A NEW RATIO CONTROL ARCHITECTURE

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Abstract

In this paper, a new ratio control architecture is proposed. It aims at achieving high performances in both setpoint following and load rejection specifications. A tuning procedure is given in order to set all the parameters in the control scheme, so that the design effort required by the user is kept at a minimum level. Simulation results show the effectiveness of the methodology.

1 Introduction

Proportional-Integral-Derivative (PID) controllers are the controllers most adopted in industry due to the good cost/benefit ratio they are able to provide for a wide range of processes. Often, they are employed as basis of more complex control schemes where couplings between simple control systems are exploited. An example is ratio control, which consists of keeping a constant ratio between two process variables. This is actually required in many applications, such as chemical dosing, water treatment, chlorination, mixing vessels, waste incinerators. For example, in combustion systems the air-to-fuel ratio has to be controlled to obtain an high efficiency, and in blending processes a selected ratio of different flows has to be maintained to keep a constant product composition.
In the last sixty years, a major effort has been provided by researchers to develop useful techniques for the implementation of the basic PID algorithm (tuning and automatic tuning methods) and of additional functionalities such as anti-windup, gain scheduling, adaptive control and so on [1]. Recently, this effort has been further motivated by the increase of the computational capability which is available in modern single-station industrial controllers and Distributed Control Systems (DCS). Conversely, the design of methodologies for the implementation of the above mentioned basic couplings has been much overlooked.
A notable exception in this context is the work of Hägglund [2] in which a new ratio control structure (the so-called 'Blend station') is proposed. Obviously, to be suitable for industrial settings, in addition to the achievement of high performances, the ease of understanding and of use of new techniques is a major requirement.
In this paper, a new ratio control architecture is proposed. The idea is somewhat similar to the one explained in [2], but, conversely to the Blend station, it aims at achieving good setpoint following and load rejection performances at the same time. A tuning procedure for the overall control scheme is devised in order to avoid any additional design effort from the user.
The paper is organised as follows. In Section 2 a short introduction of ratio control is provided. In Section 3 the new ratio control architecture is proposed. The tuning procedure is revealed in Section 4. Simulation results are presented in Section 5 and conclusions are drawn in Section 6.

2 Overview of ratio control

The aim of a ratio control system is to keep the ratio between the values of two process variables y_1 and y_2 equal to a constant value a, in order to meet some higher-level requirements, despite possible setpoint changes and load disturbances that might occur on the process.
For this purpose, the control scheme shown in Figure 1 is usually implemented. Each variable is controlled by two separate controllers C_1 and C_2 (typically of PI type) and the output y_1 of the first process is multiplied by a and adopted as the setpoint of the closed-loop control system of the second process, i.e. it is $r_2(t) = ay_1(t)$ [3]. In this way, at the steady-state, provided that the gain of the second loop is equal to unity (note that this condition is normally verified by the presence of the integral part in the controller) the requirement

$$\frac{y_2(t)}{y_1(t)} = a$$

is satisfied.
The main disadvantage of this scheme is related to the transient response to a change in the set-point r_1, as the output y_2 is necessarily delayed with respect to y_1, due to the closed-loop dynamics of the second loop. In general, the second loop is chosen as the one with the fastest dynamics. However, in order to keep the ratio at the desired value, it is often necessary to detune the first loop and therefore the obtained performances in the setpoint following task and in the rejection of the load disturbance d_1 decrease.
A possible alternative scheme is the one shown in Figure 2. In this case, provided that the two closed-loop systems have the same dynamics, high performances can be achieved in the setpoint following task, but obviously, a disturbance acting on the first process causes a large error in the ratio value. For this reason, this approach is generally not adopted in practical cases.

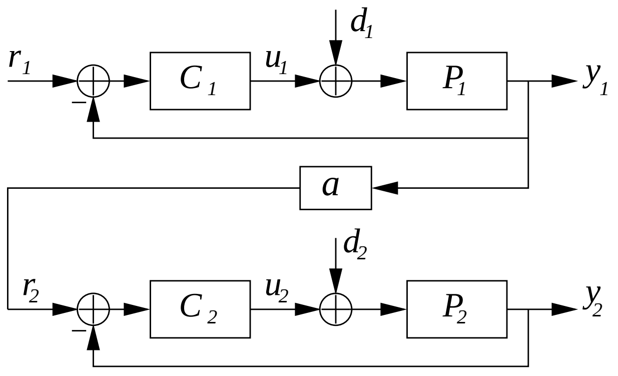

Figure 1: The typical ratio control scheme.

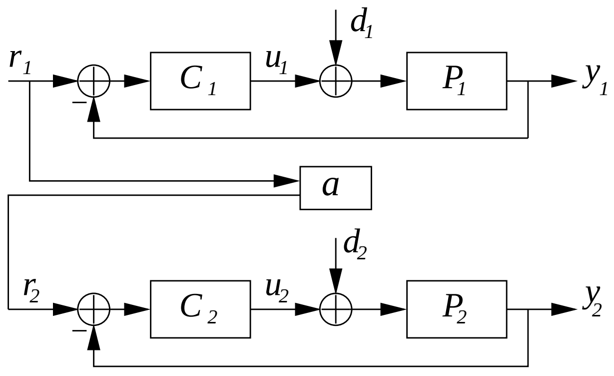

Figure 2: An alternative ratio control scheme.

To overcome the drawback of the scheme of Figure 1, Hägglund proposed an alternative architecture, named the Blend station [2]. This is shown in Figure 3. The main feature of the scheme is that the value of the set-point r_2 depends both on the value of the process output y_1 and on the value of the set-point r_1, according to the expression

$$r_2(t) = a(\gamma r_1(t) + (1-\gamma)y_1(t)). \tag{1}$$

Note that γ is a constant parameter that weights the relative influence of the set-point r_1 on r_2 with respect to y_1 (for $\gamma = 0$ the classical scheme of Figure 1 is obtained). The value of γ can be selected as the ratio of the time constants of the two closed-loop systems (or, if they are not available, as the ratio of the integral time constants of the two controllers) or, alternatively, by applying a suitable adaptive procedure, i.e. by applying the following formula [2]:

$$\frac{d\gamma}{dt} = \frac{S}{T_a}(ay_1 - y_2) \tag{2}$$

where $S \in \{-1, 0, 1\}$ is a sign parameter that takes into account if the set-point step is positive or negative. In [2] it is suggested to select the value of the adaptation rate T_a as a factor times the longest integral time of the two loops. Note that, for the two PI controllers, explicit tuning rules to be adopted in this context are not given and that the method affects performances when load disturbances d_1 occurs. Thus, it is suggested to set $\gamma = 0$ during periods of constant set-point r_1.

3 The new ratio control architecture

The ratio control architecture proposed in this paper is shown in Figure 4. The new block $F(s)$, used twice, plays a key role in the approach. The transfer function $F(s)$ is determined in such way that the transfer function from r_1 to y_1 is the same of the transfer function from r_1 to y_2 scaled by a. After trivial calculations, it results:

$$F(s) = \frac{C_1(s)P_1(s)}{C_2(s)P_2(s)}. \tag{3}$$

As it is common practice in industrial environments, both the processes are assumed to have a first order plus dead time

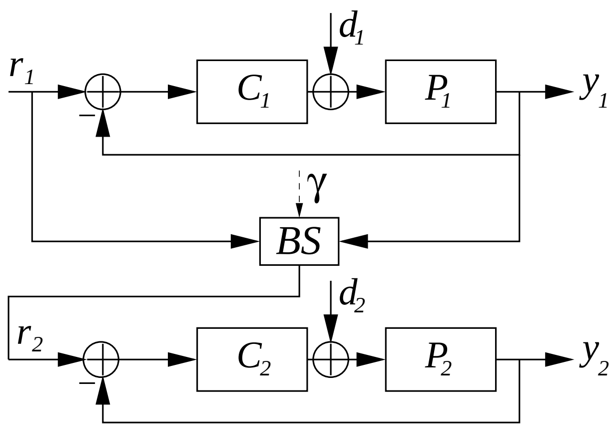

Figure 3: The ratio control scheme using the Blend station.

(FOPDT) dynamics, i.e. they are modelled according to the following transfer functions:

$$\begin{aligned} P_1(s) &= \frac{K_1}{T_1 s + 1} e^{-L_1 s} \\ P_2(s) &= \frac{K_2}{T_2 s + 1} e^{-L_2 s}. \end{aligned} \tag{4}$$

Further, according again with the industrial practice, the two controllers are of PI type, i.e. we have:

$$\begin{aligned} C_1(s) &= K_{p1}\left(1 + \frac{1}{T_{i1} s}\right) \\ C_2(s) &= K_{p2}\left(1 + \frac{1}{T_{i2} s}\right). \end{aligned} \tag{5}$$

Taking into account the expression of $F(s)$ (3) and those of the processes and of the controllers (4) and (5), it turns out that, in order for the system $F(s)$ to be causal, it must be $L_1 \geq L_2$. This relation gives a guideline on how to select the first loop, i.e. the first loop has to be selected as the one with the process with the largest dead time.

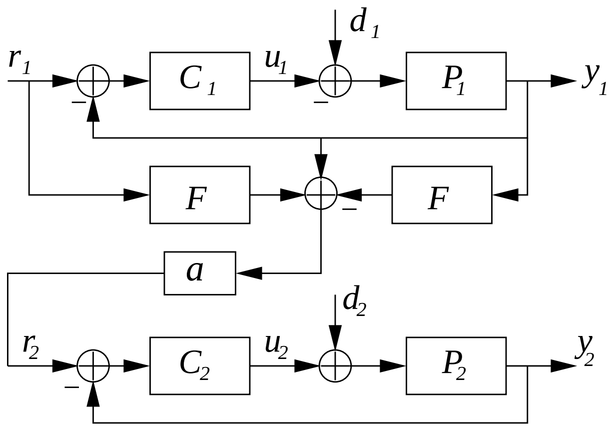

Figure 4: The new ratio control architecture.

zeros	$-\frac{1}{T_{i1}}, -\frac{1}{T_2}$
poles	$-\frac{1}{T_{i2}}, -\frac{1}{T_1}$
gain	$\frac{K_1 K_{p1} T_{i2}}{K_2 K_{p2} T_{i1}}$

Table 1: Zeros, poles, and gain of transfer function $F(s)$.

For the purpose of tuning the overall control system (see Section 4), it is worth to determine the zeros, the poles and the gain of the transfer function $F(s)$. They are reported in Table 1.

Remark 1. It is worth noting that the new architecture aims at balancing the two classic approaches described in Section 2 (see Figures 1 and 2). Apparently, with respect to the approach shown in Figure 1, achieving the desired ratio during the whole transient setpoint response is paid by a decreasing in the performances when a load disturbance occurs in the first process. However, this can be avoided by a suitable tuning, as explained in Section 4.

4 Tuning

It is assumed that an estimate of the FOPDT transfer functions of the two processes is available (for example it can be obtained by the well-known area method [1]). As already mentioned in Section 3, the first loop has to be selected as the one with the largest dead time. Then, as the new architecture guarantees that the desired ratio is obtained along the whole transient response when a setpoint change is required (provided that the two processes have actually a FOPDT dynamics), the selection of the parameters of the two controllers has to be done according to the following intuitive guidelines:

- the parameters of $C_2(s)$ have to be chosen in order to provide the best rejection of a load disturbance d_2;
- the parameters of $C_1(s)$ have to be chosen in order to provide the best rejection of a load disturbance d_1;
- the parameters of $C_1(s)$ and $C_2(s)$ have to be chosen in order to have a frequency response of $F(s)$ as low as possible (see Remark 1). In this way, the reference r_2 of the second loop is determined mainly by output y_1 of the first loop instead of the reference r_1 of the first loop (note that the transfer function from y_1 and r_2 is $a(1-F(s))$). Thus, a high performance on the desired ratio is obtained when a load disturbance is acting on the first process.

In order to achieve the mentioned goals, the following procedure can be adopted.
First, the PI controller C_1 is tuned according to the method proposed in [4], which is devoted to obtain a desired specification on the load disturbance rejection task. In this context, it it convenient to chose the value of the time constant of the desired transfer function between the load disturbance d_1 and the process output y_1 equal to the value of the time constant T_1 of the process. In this way, in addition to a good degree of robustness, a low value of the ratio K_{p1}/T_{i1} is achieved [4], which is important in order to ensure a low frequency response of $F(s)$ (see Table 1). Note also that, by choosing the process time constant as the desired time constant of the load disturbance to process output transfer function, the method employed aims at cancelling the process pole, i.e. it results $T_{i1} = T_1$.
Subsequently, the PI controller C_2 is tuned by first imposing again a pole-zero cancellation in the second loop, i.e. by setting $T_{i2} = T_2$. This is done in order to obtain a Bode plot of the transfer function $F(s)$ that is flat, i.e. the value of $|F(j\omega)|$ is the same for the whole range of frequencies (see Table 1). In other words, with the previous choices, we have simply

$$F(s) = Ke^{-(L_1-L_2)s} \tag{6}$$

where

$$K = \frac{K_1 K_{p1} T_{i2}}{K_2 K_{p2} T_{i1}}. \tag{7}$$

Then, parameter K_{p2} is selected by following basically the same idea described in [5]. Thus, in order to have good load disturbance rejection performances, K_{p2} is fixed, after solving an optimization problem, as the maximum value that guarantees that the closed-loop system is stable and that the largest value M_s of the sensitivity function is constrained. In general, typical values of M_s are chosen in the range 1.2-2.0, in order to ensure a sufficient damping of the closed-loop system. However, taking into account that in this case the setpoint response is not of concern, as it is equal to the one of the first loop, due to the ratio control architecture, it is convenient to choose a higher value of M_s, i.e. $M_s = 2.5$, in order to obtain a higher value of K_{p2} and therefore a lower value of the gain of $F(s)$. It has to be noted that the chosen value of $M_s = 2.5$ is still sensible, as a higher value is generally obtain by applying the well-known Ziegler-Nichols tuning formula [1].

Remark 2. It is worth stressing that the proposed control architecture (i.e. the scheme shown in Figure 4) can be adopted with any value of the parameters of the two controllers C_1 and C_2, achieving in any case the desired ratio in the presence of a setpoint change. Thus, the user might retain its know-how in tuning the two controllers, without impairing the effectiveness of the methodology. For example, detuning the controller of the first loop implies that when a load disturbance occurs on the first process, a slower rejection is obtained, but the desired ratio is kept better during the transient. Further, an available more accurate model of the processes can be fully exploited.

5 Simulation results

Two illustrative examples are shown in order to demonstrate the effectiveness of the devised methodology. For the sake of clarity, in both examples the desired ratio a is set equal to one.

5.1 Example 1

Consider the following two FOPDT systems:

$$\begin{aligned} P_1(s) &= \frac{1}{4s+1}e^{-3s} \\ P_2(s) &= \frac{1}{6s+1}e^{-2s}. \end{aligned} \tag{8}$$

By applying the proposed method and the proposed tuning procedure, it results: $K_{p1} = 0.57$, $T_{i1} = 4$, $K_{p2} = 2.58$, $T_{i2} = 6$. Consequently, we obtain

$$F(s) = 0.33e^{-s}.$$

Then, a unit step has been applied to the setpoint signal at time $t = 0$ s and then to the load disturbance signals d_1 and d_2 at time $t = 40$ s and $t = 90$ s respectively. The two process outputs are shown in Figure 5, whilst the reference signal r_2 of the second closed-loop system is plotted in Figure 6. It appears that a perfect ratio control is achieved in the presence of a set-point change, as expected, but performances are very satisfactory as well even in the presence of load disturbances.
For the sake of comparison, results obtained by the classic ratio control scheme (see Figure 1) are reported in Figures 7 and 8 (note that the PI controllers have been tuned as for the new method). It appears that the worst performance obtained for the set-point change is not counterbalanced by a better performance in the presence of load disturbances.

5.2 Example 2

As a second example, two systems that are not of first order are considered:

$$\begin{aligned} P_1(s) &= \frac{1}{(s+1)^4} \\ P_2(s) &= \frac{1}{(s+1)^2}e^{-s}. \end{aligned} \tag{9}$$

An estimate of a FOPDT transfer function has been obtained by means of the area method. It results: $K_1 = 1$, $T_1 = 1.84$,

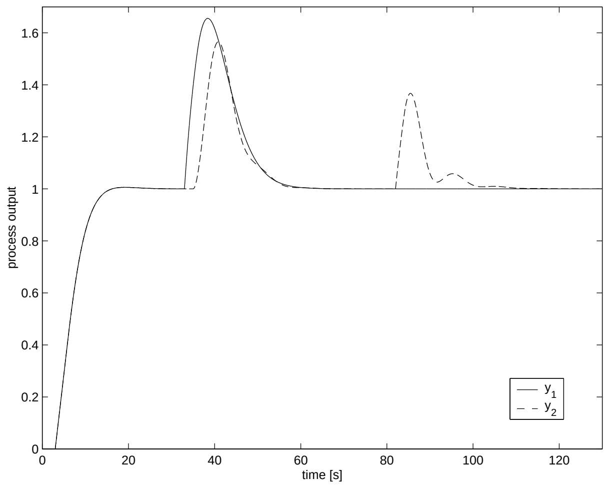

Figure 5: Process outputs with the new scheme - example 1.

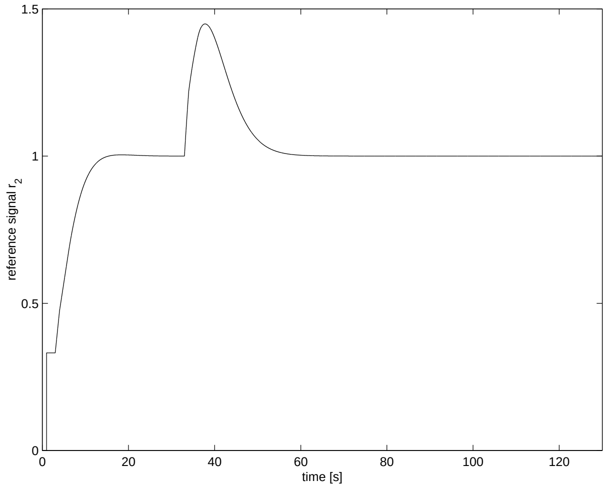

Figure 6: Reference signal r_2 with the new scheme - example 1.

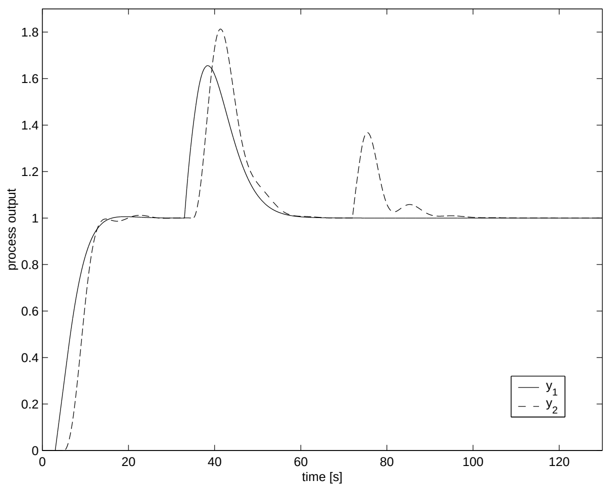

Figure 7: Process outputs with the classic scheme - example 1.

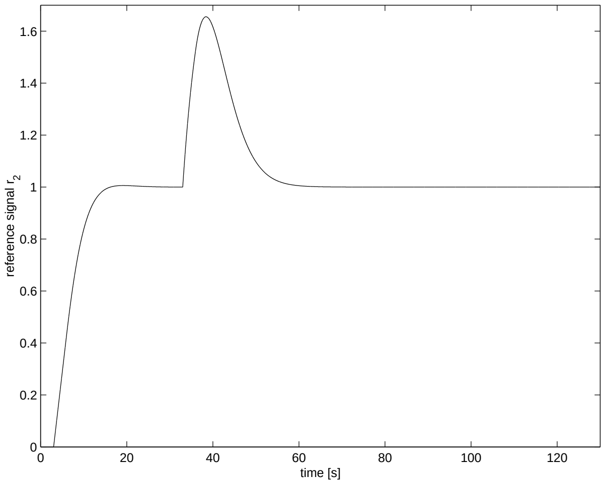

Figure 8: Reference signal r_2 with the classic scheme - example 1.

$L_1 = 1.92$, $K_2 = 1$, $T_2 = 1.39$, $L_2 = 1.57$. It appears that these processes are quite difficult to be controlled as they have a large normalised dead time (i.e. the ratio between the dead time and the time constant of the process). The tuning procedure described in Section 4 has been applied by considering the estimated process models, resulting in $K_{p1} = 0.51$, $T_{i1} = 1.92$, $K_{p2} = 0.77$, $T_{i2} = 1.39$, and

$$F(s) = 0.48e^{-0.35s}.$$

A unit step has been applied to the setpoint signal at time $t = 0$ s and then to the load disturbance signals d_1 and d_2 at time $t = 30$ s and $t = 70$ s respectively. The two process outputs are reported in Figure 9, whilst the reference signal r_2 of the second closed-loop system is shown in Figure 10. It turns out that, despite the two processes are not FOPDT, and therefore a perfect ratio control cannot be achieved, performances are still satisfactory. Again, a comparison with the classic scheme of Figure 1 has been performed. Related results are shown in Figures 11 and 12. The same considerations done for the example 1 applies also in this case.

6 Conclusions

In this paper a new ratio control architecture has been proposed. A tuning procedure has been presented so that no tuning effort from the user is needed. The methodology is easy to implement (note that no extra measurements are required with respect to the standard ratio controllers) and it is based on the use of classical PI controllers, so that it can be easily understood by operators, who retain their know-how. Thus, the overall methodology appears to be suitable to be implemented in DCS for use in the industrial context.

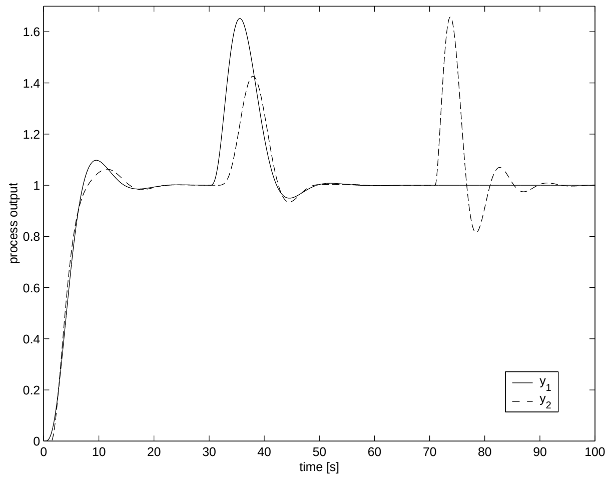

Figure 9: Process outputs with the new scheme - example 2.

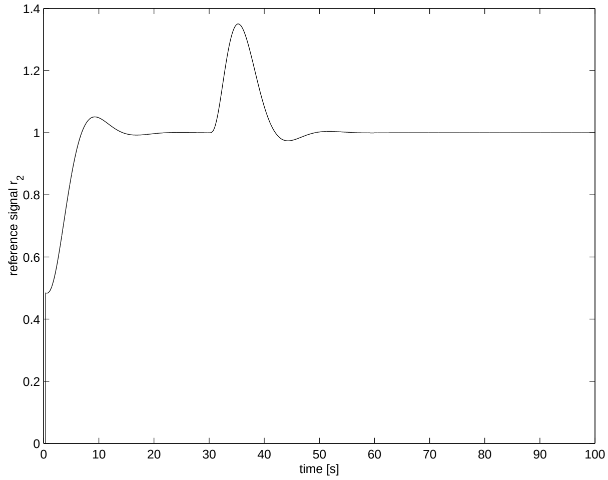

Figure 10: Reference signal r_2 with the new scheme - example 2.

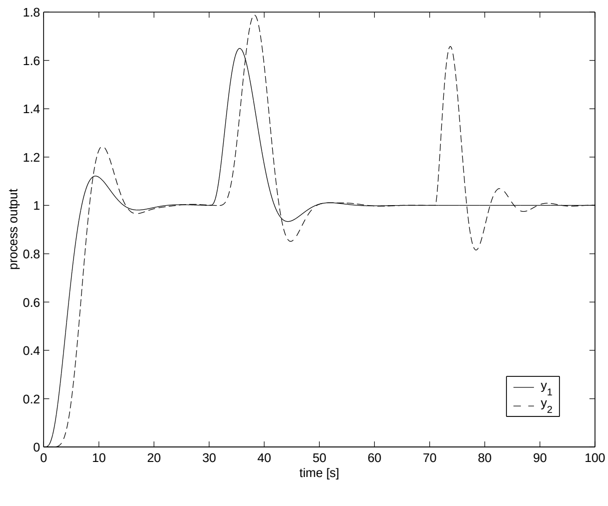

Figure 11: Process outputs with the classic scheme - example 2.

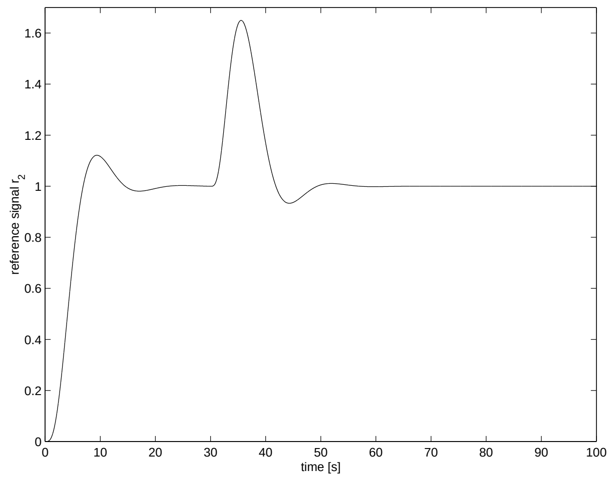

Figure 12: Reference signal r_2 with the classic scheme - example 2.

Acknowledgements

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