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Fuzzy Anti-Windup Schemes for PID Controllers

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Abstract

In this paper, we propose fuzzy compensator based on Anti Windup (AW) approaches for linear systems subject to control constraints which are in turn controlled by a standard PID controller and a fuzzy PID controller. The fuzzy compensation block provides feedback correction terms to improve the system behaviour. The fuzzy PID controller is designed to improve the control performance. Simulation results show that the proposed fuzzy method gives generally better tracking performances than the conditioning technique.

Keywords: Linear Systems, Control constraints, Compensator, Anti-Windup, Fuzzy.

Introduction

PID controller is one of the earliest industrial controllers. It has many advantages: it is economic, simple, easily tuned and robust. It has proved it effectiveness in regulating a wide range of processes. It does not require an exact model, and hence it can be used for processes whose models are considerably difficult to drive (see [1]). PID controller consists of three terms: Proportional action, Derivative action (to speed up the response) and Integral action (to eliminate the steady state error).

In practice, the constraints are inherent to all kinds of physical, chemical or real process, may arise from physical limitations on the process or may depend on its nature. In industry, for example, one can impose or have the maximum flow for valves, limitations on voltages and currents in electrical processes, limitations on pH and concentrations in chemical processes, etc. Henceforth, constrained systems are connected to a wide spread of applications and their study is of continuing interest in control community.

When limitation happens, if the controller is initially designed to operate in a linear range, the closed–loop performance will significantly deteriorate with respect to the expected linear performance. This performance deterioration is referred to as windup. Moreover, the non-linearity of the actuator is not always known in advance. A more common approach in practice to diminish the effect of windup is to add extra feedback compensation at the stage of control implementation. As this compensation aims, it is referred to as anti-windup (AW). The topic of anti-windup has been studied over a long period time by many authors, and the most popular techniques are described (see for example [2]-[6] without being exhaustive). Most real systems cannot be represented by linear dynamics. But, under some assumptions it is often possible to model the dynamical behaviour of practical systems with a linear model having some uncertainties. These are generally induced from the difference, sometimes considerable, between the real behaviour of the system and the model used to design the controller. Fuzzy controllers are rule-based nonlinear controllers; therefore, their main application should be the control of nonlinear ones. However, since linear systems are good approximations of nonlinear systems around the operating points, it is of interest to study fuzzy control of linear systems. Additionally, fuzzy controllers due to their nonlinear nature may be more robust than linear controllers even if the plant is linear [7]. Our contribution consists of proposing two anti windup schemes based on fuzzy logic design. The first one uses a classical PID controller with a fuzzy AW compensation (PID_FAW). The second uses a fuzzy PID controller with the same fuzzy AW compensation (FPID_FAW).

The paper is organized as follows: section 2 is devoted to present classical PID controller, two AW approaches: Conditioning technique in subsection 2.1 and the proposed PID_FAW in subsection 2.2. In section 3, the second approach FPID_FAW is presented. Section 4 presents simulation results on a set of benchmark systems: in subsection 4.1, tracking performances of the conditioning technique and PID_FAW are compared, while in subsection 4.2, the potential of FPID_FAW is tested.

AW approaches for Classical PID Controller

Conditioning Technique

The windup problem can be explained by the fact that when the control signal saturates the actuator, a further increase of the control signal will not lead to a faster response of the system. If integration error continues in this case, the integrator value becomes very large, without having any effect on the process output. The control error then has to be of the opposite sign for a long time to bring the integrator back to its steady state value.

Windup problems are encountered in PI / PID controllers for controlling linear systems with control input nonlinearities. To illustrate this phenomenon, consider a closed-loop control system (Fig.1) containing a PID controller and a magnitude saturation given by the following equation:

$$ur(t)=\begin{cases} u_{max} & \text{if} \quad u(t) > u_{max} \\ u(t) & \text{if} \quad u_{min} \le u(t) \le u_{max} \\ u_{min} & \text{if} \quad u(t) < u_{min} \end{cases} \quad (2.1)$$

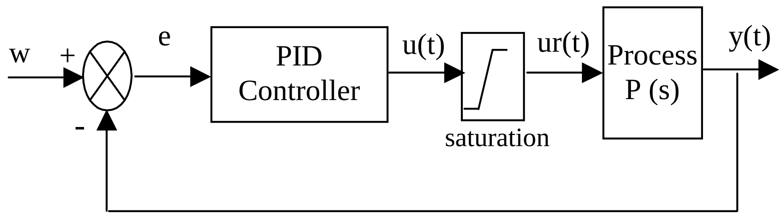

Figure 1. Closed loop control system

The PID controller can be described as follows:

$$U(s)=K\left[E(s)+\frac{1}{sT_i}E(s)-\frac{sT_d}{1+s\frac{T_d}{N}}Y(s)\right] \quad (2.2)$$

where u is the controller output, y is the process output, w is the reference signal, e=w-y is the process tracking error and the capital letters U, E and Y denote the Laplace transforms of u, e and y respectively, K is the proportional gain, T_i is the integral time constant, and T_d is the time derivative constant, the high frequency gain N is usually set between 7 and 15.

Let's suppose that the controller and the process are in steady state. A large positive step change in w causes a jump in u, so that the actuator saturates at high limit (if K>0). Thus, ur becomes smaller than u, and y is slower than in the unlimited case. The integral term increases much more than one in the unlimited case and it becomes large.

When y approaches w, ur still remains saturated or close to saturation due to the large integral term; u decreases after the error has been negative for a sufficiently long time. This leads to a large overshoot and a large settling time of the process output.

The conditioning technique (Fig.2) consists to feedback 'u-ur' to the integral term of the PID controller through a compensator with transfer function $F(s)=\frac{1}{K}$ (K is the proportional gain).

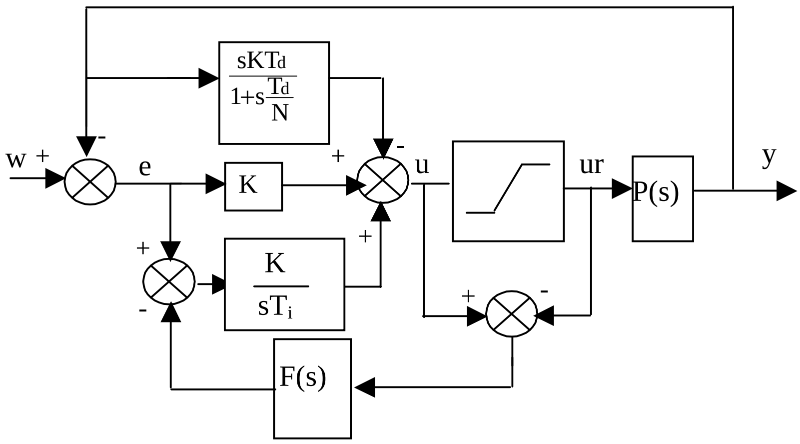

Figure 2: Conditioning Technique

PID Controller with Fuzzy AW Compensation

Actually, fuzzy logic is applied in much application area from home appliances to industrial control systems. In general employing fuzzy logic should achieve the following objectives:

- operate without human intervention, - be able to cope with highly variable, complex, nonlinear systems, - satisfy operational specifications and performance criteria...

In the case of time varying processes, fuzzy logic can be employed to adapt the parameters of PID controller. In our case, we interest to act on signals rather than on parameters to improve the PID behavior using fuzzy compensation.

The fuzzy AW compensation is designed whose aim is to reduce the integral action when the actuator saturates. It has two inputs v, dv/dt and one output ua (see Fig.3). Parameters K1, K2 and K3 are scaling gains.

If the error e is positive for a substantial time, the control signal gets saturated at the high limit u_{max}. If the error remains positive for some time subsequent to saturation, the integrator continues to accumulate the error causing the control signal to become ‘more’ saturated. The control signal remains saturated at this point because of the large value of the integral. It does not leave the saturation limit until the error becomes negative and remains negative for a long time to allow the integral part to come down to a smaller value. The adverse effect of this integral windup is in the form of large overshoots in the output y and sometimes even instability. To avoid windup, an extra feedback path is provided in the controller by measuring the actuator output u_r and forming an error signal as the difference between the output u of the controller and the actuator output u_r. This error signal v is the input of the integrator through the fuzzy AW compensator. When the actuator saturates, the feedback signal ua attempts to drive v to zero. This enables us to establish the rule base for fuzzy AW compensation (see table 1).

The following figure shows the structure of the proposed control scheme.

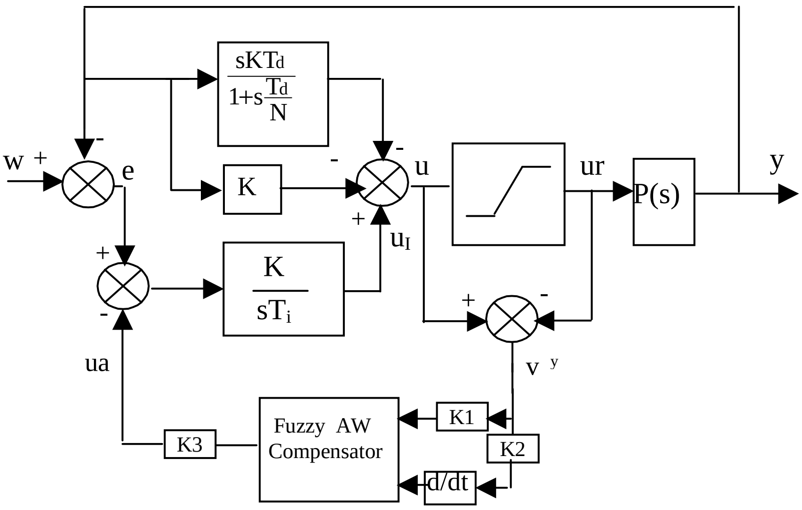

Figure 3: PID controller with fuzzy AW compensation

To design the fuzzy AW compensation we follow the standard procedure of fuzzy controller's design which consists of: fuzzification, rule base establishment and defuzzification ([9]).
All Member Functions of inputs and output are chosen triangular in form and normalized in the range [-1,1].

Table 1: Rule base for fuzzy AW compensation

		v		
		N	Z	P
	N	N	Z	P
dv/dt	Z	N	Z	P
	P	N	Z	P

Where N, Z and P are Negative, Zero and Positive fuzzy sets respectively.

The used fuzzy inference method is the "sum-prod" method which interprets the 'and' and 'then' connectives as the Cartesian product and the 'or' connector by the mean value. The deffuzification method applied is the center of gravity method.

AW Approach for Fuzzy PID Controller

In this section we describe the basic structure of the control scheme, and motivate the rationale for Fuzzy-Proportional-Integral-Derivative.

The proposed structure of the control scheme is the same as presented in Fig.3 but instead of the conventional PID controller we use a fuzzy PID controller, keeping the same fuzzy AW compensation. In the next, we present the design of the fuzzy PID controller.

A conventional PID control algorithm can be expressed as:

$$u = K\int(\dot{e} + \frac{e}{T_i} + T_d\,\ddot{e})\,dt \tag{3.1}$$

where e is the process tracking error, $\dot{e}$ and $\ddot{e}$ are the first and the second derivative of the error respectively.

If e, $\dot{e}$ and $\ddot{e}$ are fuzzy variables, equation (3.1) will become fuzzy PID control algorithm.

As there are three fuzzy inputs, the rule base is a three dimensional one and should have n^3 rules (n is the number of member functions) for a complete rule base. This will expand the rule base greatly and make the design more difficult.

In order to reduce the complexity of the rule base design and increase efficiency, a simplified fuzzy PID controller ([9]) can be presented as shown in Fig.4 by sharing a common rule-base for both Fuzzy-Proportional-Integral and Fuzzy-Proportional-Derivative parts. This simplified fuzzy PID can achieve the similar performance as the Fuzzy PID.

The simplified fuzzy PID controller is simple in structure, easy in implementation and fast in computation. The global structure of the control scheme is shown in the following figure where Ke, Kd, Ku_1 and Ku_2 are scaling gains.

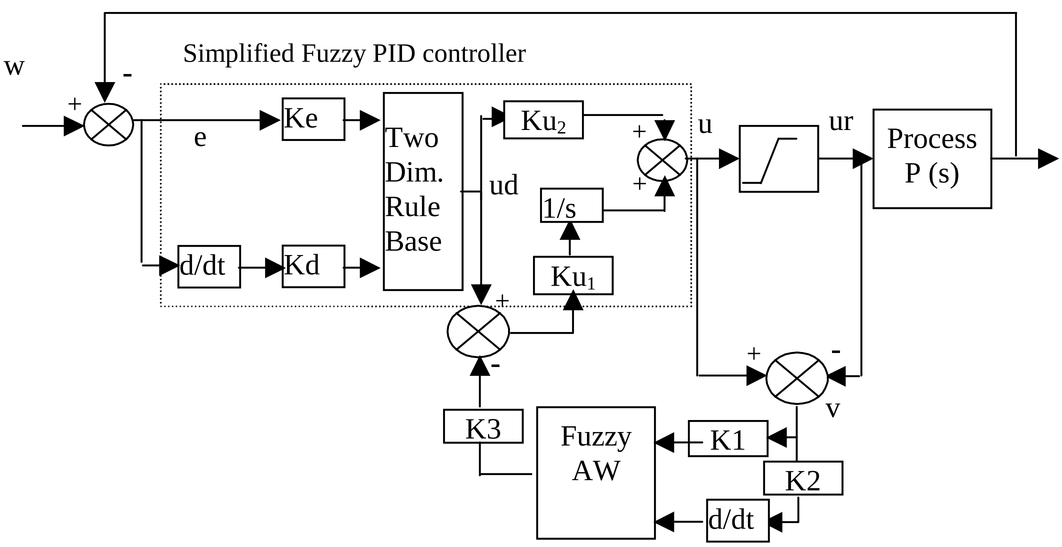

Figure 4: Fuzzy PID controller with fuzzy AW compensation

The member functions associated to fuzzy variables e, de/dt and ud are chosen triangular in form and normalized in the range [-1,1]. The following complete rule base table is applied.

Table 2: Rule base for simplified fuzzy PID controller

		e: N	e: Z	e: P
de/dt	N	GN	MN	Z
de/dt	Z	MN	Z	MP
de/dt	P	Z	MP	GP

where N, Z, P, GN, MN, GP, MP are Negative, Zero, Positive, Great Negative, Medium Negative, Great Positive, Medium Positive fuzzy sets respectively.

The defuzzification and inference methods are the same as those adopted in subsection 2.2.

Simulations and Performance Analysis

The proposed fuzzy AW methods are tested through simulation on the following benchmark systems ([9]):

$$G_1(s) = \frac{1}{s(s+1)^3}, \qquad G_2(s) = \frac{1}{(s+1)^7}, \qquad G_3(s) = \frac{1-2s}{(s+1)^3}.$$

The simulation is carried out using Simulink in Matlab.

PID_FAW and Conditioning Technique

In this subsection, tracking performances of PID_FAW and conditioning technique are compared.

The PID parameters are tuned using the method based on constrained optimization developed in [10]. For systems G_1, G_2 and G_3 the PID parameters obtained in [10] are summarized in the following table.

Table 3: PID parameters

	K	Ti	Td
G1	0.291	8.03	3.15
G2	1.067	3.26	1.85
G3	0.569	2.08	0.86

The filter factor N is taken equal to 10.

In this study, the scaling gains K1, K2 and K3 of the fuzzy AW compensation are tuned by hand. In next research paper a method for choosing these gains will be studied.

For each benchmark system, the simulation results will correspond to the following cases:

a) unlimited case : the system is controlled by only the PID with no saturation nor AW compensation
b) Limited case: the system is controlled by the PID with saturation and no AW compensation. This case will hence illustrate the windup phenomenon.
c) Conditioning Technique
d) PID_FAW

- First example: $G_1(s) = P(s) = \frac{1}{s(s+1)^3}$

The following parameter values are chosen: K1= 1; K2= 1; K3=10; umin= -0.01; umax= 0.06.

For a step change of w from 0 to 1, we obtain the following results:

As we can see, the limited case exhibits clearly the windup problem which is resolved by both AW approaches (c) and (d). The proposed PID_FAW method gives good tracking performances than the conditioning technique.

- Second example: $G_2(s) = P(s) = \frac{1}{(s+1)^7}$

The following parameter values are chosen:

K1 = 1; K2 = 1 ; K3 = 1; umin = 0; umax = 1.05.

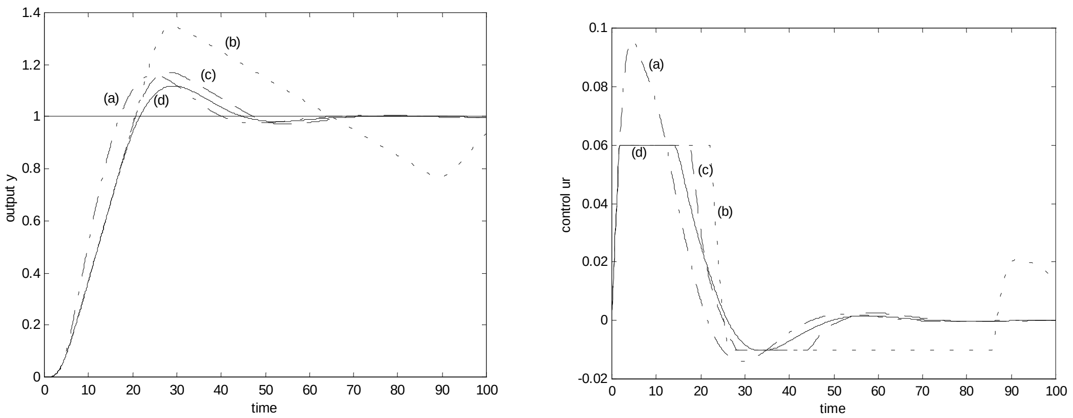

Figure 5: Step responses (left) and control signals (right) of $G_1(s)$
(a) Unlimited case, (b) Limited case, (c) Conditioning Technique, (d) PID_FAW

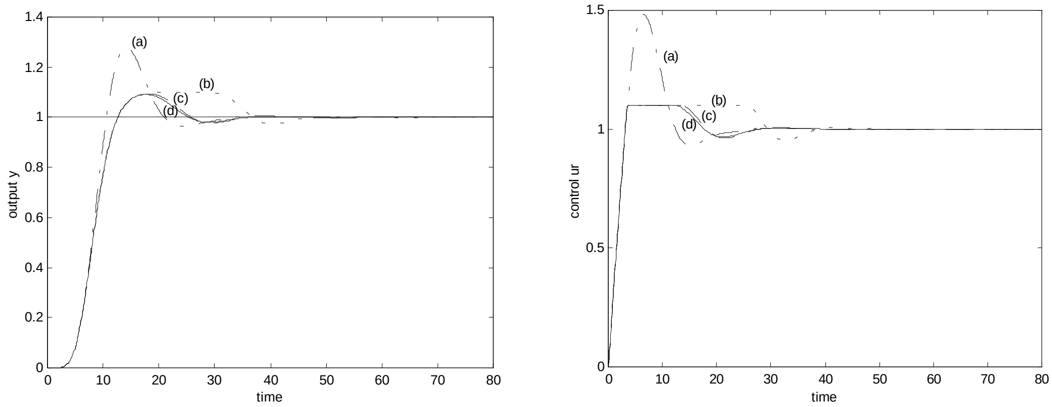

Figure 6: Step responses (left) and control signals (right) of G_2 (s)
(a) Unlimited case, (b) Limited case, (c) Conditioning Technique, (d) PID_FAW

As shown in Fig.6, we can derive the same conclusions as in the first example.

- Third example : G_3 (s) = P(s) = $\frac{1-2s}{(s+1)^3}$

The following parameter values are chosen:
K1 = 1; K2 = 1; K3 = 10; umin = 0; umax = 1.05.
Also in this case, we can derive the same conclusions as in the first example.

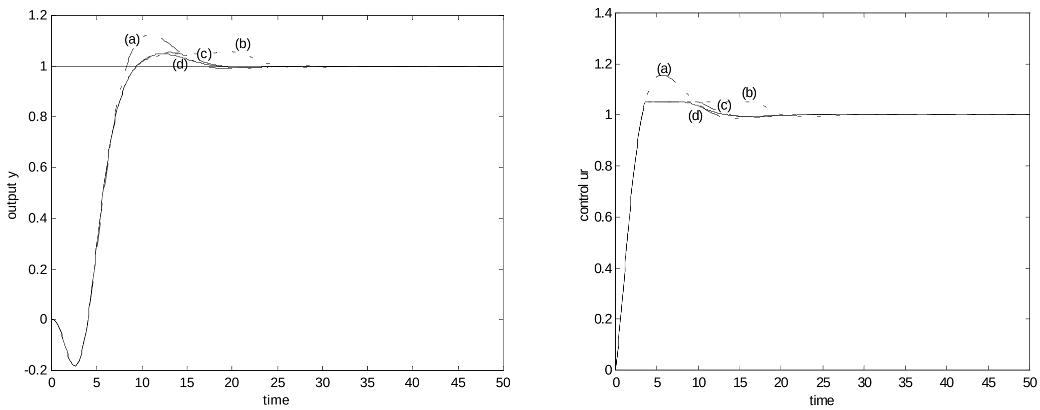

Figure 7: Step responses (left) and control signals (right) of G_3(s)
(a) Unlimited case, (b) Limited case, (c) Conditioning Technique, (d) PID_FAW

Fuzzy PID with fuzzy AW compensation (FPID_FAW)

Also in this case, for each benchmark system, the simulation results will correspond to the following cases:

a) unlimited case : the system is controlled by only the fuzzy PID with no saturation nor AW compensation

b) Limited case: the system is controlled by the fuzzy PID with saturation and no AW compensation.

c) FPID_FAW

- First example: $G_1(s) = P(s) = \dfrac{1}{s(s+1)^3}$

The following parameter values are chosen: K1 = 1; K2 = 1; K3 = 1; umin = -0.01;
umax = 0.08; Ke = .99; Kd = 6; Ku1 = 0.15; Ku2 = 0.8.
For a step change of w from 0 to 1, we obtain the following results:

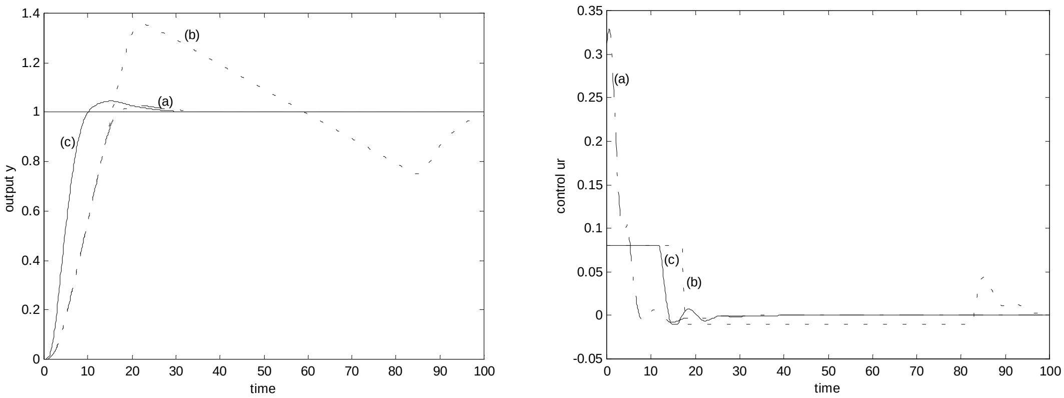

Figure 8: Step responses (left) and control signals (right) of G_1 (s)
Unlimited case, (b) Limited case, (c) FPID_FAW

As we can see, the Limited case exhibits always the windup problem which is resolved by our proposed AW approach. Also, FPID_FAW gives good tracking performances.

- Second example: G_2 (s) = $P(s) = \dfrac{1}{(s+1)^7}$

The following parameter values are chosen: K1 = 1; K2 = 1; K3 = 1; umin = 0.94;
umax = 1.05; Ke = 0.7; Kd = 2.1; Ku1 = 0.29; Ku2 = 0.9.
For a step change of w from 0 to 1, we obtain the following results:
As shown in Fig.9, we can derive the same conclusions as in the first example.

- Third example : G_3 (s) = $P(s) = \dfrac{1-2s}{(s+1)^3}$

The following parameter values are chosen: K1 = 1; K2 = 1; K3 = 1; umin = 0.94;
umax = 1.05; Ke = 0.7; Kd = 2.1; Ku1 = 0.29; Ku2 = 0.9.

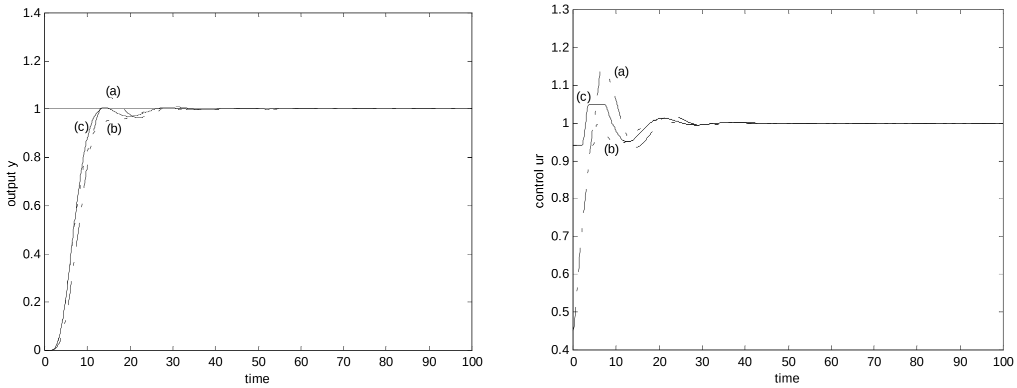

Figure 9: Step responses (left) and control signals (right) of G_2 (s)
(a) Unlimited case, (b) Limited case, (c) FPID_FAW

For a step change of w from 0 to 1, we obtain the following results

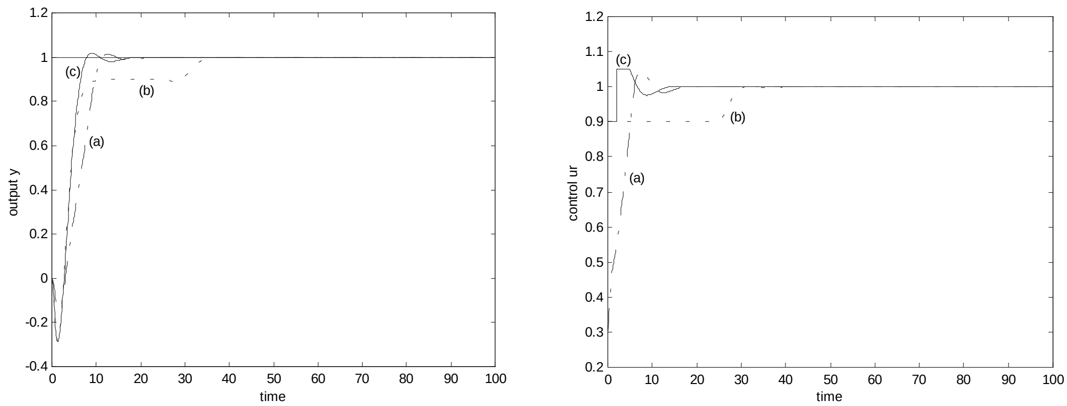

Figure 10. Step responses (left) and control signals (right) of G_3 (s)
(a) Unlimited case, (b) Limited case, (c) FPID_FAW

Also in this case, we can derive the same conclusions as in the first example.

Conclusion

In this paper, we have treated the windup problem in linear systems with input saturation and controlled by a classical PID or by a fuzzy PID controller. Two AW methods have been designed: the first one consists of the classical PID controller plus a feedback fuzzy compensation block, while the second consists of a fuzzy PID controller plus the same feedback fuzzy compensation block. The proposed methods are tested through simulation on a set of benchmark systems. The obtained results affirmed the potential of both methods to treat the windup problem. Moreover, the first method gives generally better tracking performances than the conditioning technique.

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