closed-loop response of the process should match its natural step response ; this entails the following equality:

$$\frac{C(s)G(s)}{1 + C(s)G(s)} = \frac{G(s)}{G(0)}, \quad (8)$$

hence for the controller transfer function

$$C(s) = \frac{1}{G(0) - G(s)}, \quad (9)$$

where $G(s)$ is the transfer function of the controlled process. For processes which can be represented by the FOPDT model (1) with a dominant time constant $L \ll T \Rightarrow \tau \ll 1$ so that the dead-time factor $\exp(-Ls) \approx 1 - Ls$, the controller transfer function (9) becomes

$$C(s) = \frac{1}{K_P} \frac{1 + Ts}{(L + T)s} \quad (10)$$

which yields $K = K_P^{-1}T/(L + T) = K_P^{-1}(1 - \tau)$ and $T_I = T = T_{ar}(1 - \tau)$ for the controller parameters. For small values of τ , that is to say whenever τ^2 is negligibly small, these expressions are in an agreement with the design relations (6) and (7). This is completely true for processes with a single time constant only ($\tau = 0$) ; for such processes, the proposed controller design provides a closed-loop step response equal to the natural process step response (except for the scale due to the value of the true process static gain), with in addition the disturbance rejection capability.

4. COMPARISON OF DIFFERENT TUNINGS

Balanced tuning is compared here with typical PI tunings such as the well-known Ziegler–Nichols settings and the minimization of the integrated absolute error, $\min IAE$, as considered in (Åström and Hägglund, 1995) (p. 165). Simulation tests were performed on the process

$$G(s) = \frac{1}{1 + s} \exp(-Ls) \quad (11)$$

with the time delay L ranging from 0 to 10 sec. The controller had to eliminate the effect of a unit step disturbance acting upon the process input.

Comparative results are summarized in Tab. 1, with PI controllers being indexed as follows:

- 1: Balanced tuning via (6) and (7).
- 2: Ziegler–Nichols PI tuning.
- 3: PI tuning for $\min IAE$.

The results in Tab. 1 can be set in the following two groups:

- (1) $\tau \leq 0.5$, that is to say when the time constant of the test process (11) overcomes its time delay. Then, $IAE_3 < IAE_1$, which means that the quality of $\min IAE$ control is better than that of balanced control. However, $TV_3 > TV_1$, which involves that this better quality is obtained thanks to a higher total variation of the controller output. Therefore, it is the task of the control–system designer to choose between better control quality or better actuator preservation. Big differences in the total variation can be observed for small time delays. In this case, it is possible to obtain a high quality control with the risk of often having to change weary actuators or to have a control of lower quality (mostly slower responses) keeping the actuators for a longer life–time with some reduction of the energy consumption. According to the authors' experience, in a lot of applications it is difficult to evaluate the quality of control. In this case, actuator preservation could be the main objective.
- (2) $\tau > 0.5$, that is to say when the time delay overcomes the time constant. In this group, results for $\min IAE$ criterion and balanced tuning are close to each other. Therefore, they are comparable both for the quality of the control and for the actuator preservation. Note that Ziegler–Nichols tuning provides sluggish responses for such processes.

From Tab. 1 it may be concluded that balanced tuning preserves actuators with a reasonably good quality of control. Then one can recommend to use tunings (6) and (7) at least for processes with $\tau \leq 0.8$. Controller output responses with balanced tuning are close to step changes. As forecast by (7), its initial value is between 50 and 100% of the final steady state value, with the latter being reached smoothly without big overshoots or undershoots. This provides a compromise between reasonable control quality and robustness on the one hand, and on the other hand

L	IAE_1	Δ_{TV1}	IAE_2	Δ_{TV2}	IAE_3	Δ_{TV3}
0	1.00	1.00	N	N	N	N
0.2	1.19	1.00	0.15	2.62	0.14	3.04
0.5	1.50	1.00	0.93	1.73	0.61	2.65
1.0	2.01	1.05	3.66	1.25	1.52	1.87
2.0	3.28	1.41	14.8	1.04	3.25	1.52
5.0	8.65	1.97	N	N	7.76	1.29
10	17.2	2.23	N	N	14.7	1.20

Table 1. PI control of $G(s) = \frac{1}{s+1} \exp(-Ls)$.
 Subscript 1 refers to balanced control, 2 to Ziegler–Nichols tuning and 3 to min IAE tuning. "N" means unmeasurable data or that steady state was not reached after the experiment time interval (100 sec).

small variations of the controller output, hence actuator preservation.

5. HOW ACTUATOR PRESERVATION CAN WORK ON REAL PROCESSES

The tuning relations proposed above have been tested on a laboratory process including two interconnected water tanks and they are applied in paper industry (Mondi Packaging Paper Štětí, Czech Rep.) to control the causticizing process, the first one with a view to the control of the water level in the second tank and the second one with a view to a regulator problem reducing the variance of the conductivity of alkaline liquors in the causticizer.

5.1 Water tanks

From measurements on a step response record, the following values were obtained for a first-order model of the process : $K_P = 10.6$, $T = 190 \text{ sec}$, $L = 71.7 \text{ sec}$, hence an average residence time $T_{ar} = 261.7 \text{ sec}$ and a normalized dead time $\tau = 0.27$. Then the design relations (6) and (7) for balanced tuning provide the following values for a PI controller : $K = 0.071$, $T_I = 198.9 \text{ sec}$. These values can be compared to that, $K = 0.225$, $T_I = 239 \text{ sec}$, obtained by the classical Ziegler–Nichols relations ; the latter can be used for designing controllers for processes with such a low normalized dead time, but as shown by the comparison of the parameter values they will lead to a fast aggressive control. This is confirmed by the experimental results presented in Fig. 2 : the right-hand side plots show the water level in the second tank, and the left-hand side plot the actuating variable, with broken lines for Ziegler–Nichols settings and full lines for the proposed tuning. These plots confirm the expectation that Ziegler–Nichols tuning is very aggressive, due to the high value of the controller gain : this aggressiveness leads to relatively fast closed-loop responses, with more than 10% overshoot. Balanced tuning provides much smoother control without any overshoot.

There is also a major difference in the activity of the actuating variable, balanced tuning resulting in very few

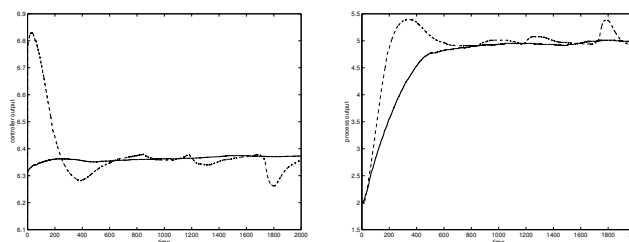


Fig. 1. Closed-loop responses for level control in a 2-tank process, with PI controller tuned via Ziegler–Nichols relations (broken lines) or for balanced tuning (full lines).

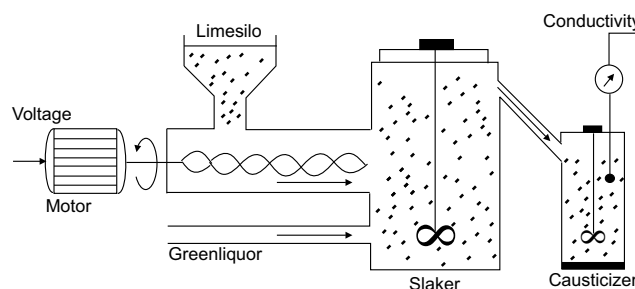


Fig. 2. A simplified scheme of the causticizer system.

variations of the latter, hence minimizing the energy needed for control. The values of the total controller output variation for the two tunings are:

- Ziegler–Nichols tuning: $\Delta_{TV} = 2.26$
- Balanced tuning: $\Delta_{TV} = 0.65$

It means that the activity of actuators in the case of the proposed tuning is more than 3.5 times lower than with Ziegler–Nichols tuning. However, similar control results are achieved, using only 30% of the energy consumed with Ziegler–Nichols tuning.

5.2 Causticizing control system

The process to be controlled consists of a motor, a lime inlet, a slaker and the causticizer itself (see Fig. 3). Control is provided by controlling the lime flow rate by means of the motor speed, the measured variable is the conductivity of alkaline liquors in the causticizer. This conductivity should be kept constant in spite of numerous unmeasurable disturbances in the process. Since a minimum of control variations is requested, PI balanced tuning has been selected and it is compared to manual control by skilled operators.

From measurements on a step response record provided by operators, the following values of the parameters were obtained for a first order model of the process : $K_P = 3.0$, $T = 37 \text{ min}$, $L = 15 \text{ min}$, hence an average residence time $T_{ar} = 52 \text{ min}$ and a normalized dead time $\tau = 0.29$. Then the design relations (6) and (7) for balanced tuning provide the following values for a PI controller : $K = 0.25$, $T_I = 40 \text{ min}$.

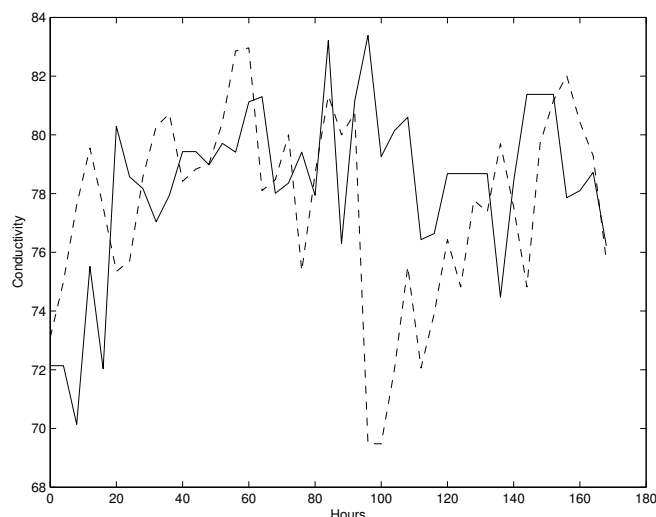


Fig. 3. Measured conductivity over the two weeks: week I (broken line), week II (full line).

Experiments over two weeks have resulted into the following evaluation of the control performance:

- Week I (August 19 to 26, 2004), manual control.
- Week II (September 30 to October 7, 2004), PI control with balanced tuning.

Fig. 4 shows the measured conductivity over the two weeks of tests. The control quality is appraised by the square root of the conductivity variance. This quality was more than 13 percent better in Week II (2.87) than in Week I (3.28). There was also a difference in the activity of the control variable:

- Week I: $\Delta_{TV} = 24.0$
- Week II: $\Delta_{TV} = 7.3$

It means that the activity of actuators in the case of the proposed tuning is more than 3 times lower than with manual control by skilled operators.

6. CONCLUSIONS

The concept of PI control with actuator preservation has been resumed and it leads to simple analytical rules allowing the designer of the control system to set the parameters of a PI controller in an easy and intuitive way. The advantageous features of such control have been illustrated by simulation results and by experiments with a real industrial process. The simulation results also establish the reduction of the controller output total variation which can be achieved by balanced tuning. Then it can be said that balanced tuning preserves actuators from untimely attrition and helps to deal with some technical limits in the control loops, for example bounds on the controller output variable.

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