Self-tuning of PI Controllers Using Fuzzy Techniques

Marian Barbu, Emil Ceangă and Sergiu Caraman

***Abstract*— The paper deals with a self-tuning algorithm based on frequency techniques of standardized PI controllers. The self-tuning system contains two blocks: one is for filtering and synthetic properties extraction and the second is for self-tuning algorithm. The filtering and the self-tuning algorithm are achieved based on fuzzy techniques. The algorithm identifies two points belonging to the frequency characteristic of the process provided with integrator: the point of superior frequency is used in tuning of the PI standardized controller; the point of inferior frequency together with the superior one is used to determine the input of the tuning fuzzy block of Sugeno type.**

***Index Terms*—Fuzzy logic, Neural networks, Self-tuning regulators, Spectral analysis.**

I. Introduction

The self-tuning regulators offer the prospective of improving the performance level obtained when controlling industrial processes, the increasing of autonomy of the control decisional system, and the reduction of the demands of human personnel qualification. There are two types of self-tuning systems: a parallel system of self-tuning [7], [10], [11] and a substitutive system of self-tuning [3], [8]. The present paper refers to the structure including a substitutive system of self-tuning illustrated in Figure 1. The self-tuning mechanism contains a relay with variable hysteresis, which makes the system provided with integrator to enter in a forced oscillation regime. The oscillation monitoring is made in “The filtering and synthetic properties extraction” block, which determines their magnitude and period. They are used in the partial identification of the frequency characteristic of the system provided with integrator. “The filtering and synthetic properties extraction” block will send the identified points to the “Self-tuning mechanism” block that will determine the PI controller parameters.

In the literature there are reveal two important aspects on which the self-tuning quality greatly depends [1], [2], [5]:

M. Barbu, “Dunarea de Jos” University of Galati, Faculty of Electrical Engineering, Str. Domneasca 111, Galati – 6200, Romania, (phone/fax: 40-236-460182; e-mail: Marian.Barbu@ugal.ro).

E. Ceangă, “Dunarea de Jos” University of Galati, Faculty of Electrical Engineering, Str. Domneasca 111, Galati – 6200, Romania, (phone/fax: 40-236-460182; e-mail: Emil.Ceanga@ugal.ro).

S. Caraman, “Dunarea de Jos” University of Galati, Faculty of Electrical Engineering, Str. Domneasca 111, Galati – 6200, Romania, (phone/fax: 40-236-460182; e-mail: Sergiu.Caraman@ugal.ro).

1) <u>The quality of the information sent by the synthetic properties extraction block</u>. The accuracy of this information depends to a large extent on the filtering quality of the output signal. The industrial experience shows that the additional random variations of the measured output (measure noise, short parasite impulses) might cause distortions in the evaluation of the synthetic properties of the process and of the entire loop having important consequences on the self-tuning quality. This led to the investigation of some evolved filters adequate to the demands of the self-tuning regulators.

2) <u>Establishing the self-tuning criterion</u>. Frequently, the self-tuning procedures demand the existence of a phase margin or/and an imposed gain margin.

This paper aims to find a new solution based on fuzzy and neuronal techniques in order to solve the two aspects mentioned above. Basically these solutions refer to:

- using new filtering procedures based on the composing of the linear with the non-linear filters by fuzzy techniques;
- neuronal analysis of the loop periodic response in the on-off control regime;
- the use of fuzzy techniques in choosing the demand concerning the system stability degree.

The paper is structured as follows: the next section contains the filtering algorithms. The third section refers to the extracting synthetic properties block in order to get synthetic indicators concerning the process dynamics. The fourth section contains the self-tuning algorithm using the fuzzy techniques and the last section is dedicated to the conclusions.

II. Filtering Algorithms

The elaboration of the filtering algorithms was based on the comparative analysis of three types of filters: a particular structure with FIR (Finite Impulse Response) filter used in [12], the non-linear adaptive band filter and the FIR filter of superior order [6], [9].

The equation of the linear filter used in self-tuning regulator described in [12] is:

$$\tilde{y}_t = \frac{1}{70}(-6y_{t-2T} + 24y_{t-T} + 34y_t + 24y_{t+T} - 6y_{t+2T}) \qquad (1)$$

where T stands for the sampling period, $\tilde{y}_t$ the process filtered output at the moment t and y_{t+kT} is the sampled value of the process output at the moment $t+kT$. The filtered signal by this method is modest as it can be seen in Figure 2.

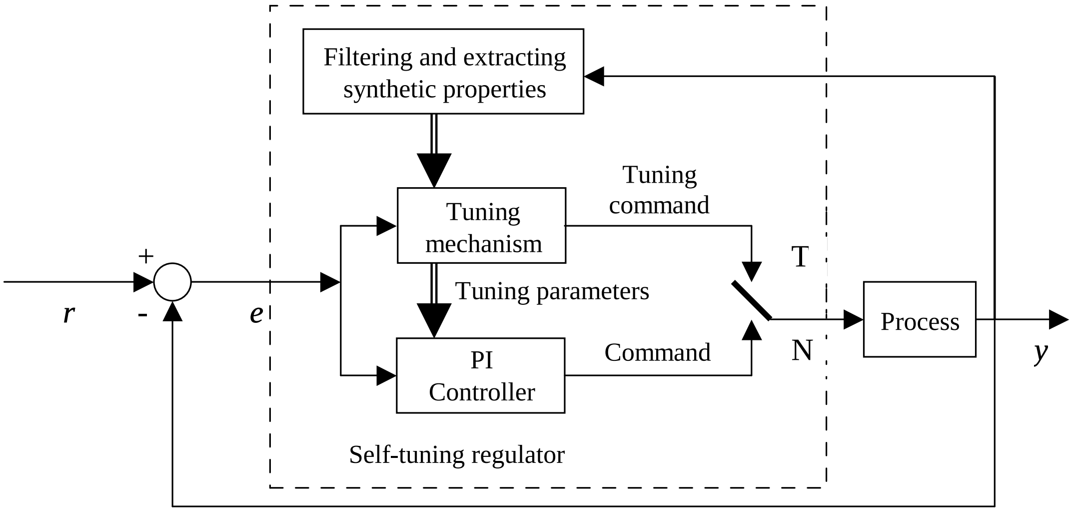

Fig. 1. Automatic system provided with standardized PI controller and self-tuning substitutive mechanism

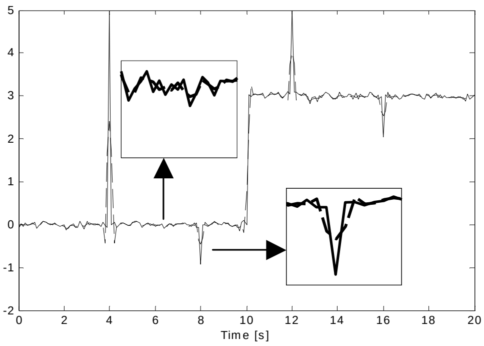

Fig. 2. The result of linear filtering (– y_t ; --- $\tilde{y}_t$)

The non-linear filtering algorithm with adaptive band is the following [4]:

 # Step1: Deducing the output $yf(k)$, using the band at the previous step L_{k-1} :

If $|\, yc(k) - yf(k\text{-}1)\, | \le L_{k-1}$
Then $yf(k) = yc(k)$
Else $yf(k) = yf(k\text{-}1) + \text{sign}(yc(k)\text{-}yf(k))\cdot L_{k-1}$

 # Step2: Adapting the band at the current step using the algorithm:

If $|\, yc(k) - yf(k\text{-}1)\, | \le L_{k-1}/2$
Then $J_k = J_{k-1} - J^0$
Else If $L_{k-1}/2 < |\, yc(k) - yf(k\text{-}1)| \le L_{k-1}/2$
Then $J_k = J_{k-1}$
Else $J_k = J_{k-1} + J^0$
End

where:

- $yc(k)$ and $yf(k)$ stand for the unfiltered signal and for the one filtered at k step;
- L_k stands for the band wideness at k step, given by the equation: $L_k = 2^{J_k} \cdot L$, where L is the initial band;
- J_k is the variable that determines the band adaptation law. The modification of this variable is made through the parameter J^0 that modifies the adaptation speed of the L_k band. It can have three values: $J^0 = 1$ for slow adaptation; $J^0 = 2$ for moderate adaptation; $J^0 = 3$ for fast adaptation.

Figure 3 illustrates that using this filter assures a very good filtering of the short parasite impulses and a fast watching of the real variations of the signal; on the contrary the noise of the high and medium frequency is poorly attenuated.

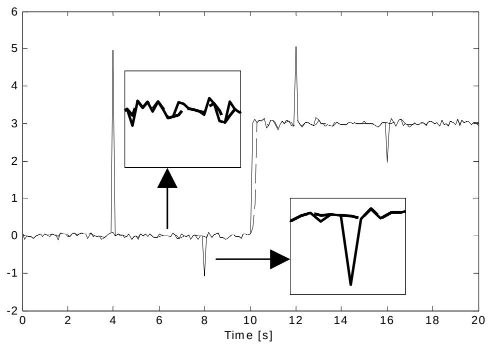

Fig. 3. The result of adaptive band filtering (–*yc*; - -- *yf*)

The FIR non-recursive linear filter of superior order assures a good filtering in the high and medium frequency domain (Figure 4). With respect to Figure 4, obtained after using a 20-degree filter, it is to be noticed that in the cases of the real variations of the signal, the FIR filter dynamics is inferior to the non-linear one with adaptive band and the short parasite impulses have effects that are not to be neglected.

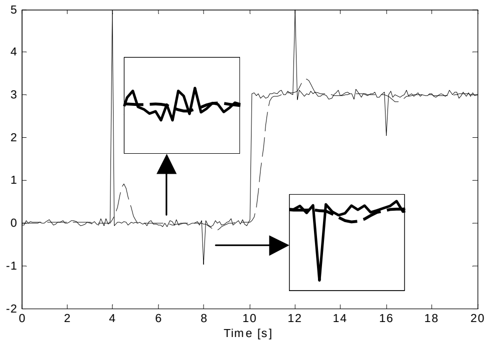

Fig. 4. The result of FIR filtering (–*yc*; - -- *yf*)

Taking into consideration the results obtained by the non-linear and the FIR filters we have used a structure that combines the two filters using fuzzy techniques of Sugeno type. The filtering structure uses the linguistic evaluation of the difference between the unfiltered value at the current moment and the filtered value at the anterior moment. The linguistic evaluation is made using two terms: *Small* and *Big*. *Small* corresponds to the use of FIR non-recursive filter to the filtering of the noise in the high and medium frequency band and *Big* corresponds to the use of adaptive band filter to the filtering of the short parasite impulses and to obtain a fast watching of the real variations of the signal. The membership functions of the fuzzy filter are shown in Figure 5 and the result of the filtering is presented in Figure 6.

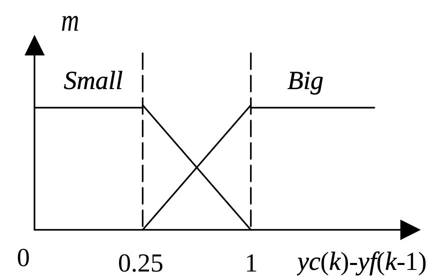

Fig.5. The membership functions of the fuzzy filter

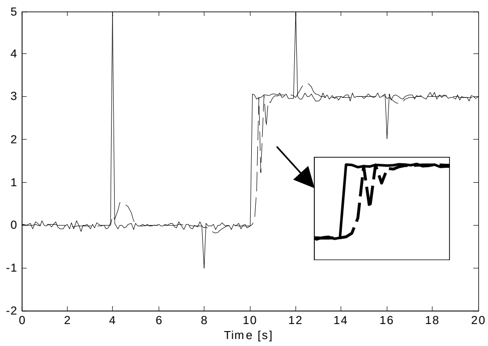

Fig.6. The result of filtering using the fuzzy filter (–*yc*; - -- *yf*)

This result illustrates the fact that the combined filter has the expected results but there are two important disadvantages:

- the parasite impulses effects though reduced, still exist. This is due to the fact that although at the moment of a parasite impulse occurrence, the filter will pass in the *Big* area, therefore filtering is with adaptive band, at future moments, by reducing the difference $yc(k)$-$yf(k$-1), the filter will pass in the *Small* area and the fuzzy filter output will be the FIR filter output, influenced by the parasite impulses;
- in the case of the modification of the useful signal value, there is an oscillation area. It is due to the variation within large limits of the fuzzy block input $yc(k)$-$yf(k$-1), which involves a fast switch from the FIR filter (whose delay is great and which becomes even greater as the filter degree is bigger) to the non-linear filter (whose delay is small). As the FIR filter degree increases, the oscillations become more important.

In order to avoid these disadvantages, the filtering algorithm was completed as follows:

- when the difference $yc(k)$-$yf(k$-1) is big (an impulse occurs), the input of the FIR filter will be no longer the unfiltered signal but the output of the adaptive band filter;
- to the fuzzy filter output a crisp filter has been added. It will achieve the filtering by the average of the fuzzy filter output at the current moment and the value at the previous moment.

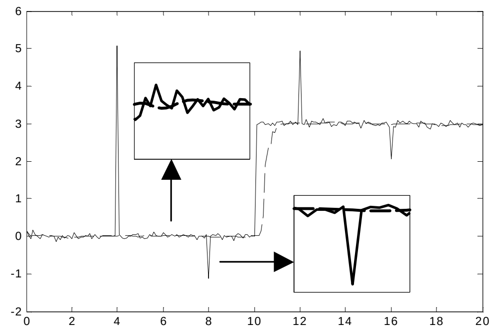

Fig. 7. The result of filtering using the fuzzy filter and the filter through mediation (–*yc*; - -- *yf*)

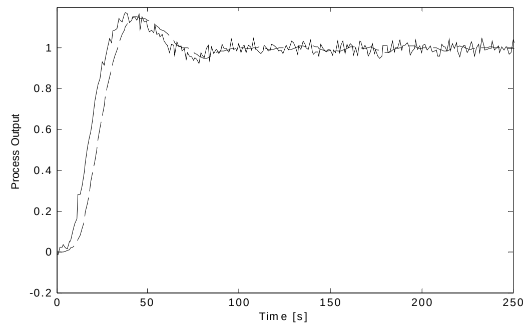

Fig. 8. The filtered output of the process using the filtering combined method (–*yc*; - -- *yf*)

Taking into considerations the modifications mentioned above in the hybrid filter structure, the performance sensibly improves as it is shown in Figure 7. The result of the filtering for a closed loop response of a process is presented in Figure 8. As it is shown, the filtering result is very good, the only problem being the delay between the filtered signal and the real one. But it does not affect the self-tuning procedures as they take place off-line.

III. Extracting Synthetical Properties

The preliminary regime of the on-off control allows the determination of some points on the Nyquist characteristic of the process provided with integrator. These points are theoretically placed at the cross between the Nyquist characteristic and the reversed negative transfer function of the relay. The coordinates of the intersection points are given by the equations:

$$\mathrm{Re}\, N_i(A) = -\frac{p\,A}{4d}\left(\sqrt{1-(e/A)^2}\right) \tag{2}$$

$$\mathrm{Im}\, N_i(A) = -\frac{pe}{4d} \tag{3}$$

where A stands for the magnitude of the forced oscillations assumed sinuous, d – the command magnitude of the relay and e – its hysteresis. According to the tuning method adopted here, it is necessary to determine two points on the Nyquist characteristic of the process. The first one corresponds to the minimum achievable values of the hysteresis. At this level a relative high pulsation of the oscillation is obtained. For the second point, a higher value of the hysteresis is chosen whose limit is imposed by the technological constraints concerning the process output variations. In this case the oscillation pulsation is sensibly reduced.

The calculus of the identified points involves the use of (2) and (3) equations where A is considered to be the sinuous oscillation magnitude obtained at the process output. In fact the oscillations of the controlled variable are not sinuous especially when the point corresponding to the high value of hysteresis is identified. In order to diminish the identification errors a neuronal analysis block of the output oscillation has been introduced whose goal is to extract the first harmonic magnitude. This variable is effectively used in (2). Consequently, "The filtering and synthetic properties extraction" block has the structure shown in Fig. 9.

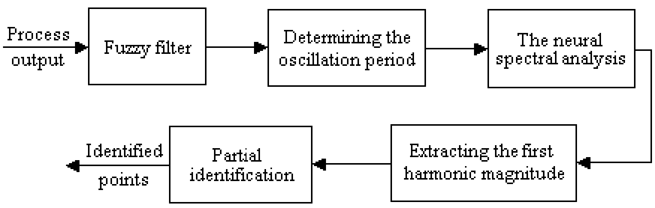

Fig. 9. The structure of the filtering and synthetic properties extraction block

The neuronal spectral analyzer is made using a single-neuron ADALINE model having $2N$ inputs to which trigonometric functions are applied:

$$\{\cos iwt, \sin iwt\} \quad i = \overline{1, N} \tag{4}$$

where the pulsation w is determined using fuzzy filter signal and N is the number of the calculated harmonics (it has been adopted N=25). The output of the ANDALINE is compared to the analyzed signal produced by the fuzzy filter. As a consequence of the training regime, the weights of the linear neuron are represented by the parameters of the trigonometric Fourier series so that it is possible to extract the magnitude of the first harmonic. Figure 10 illustrates the effects of using neuronal spectral analyzer on the identification precision of the two points on the Nyquist characteristic corresponding to 0.1 and 0.5 values of the relay hysteresis.

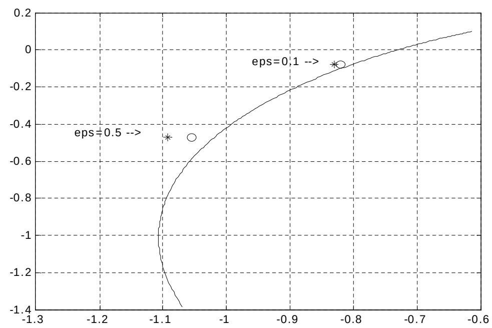

Fig. 10. The influence of the neuronal spectral analyzer on the partial identification of the process frequency characteristic (* - without spectral analyzer, o - with spectral analyzer)

IV. Self-Tuning Algorithm

After partially identifying the frequency characteristic of the process provided with integrator, two points are known: one at an inferior frequency and the other, located near the real axis, at a superior frequency. Further on is presented the tuning procedure of the standardized control law parameters. For a PI controller tuned by assuring the gain margin, the point obtained through identification at a superior frequency will be led to (-0.5+j·0) point by multiplying it by $K_1(1+T_1 s)$ polynomial. Thus the parameters of the controller, K_1 and T_1 are obtained. We have chosen (-0.5+j·0) point because it assures a gain margin of m=20·lg(1/0.5)=6 dB. For a controller tuned by assuring the phase margin, the transfer function is multiplied by the $K_1(1+T_1 s)$ polynomial, the condition imposed for the phase margin being $g = 45^0$ in the identified point.

After introducing the integrator, the processes will have a frequency characteristic similar to that in Figure 11 or 12. For the processes that have a frequency characteristic similar to the one from Figure 11, the imposing of a gain margin does not lead to obtaining a satisfactory phase margin. That is why in the case of these processes it will be used the tuning method based on the phase stability margin, which beyond the margin phase (imposed), will also determine a satisfactory gain margin. For the processes that have a frequency characteristic similar to that in Figure 12, it is to be noticed that the use of the tuning method based on the gain stability margin is to be preferred. Beyond the two cases presented above, there are intermediate situations that can be treated as fuzzy. Thus a fuzzy controller of Sugeno type is built based on a linguistic variable, the angle a, with two linguistic terms, *Small* and

Big. The line that passes trough the two identified points and the abscissa gives the angle a . Figure 13 shows the membership functions of this fuzzy block.

It is to be noticed that the two identified points have different functions:

-the point of superior frequency is used to tune the PI standardized controller based on of the gain or phase stability margin;

-the point of inferior frequency together with the superior one is used to determine the angle a , defined above. This angle is used as input in the tuning fuzzy block.

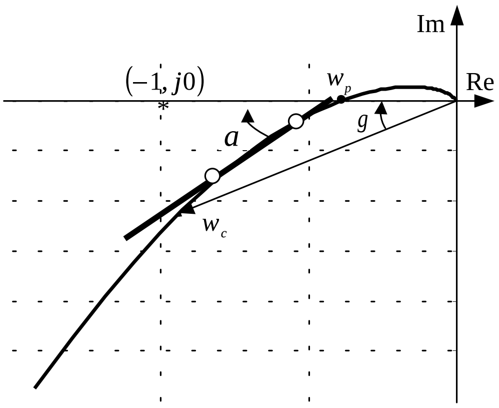

Fig. 11. The case when the phase margin reflects the stability degree

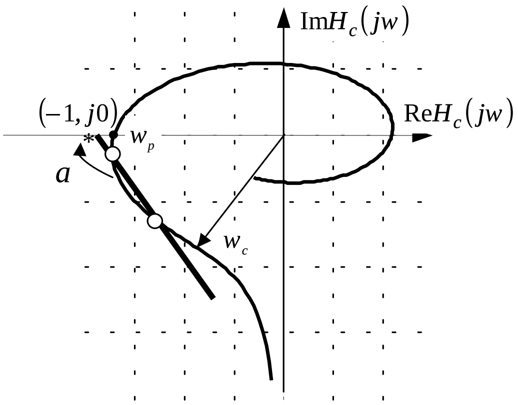

Fig. 12. The case when the gain margin reflects the stability degree

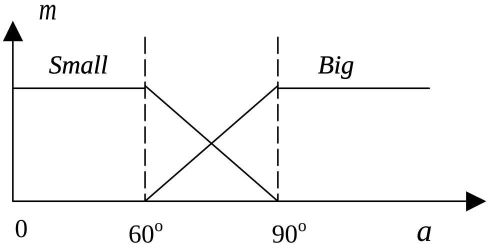

Fig. 13. The membership functions of the tuning fuzzy block

The fuzzy controller output is represented by the tuning parameters of the PI standardized controller used in the control loop:

$$\begin{cases} K_P = K_1 \cdot K_{P1} + K_2 \cdot K_{P2} \\ T_I = K_1 \cdot T_{I1} + K_2 \cdot T_{I2} \end{cases} \quad (5)$$

where K_1 and K_2 are the membership degrees of the a angle to the two linguistic variables; K_{P1}, T_{I1} and K_{P2}, T_{I2} stand for the parameters obtained through the two tuning methods based on phase stability margin and respectively the gain stability margin.

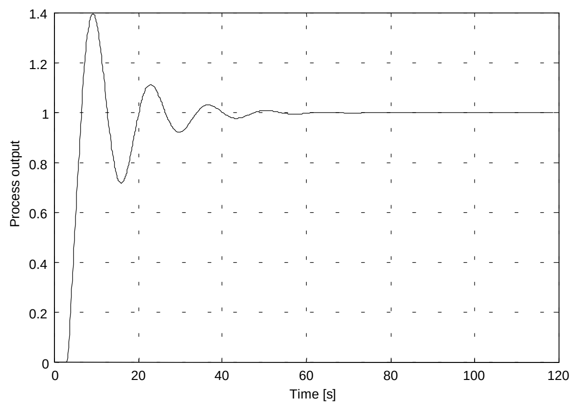

Fig. 14. The response of the process with PI controller tuned on the basis of the gain stability margin

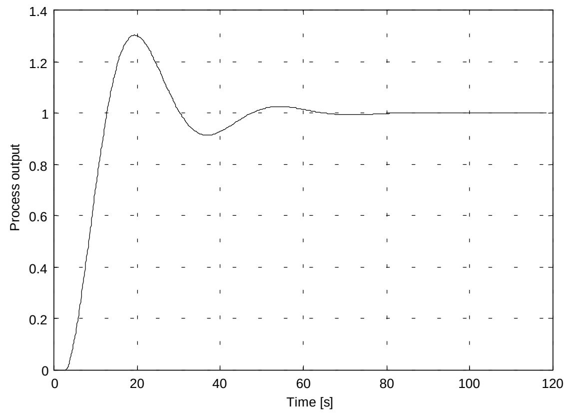

Fig. 15. The response of the process with PI controller tuned on the basis of the phase stability margin

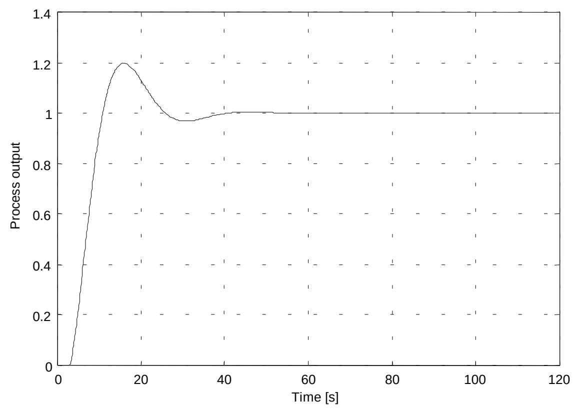

Fig. 16. The response of the process with PI controller tuned on the basis of the fuzzy block

Example: Let's consider the transfer function:

$$H(s) = \frac{5}{(4s+1)(11s+1)} e^{-2s} \tag{6}$$

Figures 14, 15 and 16 show the response of the process closed loop with PI controller tuned based on the gain stability margin, the phase stability margin and the fuzzy block designed in this section.

V. CONCLUSIONS

The paper deals with the problems of the output signal filtering of the process, as well as the processing of this signal in order to partially identify the process frequency characteristic. The quality of the information given by the synthetic properties extraction block has a great influence on the self-tuning quality. It depends on the filtering quality of the output signal.

In the synthetic properties extraction block, two points belonging to the frequency characteristic of the process provided with integrator are identified:

- the point of superior frequency is used in tuning of the PI standardized controller
- the point of inferior frequency together with the superior one is used to determine the input of the tuning fuzzy block of Sugeno type.

REFERENCES

[1] Astrom, K. J., Hagglund, T., Hang, C. C., "Automatic Tuning and Adaptation for PID Controllers - a Survey", *Control Engineering Practice*, vol.1, pag. 699 -714, 1993

[2] Astrom K.J., Ljung L., Wittenberg B., "Theory and application of self-tuning regulators", *Automatica*, vol.13, pag. 457-476, 1977

[3] Astrom K.J., Hagglund T., "Automatic tuning of simple regulators with specifications on phase and amplitude margins", *Automatica*, vol.20, pag. 645-651, 1984

[4] Călin, S., Dumitrache, I., Nitu, C., Munteanu, Fl., Iorga, V., Dumitriu, S., "Digital Control of Technologic Process", Technical Editure Tehnică, Bucharest, 1984

[5] Hagglund, T., Astrom K.J., "Automatic Tuning of PID Controllers", The Control Handbook , CRC Press, pag. 817-826, 1996

[6] Kaiser, J.F., "Digital filters: systems analysis by digital computer", John Wiley, 1966

[7] Kraus, T. W., Myron, T. J., "Self tuning PID controller uses pattern recognition approach", *Control Engineering*, pag. 106–111, 1984

[8] Leva, A., Maffezzoni, C., Scattolini, R., "Self tuning PI-PID regulators for stable systems with varying delay", *Automatica*, vol.30, pag. 1171-1183, 1994.

[9] Scheid F., "Theory and Problems of Numerical Analysis", McGraw-Hill Book Company, New York, 1968

[10] Schonberger F., "PID auto-tuning algorithm based on frequency response tehniques", Prep. Of 3rd International Symposium on Methods and Models in Automation and Robotics, vol.2, pag.551-556, Polonia, 1996

[11] Schonberger F, " Techniques and Methods of the Numerical Control Algorithms of Processes", PhD Thesis, Iasi, Romania, 1998

[12] Seem J.E., "A new Pattern recognition Adaptive Control with Application to HVAC Systems", *Automatica* vol.34, pag. 969-982, 1998