Modified anti-windup scheme for PID controllers

A. Visioli

Abstract: An anti-windup scheme for proportional-integral-derivative controllers is presented. The approach is based on the combined use of back-calculation and conditional integration anti-windup techniques. In this way, the disadvantages that can hinder previously proposed strategies are overcome. Specifically, the method can guarantee a satisfactory performance for processes with different normalised dead times, without the tuning of additional parameters being required. Therefore, considering its simplicity, it is highly suitable for implementation in industrial regulators.

1 Introduction

Despite the advent of many effective design methodologies in the control field in recent years, proportional-integral-derivative (PID) controllers are undoubtedly still the most adopted controllers in industrial settings, because they provide a cost/benefit ratio that is very difficult to ameliorate by other techniques. However, the performance of PID controllers can be severely limited in practical cases by the presence of saturation of the actuators, which causes the well-known phenomenon of integrator windup [1].

To deal with this problem, it is necessary, from a theoretical point of view, to design the controller explicitly taking into account the actuator constraints from the first stage, e.g. referring to the nonlinear systems framework. However, the overall design becomes much more complicated and therefore inappropriate in the PID control context, where the ease of implementation has to be preserved as a major feature. Therefore, the typical method to deal with the integrator windup problem is to tune the controller ignoring the actuator saturation and subsequently to add an anti-windup compensator to prevent the degradation of performance. In this context, several techniques have been devised to design the compensator [2, 3]. Basically, they belong to two different approaches, namely, conditional integration (in which the value of the integrator is frozen when certain conditions are verified) and back-calculation (in which the difference between the controller output and the actual process input is fed back to the integral terms) [4]. Note that the latter case also includes the conditioning technique [5, 6] and that a unified framework for the linear time-invariant anti-windup schemes (including the use of an observer to estimate the correct state of the controller [7, 8]) has been presented in [9].

However, these techniques can suffer from the presence of a significant dead time in the process or, to deal with processes with different normalised dead times, they might require an extra tuning effort (see Section 2), which is undesirable for industrial regulators. Therefore, it is proposed to combine the different approaches (in a very simple way) in order to overcome these problems.

2 Anti-windup strategies for PID controllers

2.1 Generalities

The integrator windup is a phenomenon that can occur in the presence of a saturation of the process input. We refer to the scheme of Fig. 1, where u is the controller output, u_s is the actual process input, y is the process output, w is the setpoint reference value and e is the system error. It is assumed that a transition from the value y_0 to the value y_1 is required for the system output and this determines the amplitude of the step signal to be applied as input to the closed-loop system. The PID controller is described by the following expression (non-interacting form) in the Laplace domain:

$$U(s) = K_p\left(E(s) + \frac{1}{T_i s}E(s) - \frac{sT_d}{1 + s(T_d/N)}Y(s)\right) \quad (1)$$

where K_p, T_i and T_d are the proportional gain and the integral and derivative time constants respectively, and N is usually set between five and 20.

The integrator windup occurs when a step change in w causes the actuator to saturate. In this case the system error decreases more slowly than in the ideal case (when there is no input limitation) and therefore the value of the integral term becomes large. Thus, even when the value of y attains that of w, the controller still saturates due to the integral term and this generally leads to large overshoots and settling times.

It has to be noted that the integrator windup mainly occurs when a step is applied to the reference setpoint signal rather than to the manipulated variable (i.e. in the

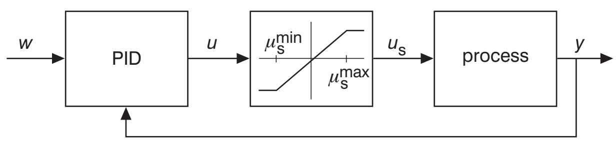

Fig. 1 *General control scheme*

IEE Proceedings online no. 20020769
DOI: 10.1049/ip-cta:20020769
Paper first received 22nd April and in revised form 20th September 2002
The author is with the Dipartimento di Elettronica per l'Automazione, University of Brescia, Via Branze 38, 25123 Brescia, Italy

presence of a load disturbance) [10]. Furthermore, the most significant effects of the integrator windup take place when the process is of low order. For these reasons, in the following we will restrict the analysis to the first-order setpoint response plus dead time systems, whose transfer function is denoted as:

$$P(s) = \frac{K}{Ts+1} e^{-Ls}. \quad (2)$$

The normalised dead time is defined as $\theta = L/T$.

2.2 Conditional integration

Conditional integration can be implemented to avoid integrator windup. With this approach (also called integrator clamping) the integral term is increased only when certain conditions are satisfied, otherwise it is kept constant. The different cases can be described as follows:

1. the integral term is limited to a selected value;
2. the integration is stopped when the system error is large, i.e. when $|e| > \bar{e}$ where $\bar{e}$ is a selected value;
3. the integration is stopped when the controller saturates, i.e. when $u \neq u_s$;
4. the integration is stopped when the controller saturates and the system error and the manipulated variable have the same sign, i.e. when $u \neq u_s$ and $e \times u > 0$.

A slightly different approach (called preloading) consists of giving a prescribed value to the integral term when the controller saturates [11].

All these methods have already been compared in the literature [4, 12] and scheme 4 has been found to be the best.

2.3 Back-calculation

An alternative approach to conditional integration is back-calculation. It consists of recomputing the integral term once the controller saturates. In particular, the integral value is reduced by feeding back the difference of the saturated and unsaturated control signal, as shown in Fig. 2 where T_t is called tracking time constant. Formally, denoting by e_i the integrator input, we have:

$$e_i = \frac{K_p}{T_i} e + \frac{1}{T_t}(u_s - u) \quad (3)$$

The value of T_t determines the rate at which the integral term is reset and its choice determines the performances of the overall control scheme. Some suggestions are to set $T_t = T_i$ [2, 3], or $T_t = \sqrt{(T_i T_d)}$ [4]. The latter formula results in $T_t = 0$ for PI control (which is often applied in industrial settings) and it will not be considered any further because of the unsatisfactory results it provides in this case.

Anti-windup strategies that combine the conditional integration and the back-calculation approaches have been presented in [1] and [2]. Specifically, in [2] it is proposed to apply an additional limit to the proportional-derivative part of the manipulated variable adopted to generate the anti-windup feedback signal. Thus, there is the significant drawback that an additional parameter has to be selected by the user. Alternatively, in [1] the summing junction that performs the feedback in the integral term is substituted by a switch that is closed when a certain condition is met.

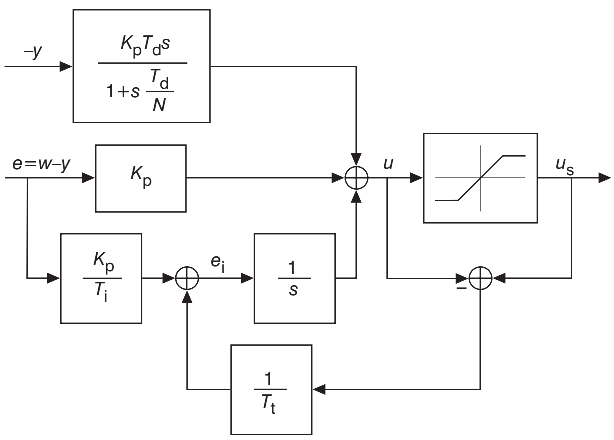

Fig. 2 *Anti-windup with back-calculation*

Table 1: Value of PID parameters for the considered processes

Parameter	$P_1(s)$	$P_2(s)$
K_p	6	1.5
T_i	4	16
T_d	1	4
N	10	10

2.4 Discussions

In order to illustrate the performances of the different methodologies, as an example, we consider the following processes with normalised dead times $\theta_1 = 0.2$ and $\theta_2 = 0.8$ respectively:

$$P_1(s) = \frac{1}{10s+1} e^{-2s} \quad (4)$$

$$P_2(s) = \frac{1}{10s+1} e^{-8s} \quad (5)$$

For each process, the same tuning of the PID parameters has been applied, according to the Ziegler-Nichols formula. The values of the parameters are reported in Table 1. Starting from null initial conditions, a positive unit step

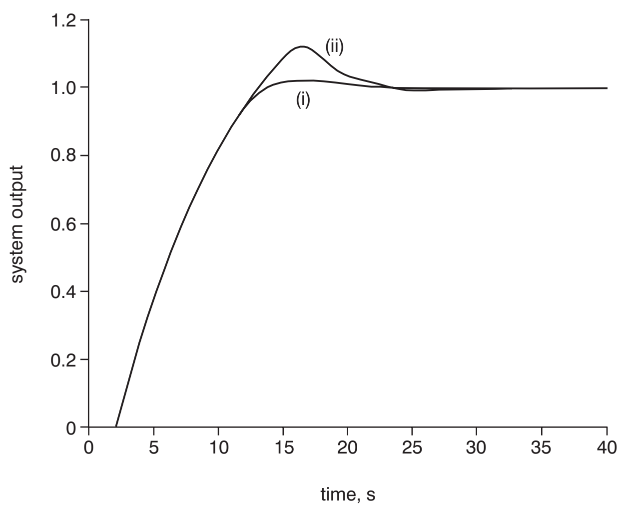

Fig. 3 *Step response for $P_1(s)$ for the considered anti-windup schemes*

(i) Conditional integration (scheme 4 in Section 2.2)
(ii) Back-calculation with $T_t = T_i$

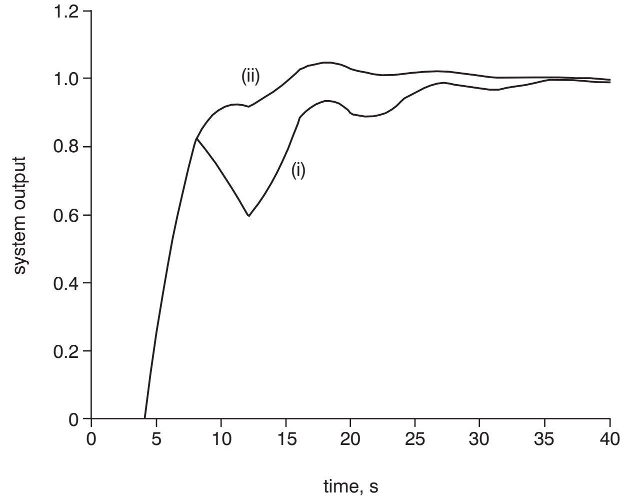

Fig. 4 *Step response for $P_2(s)$ for the considered anti-windup schemes*

(i) Conditional integration (scheme 4 in Section 2.2)
(ii) Back-calculation with $T_t = T_i$

(i.e. $y_0 = 0$ and $y_1 = 1$) has been applied to the setpoint signal and saturation limits $u_s^{max} = 1.5$ and $u_s^{min} = -1.5$ has been fixed. Figs. 3 and 4 are plots of the system output for the following schemes:

(a) conditional integration (scheme 4 in Section 2.2);
(b) back-calculation with $T_t = T_i$

To better evaluate the results, the control variables and the integral terms for the considered cases are reported in Figs. 5 and 6. It can be seen that the conditional integration provides good performances for small normalised dead times, but results in a poor transient response for large normalised dead times. This can be explained by the fact that switching off the integral term for the first part of the transient response (when the saturation is actually caused

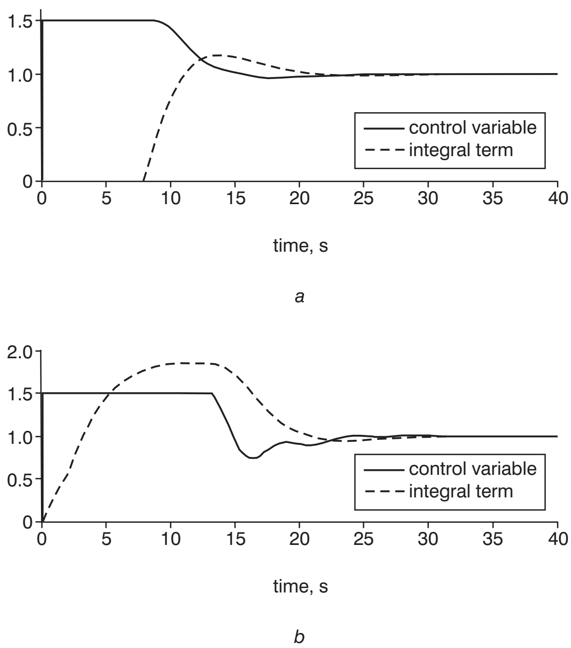

Fig. 5 *Control variable and integral term with $T_t = T_i$ ($P_1(s)$)*

a Conditional integration
b Back-calculation

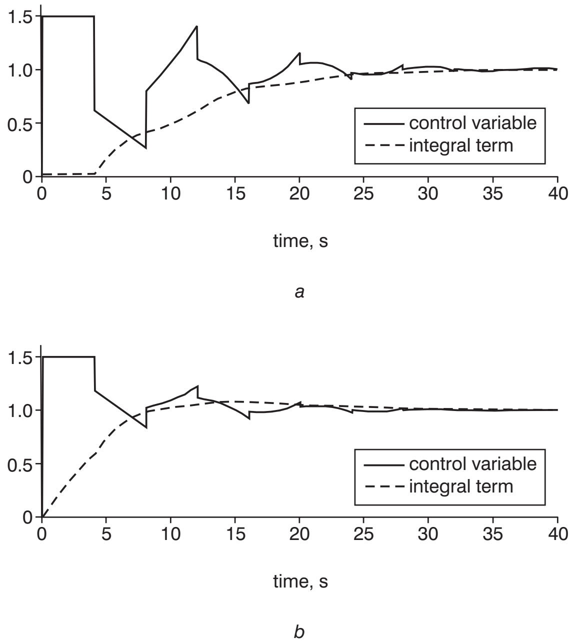

Fig. 6 *Control variable and integral term with $T_t = T_i$ ($P_2(s)$)*

a Conditional integration
b Back-calculation

by the proportional term) is not convenient, as it causes a large bump and a consequent undesired undershoot (see plot (i) of Fig. 4 and Fig. 6*a*). The back-calculation with $T_t = T_i$ provides better results for process $P_2(s)$. However, it has to be observed that for process $P_1(s)$ a significant improvement in the performances could be observed by selecting $T_t = 0.1T_i$ because in this case the integral term is appropriately more limited during the first part of the transient. Related results are reported in Figs. 7 and 8 where it can be observed that the overshoot is significantly decreased.

Summarising, it turns out that none of the proposed methods is able to provide a good performance over a wide range of processes without the need to tune an additional parameter, which is in any case undesirable for industrial regulators, as the simplicity of the implementation is a major issue.

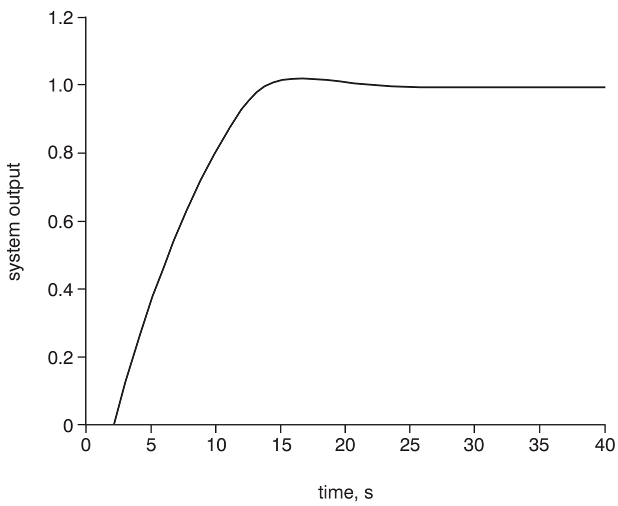

Fig. 7 *Step response with back-calculation with $T_t = 0.1T_i$ ($P_1(s)$)*

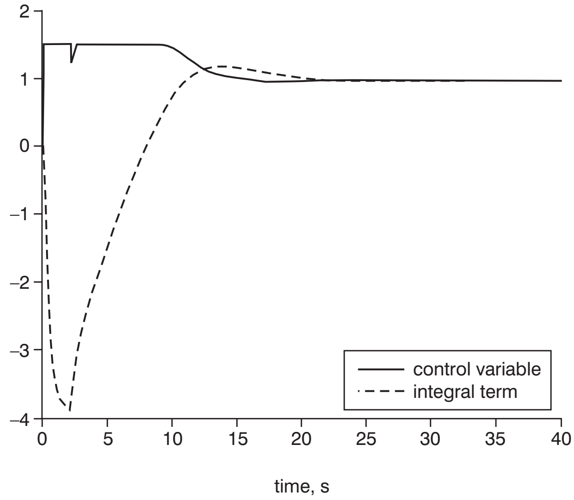

Fig. 8 *Control variable and integral term with back-calculation with $T_t = 0.1T_i$*

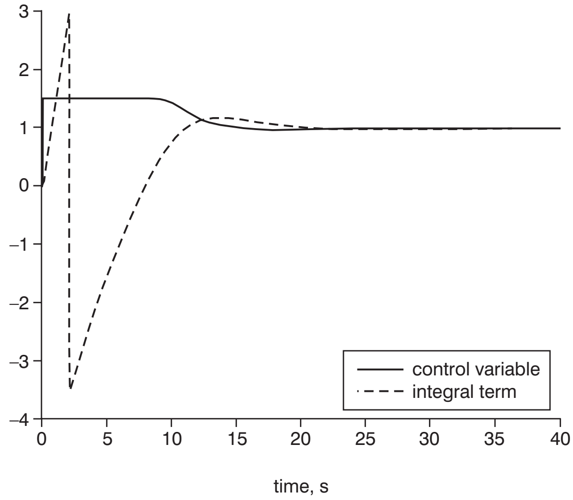

Fig. 10 *Control variable and integral term for the proposed anti-windup scheme ($P_1(s)$)*

3 The proposed approach

A simple modification is proposed to overcome the drawbacks of the methodologies previously described. A combined use of conditional integration and the back-calculation approach is adopted. Specifically, the back-calculation is employed when the controller saturates, the system error has the same sign of the manipulated variable and the system output has left its previous setpoint value. Formally, this can be stated as:

$$e_i = \begin{cases} \dfrac{K_p}{T_i}e + \dfrac{1}{T_t}(u_s - u) & \text{if } u \neq u_s \text{ and } u \times e > 0 \\ & \text{and } \begin{cases} y > y_0 & \text{if } y_1 > y_0 \\ y < y_0 & \text{if } y_1 < y_0 \end{cases} \\ \dfrac{K_p}{T_i}e & \text{otherwise} \end{cases} \quad (6)$$

The aim of (6) is to allow an increase in the integral term whilst the process output transient has not started due to the dead time. When the normalised dead time is small, the devised technique basically performs as the standard back-calculation technique. In any case, it is possible to set a unique value for T_t for the different cases and this value can be significantly lower than T_i allowing better performances for small normalised dead times.

Remark 1: In the presence of measurement noise, as is always the case in practical applications, (6) has to be slightly modified. Actually, in order to verify if the process output has left its previous steady-state value, the condition $y > y_0$ ($y < y_0$) has to be substituted with $y > NB$ ($y < NB$) where NB is the estimated noise band [13]. This estimation can be performed in a time interval before the step signal is applied to the setpoint. Note that the concept of a noise band has already been applied successfully in industrial regulators [4, p. 250].

4 Simulation results

To illustrate the effectiveness of the proposed method, it has been applied to the same processes of Section 2.4 (see (4) and (5)) with the same PID tuning (see Table 1). The value of the tracking time constant has been fixed at $T_t = 0.03T_i$ for both cases. As in the previous examples, a positive unit step, starting from null initial conditions has been applied. Results are reported in Figs. 9 and 10 for process $P_1(s)$ and in Figs. 11 and 12 for process $P_2(s)$.

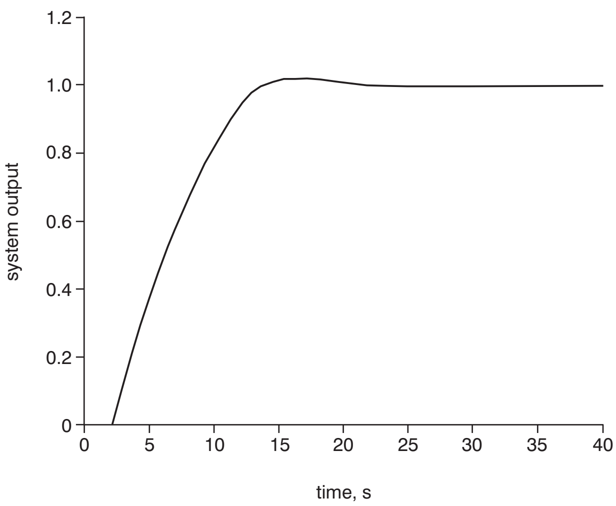

Fig. 9 *Step response for $P_1(s)$ for the proposed anti-windup scheme*

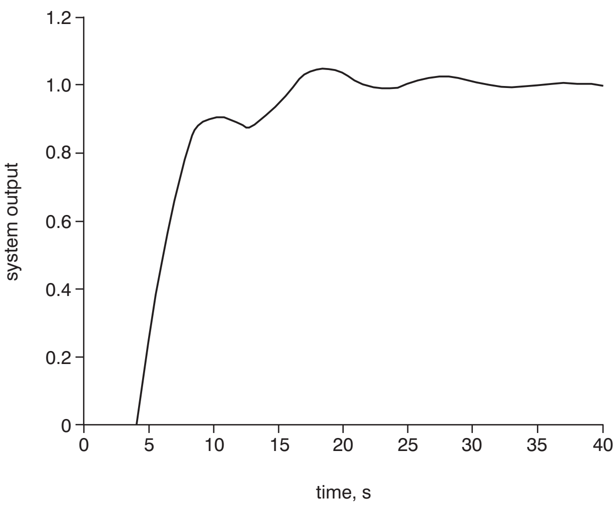

Fig. 11 *Step response for $P_2(s)$ for the proposed anti-windup scheme*

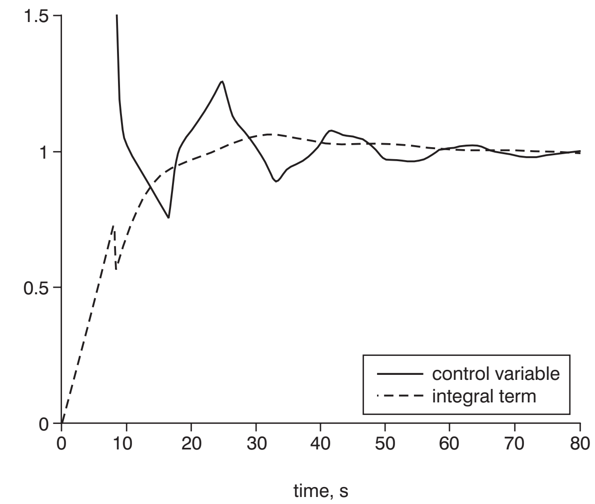

Fig. 12 *Control variable and integral term for the proposed anti-windup scheme ($P_2(s)$)*

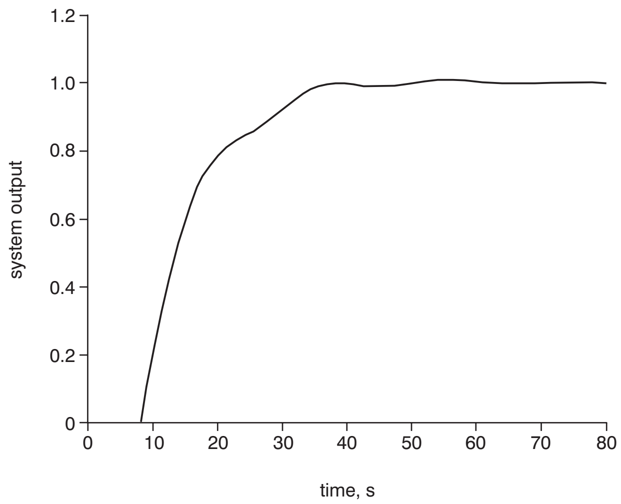

Fig. 14 *Step response for $P_2(s)$ for the proposed anti-windup scheme with $u_s^{max} = 1.2$*

Other experiments have been performed with the same parameters but with different saturation levels, i.e. by setting $u_s^{max} = 1.2$ and $u_s^{min} = -1.2$. The related unit step responses for the two processes are reported in Figs. 13 and 14. It turns out that, despite the value of the tracking time constant remaining unchanged in the different situations, the results are always satisfactory.

Finally, to verify the value of the methodology in the presence of measurement noise, it has been applied to process $P_2(s)$ with the process output corrupted by a zero-mean white noise with a variance of 1×10^{-4}. By applying a noise band $NB = 0.03$, the resulting process output is reported in Fig. 15. It can be observed that the presence of a reasonable level of noise does not prevent high performances being obtained.

Remark 2: The devised method can provide an abrupt change in the integral part of the PID controller when the dead time of the process has expired (see, for example, Fig. 10). However, this does not mean that abrupt changes also occur in the control variable since this is saturated in that moment and therefore the possible excitation of high-frequency oscillatory modes is prevented.

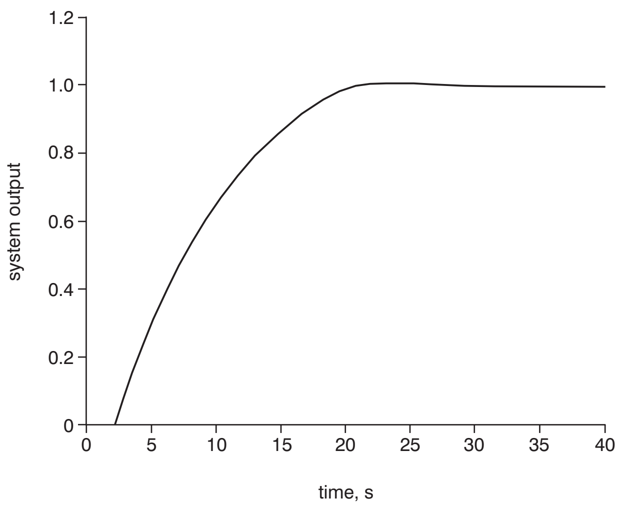

Fig. 13 *Step response for $P_1(s)$ for the proposed anti-windup scheme with $u_s^{max} = 1.2$*

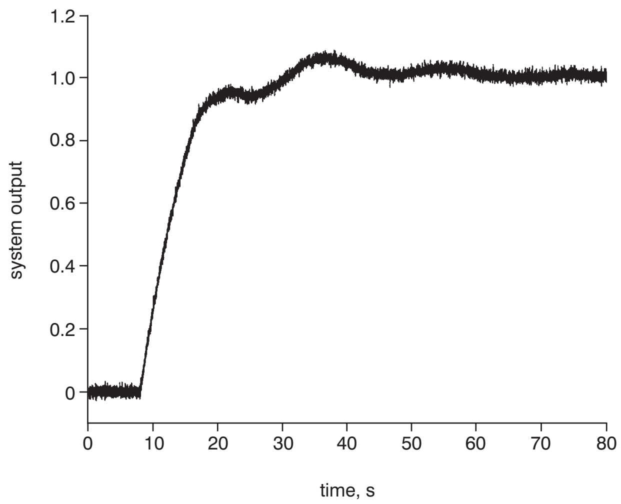

Fig. 15 *Step response for $P_2(s)$ for the proposed anti-windup scheme with measurement noise*

5 Conclusions

An anti-windup method for PID controllers has been presented. The main feature of the technique is that it guarantees a good performance for a wide range of processes without the need of a tuning effort from the user. Due to this fact, and due to its overall simplicity, it appears to be particularly suitable for implementation in industrial regulators.

6 Acknowledgment

This work was supported in part by MIUR scientific research funds.

7 References

1 SCOTTEDWARD HODEL, A., and HALL, C.E.: 'Variable-structure PID control to prevent integrator windup', *IEEE Trans. Ind. Electron.*, 2001, **48**, (2), pp. 442–451
2 BOHN, C., and ATHERTON, D.P.: 'An analysis package comparing PID anti-windup strategies', *IEEE Control Syst. Mag.*, 1995, pp. 34–40
3 PENG, Y., VRANCIC, D., and HANUS, R.: 'Anti-windup, bumpless, and conditioned transfer techniques for PID controllers', *IEEE Control Syst. Mag.*, 1996, pp. 48–57
4 ÅSTRÖM, K., and HÄGGLUND, T.: 'PID controllers: theory, design and tuning' (ISA Press, Research Triangle Park, North Carolina, 1995)

5 HANUS, R., KINNAERT, M., and HENROTTE, J.-L.: 'Conditioning technique, a general anti-windup and bumpless transfer method', *Automatica*, 1987, **23**, (6), pp. 729–739

6 WALGAMA, K.S., RONNBACK, S., and STERNBY, J.: 'Generalisation of conditioning technique for anti-windup compensator', *IEE Proc., Control Theory Appl.*, 1991, **139**, (2), pp. 109–118

7 ASTRÖM, K., and WITTENMARK, B.: 'Computer-controlled systems—theory and design' (Prentice Hall, Upper Saddle River, New Jersey, 1997)

8 RÖNNBÄCK, S., WALGAMA, K.S., and STERNBY, J.: 'An extension to the generalized anti-windup compensator' in BORNE, P., TZAFESTAS, S.G., RADHY, N.E. (Eds.): 'Mathematics of the analysis and design of process control' (Elsevier Science Publisher, Holland, 1992), pp. 275–285

9 KOTHARE, M.V., CAMPO, P.J., MORARI, M., and NETT, C.N.: 'A unified framework for the study of anti-windup design', *Automatica*, 1994, **30**, (12), pp. 1869–1883

10 VRANCIC, D.: 'Design of anti-windup and bumpless transfer protection'. PhD thesis, University of Ljubljana, Ljubljana, Slovenia, 1997

11 SHINSKEY, F.G.: 'Process control systems—application, design, and tuning' (McGraw-Hill, New York, USA, 1996)

12 HANSSON, A., GRUBER, P., and TODTLI, J.: 'Fuzzy anti-reset windup for PID controllers', *Control Eng. Pract.*, 1994, **2**, (3), pp. 389–396

13 ASTRÖM, K., HÄGGLUND, T., HANG, C.C., and HO, W.K.: 'Automatic tuning and adaptation for PID controllers—a survey', *Control Eng. Pract.*, 1993, **1**, (4), pp. 699–714