Comparison of tuning procedures based on evolutionary algorithm for multi-region fuzzy-logic PID controller for non-linear plant

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***Abstract*—The paper presents a comparison of tuning procedures for a multi-region fuzzy-logic controller used for non-linear process control. This controller is composed of local PID controllers and fuzzy-logic mechanism that aggregates local control signals. Three off-line tuning procedures are presented. The first one focuses on separate tuning of local PID controllers gains in the case when the parameters of membership functions of fuzzy-logic mechanism are know a priori. The second one consists of two major steps. In the first step, the local PID controllers gains are calibrated and in the next step the parameters of membership functions of fuzzy-logic mechanism are tuned. The third one focuses on tuning of PID controllers gains and membership functions parameters jointly. These procedures exploit evolutionary algorithm to optimize the performance of the multi-region fuzzy-logic controller with respect to integral quality criterion such as Integral Absolute Error (IAE). Effectiveness of these procedures is verified based on a well known from literature continuous non-linear pH neutralization reactor model. For comparison a single PID controller tuned for specific work point is also taken into account.**

I. Introduction

In industrial processes in most cases a classical approach of linear PID controller is used. PID controllers are simple and their algorithm nowadays is implemented in almost every platform of digital control like Programmable Logic Controllers or Programmable Automation Controllers. The main drawback of PID control is narrow operation range. In most cases PID controllers are designed to work in specific working points with minimal deviation.

However, when wider operation range is taken into consideration, the classical PID controller is not sufficient enough to maintain acceptable control quality. The field of non-linear control have been widely explored by different types of algorithms and procedures. Commonly used method to manage non-linear plants is to extend the classical linear PID control algorithm by modification of its structure to achieve non-linear PID controller as presented in [1]–[3]. Another method that utilizes PID control and widens its operation range when controlling non-linear plant is gain scheduling control as presented in [4]–[9]. Well known method that can deal with non-linearities of the controlled plant is fuzzy logic control. Fuzzy logic controller can directly manage non-linear plants due to its non-linear behavior and utilization of fuzzy logic and its operators. Applications of fuzzy logic in non-linear control are presented in [10]–[15]. Another methods presented in [16], [17] utilize multi-region controllers of PI type. The issue of stability of such controller was presented in [17]. All of those methods mentioned above need special procedures to tune or optimize their parameters. Examples of those procedures like evolution and genetic algorithms, ant colony optimization algorithms and particle swarm optimization are presented in [2], [6], [18], [19].

Multi-region fuzzy-logic controller with local PID controllers [10]–[17], presented in this paper allows accommodation to system non-linearities in wide range of working point changes. Tuning of parameters for this kind of controller is not a trivial task. In the paper three tuning methods based on appropriate optimization procedures are compared. Mentioned controller consists of several local PID controllers, in most cases tuned for specific working points of non-linear plant, based on the non-linear or linearised mathematical models of that process. Local controllers work jointly and generate separate control signals. From these local signals, global control signal for the process is derived based on the fuzzy-logic mechanism.

The number of local PID controllers taken into consideration is strongly related with the non-linearity of the controlled process. The number of local PID controllers increase with the process non-linear complexity. When new local controller is added, the number of parameters of multi-regional controller increases also. The rising number of local PID controllers entails increase in the number of membership functions and their parameters in the fuzzy-logic part of the controller and increase in number of local PID gains.

When we have to deal with large number of parameters to tune, commonly used methods like trial end error or engineering methods are inadequate. The proper tuning of large number of parameters needs a consistent procedure. With the use of the appropriate optimization method and suitable performance criterion the satisfactory control quality in a wide operation range with multi-region controller may be achieved. Most commonly used performance criteria for optimization of the gains of PID controllers are, so called, integral quality criteria like: Integral Squared Error (ISE), Integral Absolute Error (IAE) or Integral Time Absolute Error (ITAE).

Space of feasible solutions was explored by the evolutionary algorithm. It's a popular and effective optimization

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algorithm that can deal with large numbers of variables and can take into consideration linear and non-linear constraints. Proper parametrization and implementation of this algorithm may lead to fast and converging solutions.The paper presents three approaches to the problem of off-line tuning of the multi-region fuzzy-logic controller.

The first one focuses on tuning of local controllers. Each controller is tuned, one after another, to a priori selected working points of non-linear process. When optimal gains are known then the membership functions of fuzzy-logic aggregation block are selected and shaped on the basis of static characteristic and user knowledge. In this method only the parameters of local PID controllers are optimized.

The second tuning procedure consist of two major steps. In the first step, the local PID controllers gains are optimized. This step is similar to the first tuning procedure. In the next step, all parameters of membership functions of fuzzy-logic mechanism are optimized according to the performance criteria and the reference trajectory.

The third method focuses on off-line optimization of both the parameters of local PID controllers and parameters of membership functions at the same time. Shapes of membership functions are chosen by the user. In this method static characteristic is only needed to select the right number of local controllers.

These three methods of tuning mentioned above are compared with one another and also with single PID controller tuned up for one specific operation point.

II. Model of continuous non-linear pH neutralization reactor

Due to its strong non-linear behaviour the continuous *pH* neutralization reaction is considered. Based on that *pH* process, proposed in the paper tuning procedures of the multi-region fuzzy-logic controller are evaluated. The process of *pH* neutralization is presented in Fig. 1. It has two influents, one is a stream of strong acid – HCl, represented as $F_{a,in}$, and second is a stream of strong base – NaOH, represented as $F_{b,in}$. The chemical reaction in the tank is described as [20]:

$$H^+Cl^- + Na^+OH^- \longrightarrow Na^+Cl^- + H_2O \tag{1}$$

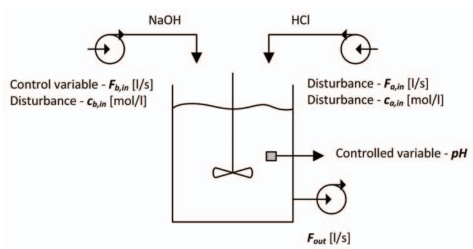

Fig. 1. Continous pH neutralization reactor

The input to the process (control variable) is the flow of base stream $F_{b,in}$. The output from the process is pH reaction (controlled variable). It is assumed that the level control of the reactor is perfect and the base and acid are mixed perfectly. The acid concentration $c_{a,in}$, flow of acid $F_{a,in}$ and base concentration $c_{b,in}$ are assumed to be disturbances of the process.

A. Non-linear model

The mathematical model of the *pH* neutralization reactor is described as follows. Equation (2) represents the equilibrium of mass flow rates (constant level of acid and base mixture).

$$F_{a,in} + F_{b,in} = F_{out} \tag{2}$$

Equation (3) represents the change in mole concentration of $[Na^+]$ ions.

$$\frac{d[Na^+]}{dt} = \frac{1}{V}(F_{b,in}[OH^-]_{in} - F_{out}[Na^+]) \tag{3}$$

Equation (4) represents the change in mole concentration of $[Cl^-]$ ions.

$$\frac{d[Cl^-]}{dt} = \frac{1}{V}(F_{a,in}[Cl^-]_{in} - F_{out}[Cl^-]) \tag{4}$$

Equation (5) is the ion multiplication of water involving equilibrium constant K_{eq} at 25 $°C$.

$$[H^+][OH^-] = K_{eq} = 10^{-14} \tag{5}$$

Equation (6) describes the electro-neutrality.

$$[Na^+] + [H^+] = [Cl^-] + [OH^-] \tag{6}$$

Substituting $[OH^-]$ from (5) to (6) we get concentration of $[H^+]$ ions.

$$\begin{aligned}[H^+] = & \frac{-([Na^+] - [Cl^-])}{2} + \\ & + \frac{\sqrt{([Na^+] - [Cl^-])^2 + 4K_{eq}}}{2}\end{aligned} \tag{7}$$

Finally from (8) we get pH reaction of the process.

$$[pH] = -\log_{10}([H^+]) \tag{8}$$

Parameters of the *pH* neutralization reactor model are presented in Table I.

TABLE I. Parameters of the pH neutralization reactor model

Acid flow rate	$F_{a,in}$	20 [l/s]
Acid concentration	$c_{a,in} = [Cl^-]_{in}$	0.2 [mol/l]
Base concentration	$c_{b,in} = [OH^-]_{in}$	1 [mol/l]
Reactor volume	V	10^4 [l]
Maximum base flow rate	$F_{b,in,max}$	100 [l/s]
Initial pH value	$pH(t=0)$	1

It is assumed that the pump of the base is modelled with first order transfer function (9) and saturation, where the parameters of the transfer function are $T = 0.5\,[s]$, $k = 1$ and saturation parameters are $F_{b,in,min} = 0$ and $F_{b,in,max} = 100$ [l/s].

$$G_p(s) = \frac{k}{1 + sT} \tag{9}$$

Static characteristic of the continuous *pH* neutralization rector model is presented in Fig. 2. Also in this figure the considered operation regions are presented. Those regions will be used to obtain linear models of *pH* reactor.

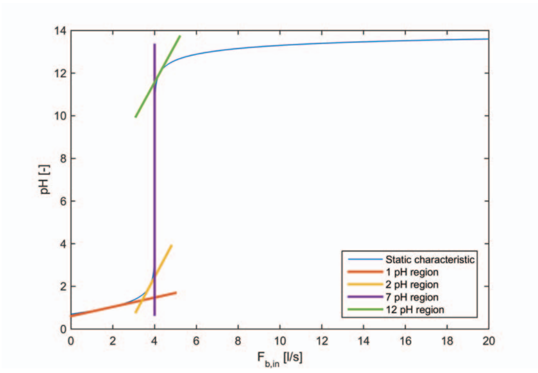

Fig. 2. Static characteristic of the continuous pH neutralization rector model

B. Linear models

Linear models were derived from non-linear model (2-8) via linearisation in selected working points. Those models are described as transfer function (10) with appropriate parameters that are summarized in Table II. Linear models were used to tune local PID controllers in the first and the second procedure.

$$\frac{\Delta pH}{\Delta F_{b,in}} = z(h_1 \frac{a_1}{s + b_1} + h_2 \frac{a_2}{s + b_2}) \tag{10}$$

TABLE II. PARAMETERS OF LINEAR PH PROCESS MODELS

	1 pH	**2 pH**	**7 pH**	**12pH**
a_1	9.1667e-05	8.4167e-05	8.3333e-05	8.2500e-05
a_2	-1.8333e-05	-1.6833e-05	-1.6667e-05	-1.6500e-05
b_1	0.0022	0.0024	0.0024	0.0024
b_2	0.0022	0.0024	0.0024	0.0024
h_1	1	1	0.5	9.9995e-11
h_2	-1	-1	-0.5	-9.9995e-11
z	4.3429	43.4294	4342900	4.3430e+11

It is assumed that the operation point of the linear models will be related to 5% of the relative error between the non-linear and linear model output (*pH*).

III. RESEARCH METHOD

The optimal tuning of multi-region fuzzy-logic PID controller is complex because of high number of parameters/variables. Parameters of this controller are divided into two groups. One group contains parameters of local PID controllers and the second group contains the parameters of membership functions of the fuzzy logic part.

Introduction doesn't show an appropriate method for off-line optimal tuning of the multi-regional PID controller. For the off-line tuning procedure it is important that the controlled process parameters shouldn't change abruptly. When the parameters change slowly over time the operator can start the off-line tuning procedure again to rearrange multi-region PID parameters. A broad knowledge (e.g. model of the plant) of the controlled plant is needed for off-line tuning procedures to achieve acceptable results.

The objectives of this work should answer the question which of the presented in the paper approach delivers better performance of multi-region fuzzy-logic PID controller for non-linear plant feedback control. All presented tuning procedures are based on evolutionary algorithm. All procedures utilizes the IAE integral quality criterion.

The first procedure finds the minimum of IAE performance index only for each local PID controller with respect to optimal parameters values. The linearised models, presented in subsection (II-B) are used. Parameters of membership functions are known a priori and are constant during optimization.

The second method optimizes PID and membership functions parameters separately in two steps. First step is similar to the first procedure. Second step optimizes membership functions of the fuzzy-logic part of the controller with respect to IAE criterion as well. Those functions must compromise specified constraints:

1) all elements from the universe of discourse must be mapped by membership function,
2) shapes of the proposed functions must be preserved,
3) boundaries of the membership functions must not overlap with the core of other, functions.
4) core of each membership function must at least partially cover the operation range of the appropriate linear model.

The third method finds the minimum of ISE performance index for the entire multi-region controller (PID gains and parameters of membership functions) for specified reference trajectory that passes through all considered operation points. The third method utilize non-linear model of the plant and constraints 1, 2 and 3 presented above for membership functions.

The main contribution of this work is introduction and comparison of three different procedures for off-line tuning of multi-regional PID controller. Those procedures has been implemented on widely used fast prototyping software – Matlab/Simulink 2014b [21] and then validated by analysis of obtained results. Validation was carried out with the non-linear *pH* neutralization reactor model presented in section II.

IV. SOLUTION

A. pH control structure – modelling and implementation

The principal of operation of multi-region fuzzy-logic PID controller is presented in Fig. 3

Fuzzy logic rule base is as follows:
IF LV is $\tilde{A}_{I1,1}$ THEN $u = K_{p1}e_p + K_{i1}e_i + K_{d1}e_d$
IF LV is $\tilde{A}_{I1,2}$ THEN $u = K_{p2}e_p + K_{i2}e_i + K_{d2}e_d$
IF LV is $\tilde{A}_{I1,3}$ THEN $u = K_{p3}e_p + K_{i3}e_i + K_{d3}e_d$

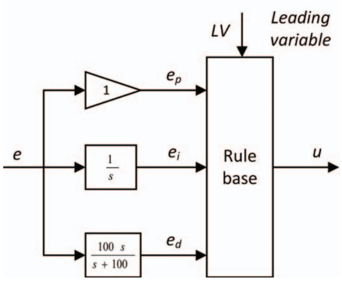

Fig. 3. Mulit-region fuzzy-logic PID controller

IF LV is $\tilde{A}_{I1,4}$ THEN $u = K_{p4}e_p + K_{i4}e_i + K_{d4}e_d$

where: LV is leading variable, $\tilde{A}$ are membership functions and K_p, K_i, K_d are local PID controllers gains. All optimization procedures presented bellow utilize Z-shape, π-shape and S-shape membership functions [13], [21].

Global control signal from the controller u after defuzzification is computed as (11):

$$u = \frac{\sum_{j=1}^{4} \mu_j(LV, \tilde{A}_{I1,j})(K_{pj}e_p + K_{ij}e_i + K_{dj}e_d)}{\sum_{j=1}^{4} \mu_j(LV, \tilde{A}_{I1,j})} \tag{11}$$

where: μ_j is membership for rule consequent.

Final *pH* control structure is presented in Fig.4.

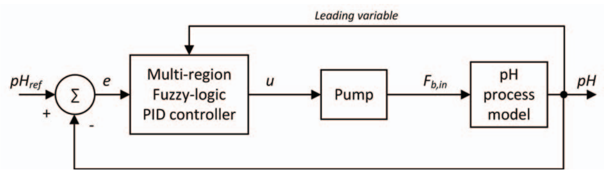

Fig. 4. *pH* neutralization control system

Where pH_{ref} is reference *pH* trajectory, *e* is control error, *u* is control signal and $F_{b,in}$ is base flow rate.

B. First optimization procedure

Optimization task of the first procedure is specified by

$$\min_{\mathbf{x_I}} f(\mathbf{x_I}) \quad such\ that \quad \mathbf{lb_I} \leq \mathbf{x_I} \tag{12}$$

where $\mathbf{x_I} = [k_p\ k_i\ k_d]^T$ is the vector of local PID controller gains, $\mathbf{lb_I} = [0\ 0\ 0]^T$ is the vector of lower bounds, and $f(\mathbf{x_I})$ is defined as:

$$f(\mathbf{x}) = \int_0^{T_{ss}} |e(\mathbf{x})| dt \tag{13}$$

where $\mathbf{x}$ is decision variables vector and T_{ss} is estimated time to reach steady state.

The first optimization procedure, based on evolutionary algorithm, utilizes linear models of the *pH* reactor in vicinity of four predefined working points to derive optimal parameters for local PID controllers with respect to performance index (13) and 5% *pH* step increase from working point. Notice, that the membership functions in this procedure are chosen a priori. Those functions have significant impact on the optimization results with (13). Those functions has been chosen with the following conditions: core of each membership function covers *pH* operation range of the linear models, sum of the membership functions equals one.

C. Second optimization procedure

Optimization task of the second procedure is very similar to the first procedure. The main difference is that optimization task firstly finds the optimum parameters of the local PID controllers with respect to (12) and (13). In the second step defined by (14) optimization task, analogous to (12) with different constraints and decision variables vector structure, is solved. This vector contains only parameters of membership functions. Second step of this optimization procedure also needs a well defined reference trajectory that transits through all desired operation points.

$$\begin{gathered} \min_{\mathbf{x_{II}}} f(\mathbf{x_{II}}) \quad such\ that \\ \mathbf{lb_{II}} \leq \mathbf{x_{II}} \leq \mathbf{ub_{II}} \quad and \quad \mathbf{A_{II}x_{II}} \leq \mathbf{b_{II}} \end{gathered} \tag{14}$$

Constraints for the vector $\mathbf{x_{II}}$ and description of his elements are presented in Tab.III. Linear inequality constraints are presented in Tab. IV.

TABLE III. **LB**, **UB** AND DESCRIPTION OF **X** VECTOR OF SECOND OPTIMIZATION TASK

Param.	$\mathbf{lb_{II}}$	$\mathbf{ub_{II}}$	Description
$x_{II,1}$	0	1.211	Left point of Z–shaped MF 1pH
$x_{II,2}$	0	14	Right point of Z–shaped MF 1pH
$x_{II,3}$	0	14	Left base point of π–shaped MF 2pH
$x_{II,4}$	1.656	14	Left top point of π–shaped MF 2pH
$x_{II,5}$	0	2.245	Right top point of π–shaped MF 2pH
$x_{II,6}$	0	14	Right base point of π–shaped MF 2pH
$x_{II,7}$	0	14	Left base point of π–shaped MF 7pH
$x_{II,8}$	6.003	14	Left top point of π–shaped MF 7pH
$x_{II,9}$	0	8.111	Right base point of π–shaped MF 7pH
$x_{II,10}$	0	14	Right base point of π–shaped MF 7pH
$x_{II,11}$	0	14	Left point of S–shaped MF 12pH
$x_{II,12}$	11.62	14	Right point of S–shaped MF 12pH

TABLE IV. LINEAR INEQUALITY CONSTRAINTS FOR SECOND AND THIRD OPTIMIZATION PROCEDURE (.)

Shape	Core overlap	Boundaries
$x_{(.),1} \leq x_{(.),2}$	$x_{(.),2} \leq x_{(.),4}$	$x_{(.),3} \leq x_{(.),2}$
$x_{(.),3} \leq x_{(.),4}$	$x_{(.),1} \leq x_{(.),3}$	$x_{(.),7} \leq x_{(.),6}$
$x_{(.),4} \leq x_{(.),5}$	$x_{(.),5} \leq x_{(.),7}$	$x_{(.),11} \leq x_{(.),10}$
$x_{(.),5} \leq x_{(.),6}$	$x_{(.),6} \leq x_{(.),8}$	
$x_{(.),7} \leq x_{(.),8}$	$x_{(.),9} \leq x_{(.),11}$	
$x_{(.),8} \leq x_{(.),9}$	$x_{(.),10} \leq x_{(.),12}$	
$x_{(.),9} \leq x_{(.),10}$		
$x_{(.),11} \leq x_{(.),12}$		

D. Third optimization procedure

Third procedure for the multi-regional PID controller finds optimal parameters in a single optimization task. This procedure is analogous to (14) with differences in $\mathbf{x_{III}}$, $\mathbf{lb_{III}}$ and $\mathbf{ub_{III}}$ vectors. Vectors $\mathbf{lb_{III}}$, $\mathbf{ub_{III}}$ and descriptions of elements of vector $\mathbf{x_{III}}$ are presented in Tab.V. Linear inequality constraints related with $\mathbf{A_{III}}$ and $\mathbf{b_{III}}$ vectors are the same as for second optimization procedure (Tab.IV). Third procedure utilizes non-linear model (2-8) rather than several linear models. This approach also needs a well defined reference trajectory as in the second procedure. However dynamics in selected reference trajectory will have influence on the controller performance in verification phase.

TABLE V. LB, UB AND DESCRIPTION OF X VECTOR OF THIRD OPTIMIZATION TASK

Param.	lb	ub	Description
$x_{III,1}$	0	14	Left point of Z–shaped MF 1pH
$x_{III,2}$	0	14	Right point of Z–shaped MF 1pH
$x_{III,3}$	0	14	Left base point of π–shaped MF 2pH
$x_{III,4}$	0	14	Left top point of π–shaped MF 2pH
$x_{III,5}$	0	14	Right top point of π–shaped MF 2pH
$x_{III,6}$	0	14	Right base point of π–shaped MF 2pH
$x_{III,7}$	0	14	Left base point of π–shaped MF 7pH
$x_{III,8}$	0	14	Left top point of π–shaped MF 7pH
$x_{III,9}$	0	14	Right base point of π–shaped MF 7pH
$x_{III,10}$	0	14	Right base point of π–shaped MF 7pH
$x_{III,11}$	0	14	Left point of S–shaped MF 12pH
$x_{III,12}$	0	14	Right point of S–shaped MF 12pH
$x_{III,13}$	0	-	Proportional gain of PID 1pH
$x_{III,14}$	0	-	Integral gain of PID 1pH
$x_{III,15}$	0	-	Derivative gain of PID 1pH
$x_{III,16}$	0	-	Proportional gain of PID 2pH
$x_{III,17}$	0	-	Integral gain of PID 2pH
$x_{III,18}$	0	-	Derivative gain of PID 2pH
$x_{III,19}$	0	-	Proportional gain of PID 7pH
$x_{III,20}$	0	-	Integral gain of PID 7pH
$x_{III,21}$	0	-	Derivative gain of PID 7pH
$x_{III,22}$	0	-	Proportional gain of PID 12pH
$x_{III,23}$	0	-	Integral gain of PID 12pH
$x_{III,24}$	0	-	Derivative gain of PID 12pH

V. Simulation Results

To compare optimization procedures three different tracking scenarios were performed. Those scenarios included comparison with single PID controller tuned for 7 *pH* working point. First scenario was related with the stepwise reference trajectory. That scenario was used in second and third optimization procedure. Second and third scenario are based on the sinusoid reference trajectory with different frequencies. All simulation results, including IAE outcome, with these scenarios are presented in Fig.5 – 7. Shapes of membership functions that were used/derived in the optimization procedures are presented in Fig.8. Membership functions of the second and third procedure are the result of appropriate optimization procedures. They fulfil constraints presented in Tab.III and Tab.V respectively.

It can be seen that the multi-region fuzzy-logic PID controller, tuned with different methods, can provide better control quality in comparison with single PID controller. Multi-region controller tuned with third method proved to be more accurate in tracking the reference *pH* trajectory in first and second scenario. Third procedure is the best choice when we have to deal with tuning of the parameters for specified trajectory. However, in the case of reference trajectory with altered dynamics (Fig. 6, 7) it is necessary to take it into account in optimization procedure. In third scenario controller tuned with the third procedure had inferior performance index (Fig. 7). On the other hand the control signal is smoother in the case of second procedure, but control signal effort is smaller in the case of third procedure.

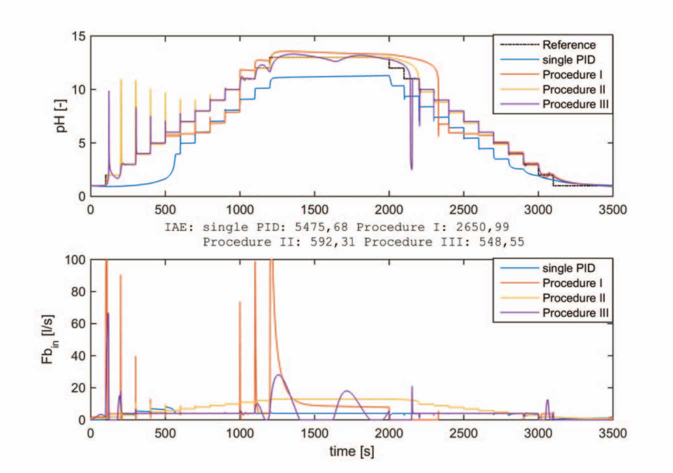

Fig. 5. Stepwise trajectory tracking scenario, *pH* value, control signal – $F_{b,in}$ and IAE scores.

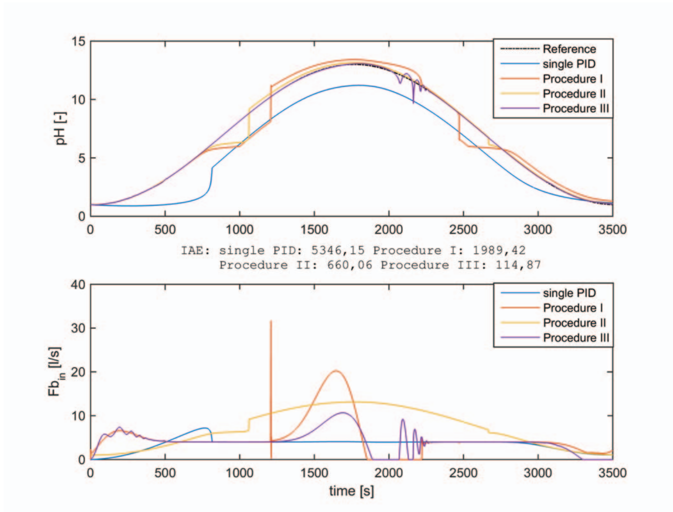

Fig. 6. Sinusoid trajectory tracking scenario, *pH* value, control signal – $F_{b,in}$ and IAE scores.

Multi region fuzzy-logic PID controller tuned with all presented procedures had problems with keeping up with reference trajectory when the *pH* value was going down. It is closely related with the control strategy – constant medium level in the reactor (2).

VI. Conclusions

This paper showed that in the field of non-linear feedback control the multi-region fuzzy logic PID controller can be a promising algorithm. The main advantage of this controller is simplicity. Another advantage is the expandability of the commonly known classical PID controller in a simple manner. However, it still need computational effort to solve optimization tasks. In this paper three methods of tuning multi-region controller were compared. The first one focuses on separate tuning of local PID controllers gains. The second one tunes the parameters of local PID controllers and membership functions in two major steps. The third one focuses on tuning of PID controllers gains and membership functions parameters jointly. Comparison were preformed with different trajectory tracking

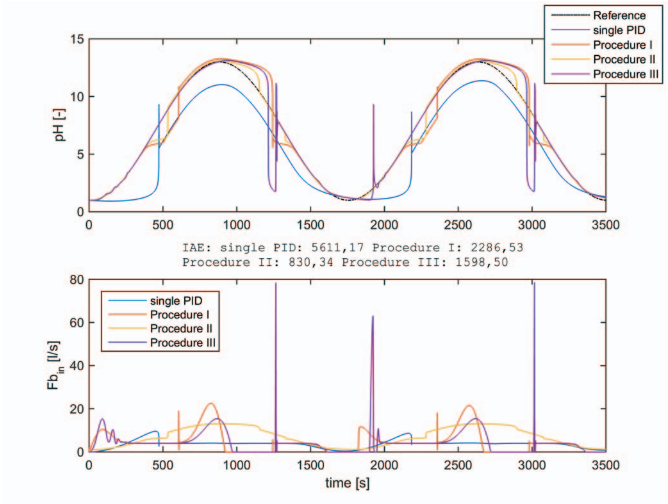

Fig. 7. Sinusoid with doubled frequency trajectory tracking scenario, *pH* value, control signal – $F_{b,in}$ and IAE scores.

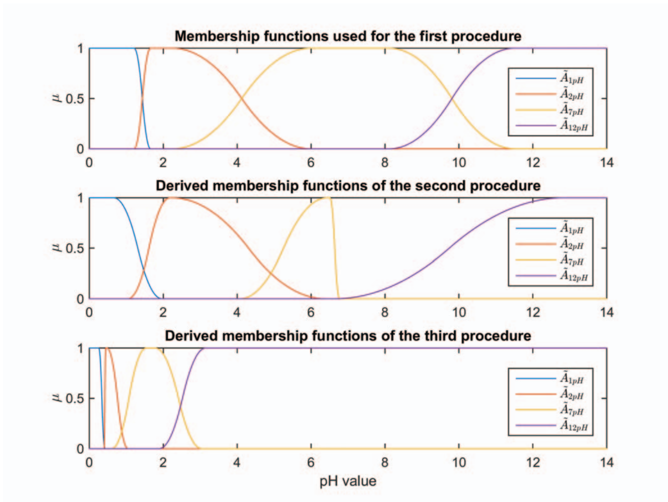

Fig. 8. Shapes of membership functions used/derived in optimization procedures

scenarios. Result show that when we consider well known trajectory the third procedure is the best choice. But when the dynamics of the reference trajectory is unknown then we have to choose between the second and the third of the presented methods. Variations of common methods presented in [2], [6], [19] focus on tuning of PID controller parameters only. Method presented in [18] is vary similar to third method described in this paper. It takes into account all controller parameters in the one optimization procedure, but used by authors neuro-fuzzy controller is more complex and has more parameters to optimize.

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