Performance assessment and retuning of PID controllers

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Workshop on Advanced Topics in
PID Control System Design, Automatic Tuning and Applications

Credits

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- Julio Normey-Rico, Rafael Sartori, René Pereira, Bismark Torrico
- José Luis Guzman, Tore Hagglund

Introduction

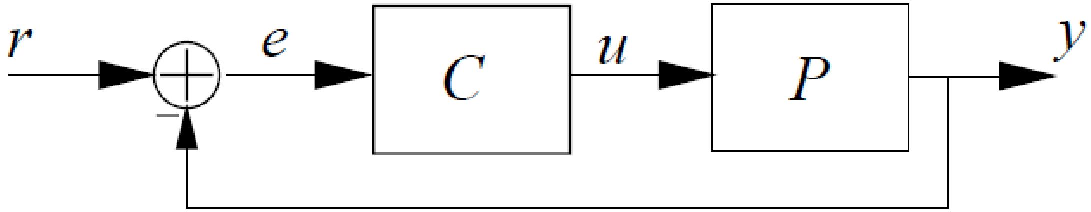
- Performance monitoring is very important, in general, as it plays a key role in saving costs related to maintenance and unexpected stops of the process operations.
- This is especially relevant nowadays in the Industry 4.0 paradigm.
- The performance assessment of (low-level) feedback controllers is, of course, the basis for a general architecture.
- Once it is realized that the performance can be improved, it is very useful to provide a new tuning for the controller parameters.
- It is important to have procedures that use routine operating data.

Deterministic and Stochastic performance

Performance assessment techniques are generally divided into two categories:

- *stochastic performance monitoring*, in which the capability of the control system to cope with stochastic disturbances is of main concern (works that fall in this class mainly rely on the concept of minimum variance control);
- *deterministic performance monitoring*, in which performances related to more traditional design specifications such as set-point and load disturbance step response parameters are taken into account.

Set-point following task



- The main idea is to evaluate the set-point response of the control system and, if the performance is not satisfactory, to retune the PID controller appropriately.
- In order to assess a control performance, a benchmark, which represents the desired performance, has to be selected so that the current control performance can be evaluated against it.
- For this purpose, the set-point following performance achieved by the PID controller designed according to SIMC tuning rule can be employed.
- In this context, the estimation of the process transfer function is essential (indirect method).

Skogestad's "half rule"

The largest neglected (denominator) time constant is distributed evenly to the effective dead time and the smallest retained time constant.

$$P(s) = \frac{\mu}{\prod_i(\tau_{i0}s+1)}e^{-\theta_0 s}$$

where the time constants are ordered according to their magnitude (namely, $\tau_{10} > \tau_{20} > \cdots$). Then, a first-order-plus-dead-time (FOPDT) transfer function

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

is obtained by setting

$$\tau = \tau_{10} + \frac{\tau_{20}}{2}, \qquad \theta = \theta_0 + \frac{\tau_{20}}{2} + \sum_{i \geq 3} \tau_{i0}.$$

Note that the sum of the time constant(s) of the process and of the dead time remains the same.

PID controller

The series (interacting) form is considered

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

but the other forms (ideal, ISA, parallel) can be also derived by applying suitable conversion formulae.
Obviously the derivative term has to be filtered (this issue will be neglected hereafter).

PI controller tuning

With respect to the set-point following task, the PI controller parameters can be effectively selected by applying the Internal Model Control (IMC) paradigm where the desired closed-loop time constant is chosen to be equal to the process dead time, namely by selecting

$$K_p = \frac{\tau}{2\mu\theta}, \qquad T_i = \tau.$$

By defining as T_0 the sum of the time constant and of the dead time of the process, namely,

$$T_0 := \tau + \theta,$$

it is trivial to verify that

$$T_0 = \tau + \theta = T_i + \frac{T_i}{2\mu K_p}.$$

Desired closed-loop transfer function

The SIMC tuning rule aims at achieving a closed-loop transfer function (this can be easily ascertained by approximating again the delay term as $e^{-\theta s} = 1 - \theta s$)

$$F(s) := \frac{C(s)P(s)}{1 + C(s)P(s)} \cong \frac{1}{\theta s + 1} e^{-\theta s}$$

for which the step response integrated absolute error is

$$IAE = \int_0^\infty |e(t)| dt = 2A\theta.$$

where $e(t) = r(t) - y(t)$ and A is the amplitude of the set-point step.

Estimation of process parameters - dead time

The apparent dead time θ_m of the system can be evaluated by considering the time interval from the application of the step signal to the set-point and the time instant when the process output attains the 2% of the new set-point value A, namely, when the condition $y > 0.02A$ occurs.
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 (whose amplitude should be equal to the amplitude of the measurement noise) and to rewrite the condition as $y > NB$.

Estimation of process parameters - DC gain

The process gain μ can be determined by considering the following trivial relations which involve the final steady-state value of the control variable u:

$$\lim_{t\to+\infty} u(t) = \frac{K_p}{T_i}\int_0^{\infty} e(t)dt = \frac{A}{\mu}$$

and therefore we have

$$\mu = A\frac{T_i}{K_p \int_0^{\infty} e(t)dt}.$$

Estimation of process parameters - time constant

The determination of the value of T_0 can be performed by considering the following variable:

$$e_u(t) = \mu u(t) - y(t).$$

By applying the Laplace transform and by expressing u and y in terms of r we have

$$E_u(s) = \mu U(s) - Y(s) = \frac{C(s)(\mu - P(s))}{1 + C(s)P(s)} R(s).$$

which can be rewritten as

$$E_u(s) = \frac{\mu K_p(T_i s + 1)}{T_i s(\tau s + 1) + \mu K_p(T_i s + 1)e^{-\theta s}}((\tau s + 1) - e^{-\theta s})R(s).$$

By applying the final value theorem to the integral of e_u when a step is applied to the set-point signal we finally obtain

$$
\begin{aligned}
&\lim_{t\to+\infty}\int_0^t e_u(v)dv \\
&= \lim_{s\to 0} s\frac{A}{s}\frac{\mu K_p(T_i s+1)}{T_i s(\tau s+1)+\mu K_p(T_i s+1)e^{-\theta s}}\frac{(\tau s+1)-e^{-\theta s}}{s} \\
&= A\lim_{s\to 0}\left\{\frac{1-e^{-\theta s}}{s}+\frac{(\tau s+1)-1}{s}\right\} \\
&= A\left(\theta+\tau\right) \\
&= AT_0.
\end{aligned}
$$

Thus, the sum of the lag and of the dead time of the process can be obtained by evaluating the integral of $e_u(t)$ at the steady-state and by dividing it by A.

Remarks

- The sum of the lag and of the dead time of the process can be obtained by evaluating the integral of $e_u(t)$ at the steady-state (which does not depend on the PID parameters) when a step signal is applied to the set-point and by dividing it by the amplitude A of the step.
- It is worth noting that both the value of the gain and of sum of the lags and of the dead time of the process are determined by considering the integral of signals and therefore the method is inherently robust to the measurement noise.

Performance assessment

For the purpose of assessing the controller performance it is worth considering the following performance index, named Close-loop Index CI:

$$CI = \frac{2A\theta_m}{\int_0^\infty |e(t)|dt}$$

In principle, the performance obtained by the control system is considered to be satisfactory if $CI = 1$. However, it has been found from a large number of simulations that, from a practical point of view, the controller can be considered to be well-tuned if $CI > CI_d$ with $CI_d = 0.6$.

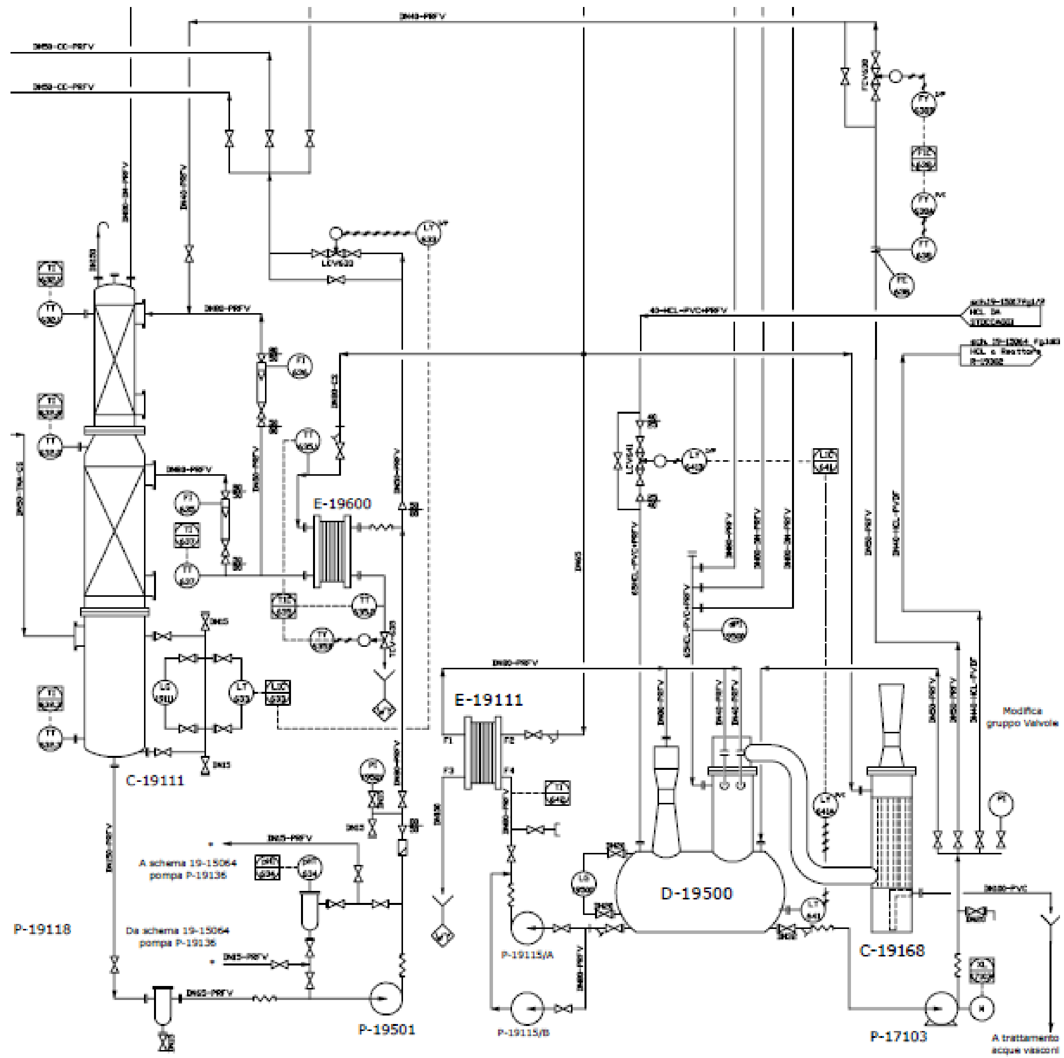
Retuning

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 setting

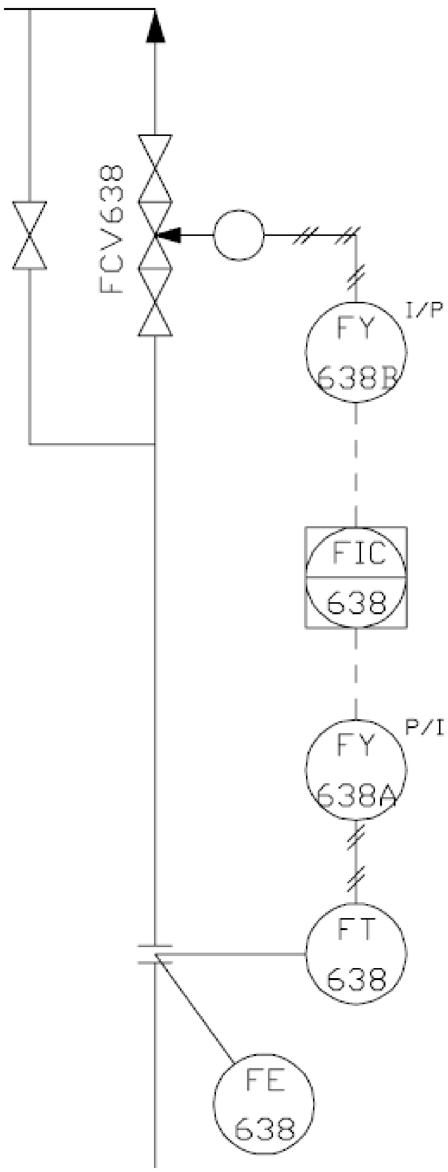
$$K_p = \frac{T_0 - \theta_m}{2\mu\theta_m}$$

$$T_i = T_0 - \theta_m$$

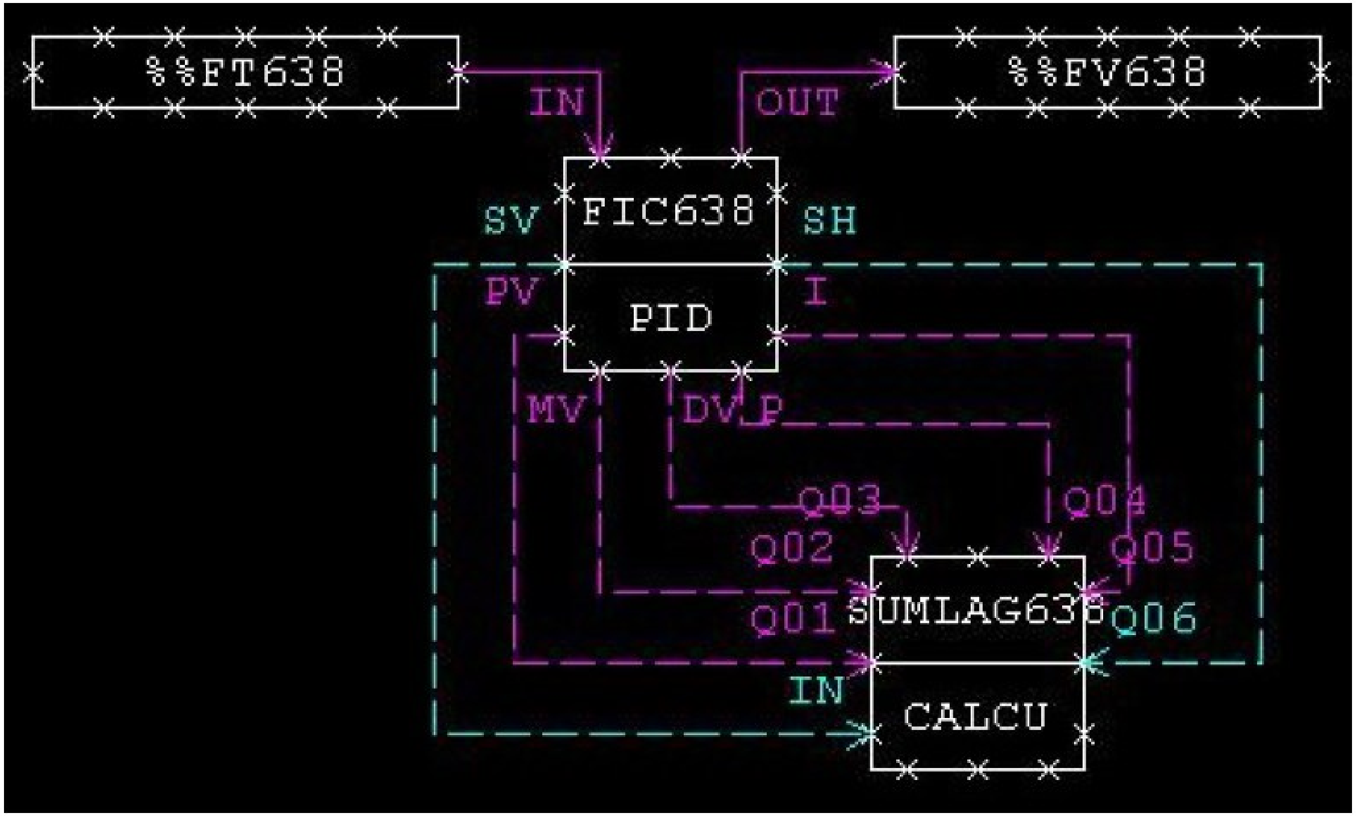
Application example - flow control loop



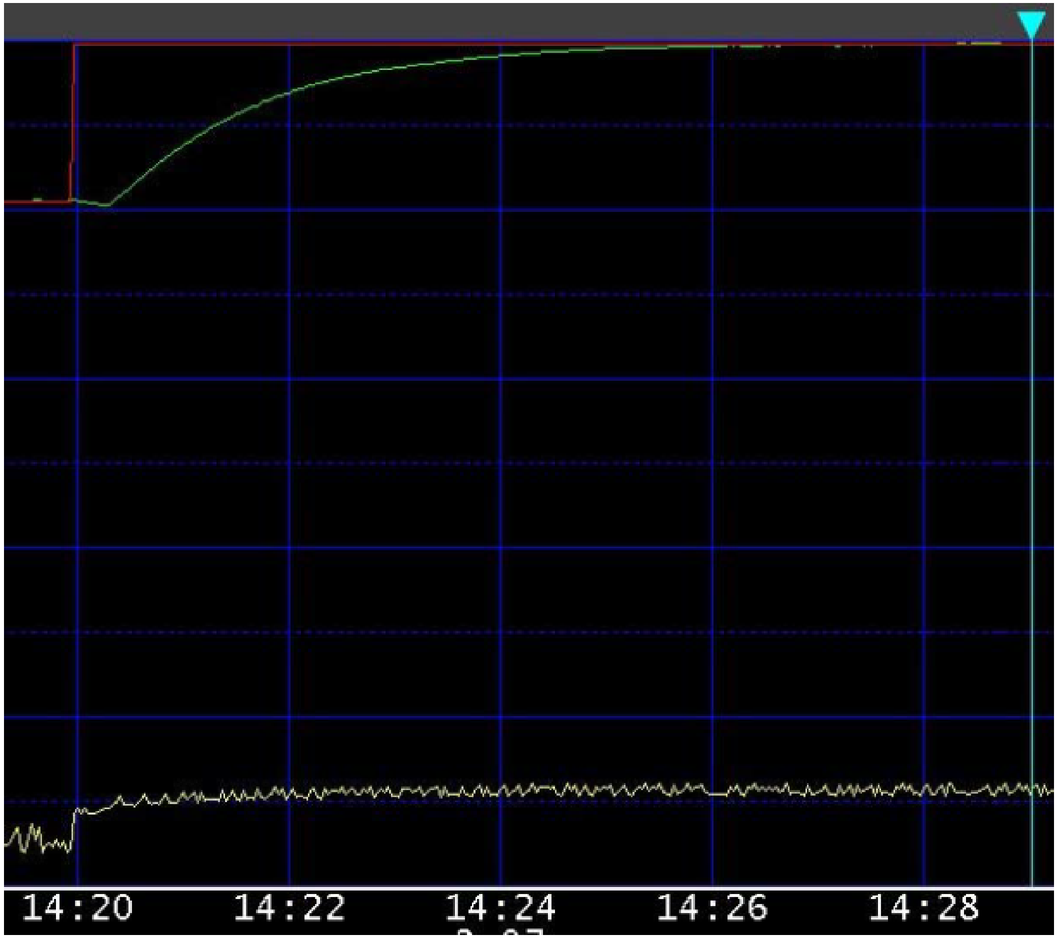
Application example - flow control loop



Application example - flow control loop



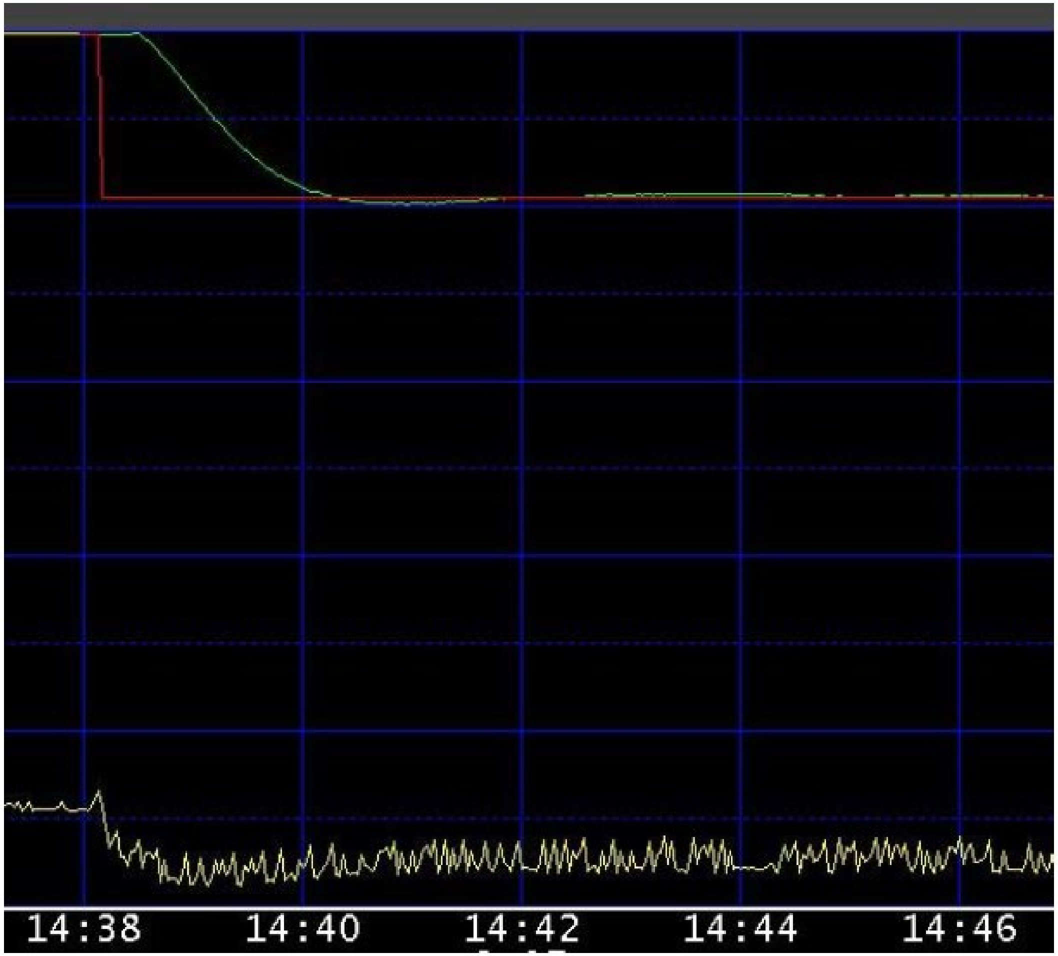
Application example - flow control loop



$$PB = 500, \quad T_i = 60 \quad \Rightarrow \quad IAE = 7.585$$

$$\theta_m = 19 \text{ s}, \quad \mu = 3.125, \quad T_0 = 58 \quad \Rightarrow \quad CI = 0.35$$

After the retuning



$PB = 304.5, \quad T_i = 39 \quad \Rightarrow \quad IAE = 4.01 \quad CI = 1$

Load disturbance rejection task

The retuning procedure can be employed also by evaluating a step load disturbance response. It is assumed that the load disturbance is a step-like signal and that the time instant of its application is known. Then, its amplitude A_d can be estimated as:

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

Then, the process gain can be estimated as:

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

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

$$v(t) := \mu(u(t) + d(t)) - y(t) \quad (d(t) = A_d).$$

and then by calculating

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

Retuning for load disturbance rejection

The desired transfer function between disturbance and output is selected as

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

where τ_c is a design parameter: a sensible choice is $\tau_c = \theta$, which represents typically an effective trade-off between robustness and aggressiveness.
By modelling the process with a FOPDT transfer function in which the main lag is $\tau = T_0 - \theta_m$, and by choosing $\tau_c = \theta_m$, the resulting tuning formulae are

$$K_p = \frac{28T_0 - 41\theta_m}{27\mu\theta_m}$$

$$T_i = \frac{\theta_m}{4}\frac{28T_0 - 41\theta_m}{2T_0 - \theta_m}$$

$$T_d = \frac{\theta_m(11T_0 - 19\theta_m)}{28T_0 - 41\theta_m}$$

Performance assessment

Since the ideal closed loop transfer function has only real poles, its response exhibits no oscillations and no overshoot, provided that τ_c has been chosen higher than $\theta/2$ (i.e., $\tau_c \geq \theta/2$). Hence the integrated absolute error (IAE) can be compared with the absolute value of the integrated error IE, which is equal to $A_d T_i / K_p$. Thus, a performance index for the load rejection task ($LRPI$: Load Rejection Performance Index) can be easily defined by replacing K_p, T_i and T_d with the values suggested by the tuning formulae.

$$LRPI = \frac{27 A_d \mu \theta_m^2}{4(2T_0 - \theta_m) \int_0^\infty |e(t)| dt}.$$

It should be equal to one for a well-tuned controller.

Recovering of set-point following task

The closed-loop transfer function for set-point step change results

$$F(s) = \frac{\left(T_i T_d s^2 + T_i s + 1\right)\left(1 + \frac{\theta}{2}\right)}{(1 + s\tau_c)^3} e^{-s\theta}.$$

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

$$H(s) := \frac{c T_i T_d s^2 + b T_i s + 1}{T_i T_d s^2 + T_i s + 1}$$

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

$$b = \frac{2\theta}{T_i}, \quad c = \frac{T_i b^2}{4 T_d} = -\frac{1}{\theta}$$

By including in the set-point filter $H(s)$ an additional lag equal to $\frac{\theta}{2}$, the overall transfer function between the set-point and the controlled variable results

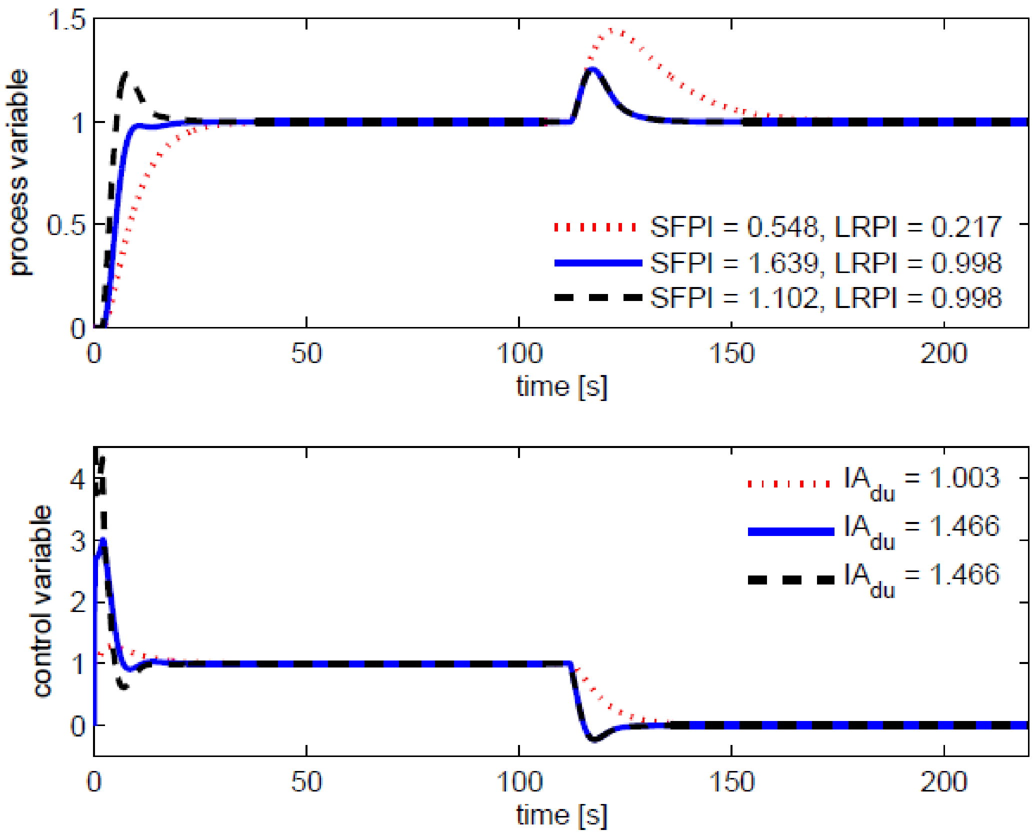
$$\tilde{F}(s) = H(s)F(s) = \frac{e^{-s\theta}}{1+s\tau_c}$$

for which the step response integrated absolute error is

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

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 $SFPI$ index (Set-point Following Performance Index):

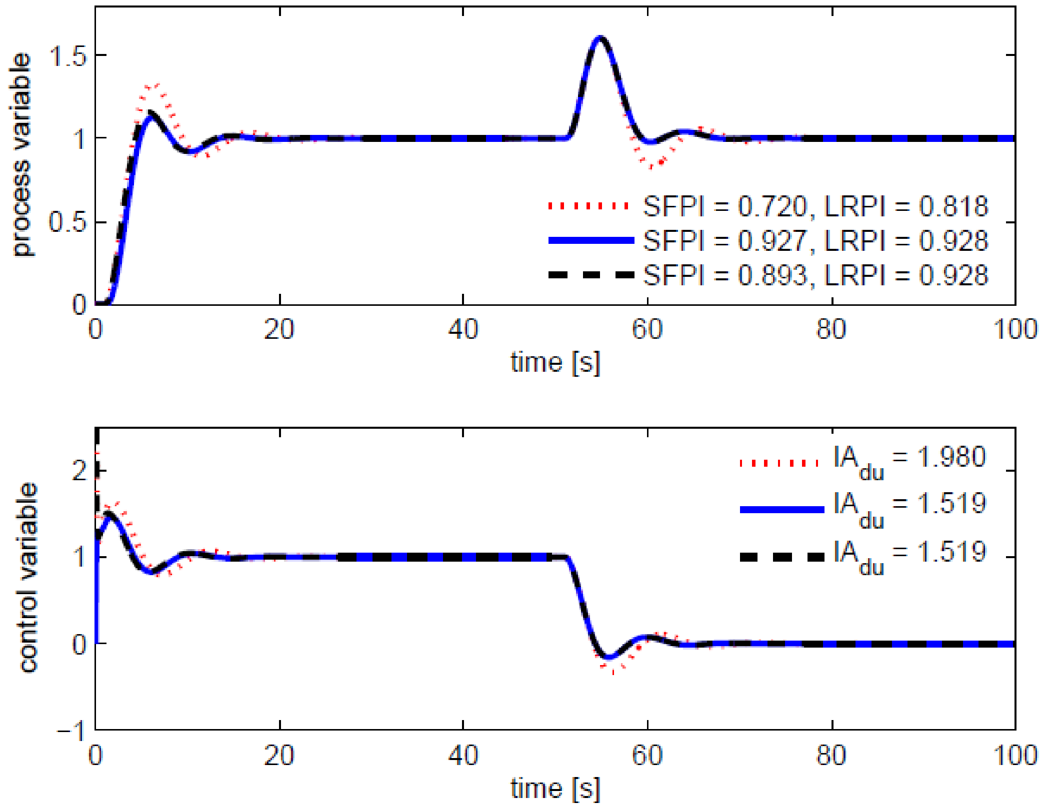
$$SFPI = \frac{2A_s\theta}{\int_0^{+\infty} |e(t)|dt}$$



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

$$K_p = 1, \quad T_i = 10, \quad T_d = 0 \quad \Rightarrow \quad K_p = 1.785, \quad T_i = 14.064, \quad T_d = 2.087$$

Illustrative example - 2



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

$$K_p = 1, \quad T_i = 2, \quad T_d = 0.5 \quad \Rightarrow \quad K_p = 1.090, \quad T_i = 2.903, \quad T_d = 0.468$$

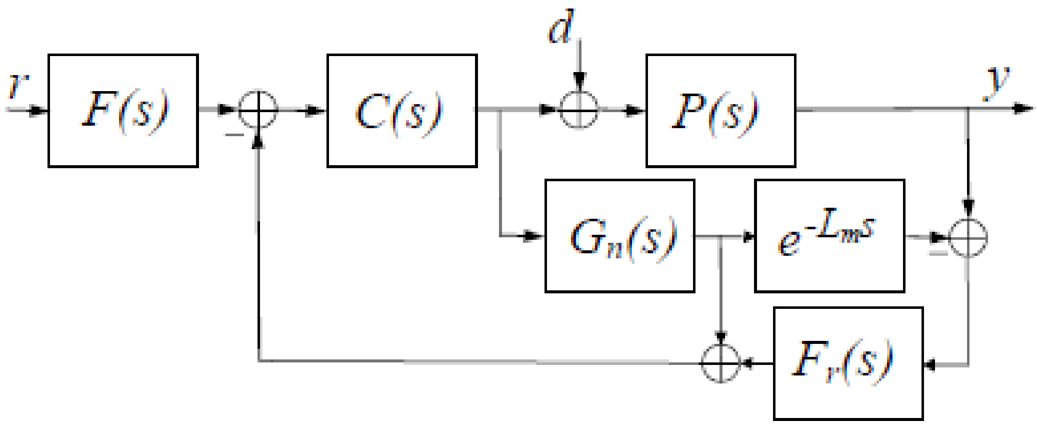
Summarizing

The approach is based on the following steps:

1. select a benchmark: tuning rule and corresponding integrated absolute error;
2. evaluate a step response and estimate the process model;
3. compare the obtained integrated absolute error with the benchmark one;
4. if the performance can be improved retune the PID controller by applying the benchmark tuning rules with the estimated model.

This can be applied for either set-point following or load disturbance rejection task.
The estimation of the model is performed by exploiting the final value theorem and the integrals of signals and it is independent from the current PID parameters.

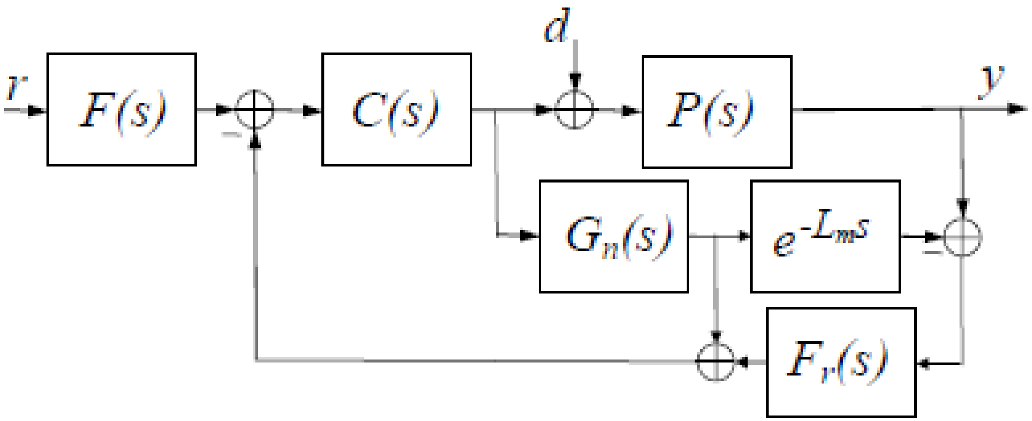
Unified dead time compensator



This control scheme can be used for different processes with large dead times

- self-regulating processes
- integral processes
- unstable processes

Unified dead time compensator - FOPDT processes



$$P_n(s) = \frac{K_m}{T_m s + 1} e^{-L_m s}$$

$$C(s) = K_p \frac{T_i s + 1}{T_i s} \quad T_i = T_m, \;\; K_p = T/(K_m T_r)$$

$$F_r(s) = \frac{(T_r s + 1)(\beta_1 s + 1)}{(T_0 s + 1)^2} \quad \beta_1 = T_m[1 - (1 - T_0/T_m)^2 e^{-L_m/T_m}] \quad F(s) = 1$$

$$H_r(s) = \frac{e^{-L_m s}}{1 + sT_r} \qquad H_d(s) = P_n(s)\left[1 - \frac{1 + s\beta_1}{(1 + sT_0)^2} e^{-L_m s}\right]$$

Estimation of the parameters

$$K = \frac{A_s}{\frac{K_p T_r}{T_m(2T_0 - \beta_1 + L_m)} \int_0^\infty e_f(t)dt}$$

where

$$E_f(s) = \frac{1}{F_r(s)}\frac{A_s}{s} - Y(s).$$

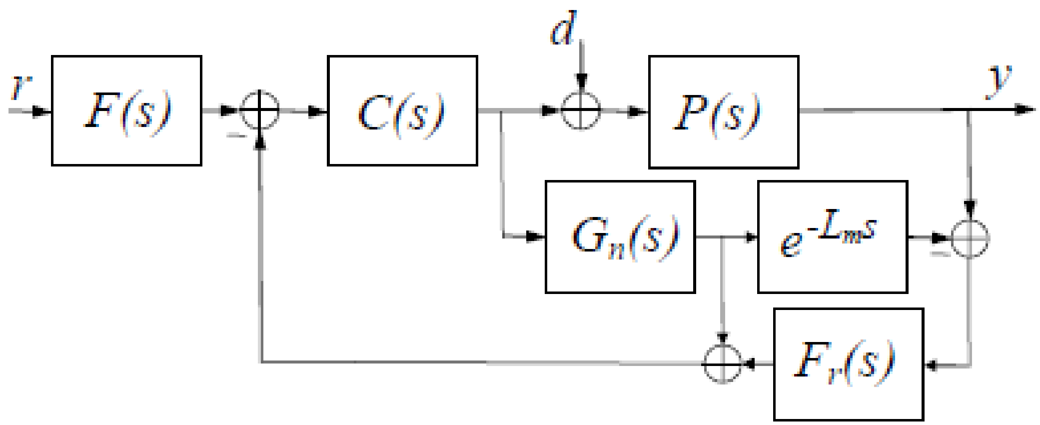
and

$$T = \frac{1}{A_s}\int_0^\infty e_u(t)dt - L$$

where

$$e_u(t) = Ku(t) - y(t)$$

A similar procedure can be applied also in the presence of a step load disturbance when the time instant of its occurrence is known.



$$P_n(s) = \frac{K_m}{s} e^{-L_m s}$$

$$C(s) = K_p \quad K_p = 1/(K_m T_r)$$

$$F_r(s) = \frac{(T_r s + 1)(\beta_1 s + 1)}{(T_0 s + 1)^2} \quad \beta_1 = 2T_0 + L_m \quad F(s) = 1$$

$$H_r(s) = \frac{e^{-L_m s}}{1 + sT_r} \quad H_d(s) = P_n(s)\left[1 - \frac{1 + s\beta_1}{(1 + sT_0)^2} e^{-L_m s}\right]$$

Estimation of the parameters

$$K = \frac{A_s}{\int_0^\infty u(t)}$$

and

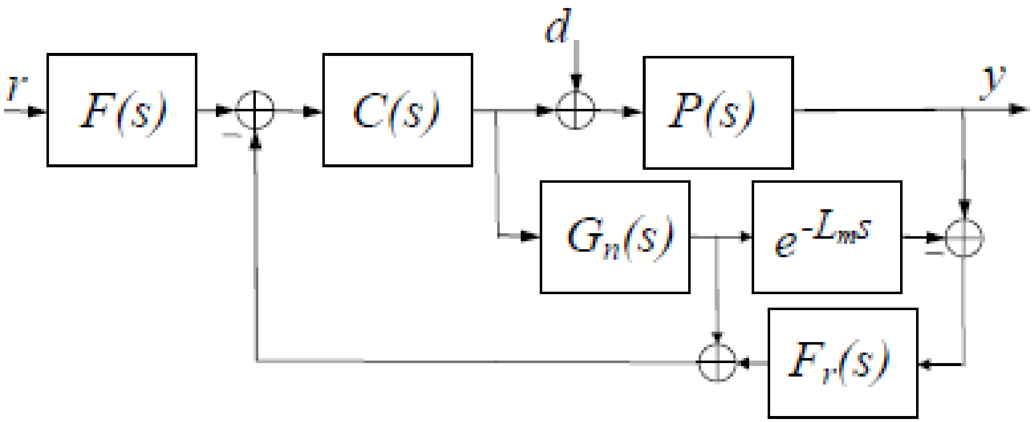
$$L = \frac{\int_0^\infty e_{iu}(t)dt}{A_s}$$

where

$$e_{iu}(t) = K \int_0^t u(v)dv - y(t)$$

Also in this case similar procedure can be applied also in the presence of a step load disturbance when the time instant of its occurrence is known.

Unified dead time compensator - UFOPDT processes



$$P_n(s) = \frac{K_m}{T_m s - 1} e^{-L_m s}$$

$$C(s) = K_p \frac{T_i s + 1}{T_i s} \quad K_p = (T_r + 2T_m)/(K_m T_r) \quad T_i = T_r(2 + T_r/T_m)$$

$$F_r(s) = \frac{(T_r s + 1)^2(\beta_1 s + 1)}{(T_i s + 1)(T_0 s + 1)^2} \quad \beta_1 = T_m[(1 + T_0/T_m)^2 e^{L_m/T_m} - 1] \quad F(s) = \frac{T_r s + 1}{T_i s + 1}$$

$$H_r(s) = \frac{e^{-L_m s}}{1 + sT_r} \qquad H_d(s) = P_n(s)\left[1 - \frac{1 + s\beta_1}{(1 + sT_0)^2} e^{-L_m s}\right]$$

Estimation of the parameters

$$K = \frac{A_s}{\frac{K_p}{K_p K_m (2T_0 - \beta_1 - 2T_r + L_m + T_i) - T_i} \int_0^\infty e_f(t)dt}$$

where

$$E_f(s) = \frac{F(s)}{F_r(s)} \frac{A_s}{s} - Y(s)$$

and

$$T = L - \frac{1}{A_s} \int_0^\infty e_{uu}(t)dt$$

where

$$e_{uu}(t) = -Ku(t) - y(t)$$

Also in this case similar procedure can be applied also in the presence of a step load disturbance when the time instant of its occurrence is known.

Performance assessment

For set-point step response:

$$IAE_{sp} = A_r(T_r + L_m).$$

For load disturbance step response:

$$IAE_{load} = K_m A_d \left[2T_0 + L_m - T_m + T_m(1 - T_0/T_m)^2 e^{-L_m/T_m} \right]$$

for FOPDT processes,

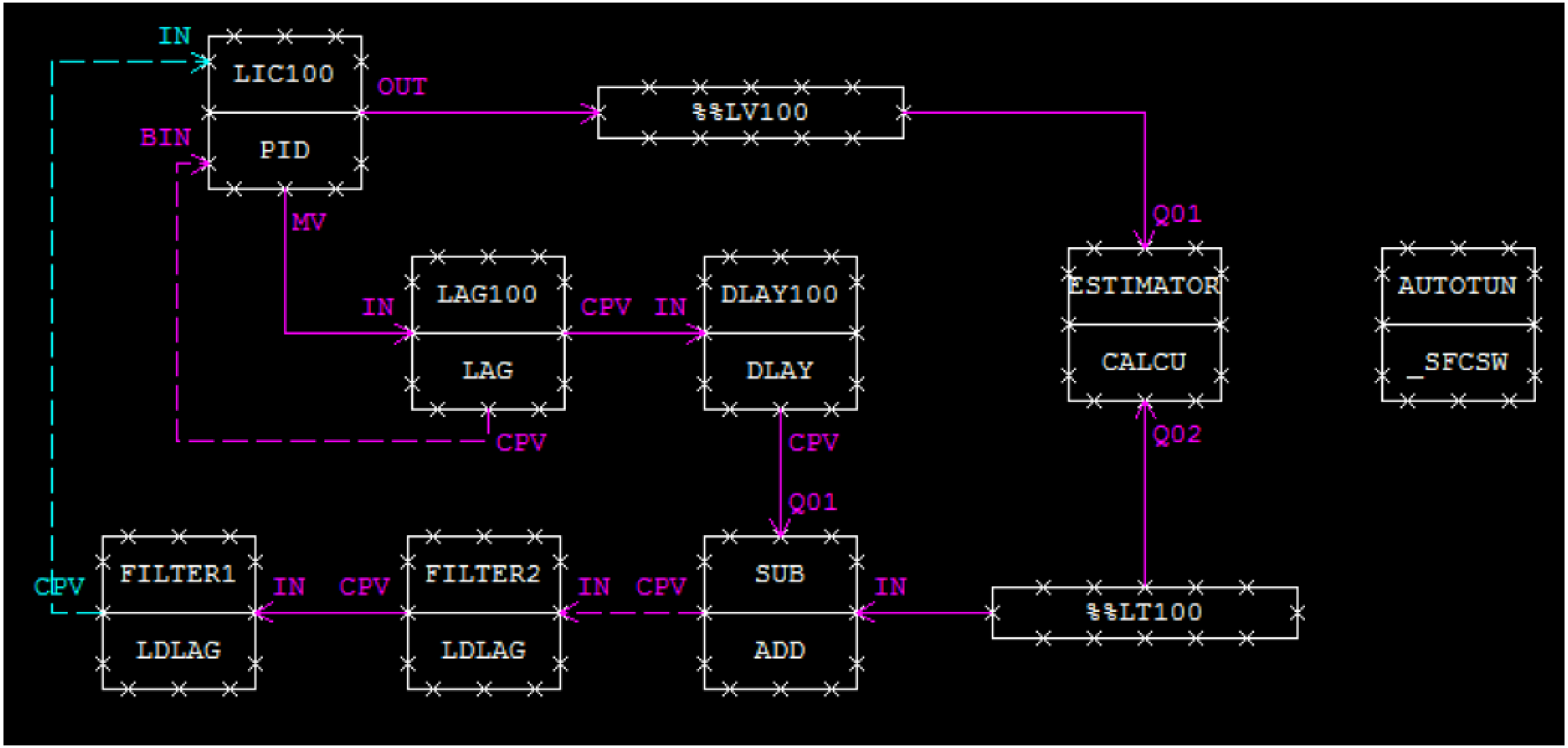
$$IAE_{load} = \frac{K_m A_d}{2} (L_m^2 + 4L_m T_0 + 2T_0^2)$$

for IPDT processes, and

$$IAE_{load} = K_m A_d \left[2T_0 + L_m + T_m - T_m(1 - T_0/T_m)^2 e^{L_m/T_m} \right].$$

for UFOPDT processes.

Implementation



Experimental results - level control

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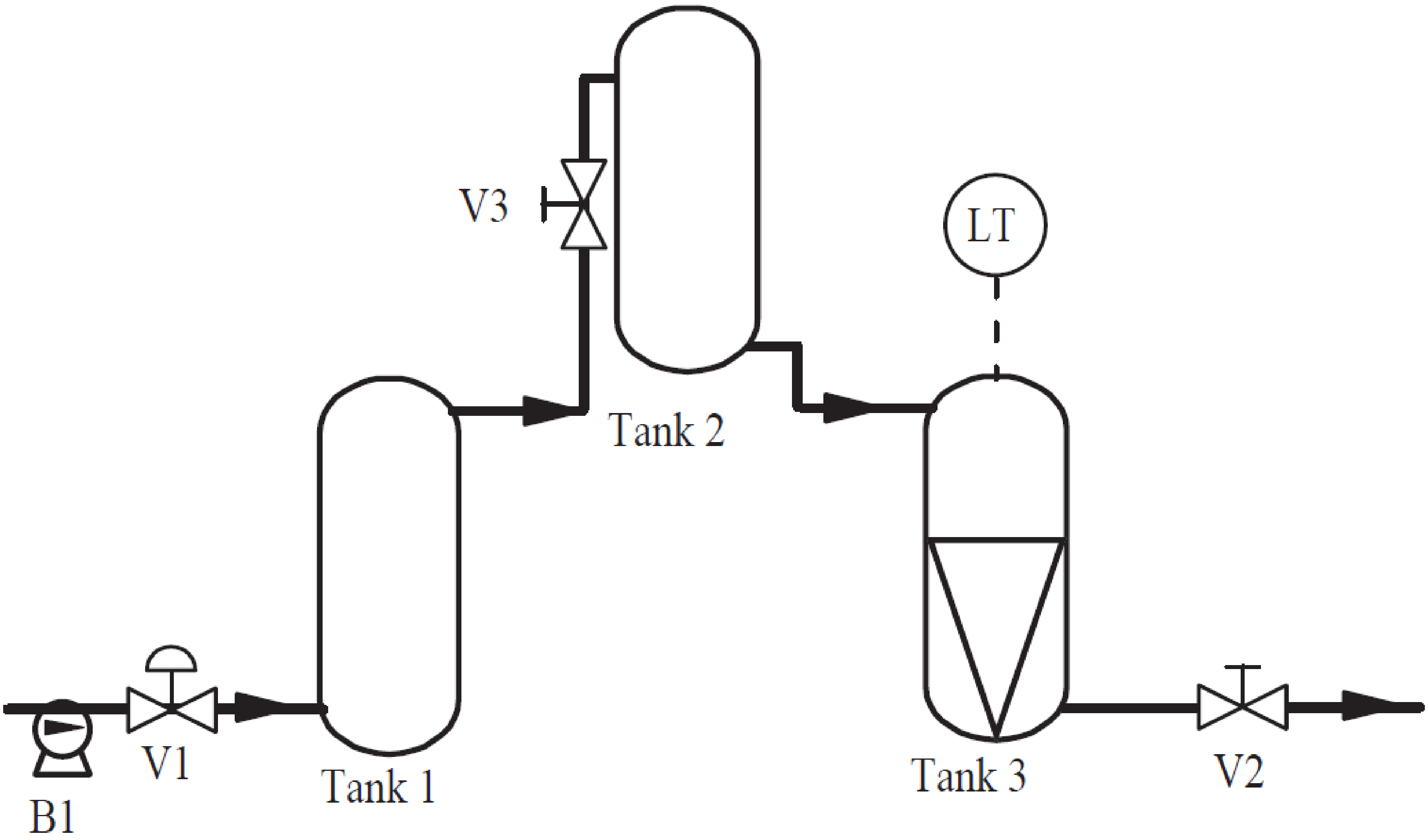
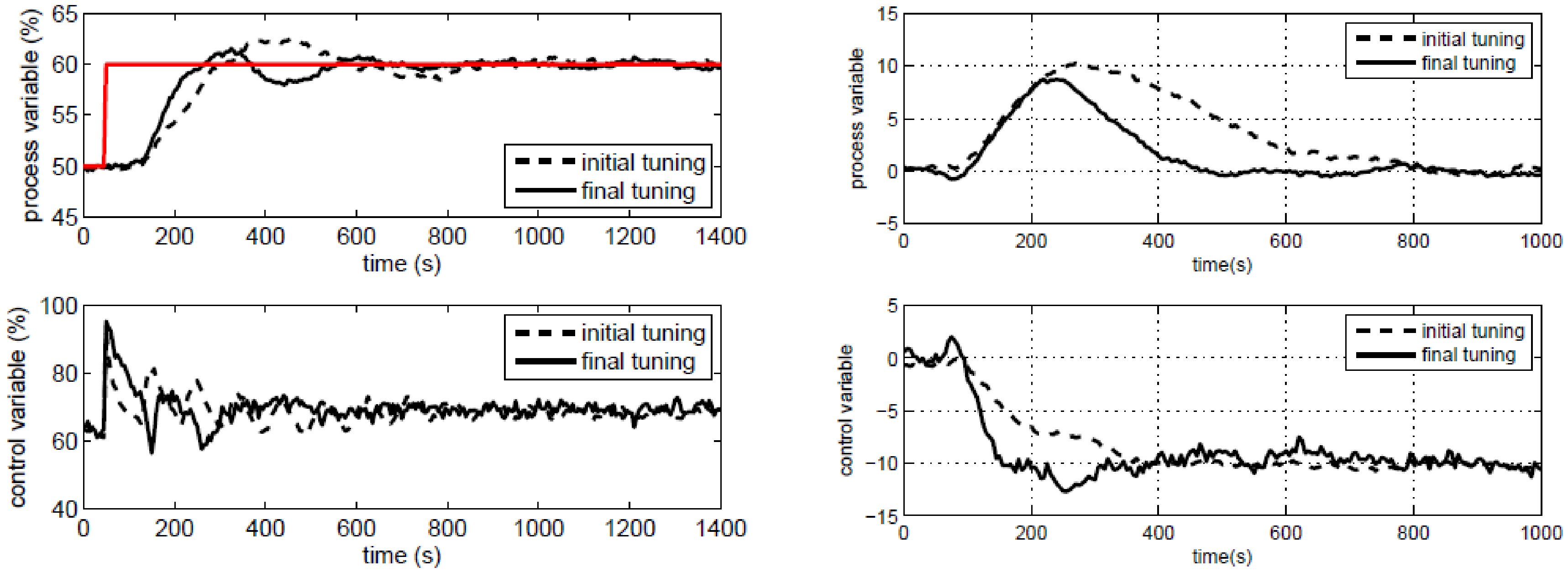


Experimental results - level control



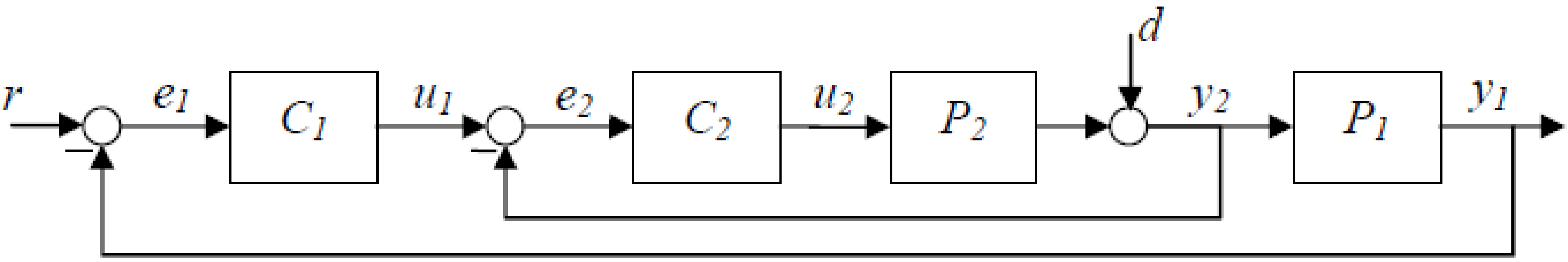
$$P_m(s) = \frac{1.61}{100s+1}e^{-261s}$$

$$IAE_{sp} = 2419 \Rightarrow 1840$$

$$IAE_{load} = 3596.8 \Rightarrow 1754.9$$

Cascade control

$$P_j(s) = \frac{\mu_j e^{-s\theta_j}}{q_j(s)} \quad j = 1, 2$$



$$C_1(s) = K_{p1}\left(\frac{T_{i1}s+1}{T_{i1}s}\right)\left(\frac{T_{d1}s+1}{T_{g1}s+1}\right)$$

$$C_2(s) = K_{p2}\left(\frac{T_{i2}s+1}{T_{i2}s}\right)\left(\frac{T_{d2}s+1}{T_{g2}s+1}\right)$$

Note: P_1 can be also non self-regulating.

Parameters estimation

The gains can be estimated as:

$$\mu_1 = \frac{T_{i1} A_s}{K_{p1} \int_0^\infty e_1(t)dt}, \quad \mu_2 = \frac{T_{i2} A_s}{\mu_1 K_{p2} \int_0^\infty e_2(t)dt}$$

while the sum of the lags and of the dead time for the primary loop can be estimated by considering

$$v(t) = \mu_1 u_1(t) - y_1(t)$$

and by determining

$$T_{01} = \frac{1}{A_s} \int_0^\infty v(t)dt - \frac{T_{i2}}{\mu_2 K_{p2}}.$$

For the secondary loop:

$$T_{02} = \frac{\mu_1}{A_s} \int_0^\infty w(t)dt \quad \text{where} \quad w(t) = \mu_2 u_2(t) - y_2(t).$$

Non self-regulating processes

$$v(t) := \mu_1 \int_0^\infty u_1(t)dt - y_1(t)$$

$$\mu_1 = A_s \frac{T_{i1}}{K_{p1} \int_0^\infty \int_0^t e_1(\nu)d\nu dt}$$

$$T_{01} = \frac{1}{A_s} \int_0^\infty v(t)dt - \frac{T_{i2}}{\mu_2 K_{p2}}$$

$$\mu_2 = \frac{T_{i2} A_s}{\mu_1 K_{p2} \int_0^\infty \int_0^t e_2(\nu)d\nu dt}$$

$$T_{02} = \frac{\mu_1}{A_s} \int_0^\infty \int_0^t w(\nu)d\nu dt$$

Tuning - secondary controller

$$K_{p2} = \frac{\theta_2/2}{\mu_2(\lambda_2 + \theta_2)}, \quad T_{i2} = \frac{\theta_2}{2}, \quad T_{d2} = \tau_2, \quad T_{f2} = \frac{\lambda_2\theta_2}{2(\lambda_2 + \theta_2)}$$

where

$$\lambda_2 = \max\{0.25\theta_2,\ 0.2\tau_2\}$$

With these parameters the inner loop transfer function results (by employing a first-order Padé approximation):

$$G_2(s) = \frac{1}{\lambda_2 s + 1} e^{-\theta_2 s}$$

Tuning - primary controller

Denote as $G(s)$ the process seen by the primary controller, given by the series of $G_2(s)$ and $P_1(s)$. Its transfer function can be written as:

$$G(s) := G_2(s)P_1(s) = \frac{\mu_1}{(\lambda_2 s + 1)(\tau_1 s + 1)} e^{-(\theta_2+\theta_1)s}$$

Then,

$$K_{p1} = \frac{T_{01} - \theta_1}{\mu_1(\lambda_1 + \theta)}, \quad T_{i1} = T_{01} - \theta_1, \quad T_{d1} = \lambda_2,$$

where

$$\theta = \theta_1 + \theta_2, \quad \lambda_1 = \theta.$$

For integral processes:

$$K_{p1} = \frac{1}{2\mu_1 \lambda_1}, \quad T_{d1} = T_{01} - \theta_1 + \lambda_2$$

where, again,

$$\lambda_1 = \theta.$$

Performance assessment

With the proposed tuning, we have:

$$\int_0^\infty e_1(t)dt = \frac{A_s T_{i1}}{\mu_1 K_{p1}} = A_s(\lambda_1 + \theta) = 2A_s\theta.$$

Thus, a performance index can be defined as

$$J = \frac{2A_s\theta}{\int_0^\infty |e_1(t)|dt}.$$

Illustrative example

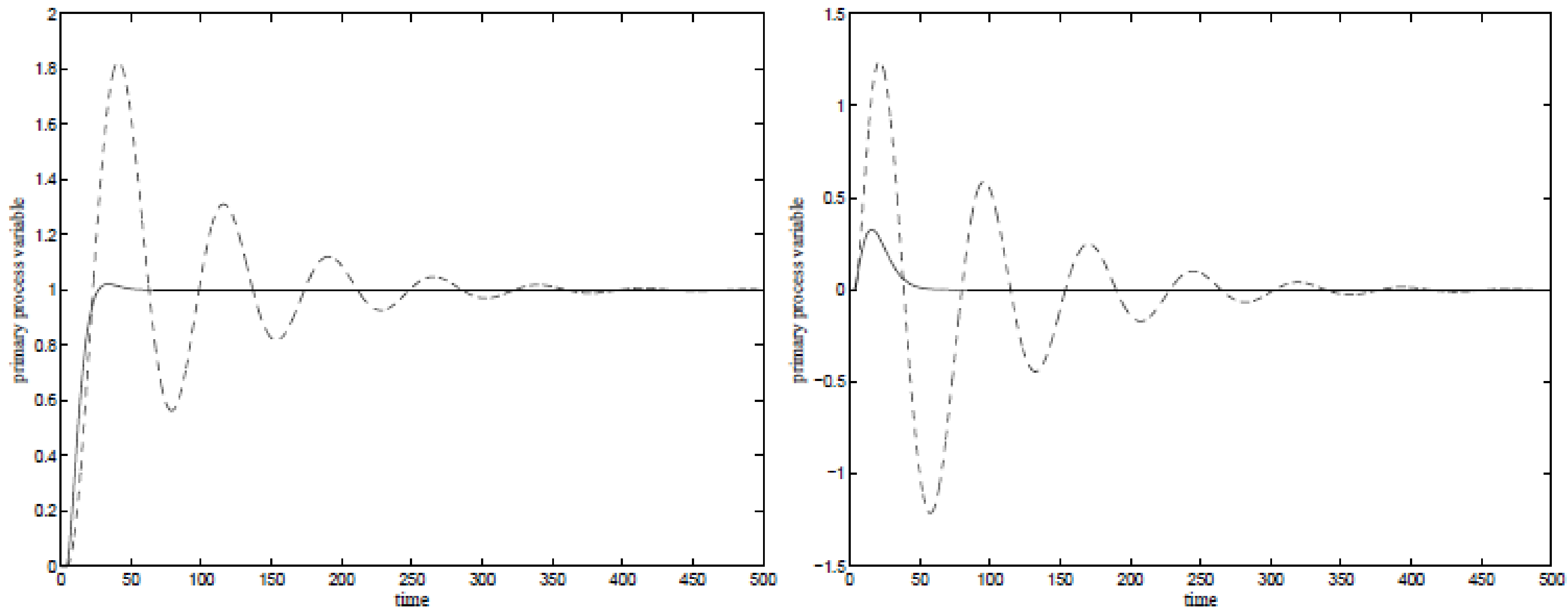
$$P_1(s) = \frac{e^{-3s}}{s(1+10s)(1+2s)}, \qquad P_2(s) = \frac{e^{-0.5s}}{1+s}$$

Initial tuning:

$$K_{p1} = 0.1, \quad T_{i1} = 50, \quad T_{d1} = 2, \quad T_{f1} = 0.02$$
$$K_{p2} = 1, \quad T_{i2} = 2, \quad T_{d2} = 0, \quad T_{f2} = 0$$

After the estimation of the process parameters, the tuning formulae give:

$$K_{p1} = 0.079, \quad T_{d1} = 9.79, \quad T_{f1} = 0.098$$
$$K_{p2} = 0.467, \quad T_{i2} = 0.252, \quad T_{d2} = 0.22.$$



The value of the performance index is improved from $J = 0.19$ ($IAE_{sp} = 65.82$ and $IAE_d = 97.66$) to $J = 0.78$ ($IAE_{sp} = 13.34$ and $IAE_d = 7.45$).

Conclusions

- Simple methods for the estimation of the process transfer functions starting from routine operating data can be applied to different kinds of processes and control structures.
- The estimation procedures are mainly based on the integrals of signals and therefore they are inherently robust to measurement noise.
- The performance achieved by a controller can be achieved by comparing it with the desired one, which does not necessarily means the “optimal” one, as the robustness (and control effort) of the control system has to be taken into account.
- The overall retuning methodology is flexible, as different tuning rules and different thresholds for the retuning of the parameters can be selected depending on the control requirements.

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