PERFORMANCE ASSESSMENT OF CONTROL LOOPS:
controller evaluation for frequent set-point changes

Riccardo Bacci di Capaci[a], Claudio Scali[a]

[a]University of Pisa, Department of Civil and Industrial Engineering, Italy
claudio.scali@unipi.it

INTRODUCTION

The high seasonality and variability of electricity production from renewable sources has enormous impact on both production and distribution networks. Among the many aspects, several traditional power plants, especially, combined cycle plants, but also coal-fired plants, now operate intermittently with variable set points due to fluctuations of energy load which they are requested to deliver [1]. Thus, a specific analysis of control system performance during these transient cyclic phases, as reference changes, operations of start up and shutdown, is highly desirable.
Generally speaking, monitoring and assessment of performance of control systems of industrial plants are important topics in process control. The deterioration in performance is, in fact, a fairly common phenomenon and manifests with sluggish or oscillating trends of control variables. Oscillations in control loops can cause many problems which affect normal operation of process plants. Typically, fluctuations increase variability of product quality, accelerate wear of equipment, move operating conditions away from optimality, and, in general, cause excessive or unnecessary consumption of energy and raw materials [2].
This paper introduces a technique for the analysis of performance of basic control loops when process is subject to changes of operating conditions. The method employs the well-established approach of Internal Model Control, IMC. After establishing lower limit for the absolute value of the integral (IAE) of control error and the total variation (TV) of control action, such limits are assumed as reference values for a control considered "optimal", or anyway "good". A performance index is thus based on IMC and is properly defined with respect to lower limit of IAE and TV. With this approach, the validity of tuning of PID-type controller in response to any reference change can be assessed. In particular, one can successfully evaluate closed-loop performance for setpoint changes, as steps, ramps, or generic trends, as for the common case of preset programs of variable load of power plants.

1 THE PROPOSED METHOD

1.1 Overview of the approach

In a feedback SISO control loop (Figure 1a), *P(s)* and *C(s)* are transfer functions of the process and of PID-type controller, respectively. The signals *r(t)*, *u(t)* and *y(t)* are the reference (setpoint, SP), the control action (OP) and the controlled variable (PV), respectively. Tuning rules of PID controllers based on the IMC method are now widely adopted in the industrial practice, since they typically allow a good balance between three conflicting factors in a control loop: that is, ability of tracking reference, limited control effort, and robust stability in closed-loop [3].
The reference tracking ability is commonly evaluated by the Integral of Absolute Error (IAE):

$$IAE = \int_{t=0}^{\infty} |e(t)|dt = \sum_{i=1}^{N} |SP_i - PV_i| \cdot T_s \qquad (1)$$

where *e(t)* = SP - PV, is the control error.
Then, the control effort is usually quantified by the total variation (TV) of the control action:

$$TV = \sum_{i=1}^{N-1} |OP_{i+1} - OP_i| \quad (2)$$

where OP is the control action, i.e. the controller output. Finally, the robust stability is assessed in the frequency domain, by means of maximum value of the sensitivity function.

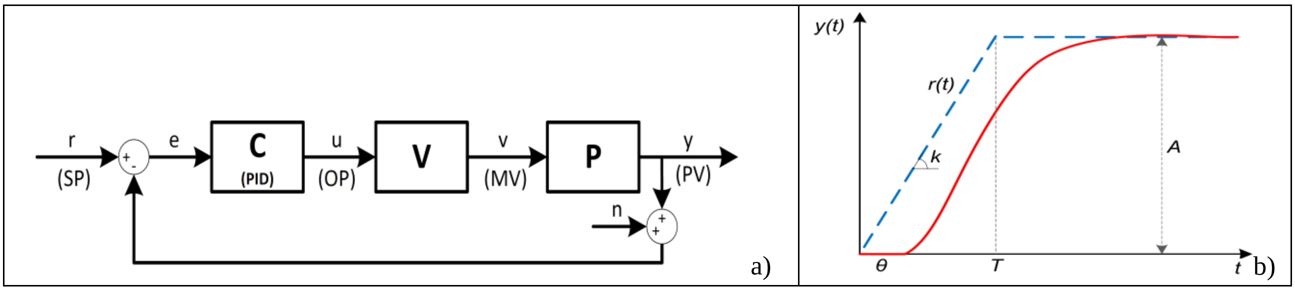

Fig. 1. a) Diagram of a feedback control loop (SISO type); b) reference change as a ramp signal

In Ref. [4-6] the lower limit for the IAE index (IAE_0) and for the TV index (TV_0) have been derived by using a IMC-based controller, for closed-loop response subject to different reference changes: step, ramp and generic. It is to be pointed out that lower limits in the case of ramp and for general types of setpoint changes have not been studied in the literature with the same attention of step change. Details of these derivations are here omitted for the sake of space.

Moreover, in industrial practice, in particular in power plants, reference changes of control loops - and thus of operating conditions of process - are mostly obtained with gradual programs of ramps, rather than with sudden step changes. In addition, in many cases, values of ramp parameters are known a priori. The load demand as setpoint is typically received from a power-grid control centre, so that the new desired value $A = k \cdot T$ is known in advanced, while the variation rate (the slope) k and the time duration T for the ramp are preset parameters by operators (see Figure 1b).

The lower limits (IAE_0 and TV_0) are then taken as reference values for a new index of performance. Two dimensionless ratios are firstly defined (η_{IAE}, η_{TV}) and then a global index (η):

$$\eta_{IAE} = \frac{\min(IAE_{Act}, IAE_0)}{\max(IAE_{Act}, IAE_0)} \qquad \eta_{TV} = \frac{\min(TV_{Act}, TV_0)}{\max(TV_{Act}, TV_0)} \qquad \eta = \eta_{IAE} \cdot \eta_{TV} \quad (3)$$

where IAE_{Act} is the (actual) integral index of the absolute error, as in Eq. 1. Similarly, TV_{Act} is the (actual) total variation of the control action, as in Eq. 2. Both performance indices assume values in the interval [0, 1], with ideal value equal to 1. Combining the two indices (η_{IAE}, η_{TV}), the global index of performance (η) is defined, which also lies in [0,1], with ideal value of 1.

In details, if $\eta \rightarrow 1$, the actual performance is regarded as satisfactory, since the actual controller tends to the reference one, tuned with the IMC tuning rules. In particular, both IAE_{Act} and TV_{Act} are close to reference values: IAE_0 and TV_0. On the opposite, if $\eta \rightarrow 0$, the actual performance is far from what obtained by a PID regulator tuned with IMC rules; i.e., at least one index between IAE_{Act} and TV_{Act} is away from reference value.

It must be observed that index η, being based on IAE and TV, considers simultaneously the closed-loop response and control action. Note that the actual integral of absolute error could be even lower than the reference value: $IAE_{Act} < IAE_0$. However, this situation is not to be preferred, since actual controller could have lower robust stability and it could cause unacceptable variations in the control action. In addition, note that η provides a measure of control loop performance in the case of setpoint tracking, regardless the tuning rule followed by the actual controller, and it is also applicable to any type of industrial control scheme.

Anyway, some limitations of this method have to be pointed out. In particular, the process must be linear and time-invariant (LTI), and loop instruments (sensors, actuators, valves) must work properly. This implies that the eventual source of malfunction is of linear type, due to an internal source (controller tuning) or at the limit an external source (process disturbances).

1.2 Phases of the analysis

Under the assumptions and constraints previously cited, phases of proposed methodology are:

1. Collect data of input $u(t)$ and output $y(t)$, estimate process dynamics with a model $\underline{P}(s)$ of first order plus time-delay (FOPTD), and then evaluate key parameters: K, τ and θ. On the basis of setpoint $r(t)$ and controller transfer function $C(s)$, estimate the closed-loop response as $\underline{y}(t)$. If $\underline{y}(t)$ well captures dynamics of real data $y(t)$ - typically if a fitting index is sufficiently high, e.g. F_{PV} > 80% - go to step 2; otherwise choose another data set, and repeat step 1.
2. Choose the time constant τ_c of the reference response in closed-loop [3]. Suitable values can be the estimate of process time-delay $\tau_c = \theta$, or the time constant of the whole closed-loop system identified with a FOPTD. In these two cases, proceed directly to step 3, otherwise follow indications given by Ref. [4-5], on the basis of the specific reference change. For example, in the case of ramp, τ_c depends on the slope k and the amplitude A.
3. Compute IAE_{Act} as in Eq. 1, estimate the reference value IAE_0 according to Ref. [4-6] and evaluate the performance index η_{IAE}. On the basis of the process model $\underline{P}(s)$, obtain the estimate of control action as $\underline{u}(t)$. Then, compute the total variation TV_{Act} of control action as in Eq. 2. Finally, estimate the reference value TV_0 according to Ref. [5-6], and compute the performance index η_{TV}.
4. Finally, compute the global index η. If η is large enough, typically if $\eta \geq 0.8$, then the control loop has acceptable performance. Otherwise, the performance is considered poor and corrective actions, as controller retuning or adoption of different schemes, are recommended.

2 SIMULATION EXAMPLES

In order to demonstrate the effectiveness of the proposed method, some simulation examples are presented below. The process dynamics $P(s)$ is a FOPTD model. A white noise signal, with zero-mean and variance equal to 0.1, is introduced into the process variable, producing a situation of noise signal ratio (NSR) equal around 20%. The setpoint program consists of a series of 5 different ramps. Four cases are analyzed, with different tuning parameters for the PI controller (Table 1). For each case, time trends of response $y(t)$ to the ramp, and the control action $u(t)$ are shown in Fig. 2. Based on these signals, each time a FOPTD model $\underline{P}(s)$ is identified (Table 2).

Table 1. Tuning features and corresponding parameters

Case #	Tuning	K_c	τ_i
1	Aggressive	3.5	60
2	Sluggish	1.5	200
3	Good	2.38	100
4	Fair	2.74	103.5

Table 2. Process dynamics and identified FOPTD models

Process	Case #	1	2	3	4
$\frac{3}{100s+1}\cdot e^{-7s}$	$\underline{P}(s)$	$\frac{2.931}{98.74s+1}\cdot e^{-7s}$	$\frac{2.949}{100.83s+1}\cdot e^{-7s}$	$\frac{2.939}{99.64s+1}\cdot e^{-7s}$	$\frac{2.936}{99.39s+1}\cdot e^{-7s}$

Then, for each case, the estimate of process time-delay is imposed as the time constant of the reference response in closed-loop: $\tau_c = \theta$. Two simulations are performed: i) with the actual controller, to get $\underline{y}(t)$ and reduce the effect of noise on numerical values of indices, ii) with the ideal controller, tuned with IMC rules, for definition of references. Then, performance index for IAE and TV are evaluated, and finally global index η is computed. All the values are shown in Table 3.
It can be observed that for case #1, corresponding to an aggressive tuning, a low performance index η is obtained, due to a excessively variable control action, which implies η_{TV} = 0.62. The case #2, expression of a sluggish tuning, is actually assessed with poor performance: η = 0.30. In this case, both indices, η_{IAE} and η_{TV}, are very low. On the contrary, case #3, expression of an appropriate

tuning, is particularly effective. In fact, actual performance tends to the ideal value ($\eta \to 1$) since the controller is tuned just according to IMC rules, which constitute the reference. Also case #4, when the controller follows the rules of a different tuning technique, represents a valid situation. The performance index is greater than threshold value ($\eta > 0.8$); that is, the controller has an acceptable behavior, although little inferior than the reference IMC controller.
The method has also been tested on control loop of a pilot plant and included in the last version of a well-established software for performance monitoring ([6], results omitted here for brevity's sake).

Table 3. Results of loop performance evaluation

Case #	θ	τ_c	IAE_0	IAE_{Act}	η_{IAE}	TV_0	TV_{Act}	η_{TV}	η	F_{PV} [%]	Verdict
1	7	7	1783.7	1648.4	0.92	308.9	494.4	0.62	0.57	97.2	Not Good
2	7	7	1783.7	3942.2	0.45	312.6	209.4	0.67	0.30	96.9	Not Good
3	7	7	1783.7	1807.6	0.99	310.2	305.4	0.98	0.97	97.2	Good
4	7	7	1783.7	1682.8	0.94	309.7	342.4	0.90	0.85	97.3	Good

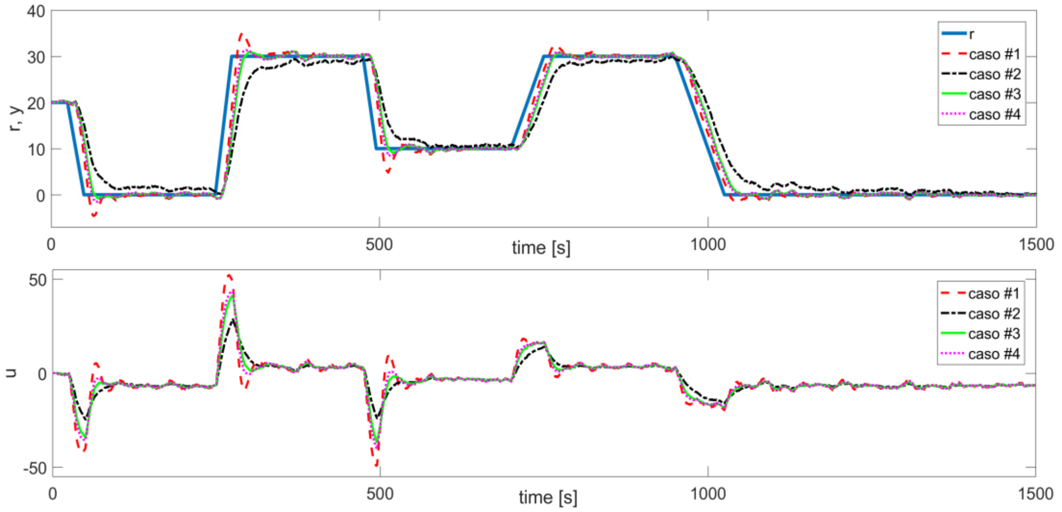

Fig. 2. Time trends for the setpoint changes (series of ramps): top) controlled variable; bottom) control action

3 SUMMARY

The proposed methodology allows one to achieve a correct assessment of the performance of control loop and a reliable evaluation on the validity of controller tuning in the cases of reference change. The relative simplicity of the technique makes it appealing for industrial application in cases of frequent set-point changes, as encountered nowadays in traditional power plants.

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