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# LOW COST FUZZY CONTROLLERS FOR CLASSES OF SECOND-ORDER SYSTEMS

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Abstract: The paper proposes a development method for PI-fuzzy controllers of Mamdani-type and of Takagi-Sugeno-type meant for two classes of second-order systems. The controllers are developed by starting from basic PI controllers tuned in terms of the Extended Symmetrical Optimum method, followed by applying the modal equivalences principle resulting in useful development steps. The developed fuzzy controllers belong to the class of low cost automation solutions. The controllers and development method are validated by two case studies and digital simulation results that can correspond to the speed control of an electrical drive. *Copyright © 2002 IFAC*

Keywords: fuzzy control, conventional control, dynamics, second-order systems, PI controllers, optimization, digital simulation.

## 1. INTRODUCTION

Low cost automation (LCA) involves the use of low cost control architectures and equipment, and of control solutions that can be easily developed and implemented. These automation solutions use control structures and algorithms with dynamics that can ensure:

- good control system performance for many situations;
- well established parameter tuning methods;
- wide implementation possibilities;
- additional requirements to be overlapped on the basic control structure and algorithm.

In control applications treated as LCA solutions it is frequently used the characterization of controlled plant by means of the following two forms of its transfer functions:

$$H_P(s) = k_P/[s(1+sT_\Sigma)] \,, \tag{1}$$

$$H_P(s) = k_P/[(1+sT_\Sigma)(1+sT_1)] \,, \tag{2}$$

where: $T_1$ – large time constant, $T_\Sigma$ – small time constant or time constant corresponding to the sum of parasitic time constants ($T_\Sigma < T_1$), and $k_P$ – gain.

The second-order systems (1) and (2) as controlled plants can be placed on the lower hierarchical level of complex, large-scale systems (Precup, *et al.*, 2001) and, at the same time, the transfer functions (1) and (2) can be seen as simplified models of more complex plants having nonlinearities. The assurance of good control system performance for these systems by means of LCA solutions based on conventional controllers (PI, PID) represents a basic requirement which is a difficult but challenging task.

For controlling both classes of systems the considered control system structure is a conventional one, presented in Fig.1. The blocks and variables from Fig.1 have the following meaning: C – controller, P – controlled plant, Fw – reference filter, w – reference input, $w^{\sim}$ – filtered reference input, e – control error, u – control signal, y – controlled output, $v_1$, $v_2$, $v_3$, $v_4$ – possible disturbance inputs (generally denoted by v).

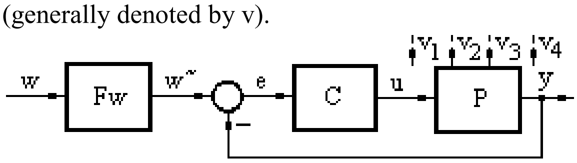


Fig. 1. Control system structure.

For the plant with the transfer function (1), the use of PI controllers with the transfer function (3):

$$H_c(s) = (k_c/s)(1+ sT_i) , \qquad (3)$$

with $k_C$ – controller gain and $T_i$ – integration time constant, tuned in terms of the Extended Symmetrical Optimum (ESO) method, offers very good control system performance (Preitl and Precup, 1999, 2000a).

This tuning methodology has the following advantages:
- it ensures a large domain for control system performance that can be obtained as functions of a single parameter;
- it has large possibilities for application to the field of electrical drives, in particular to those with nonlinearities or with variable inertia resulting in variable $k_P$ (Preitl and Precup, 2000b).

For the plants with the transfer function (2), the use of PI controllers (3) tuned according to Kessler's Modulus Optimum (MO) method (Åström and Hägglund, 1995) leads to good control system performance with respect to the reference input w. Exceptions occur in the following two situations:
- the time constant $T_1$ is significantly large ($T_1 >> T_\Sigma$), when the controller implementation can rise some problems, and
- the load disturbance (v) is fed to the plant input (a disturbance of type $v_1$), when the rejection of disturbance effects is done very slowly.

In such situations there exist two classical versions for treating the problem (Dragomir and Preitl, 1979):
- the use of P controllers tuned according to the MO method; the result is in control systems with non-zero static coefficient;
- the use of PI controllers tuned according to Kessler's Symmetrical Optimum method (Åström and Hägglund, 1995); but, the large overshoot in this case is not a generally acceptable solution.

Another solution with much better results for controlling the plant (2) consists in the use of PI controllers in the conditions of applying the optimization relations in terms of the ESO method (Preitl, 2000).

A way to fulfil this goal, of very good control system performance by means of low cost automation solutions, is firstly represented by conventional control under the form of PI controllers as it was mentioned before.

An alternative and, at the same time, completing way to fulfil the goal of very good control system performance by means of LCA solutions is represented by the use of fuzzy control employing fuzzy controllers with dynamics. The development of fuzzy control systems is usually performed by heuristic means, incorporating human skills, but the drawback is in the lack of systematic development methods, devoted to relatively simple fuzzy controllers. One way to do this job is proposed here by firstly developing conventional PI controllers for the accepted plants (1) and (2) and, then, by the incorporation the knowledge on these controllers in the development of fuzzy controllers with dynamics under the form of PI-fuzzy controllers.

The development of fuzzy controllers for the linear plants (1) and (2) does not represent an aim in itself, but it can be considered as a first step in the development of complex control structures including these plants. The simplicity of the presented development method and of the developed controllers justifies the use of these structures in cases that can involve from one application to another either variable parameters of controlled plant (for example, $k_P$) or the plant placed at the lower hierarchical level of large-scale systems. Furthermore, fuzzy control can compensate the nonlinearities mentioned before.

The paper is organized as follows. The ESO method together with its extension in applying it to the plant (2) will be shortly discussed in the Section 2. Then, Section 3 is dedicated to the presentation of the proposed PI-fuzzy controllers and of their development method. There is treated in Section 4 an application of the development method fuzzy controllers, with digital simulation results, for two case studies that can correspond to the speed control of an electrical drive, and the final part of the paper points out the conclusions.

## 2. A SHORT OVERVIEW ON EXTENSIONS OF SYMMERICAL OPTIMUM METHOD (ESO)

The generalized optimization conditions according to the ESO method (Preitl and Precup, 1999) are given by the equations (4):

$$\beta^{1/2} \cdot a_0 \cdot a_2 = a_1^{\,2} , \; \beta^{1/2} \cdot a_1 \cdot a_3 = a_2^{\,2} , \qquad (4)$$

where the coefficients $a_k$ ($k = 0 \ldots 3$) belong to the general form of the closed-loop transfer function:

$$H_w(s)= \frac{H_0(s)}{1+H_0(s)} = \frac{b_0+b_1 s}{a_0+a_1 s+a_2 s^2+a_3 s^3} , \qquad (5)$$

where $H_0(s)$ is the open-loop transfer function:

$$H_0(s) = H_C(s)H_P(s) . \qquad (6)$$

In the case of the controlled plant (1), the optimized transfer functions $H_0(s)_{opt}$ and $H_w(s)_{opt}$ are expressed as (7) and (8), respectively:

$$H_0(s)_{opt} = \frac{1 + \beta T_\Sigma s}{\beta \beta^{1/2} T_\Sigma^{\,2} s^2 (1+T_\Sigma s)} = \frac{k_0 (1+\beta T_\Sigma s)}{s^2 (1+T_\Sigma s)} , \quad (7)$$

$$H_w(s)_{opt} = \frac{1+\beta T_\Sigma s}{1+\beta T_\Sigma s + \beta \beta^{1/2} T_\Sigma^{\,2} s^2 + \beta \beta^{1/2} T_\Sigma^{\,3} s^3} , \qquad (8)$$

with:

$$k_0=k_C k_P \quad (b_0 = a_0 , \; b_1 = a_1) . \qquad (9)$$

The control system performance indices with respect to the unit step variation of w – the overshoot $\sigma_1$, the settling time $t_s$, the first settling time $t_1$ (Fig.2-a) and the phase margin $\varphi_r$ – depend favorable on the value of the design parameters β (Fig.2-b, with $\hat{t_1}=t_1/T_\Sigma$, $\hat{t_s}=t_s/T_\Sigma$). These indices can be modified within large domains of values by the appropriate modification of the values of β.

The tuning relations for PI controller parameters are obtained by applying (4) resulting in (10):

$$k_c = 1/(\beta\, \beta^{1/2} T_\Sigma^{2} k_P)\,,\ \ T_i = \beta T_\Sigma\,. \qquad (10)$$

The recommended domain of values for β is $4 \le \beta \le 16$ (20) (Preitl and Precup, 1999).

In the case of the controlled plant (2) and the PI controller with $H_C(s)$ having the form (3), after the computation of the coefficients of $H_w(s)$ (5), these can be expressed in terms of (11):

$$a_0 = k_c k_P\,,\ \ a_1 = 1+k_c k_P \cdot T_i\,,\ a_2 = T_1+T_\Sigma\,,\ \ a_3 = T_1 T_\Sigma\,. \qquad (11)$$

Based on the optimization conditions (9) and on introducing the following notation (Preitl, 2000):

$$m = T_\Sigma/T_1\,,\ \ m << 1\,, \qquad (12)$$

where m characterizes the controlled plant, the controller tuning parameters for this extension of the ESO method are obtained in the form of (13):

$$k_c = \frac{(1+m)^2}{\beta\cdot\beta^{1/2}\cdot k_P\cdot T_\Sigma'\cdot m}\,,\ \ T_i = \frac{\beta\, T_\Sigma'\, \Delta_m(m)}{(1+m)^2} = \beta\, T_{\Sigma m}\,, \qquad (13)$$

where:

$$T_\Sigma' = T_\Sigma/(1+m)\,,\ \ T_{\Sigma m} = T_\Sigma\, \Delta_m(m)/(1+m)^3\,,$$
$$\Delta_m(m) = m^2 + (2-2^{1/2})\cdot m + 1\,, \qquad (14)$$

with the recommended values for β (that can adjust the control system performance), $4 \le \beta \le 16$ (20).

Some significant remarks related to the extension of the ESO method are highlighted as follows. So, if $\beta \in \{4, 9, 16\}$, the relations (13) and (14) will obtain much simpler particular forms.

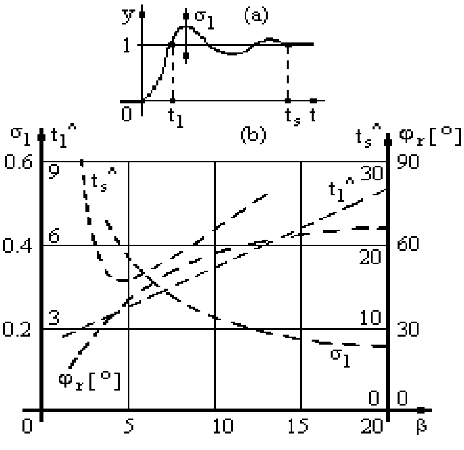


Fig. 2. Definition of control system performance indices (a) and their variations versus β.

For several values $0.01 \le m \le 0.25$ and $4 \le \beta \le 16$, the expressions $k_c(m)$ and $T_i(m)$ can be given in a tabled form. On the basis of these tables there can be built the correction diagrams of controller parameters $\{k_c, T_i\}$, illustrated in Fig.3, where the lower index 0 corresponds to m = 0. Values m > 0.25 permit the framing of the method in the MO method.

The expressions of the t.f.s $H_0(s)_{opt}$ and $H_w(s)_{opt}$, can be expressed in the forms (15) and (16), respectively:

$$H_0(s)_{opt} = \frac{(1+s\beta T_{\Sigma m})(1+m)^3}{\beta\, \beta^{1/2}\, T_\Sigma^{2} s(s+1/T_1)(1+sT_\Sigma)}\,, \qquad (15)$$

$$H_w(s)_{opt} = (1 + \beta\cdot T_{\Sigma m} s)/\Delta(s)\,, \qquad (16)$$

with:

$$\Delta(s) = [\,\beta\, \beta^{1/2}\, T_\Sigma^{3}/(1+m)^3]s^3 + [\beta\, \beta^{1/2}\, T_\Sigma^{2}/(1+m)^2\,]s^2 + \{[\beta\, \beta^{1/2}\, T_\Sigma/(1+m)^3]m + \beta\cdot T_\Sigma\cdot m\,\}s + 1\,. \qquad (17)$$

The relations (15) … (17) outline that, for $m \to 0$ ($T_1 >> T_\Sigma$), there are found again the tuning relations specific to the ESO method. The explanation consists in the fact that from a theoretical point of view, $H_P(s)$ has a quasi-integral behavior.

The analysis in the frequency domain and the root loci (families of root loci for m and β – parameters) can enlarge the image on the potential and possibilities for using the presented method (Preitl, 2000).

Concerning the behavior of the control system with respect to the disturbance input (v), if a $v_1$-type disturbance input is considered to be fed to the controlled plant (Fig.1), the closed-loop transfer function with respect to this disturbance input, $H_{yv}(s)$, can be expressed:

$$H_{yv}(s) = \frac{H_P(s)}{1+H_C(s)H_P(s)}\,, \qquad (18)$$

When the PI controller has the parameters tuned according to (13) and (14), the result will be:

$$H_{yv}(s) = s\cdot k_P/\Delta(s)\,. \qquad (19)$$

Therefore:

- the control system will have zero static coefficient,

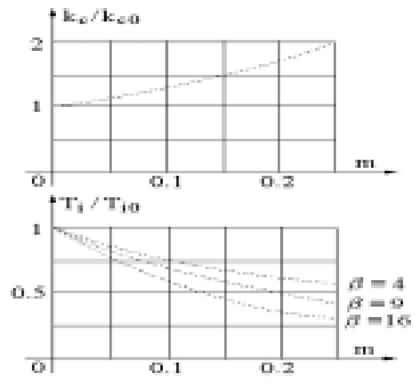


Fig. 3. Diagrams for $k_c$ and $T_i$ versus m.

- the dynamics of the control system with respect to the disturbance input $v_4$ will be convenient and relatively fast as in (Preitl, 2000).

## 3. DEVELOPMENT OF FUZZY CONTROLLERS

There will be developed two versions of PI-fuzzy controllers (PI-FCs), easy to implement as LCA solutions:
- a Mamdani-type PI-fuzzy controller (M-PI-FC) (Mamdani, 1974), which is a type II fuzzy system according to (Koczy, 1996; Sugeno, 1999);
- a Takagi-Sugeno PI-fuzzy controller (TS-PI-FC) (Takagi and Sugeno, 1985), which is a type II fuzzy system according to (Koczy, 1996; Sugeno, 1999).

Both fuzzy controllers have the same structure, presented in Fig.4 and replace the block C from Fig.1. According to Fig.4, the dynamics is introduced in the structure of the fuzzy controller (FC is a nonlinear block without dynamics) by differentiating the control error ($e_k$) and integrating the increment of control signal ($\Delta u_k$).

In the development phase, the membership functions of both PI-FCs are of regularly distributed triangular type with an overlap of 1 for the inputs ($e_k$ and $\Delta e_k=e_k-e_{k-1}$ – the increment of control error), and, for the version of M-PI-FC, of regularly distributed singleton type for the output ($\Delta u_k$) (Fig.5).

The M-PI-FC is based on Mamdani's compositional rule of inference assisted by the rule base expressed in terms of MacVicar-Whelan-type decision table presented in Table 1, and it uses the center of gravity method for defuzzification.

The TS-PI-FC uses the max and min operators in the inference engine, assisted by the rule base expressed by the decision table from Table 2, and employs the weighted average method for defuzzification (Babuska and Verbruggen, 1996).

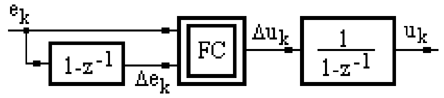


Fig. 4. Structure of PI-FCs with integration on controller output.

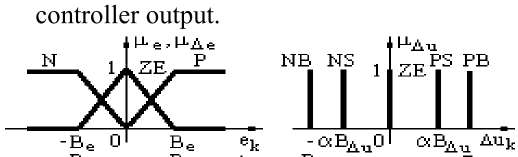


Fig. 5. Accepted membership functions of input (for M-PI-FC and TS-PI-FC) and output (for M-PI-FC) linguistic variables.

Table 1 Decision table of M-PI-FC

| | | $e_k$ | | |
|---|---|---|---|---|
| | | N | ZE | P |
| | P | ZE | PS | PB |
| $\Delta e_k$ | ZE | NS | ZE | PS |
| | N | NB | NS | PS |

Table 2 Decision table of TS-PI-FC

| | | $e_k$ | | |
|---|---|---|---|---|
| | | N | ZE | P |
| | P | 0 | $\Delta u_k$ | $\gamma \cdot \Delta u_k$ |
| $\Delta e_k$ | ZE | $\Delta u_k$ | 0 | $\Delta u_k$ |
| | N | $\gamma \cdot \Delta u_k$ | $\Delta u_k$ | 0 |

Fig.5, Table 1 and Table 2 point out the three strictly positive parameters of both PI-FCs to be determined in the sequel by means of the proposed development method: $\{B_e, B_{\Delta e}, B_{\Delta u}, \alpha\}$ for M-PI-FC and $\{B_e, B_{\Delta e}, \gamma\}$ for TS-PI-FC. The parameters $\alpha$ and $\gamma$ can introduce additional nonlinearities that can be useful for control system performance enhancement especially when controlling complex plants, nonlinear or with variable parameters (Boverie, *et al.*, 1992), where the stability analysis is necessary (Aracil, *et al.*, 1992; Garcia-Cerezo and Ollero, 1992).

For the development of M-PI-FC and TS-PI-FC it is firstly necessary to discretize the continuous linear PI controller with the transfer function (3) and the tuning parameters computed by means of (10) or (13). Based on Tustin's discretization method an incremental version of the quasi-continuous digital PI controller is obtained:

$$\Delta u_k=K_P\Delta e_k + K_I e_k \, , \; K_P=k_c(T_i-h/2) \, , \; K_I=k_c h \, , \quad (20)$$

where h represents the sampling period, and the index k stands for the current sampling interval.

For ensuring the quasi-PI behavior of both versions of PI-fuzzy controllers, the modal equivalences principle (Galichet and Foulloy, 1995) is applied, and the following useful relations will be obtained:

$$B_{\Delta e} = (K_I/K_P)B_e \, , \quad (21)$$

$$B_{\Delta u} = K_I B_e \, . \quad (22)$$

The relations (21) and (22) are used for the version of M-PI-FC, but for the version of TS-PI-FC only the relation (21) is used.

The degrees of freedom in the development of the fuzzy controllers are represented by the strictly positive parameters $B_e$ and $\alpha$ for M-PI-FC, and $B_e$ and $\gamma$ for TS-PI-FC.

By using the preparatory aspects presented above, the proposed development method for the two versions of fuzzy controllers, the M-PI-FC and TS-PI-FC results in the following development steps:
- express the simplified mathematical model of controlled plant in the forms (1) or (2) and compute the parameter m by means of (12) for the form (2);
- choose the value of the design parameter $\beta$ as a compromise between the desired / imposed control system performance by using the diagrams (for $\sigma_1$, $t_1$, $t_s$ and $\varphi_r$) illustrated in Fig.2-b;
- obtain the tuning parameters $\{k_c, T_i\}$ of the continuous linear PI controller by applying for the plant (1) the relation (10), and for the plant (2) the relation (13) of the diagrams from Fig.5;

- choose a sufficiently small sampling period, h, accepted by quasi-continuous digital control, take into account the presence of a zero-order hold, discretize the continuous linear PI controller and compute the parameters $\{K_P, K_I\}$ of the resulted quasi-continuous digital PI controller from (20);
- choose the values of the parameters $B_e$ and $\alpha$ of the M-PI-FC, and $B_e$ and $\gamma$ for the TS-PI-FC and use (21) and (22) from which there will be obtained values of $B_{\Delta e}$ and $B_{\Delta u}$; for the M-PI-FC, and the value of $B_{\Delta e}$ for the TS-PI-FC;
- design the reference filter Fw; for the conventional case, there are recommended in the case of ESO method two filters by Preitl and Precup (1999), and the simplest one has the transfer function $H_{Fw}(s)$ expressed ad:

$$H_{Fw}(s) = 1/(1+sT_i)\,, \tag{23}$$

The basic values of the parameters $B_e$ and $\alpha$ (or $\gamma$) are chosen in accordance with the experience of an expert in control systems, or they can be obtained by using adaptive structures. The values of the parameter $B_e$ are in connection with the domains of variation of the reference input. The parameters $\alpha$ and $\gamma$ are introduced for improving the dynamics of the fuzzy control system, the recommended domains being $\alpha, \gamma \in (0, 1]$ as it is done by Precup and Preitl (1998) for a version of M-PI-FC.

By increasing the number of linguistic terms and accepting the modification according to the needs of the support and distribution of output singletons it can be obtained the nonlinear character which is adequate for the FC.

The hardware and software implementation of such a control solution does not rise any special problems.

It has to be highlighted that the replacement of the block FC from Fig.4 by an adder will convert the fuzzy controller into a conventional PI one.

## 4. CASE STUDIES

There are treated two basic case studies specific to LCA application examples of the proposed development method. These case studies can correspond to the speed control of an electrical drive with its linearized simplified form having the transfer functions (1) and (2). By using the above presented development method, for each case study there are developed:
- the conventional PI controllers, using the presented extensions of the ESO method;
- two versions of PI-fuzzy controllers (PI-FCs): the Mamdani-type PI-fuzzy controller (M-PI-FC) and the Takagi-Sugeno-type PI-FC (TS-PI-FC).

The control system (CS) performance achieved by the developed fuzzy control systems are compared with the CS performance achieved by the conventional control solutions (with linear PI controllers).

### *4.1 Case Study 1.*

The controlled plant is characterized by the transfer function (1) with the parameters $k_P = 1$ and $T_\Sigma = 1$ sec. The steps presented in Section 3 enable the development of the two versions of PI-FCs resulting in the following values of the parameters:
- for the basic conventional controller: $\beta = 9$, $k_c = 0.037$, $T_i = 9$ sec,
- for the M-PI-FC: h= 0.02 sec, $K_P = 0.333$, $K_I = 0.00074$, $B_e = 0.5$, $\alpha = 0.8$, $B_{\Delta e} = 0.0011$, $B_{\Delta u} = 0.00037$;
- for the TS-PI-FC: h= 0.02 sec, $K_P = 0.333$, $K_I = 0.00074$, $B_e = 0.05$, $\gamma = 0.35$, $B_{\Delta e} = 0.00011$,

with $\beta$, $k_c$ and $T_i$ from the conventional controller.

Part of the digital simulation results are presented in Fig.6 for the CS with linear PI controller, Fig.7 for the CS with M-PI-FC and Fig.8 for the CS with TS-PI-FC in the following simulation conditions: a unit step modification of w followed by a $-0.5$ step modification of $v_4$ (after 75 sec). The continuous line is used for illustrating y, and the dotted line for u.

### *4.2 Case Study 2.*

The P is characterized by the transfer function (2) with the parameters $k_P = 1$, $T_\Sigma = 1$ sec and $T_1 = 10$ sec (fulfilling the condition (12)). By proceeding the development steps from Section 3, the following values for the parameters of the two versions of PI-FCs will be obtained:
- for the basic controller: $\beta = 9$, m= 0.1, $k_c = 0.493$, $T_i = 7.2256$ sec,
- for the M-PI-FC: h= 0.02 sec, $K_P = 3.557$, $K_I = 0.0099$, $B_e = 0.5$, $\alpha = 0.8$, $B_{\Delta e} = 0.0014$, $B_{\Delta u} = 0.0049$,
- for the TS-PI-FC: h= 0.02 sec, $K_P = 3.557$, $K_I = 0.0099$, $B_e = 0.15$, $\gamma = 0.35$, $B_{\Delta e} = 0.00041$,

with $\beta$, m, $k_c$ and $T_i$ from the PI controller.

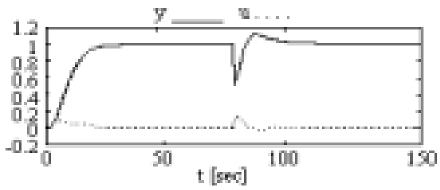


Fig. 6. y and u versus time for CS with PI controller (case study 1).

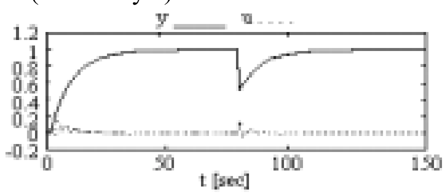


Fig. 7. y and u versus time for CS with M-PI-FC (case study 1).

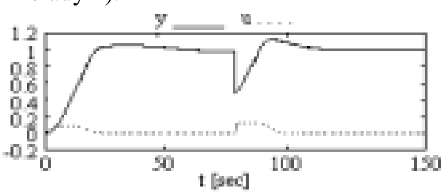


Fig. 8. y and u versus time for CS with TS-PI-FC (case study 1).

Part of the digital simulation results are presented in Fig.9, 10 and 11 for the CS with linear PI controller, the CS with M-PI-FC and the CS with TS-PI-FC, respectively, in the same simulation conditions as in the case study 1.

## 5. CONCLUSIONS

The paper proposes two LCA solutions under the form of a development method for:
- the conventional PI controller,
- a Mamdani-type PI-fuzzy controller, and
- a Takagi-Sugeno-type PI-fuzzy controller,

meant for controlling two classes of second-order systems, with integral and non-integral character and variable parameters, eventually nonlinearities, in the primary mathematical models of controlled plants.

The development of the fuzzy controllers is based on applying the tuning relations for the conventional PI controllers, specific to the ESO method and its extension, followed by the modal equivalences principle.

The result is in the same development steps for both fuzzy controllers, and this is shown also in the analyzed case studies. The controllers differ by their structure and by the fact that the TS-PI-FC has one less parameter in comparison with the M-PI-FC.

The method was applied and validated by digital simulation results to the development of PI-fuzzy controllers, and it highlights that the proposed versions of PI-FCs can successfully cope with control of plants from the field of electrical drives. In such applications the use of an auto-tuning procedure (Cheng-Ching, 1999) is recommended for further performance enhancement.

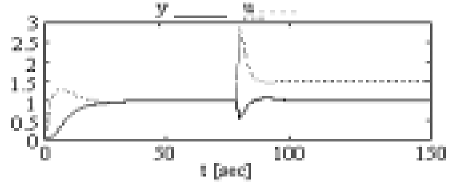


Fig. 9. y and u versus time for CS with PI controller (case study 2).

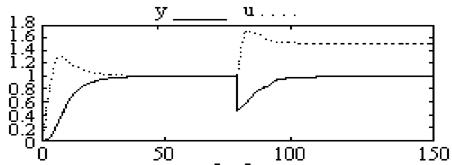


Fig. 10. y and u versus time for CS with M-PI-FC (case study 2).

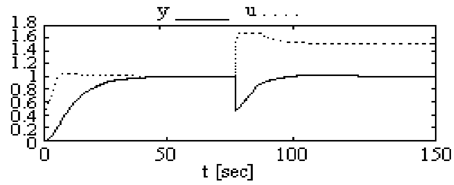


Fig. 11. y and u versus time for CS with TS-PI-FC (case study 2).

The proposed fuzzy controllers and development method and steps fulfil the twofold goal of performance enhancement by means of low cost. The low cost is ensured by the small number of linguistic terms of the PI-FCs, by the relatively simple rule bases and by the development method itself.

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