Design and Investigation of Adaptive Fuzzy Level Control System for Carbonisation Column

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Abstract—**The aim of this research is the design of PID Sugeno fuzzy logic controller (FLC) for the control of level in carbonisation column for the production of soda ash, without using a model of the process and with online fuzzy adaptation of its parameters. The controller is developed on the basis of a PD FLC with inputs the system error and its derivative, a parallel integrator of error and a Sugeno module for online tuning of the parameters according to the measured level or its reference. The adaptive FLC is implemented in a programmable logic controller for real time control. The closed loop system is investigated by experiments in industrial environment and an operating carbonisation column. The designed system reduces the mean squared error and the control variance. It also compensates the industrial disturbances and the changes in the process, and prolongs the life of the final control elements.**

Index Terms — **Fuzzy control, Level control, Adaptive systems, Takagi-Sugeno model, Control design.**

I. INTRODUCTION

Level control systems are among the widest spread in the process industry. In number of cases, there are difficulties with control because of plant nonlinearity. That is why researchers look for new and better control strategies compared to the classic PID controller. Most of the researches focus on fuzzy logic controllers (FLC). The reason is that they are relatively easily designed nonlinear controllers that provide robustness and good control performance. FLC are suitable to control plants that are nonlinear, complex, with variables coupling, time variant, with uncertainties and disturbances [1]. They can be designed on the basis of empirical knowledge without a model of the process - Mamdani and Sugeno FLC and on the basis a derived Takagi-Sugeno-Kang (TSK) plant model - FLC with parallel distributed compensation (PDC) [1]. The main shortcomings of the FLC are the translation of expertise into "IF-THEN" rules, the subjectivity in its presentation and the difficulties with the implementation in industrial conditions at the presence of noise and disturbances and limited resources of the programmable logic controllers (PLC) used.

In [2] some of the most popular structures of FLC are analyzed. They are based on PD FLC with a fuzzy unit (FU) with inputs - the system error e and its derivative de. The error is computed as $e = H_r - H$ where H is the measured level and H_r is the reference. The inputs are often normalized by scale factors.

In the first structure a PD FLC with a parallel linear integrator (I) of the error is suggested, resulting in PID (PD + I) FLC. In the second variant, the FU output of the PD FLC is integrated to obtain a PI FLC, and then its output is summed with $K_d.de$ (K_d is the differentiator scaling factor) to result in a PID (PI + D) FLC. The third option is a combination of the previous to obtain a fuzzy PID (PI + PD). The three structures of FLC are designed and investigated to control the tank level through simulations in MATLAB™. The best control system performance of the nonlinear plant is reported for the (PI + PD) FLC.

In [3] PD, PI and PID FLC are described and the Han-Xiong Li methodology for their tuning is investigated. The two-input FU is used. After the FU, there is post-processing in the structure of the controller to obtain the three variants of FLC. The conventional PI and PID controllers are compared with PI FLC and PID FLC. The parameters of the conventional PI and PID are defined for instanced linear plants of first, second and higher order with and without delay. From the research through simulation in MATLAB™/SIMULINK have determined improvement of the performance indicators of the transient processes in the both FLC.

In [4] a PI FLC is developed for level control. A laboratory trainer of two tanks is used. The PI FLC has two inputs "Level" and "Reference" for one of the tanks, and its output controls a booster pump. The control algorithm is developed in the LabVIEW environment and the real time experiments show good control performance at different operating points despite the nonlinearity of the controlled level.

When the operating conditions, the characteristics of the technological process, the nature of the disturbances and so on is changed, the performance indicators of the closed loop system can be worsen significantly [5]. One way to deal with this problem is to use adaptive systems. In [6] an adaptive FLC (AFLC) for level control in the second tank on a laboratory setup with two-tank system is studied. The AFLC structure is a classical linear PID. Its parameters Kp (P part), Ki (I) and Kd (D) are adaptively tuned by the three outputs of a FU with two inputs - the error and its derivative. For comparison aim a linear PID controller is tuned by the Ziegler-Nichols method for a linearized mathematical model of the plant. The efficiencies of AFLC and classical PID are compared by Integral Absolute Error computed from experiments. For the AFLC, the three parameters values are changed in the interval between 0 and the optimum, which explains why its performance indicators are inferior to the classical PID.

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In [7] a PI AFLC is designed for level control in a couple tank system. In parallel with the classical linear PI there is a PD FLC with two outputs, which are summed respectively with the signals from the proportional and integral components of the PI controller. The parameters of the PI controller are assigned by the Ziegler-Nichols method. It is shown by simulation in MATLAB™/SIMULINK and by experiments that the performance indicators of the step responses of the system with PI AFLC are better than the linear PI.

An adaptive PID (APID) and a PD AFLC, which consists of a FU with two inputs, are compared in [8] when they control the level in a laboratory tank. The nonlinear static characteristic of the level is divided into 4 linearized zones. The computed for each zone parameters of the APID, membership functions (MF) and rules of the PD AFLC are switched over by the measured level or by the reference. The conducted experiments is evaluated based on 4 performance indicators and most of them are better for PD AFLC. The main problems are the abrupt change of the parameters, the MF and the rules of the PD AFLC when moving from one zone to another due to the fixed crisp linear sections.

A common shortcoming of the approaches presented so far is that there are no industrial applications. Most of the researches are conducted by simulations or experiments on laboratory systems, with little regard to the impact of industrial noise and disturbances. In real manufacturing conditions, there are additional factors that complicate the level control and increase the influence of nonlinearities. Among them are the dependence on the load of the installation, wear, pollution or deposits, the interconnection between the units, for example through common supply collectors and so on.

Moreover, the most of the existing FLC tuning methods are onetime and use difficult and expensive to obtain models of the controlled plant, which do not take into account its changes. In addition, the application of adaptive tuning of the type gain scheduling leads to an abrupt change in the parameters, MF and rules of the controllers, which worsens the performance indicators.

The aim of the present study is to develop a Sugeno PID FLC with fuzzy online parameter tuning without using a plant model in order to improve the performance of the level control in a carbonization column in soda ash production. The PID AFLC should have a simple algorithm that facilitates its implementation in a general purpose PLC for real time control of industrial installation. Besides its design should be easy and accounting the impact of the operation conditions. Its implementation is based on the existing distributed control system (DCS) Experion®PKS (Process Knowledge System) of Honeywell [9], which controls the production process in "Solvay Sodi" SA, Devnya, Bulgaria. The lack of specialized fuzzy logic functions in the DCS requires the FLC to be represented by the available basic logic and arithmetic function blocks.

This paper is organized as follows. In Section 2 the process to be controlled is described. In Section 3 the design of the Sugeno PID AFLC for level control is presented. Section 4 contains the industrial implementation of the developed PID AFLC. The experimental investigations, the assessed indicators of the system performance and the analysis are described in Section 5. In Section 6 the conclusion and the future work are outlined.

II. DESCRIPTION OF THE PLANT TO BE CONTROLLED

The carbonization process in the production of synthetic soda ash [10] is carried out in tower units, called carbonization columns (CCl). They have continuous service, operating on the principle of counter current. The full functional cycle of each CCl consists two modes - operation (settling mode) and washing. In the terms of duration, the ratio is 72 hours to 24 hours or 3:1. The CCl is a vertical cylindrical tower with a height of 28 m, assembled by cylindrical rings with a diameter of 3 m. In the lowest ring there is a hole (so called I input), through which "rich gas" with a concentration of 80-85% CO_2 is entered, and in the middle in height (so called II input) "poor gas" is entered with a concentration of 38-42% CO_2.

The CCl functional diagram is shown in Fig. 1. The liquid that feeds the CCl is precarbonized solution (PCS) and is entered into one of two top CCl rings.

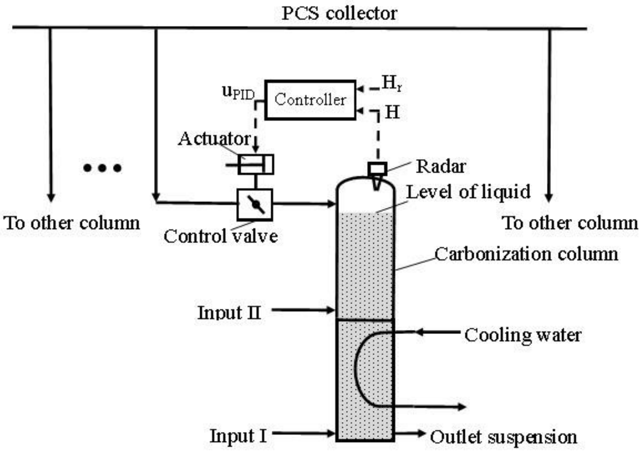

Fig. 1. Functional diagram of carbonization column

A level controller controls the incoming amount of PCS via a butterfly control valve. The upper half of the CCl is called the bubbling section and it is constructed so that there is better contact of the gases with the liquid. The lower half is the cooling section and the heat of the ongoing exothermic reaction - crystallization of bicarbonate ($NaHCO_3$) is taken away by cooling water. The bicarbonate suspension obtained in CCl, contains about 30 weight % of $NaHCO_3$, settles down and flows out from the base of the column, under the pressure of the liquid height in it, and the outgoing amount is controlled by an outlet control valve. The level is measured in the upper 4 m by a radar level meter mounted at the top of the column and with an antenna inside it, the CCl itself is a vessel under pressure. The radar level meter transmits 4-20 mA signal proportional to the 0-100% level to the analog input of the DCS. The “PID AFLC” block in Fig. 1 is configured in the DCS. Its 4-20 mA output, proportional to 0-100% control, is connected to the control butterfly valve DN150 for PCS. The valve is driven by a double acting pneumatic cylinder and it is equipped with a smart positioner.

The CCl is an essential technological unit in the soda ash production and therefore it is very important to automatically control its process variables. The change of the load is done by changing the amount of gases entering into I and II inputs, and after a certain delay and depending on the temperature reacts the valve controlling the released bicarbonate suspension and the valve for cooling water. The level in the CCl is related to these changes in operating mode, but the leading disturbance is the difference between the PCS pressure in the supply collector and the gas pressure in the uppermost part of the CCl. Since the gas pressure is not measured and it is approximately constant, the PCS pressure in the collector is chosen as the main disturbance. Additional disturbances are the change of: the load, the position of the control valve for outlet bicarbonate suspension, the temperature regime of the column and the parameters of PCS - temperature and concentrations of dissolved NaCl and NH_3. Some of the listed disturbances are nonlinearly related to each other, and their overall impact is complicated to be determined. This causes serious difficulties in finding a model of the level in the column as a controlled plant. This plant is nonlinear, connected by the common collector with the another CCl, prone to fluctuations of the process variable *H*, which are caused by the nature of the processes - gases in counter flow, leak of solution from above, sensitive level sensor and more.

III. DESIGN OF ADAPTIVE PID FUZZY LOGIC CONTROLLER FOR LEVEL IN CARBONIZATION COLUMN

Fig. 2 shows the functional block diagram of the designed PID AFLC for the level control.

The radar level meter signal (*H*) is filtered by noise with the exponential filter F1 with transfer function:

$$W^{F1}(s) = \frac{1}{T_f s + 1} \qquad (1)$$

and the time constant T_f = 12s, then subtracted from the value of the reference (H_r) entered by an operator. The deriving error is entered into the PD FLC, where it is normalized by the coefficient K_e and the result e^n [-1, +1] ingoing to the FU.

At the same time, the error is differentiated numerically by using a finite difference. The influence of the noise on the obtained derivative is reduced by using a smoothing filter F2 type "sliding average" for *n*=30 values. The value of the smoothed derivative de_k^{F2} at the moment t_k ($k>n$) is obtained at the output of F2: $de_k^{F2} = \frac{1}{n} \sum_{m=k-n}^{k} de_m$, where de_m is the value of the derivative at the moment t_m.

The smoothed value is normalized by the coefficient K_{de} and the result de^n [-1, + 1] is fed to the other input of the FU. The normalization coefficients K_e=K_{de}=0.05 are determined by the maximum assumed change of the reference 20% of absolute value.

The output of FU o^n is also in the range [-1, +1] and it is denormalized by the scale factor K_d or K_{da} to obtain the control signal u_{PD} [0, 100] % of PD FLC, $u_{PD} = K_d o^n$. The output u_{PID} [0, 100] % of PID FLC, by which is controlled the control valve is a sum of u_{PD} and the signal of error integrator with time constant T_I or T_{Ia} [3]:

$$u_{PID}(t) = u_{PD}(t) + \frac{1}{T}\int e(t)dt \qquad (2)$$

It is empirically known that the number of MF is chosen 3, 5 or 7. Besides, triangular (for inner) and trapezoidal (for both ends) MF are used. This leads to facilitation of their implementation in a PLC without special fuzzy functions.

For the normalized e^n and de^n inputs of the Sugeno FU, are chosen 5 and 3 standard orthogonal MF with triangles and trapezoids, respectively, for the endpoints, which are shown in Fig. 3.

The MF of the FU output are singletons: K1 = -1 (NG), K2 = -0,6 (NS), K3 = -0,2 (N), K4 = 0 (Z), K5 = 0,2 (P), K6 = 0,6 (PS), K7 = 1 (PG), such as P = positive, N = negative, Z = zero, S = small, G = great. A standard base of soft fuzzy rules, a method for aggregation MIN of the two sub conditions related to AND, a fuzzy Mamdani implication, an accumulation and a defuzzification by the weighted average method was chosen. In general, the rules look like this:

R_p: IF e^n is m_i **AND** de^n is n_j **THEN** $o_p^n = K_q$,
i=[1,5], *j*=[1,3], *p*=[1,15], *q*=[1,7]

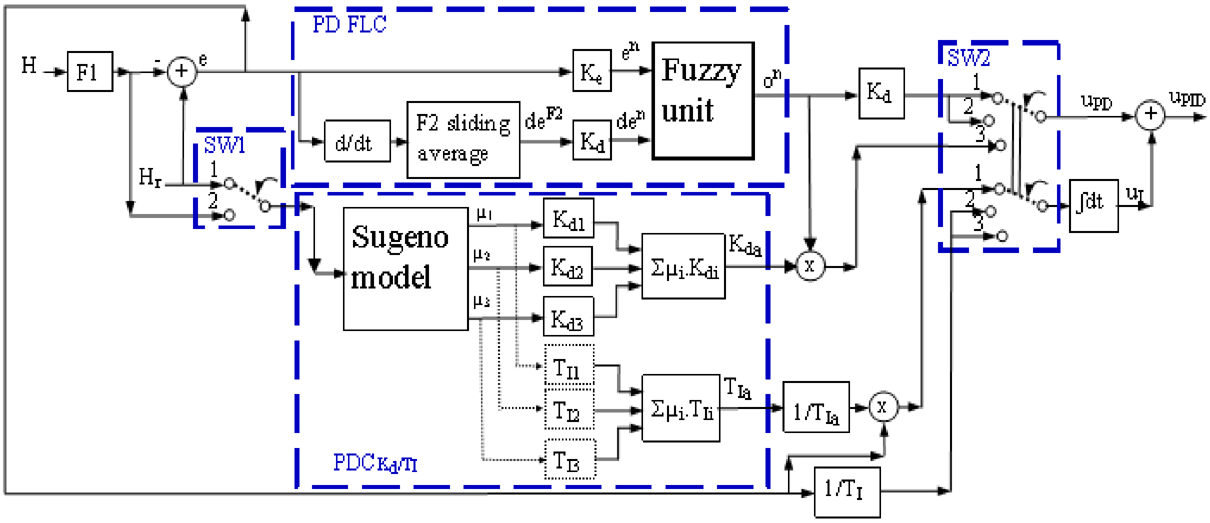

Fig. 2. Functional block diagram of adaptive PID fuzzy logic controller for carbonization column level

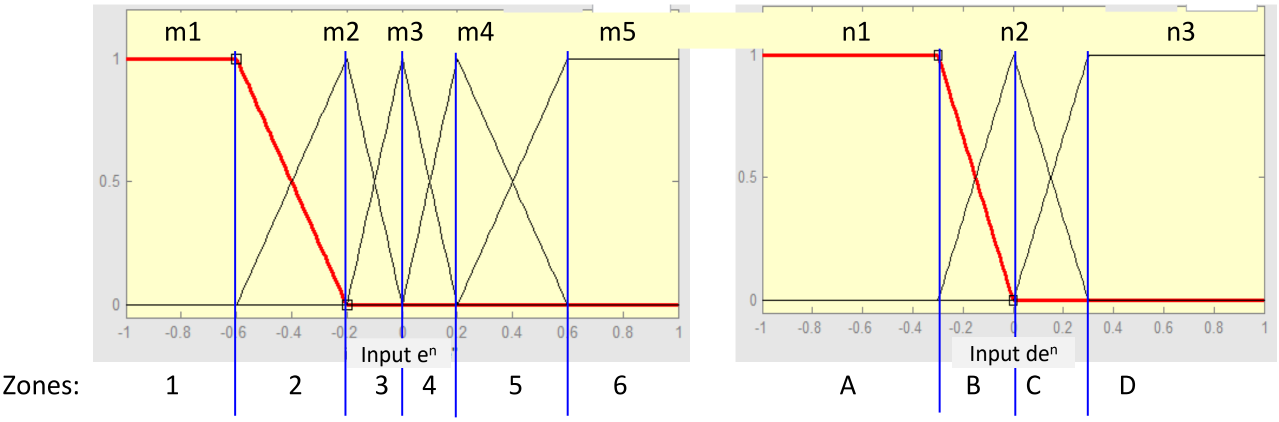

Fig. 3. Membership functions for *e* and *de*

The PDCK_d/T_I module for nonlinear online change of the scaling coefficient K_d at the output of the PD FLC or the time constant T_I of the integrator is developed on the principle of parallel distributed compensation (PDC) [11]. It contains a Sugeno model with input H or H_r, selected via the switch SW1 and a linear part of the local values for K_d and T_I. The MF for the input are defined by expert and they are standard and orthogonal LZ_1 = [0 0 35 50], LZ_2 = [35 50 65], LZ_3 = [50 65 100 100], which define 3 linearization zones LZ_l, l = [1,3] around the most used operating points for H or H_r, 40%, 50% and 60% respectively. The Sugeno model has 3 outputs with MF singletons 1 and 0. The outputs present the degrees of membership μ_l to the three fuzzy defined zones according to the following fuzzy rules:

***R*1: IF** H (or H_r) is LZ_1
THEN $output1_1$=**1 AND** $output2_1$=**0 AND** $output3_1$=**0**
***R*2: IF** H (or H_r) is LZ_2
THEN $output1_2$=**0 AND** $output2_2$=**1 AND** $output3_2$=**0**
***R*3: IF** H (or H_r) is LZ_3
THEN $output1_3$=**0 AND** $output2_3$=**0 AND** $output3_3$=**1**

Thereby, if a specific measurement of H or a reference H_r belongs to LZ_1 with degree μ_1, to LZ_2 with degree μ_2 and to LZ_3 with degree μ_3, then according to the weighted average for the first output is obtained:

$$output1=\mu_1.output1_1+\mu_2.output1_2+\mu_3.output1_3=\mu_1, \quad (3)$$

and likewise $output2=\mu_2$ and $output3=\mu_3$.

The local gains K_{d1}=40%, K_{d2}=50% and K_{d3}=70% and the local time constants of integration T_{I1}=0.3min, T_{I2}=1.4min and T_{I3}=1.7min are determined empirically for each of the three accepted linearization zones. In the upper position (Fig. 2) of the 3-position switch SW2 (pos.1) the PID AFLC operates with a fixed scaling coefficient K_d=const=55% and an adaptive time constant of integration T_{Ia} depending on H or H_r. In the middle position (pos.2) K_d=const=55% and T_I=const=2.3min are fixed, calculated for settled level of 50%. In the lower position (pos.3) the Sugeno model is used to adapt the scaling coefficient K_{da} depending on H or H_r, and the time constant of integration is fixed T_I=const=2.3min.

IV. INDUSTRIAL IMPLEMENTATION OF THE DEVELOPED ADAPTIVE PID FUZZY LEVEL CONTROLLER

The designed PID AFLC in Fig. 2 is implemented in the DCS PLC with a sampling time of 1s. For each discrete time t_m the level is measured, the noise is filtered and the error and its derivative are calculated. After normalization, the respective MF are determined from these values. Because the PLC does not support fuzzy logic, the MF, the fuzzy rules, the fuzzy inference, and the defuzzification are expressed by classical logic and simple mathematical expressions. The MF $m1$(NG); $m2$(N); $m3$(Z); $m4$(P) and $m5$(PG) of the input linguistic variable e^n of FU are calculated according to their mathematical description in each of the zones defined in Fig.3, and they set in the conditions of the logical rules:

IF $-1<=e^n<-0{,}6$ ($e^n \in$ zone 1)
THEN $m1=1$; $m2=0$; $m3=0$; $m4=0$; $m5=0$
IF $-0{,}6<=e^n<-0{,}2$ ($e^n \in$ zone 2)
THEN $m1=-2{,}5e^n-0.5$; $m2=2{,}5e^n+1.5$; $m3=0$; $m4=0$; $m5=0$
IF $-0{,}2<=e^n<0$ ($e^n \in$ zone 3)
THEN $m1=0$; $m2=-5e^n$; $m3=5e^n+1$; $m4=0$; $m5=0$
IF $0<=e^n<0{,}2$ ($e^n \in$ zone 4)
THEN $m1=0$; $m2=0$; $m3=-5e^n+1$; $m4=5e^n$; $m5=0$
IF $0{,}2<=e^n<0{,}6$ ($e^n \in$ zone 5)
THEN $m1=0$; $m2=0$; $m3=0$; $m4=-2{,}5e^n+1{,}5$; $m5=2{,}5e^n-0{,}5$
IF $0{,}6<=e^n<=1$ ($e^n \in$ zone 6)
THEN $m1=0$; $m2=0$; $m3=0$; $m4=0$; $m5=1$

Likewise are defined MFs $n1$(N), $n2$(Z) and $n3$(P) for the other input variable de according to the zones in Fig. 3 as follow:

Zone *A* for $-1<=(de^n)<-0{,}3$: $n1=1$; $n2=0$; $n3=0$
Zone *B* for $-0.3<=(de^n)<0$: $n1=-3{,}33(de^n)$; $n2=3{,}33(de^n)+1$; $n3=0$
Zone *C* for $0<=(de^n)<0{,}3$: $n1=0$; $n2=-3{,}33(de^n)+1$; $n3=3{,}33(de^n)$
Zone *D* for $0{,}3<=(de^n)<=1$: $n1=0$; $n2=0$; $n3=1$

The implementation of fuzzy associative memory and rules inference are shown in Table 1.

The procedure for solving the rules and obtaining the control output of the PD FLC is as follows:

- using Table 1 is determined the inferences for each rule $o^n=K_q$ and the degrees of activation of the rules for all combinations $w_p=\min(m_i, n_j)$, on the obtained m_i and n_j;

- The qualified individual inferences are calculated in the rules by the products $S_p=K_q*w_p$ on the cells of Table 1 (for example $S_{10}=K_6*w_{10}$);

- The defuzzicated output of FU $o^n=\sum S_p/\sum w_p$ is calculated;

- The control of the PD FLC is obtained after denormalization of o^n by K_d:

$$u_{PD}=K_d o^n \tag{4}$$

or by multiplying with K_{da}.

TABLE 1
FUZZY RULES AND DEGREE OF ACTIVATION

$e^n \Rightarrow$ $de^n \Downarrow$	**m1 (NG)**	**m2 (N)**	**m3 (Z)**	**m4 (P)**	**m5 (PG)**
n1 (N)	$K1$ ($w1=\min(m1,n1)$)	$K2$ ($w2$)	$K3$ ($w3$)	$K4$ ($w4$)	$K5$ (w5)
n2 (Z)	$K2$ ($w6$)	$K3$ ($w7$)	$K4$ ($w8$)	$K5$ ($w9$)	$K6$ ($w10$)
n3 (P)	$K3$ ($w11$)	$K4$ ($w12$)	$K5$ ($w13$)	$K6$ ($w14$)	$K7$ ($w15$)

The MF at the input of the Sugeno model from the PDCK_d/T_I module are calculated on the basis of their mathematical description according to the zones which are assigned as ordinary logical conditions, similar to the MF of e^n and de^n:

IF $0<=H(\text{or } H_r)<=35$ **THEN** $\mu_1=1,\ \mu_2=0,\ \mu_3=0$
IF $35<H(\text{or } H_r)<=50$ **THEN** $\mu_1=-a.H+b,\ \mu_2=a.H-c,\ \mu_3=0$
IF $50<H(\text{or } H_r)<=65$ **THEN** $\mu_1=0,\ \mu_2=-a.H+d,\ \mu_3=a.H-b$
IF $65<H(\text{or } H_r)<=100$ **THEN** $\mu_1=0,\ \mu_2=0,\ \mu_3=1$

where: $a=1/15$, $b=10/3$, $c=7/3$ and $d=13/3$.

For each measured and filtered value of H or H_r, specific values of μ_1, μ_2 and μ_3 are obtained. For example, for $H=56\%$ $\mu_1=0$, $\mu_2=0.6$ and $\mu_3=0.4$, since for the determined orthogonal MF $\mu_1+\mu_2+\mu_3=1$. In this case, with pos. 3 of the switch SW2 and the H-pointed of 2 position switch SW1, the scaling gain K_{da} will be adapted depending on the level according to:

$$K_{da}=\mu1.K_{d1}+\mu2.K_{d2}+\mu3.K_{d3}=0.(40)+0.6.(50)+0.4.(70)=58\%.$$

V. EXPERIMENTAL INVESTIGATION OF THE DESIGNED SYSTEM AND PERFORMANCE ASSESSMENT

The system with the designed PID AFLC is investigated in an industrial environment. The aim is to analyse the influence of the fuzzy adaptation of K_d and T_I on the accepted performance indicators in comparison with PID FLC system, which operates by fixed K_d and T_I.

The experiments are realized in real time according to the following plan. Initially, the level is settled to $H=H_r=50\%$ and the corresponding FLC type is switched on by SW1 and SW2. The step responses are obtained by changing the reference at 60%, 50%, 40% and 50% and the data are recorded by the existing MES (Manufacturing Execution System). Finally, in the MATLAB™ environment [12] the results graphically are presented and the performance indicators are calculated. The step responses are obtained for the level, control output and random changing pressure of PCS in distribution collector, considered as main disturbance. The pressure of the PCS is different on every experiment done by industrial installation and it is around 1,4barG (the measured range is 0-4barG). The next control systems are considered:

- System 1 with PID FLC with fixed parameters K_d=const=50% and T_I=const=2.3min. It is obtained at the position of the switches SW1=NA, SW2=1 and the step responses are shown in Fig. 4, where the level, control and pressure of the PCS are denoted by *H*50, *U*50 and *P*50, respectively;

- System 2 with PID AFLC with adaptive K_{da} depending on H_r and fixed T_I=const=2.3min. It is obtained in the position of the switches SW1=1, SW2=3 and the step responses are shown in Fig. 5, where the level, control and pressure of the PCS are denoted by *H*o, *U*o and *P*o, respectively;

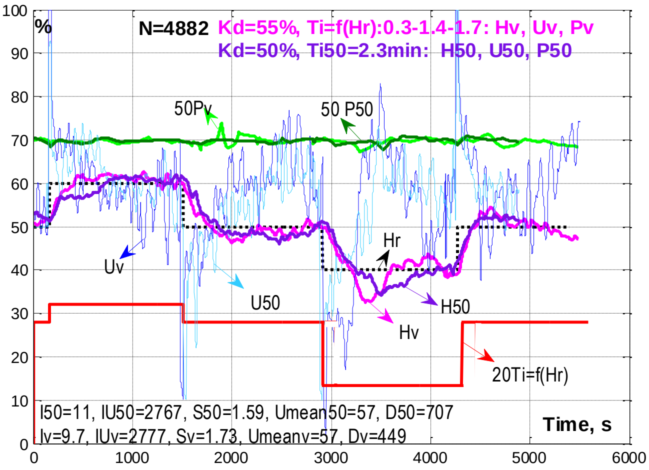

Fig. 4 Step responses for System 1 and System 4

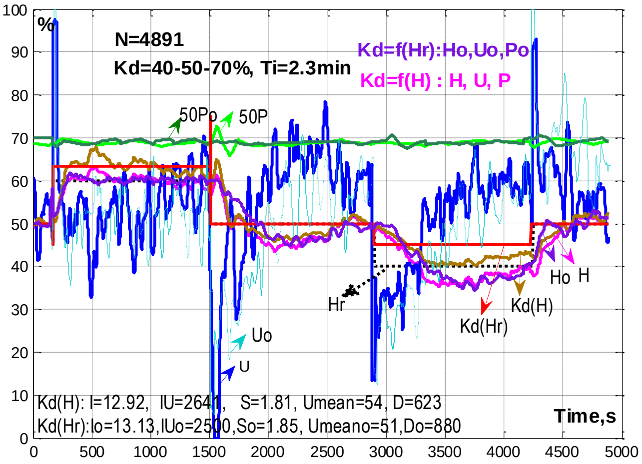

Fig. 5 Step responses for System 2 and System 3

- System 3 with PID AFLC with adaptive K_{da} depending on H and fixed T_I=const=2.3min. It is obtained in the position of the switches SW1=2, SW2=3 and the step responses are shown in Fig. 5, where the level, control and pressure of the PCS are denoted by *H*, *U* and *P* respectively;

- System 4 with PID AFLC with fixed K_d=const=55% and adaptive T_{Ia} depending on H_r. It is obtained at the position of the switches SW1=1, SW2=1 and the step responses are shown in Fig. 4 and Fig. 6, where the level, control and pressure of the PCS are denoted by *H*v, *U*v and *P*v respectively;

- System 5 with PID AFLC with fixed K_d=const=55% and adaptive T_{Ia} depending on H. It is obtained at position of switches SW1=2, SW2=1 and the step responses are shown in Fig. 6, where the level, control and pressure of PCS are denoted by H_a, U_a and P_a, respectively.

The following indicators have adopted to evaluate the performance of control, with N denoting the number of discrete time values that determine the duration of the respective experiment.

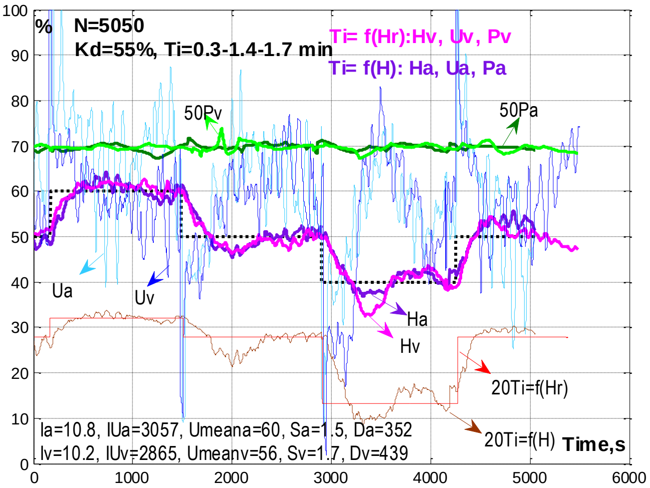

Fig. 6 Step responses for System 4 and System 5

- I – mean square error, $I=\dfrac{1}{N}\sum\limits_{m=1}^{n} e_{\mathrm{m}}^{2}$;

- D – variance of the control action u per unit reference H_r relative to the variance of the pressure, $D=\dfrac{D\left(\dfrac{u}{H_r}\right)}{D(P)}$,

where: $$D\left(\frac{u}{H_r}\right)=\frac{1}{N}\sum_{m=1}^{N}\left[\frac{u_{\mathrm{m}}}{H_{\mathrm{rm}}}-M\left(\frac{u}{H_r}\right)\right]^2,$$

$$D(P)=\frac{1}{N-1}\sum_{m=1}^{N}\left[P_{\mathrm{m}}-M(P)\right]^2,\quad M\left(\frac{u}{H_r}\right)=\frac{1}{N}\sum_{m=1}^{N}\frac{u_{\mathrm{m}}}{H_{\mathrm{r_m}}}$$

and $M(P)=\frac{1}{N}\sum\limits_{m=1}^{N}P_{\mathrm{m}}$ - the estimates of the mathematical expectations for $\frac{u}{H_r}$ and P respectively.

- Overshoot $\sigma=\dfrac{\Delta H}{\Delta H_r}.100[\%]$, where:

$$\Delta H=\begin{cases}(H\mathrm{max}-H_r\mathrm{new})\ \text{for}\ \Delta H_r>0\\(H\mathrm{min}-H_r\mathrm{new})\ \text{for}\ \Delta H_r<0\end{cases},\ \Delta H_r=H_r\mathrm{new}-H_r\mathrm{old}\ \text{with}$$

$H_r$new and $H_r$old are the new and the old values of the reference. Hmax and Hmin are the maximal and the minimal value of the level.

In Table 2 are given the calculated control performance indicators for each of the listed systems. A lower value for each of the indicators shows a better performance of the system.

The numbers in bold indicate the lowest values, which are the best, and on a dark background are the highest and worst indicators. From the data in Table 2 it can be seen that System 4 has the best mean square error I, System 5 has the control with the lowest variance D, and System 2 has the least overshoot. The value of the mean square error I is similar for System 1 and System 5. System 1 has a better overshoot than System 5. The main difference between these two systems is in the variance D, which reflects the conditions of the real time experiments and basically the pressure P of PCS as an essential disturbance. In the industrial plant it is not possible to ensure fully equal conditions for all experiments, which makes the variance D an important indicator.

TABLE 2
PERFORMANCE INDICATORS FOR THE DIFFERENT CONTROL SYSTEMS

Performance indicators	Controller's parameters				
	System 1	System 2	System 3	System 4	System 5
	K_d=50% Ti=2.3 min N=4882	$K_d(H_r)$% Ti=2.3 min N=4891	$K_d(H)$ % Ti=2.3 min N=4891	K_d=55 % Ti(H_r) min N=5050	K_d=55 % Ti(H) min N=5050
$I=\Sigma e^2/N$ I/Imax	11 0.84	13.13 1	12.92 0.99	**10.2** **0.78**	10.8 0.82
$D=D(u/H_r)/D(P)$ D/Dmax	707 0.8	880 1	623 0.71	439 0.5	**352** **0.4**
$\sigma=\Delta H/\Delta H_r$.100, % σ/σ max	53.8 0.7	**33.3** **0.43**	66.7 0.87	76.9 1	55.6 0.72
Σ=I/Imax+D/Dmax+σ/σmax	Σ=2.34	Σ=2.43	Σ=2.57	Σ=2.28	Σ=1.94

The normalization of the indicators according to their highest value for all systems allows to introduce a generalized indicator - a sum (Σ) of the dimensionless relative indicators. This makes it possible to compare the studied systems. The normalized indicators are given in Table 2, under the mains. The best is System 5, which adapts T_I depending on H, with Σ=1.94, followed by System 4, which adapts T_I depending on H_r, with Σ=2.28. Both systems have completely nonlinear control - PD FLC main controller and parallel linear integrator of the error with online adaptive time constant.

VI. CONCLUSION

The main results achieved in the research can be summarized as follows. A PID AFLC is developed for improving of the performance of the liquid level control in a carbonisation column. The PID AFLC is designed on the basis of a Sugeno PD FLC and a parallel integrator of the error. The PDC module provides adaptive fuzzy online tuning of the parameters of the PD FLC and the integrator depending on the current level or its reference. The novelty is that the controller design does not use a classical model of the plant, it reflects the influence of the industrial environment, and the tuning is simplified and takes into account the changes in the real nonlinear process.

The controller is implemented through the application software of the DCS, which controls the production process of "Solvay Sodi" SA. The novelty is the conversion of the fuzzy logic to easily executable and resource saving DCS PLC commands, which is facilitated by the singletons in the rule conclusions of the controller's FU. This conversion overcomes the lag of special functions for fuzzy logic in the DCS PLC.

Experiments with the PID AFLC close loop system have been performed, which show an increase of the dynamic accuracy and reduction of the control variance. A novelty is the introduction of a control variance indicator, which reflects the main disturbance and its reduction prolongs the lifetime of the expensive final control elements.

Also, the experiments show that the best improvements are reached by adapting the integration time constant with respect to the current level.

The aim of future research is the optimization of the local values of the tuned parameters and study of their simultaneous adaptation.

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