The Development of a Neuro-Fuzzy Expert System for Wastewater pH Control

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Abstract: This paper presents the development of a hardware-software prototype system for pH control (SENFpHCTRL) in the studied wastewater treatment plant from a Romanian refinery. Our hybrid system is based on two artificial intelligence techniques, the so-called adaptive neuro-fuzzy inference systems combined with expert systems. In order to test the software component, i.e. the developed neuro-fuzzy controller and the expert system, an automatic system for pH control named ANFISpHControl was built in MATLAB/Simulink. For that, the flowrates and the volume from the studied plant were used, and a set of experiments were made - with and without the expert sytem. The goal was to highlight the advantages of adding an expert system to the software component. In addition, a mathematical model for the process of wastewater pH neutralization was validated for the industrial data from the studied plant through a set of simulations and experiments presented in this paper.

Keywords: pH, wastewater, neutralization process, neuro-fuzzy, expert system, control, controller.

1. INTRODUCTION

Besides conventional methods (PID-based) for processes control, advanced techniques are widely used on industrial scale. Some of these methods belong to the artificial intelligence (AI) domain, such as adaptive neuro-fuzzy inference systems (ANFIS), expert systems (ES), fuzzy logic, artificial neural networks (ANN) or genetic algorithms. The usage of any control method (conventional or AI-based) depends on the behavior of the analyzed process. Because of the high nonlinearity of the wastewater pH neutralization process in the studied wastewater treatment plant (WWTP), a set of tuning parameters for PID controller is not available for the entire pH domain, as we discuss later in the paper.

Regarding the ANFIS, the rules and the membership functions (MFs) are generated using an artificial neural network (ANN). Such a network adds new intelligent features to fuzzy systems, such as learning, adaptation, fault-tolerance and generalization (Shaw, 1998). The ES also comes with a set of heuristic knowledge, useful for a WWTP operator. These two combined intelligent tools (ANFIS and ES) provide solutions to problems that may arise during intelligent controller development process. (Shaw, 1998) defines the concept "neuro-fuzzy" as *the incorporation of a neural network into an existing fuzzy system.* Further on, applying an ES to an ANFIS system leads to *an intelligent computer program that applies knowledge and reasoning (inference) procedures in order to solve problems which require human experience (expert) acquired by many years of activity in a given domain* (Rutkowsky, 2008). In order to achieve the process control using this type of system, ES can also be implemented to work as controllers which behave similar to fuzzy controllers from a conceptual point of view.

The AI-based systems developed for process control, monitoring, diagnosis and analysis are widely described in literature: GESCONDA (Gibert, 2006), ISCWAP (Serra et al., 1997), BIOEXPERT (Lapointe et al., 1989), EXPERT-AT (Oprea, 2002), TELEMAC (Dixon et al., 2007), EnvMAS (Oprea et al., 2011), fuzzy-logic-based systems for pollution-level analysis of a WWTP emissary (Cărbureanu, 2011). The pH control problem is also covered by AI-based techniques such as fuzzy logic (Benz et al., 1996; Fuente et al., 2006) and artificial neural networks (Doherty, 1999; Valarmathi et al., 2009). According to (Marinoiu and Paraschiv, 1992) the pH neutralization process has a high nonlinear dynamic behavior, which suggests using an AI-based control approach (Robescu et al., 2008).

In this paper it is presented a hardware-software prototype system - a **N**euro-**F**uzzy **E**xpert **S**ystem (SENFpHCTRL) for wastewater pH control. In order to achieve a fully functional industrial controller, the software component – the neuro-fuzzy controller combined with an ES – was developed. The developed neuro-fuzzy controller was tested in MATLAB/Simulink environment by attaching it to an ANFIS-based control system (ANFISpHControl) previously built for this purpose. To highlight the advantages of adding an ES to the developed ANFIS controller, a number of experiments with SENFpHCTRL system (with and without the ES) were achieved. Our proposed system is designed to work with a volume and flowrates specific to industrial cases.

The paper is organized as follows:

1. A short description of the wastewater pH neutralization process from the studied industrial refinery;

2. Validation of the mathematical model from the literature (Ibrahim, 2008) for pH neutralization, using industrial data, through a set of simulations and experiments;

3. Development of SENFpHCTRL software component (ANFIS combined with ES). The neuro-fuzzy controller (R-ANFIS.fis) was tested in MATLAB/Simulink using a simulated ANFISpHControl control system. The supplied results of the simulations are discussed. Also it is presented the ES (knowledge base – KB and inference engine - IE) development, ES added to the ANFIS controller.

4. Development and tests of the final prototype hardware-software SENFpHCTRL system. The experimental results are also discussed.

2. INDUSTRIAL CASE STUDY - THE WASTEWATER pH NEUTRALIZATION PROCESS

The Wastewater Chemical and Biological Treatment Plant (WCBTP) in the considered Romanian refinery is composed of three subsystems: WCBTP1, WCBTP2 and WCBTP3. The wastewater pH neutralization process takes place in the chemical step of WCBTP1 and WCBTP2. The chemical step units associated to the WCBTP1 are: the admixture-reaction tank, a flotator decanter and a station for air dissolution. The chemical step associated to the WCBTP2 is composed of a homogenization basin, an admixture-reaction tank, a flotator decanter and an air-dissolution station. The chemical processes in both WCBTP1 and WCBTP2 are similar. Wastewater treatment is performed in both admixture-reaction tanks with chemical agents such as $Ca(OH)_2$, H_2SO_4 and polyelectrolytes. Both tanks are separated in two compartments which are passed consecutively by the wastewater during treatment. The first compartment is used for chemical treatment and mechanical mixing. For a pH value greater than 10, the H_2SO_4 dosage pump is automatically started. The wastewater is then transferred to the second compartment where the pH is neutralized, then directed towards two decanters. Further on, the neutralized wastewater is directed to the biological step (Operating Manual, 2010).

According to the neutralization plant operating manual, the acid pH neutralization is performed with a solution of 10% hydrated lime ($Ca(OH)_2$), while the alkaline pH neutralization is performed with H_2SO_4 95%. Both neutralizers are injected through dedicated pumps. Table 1 (Operating Manual, 2010) shows the following parameters: F_1 - H_2SO_4 flowrate with concentration C_1 (95%), F_2 - $Ca(OH)_2$ with concentration C_2 (10%) and V – volume of admixture-reaction tank.

Table 1. Industrial case study – chemical step reactants parameters

F_1 [liters /hr]	C_1		F_2 [liters /hr]	C_2		V [liters]
	[%]	[mol/ liter]		[%]	[mol/ liter]	
[25 - 300]	95	17.74	[5000-7000]	10	1.5	4000

3. THE MATHEMATICAL MODEL VALIDATION FOR THE INDUSTRIAL CASE STUDY

For the wastewater pH neutralization process, the mathematical model described in (Ibrahim, 2008) was chosen. The model's main equations are two differential equations that emphasize the dynamic behavior of the process:

$$V\frac{d\alpha}{dt} = F_1C_1 - (F_1 + F_2)\alpha \quad (1)$$

$$V\frac{d\beta}{dt} = F_2C_2 - (F_1 + F_2)\beta \quad (2)$$

In equations (1) and (2), F_1 is the acid stream flowrate with concentration C_1, F_2 is the alkaline stream flowrate with concentration C_2, V is the pH neutralization compartment volume, α and β - concentrations of acid and alkaline components in neutralization basin. Figure 1 describes the MATLAB/Simulink model implementation achieved by the author.

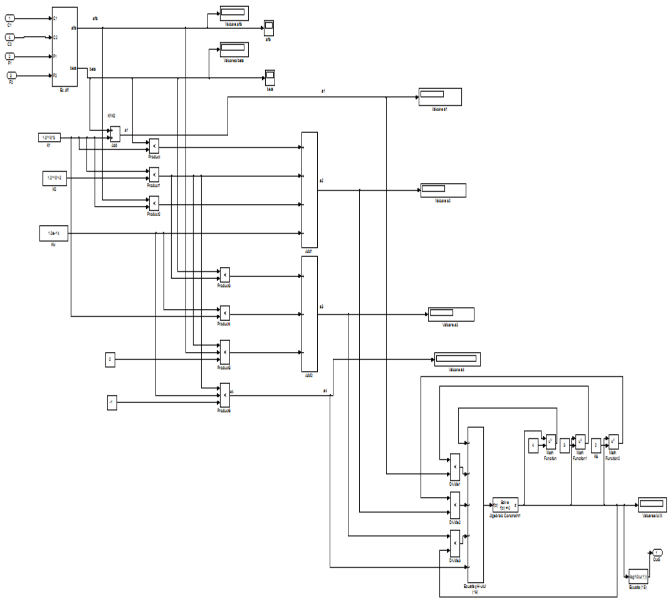

Fig. 1. The process mathematical model implementation in MATLAB/Simulink.

To validate this model for industrial-scale flowrates step changes and volumes, the data described in Table 1 was used, and the following process parameter values were identified: process gain (K_p), transient time (T_{tr}) and dead- time (τ), for F_1 and F_2 step change on the entire pH domain. To verify if the model response for de input data from Table 1 is similar to the static characteristics (CS) form literature (Liteanu, 1972; Luca, 1983; Marinoiu and Paraschiv, 1992; Nenițescu, 1972; Pietrzyk, 1989; Skoog, 1988), a set of simulations were run and the results are presented in Table 2. The inputs (F_1, F_2) step changes corresponds to time=1hr (marked in figures with a vertical line).

Fig. 2 and Fig. 3 present the simulated neutralization process responses described in Table 2, and the output process parameters are presented in Table 3.

Table 2. Simulated process response

Simulation no.	F1 step change [liters/hr]	F2 step change [liters/hr]	pH
1	25 ... 260	6000	14 ... 3.21
2	220.89 ... 220.9	5225	9.77 ... 6.50
3	260	6000 ... 7000	3.21 ... 13.24
4	259.996	6149.7... 6150	6.55 ... 9.72

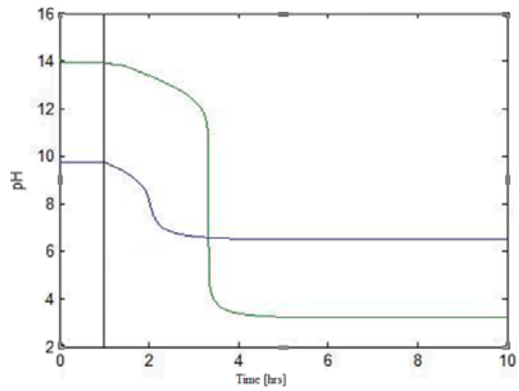

Fig. 2. Simulated process response at F_1 step change (simulations 1 and 2).

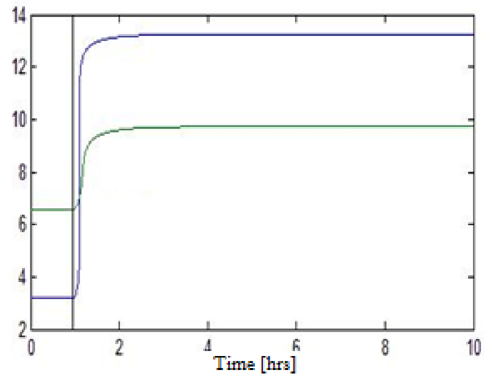

Fig. 3. Simulated process response at F_2 step change (simulations 3 and 4).

Table 3. Simulated process parameters

Simulation no.	Control agent	K_p	T_{tr} [hrs]
1	F_1	-0.91	2hrs56min
2	F_1	-5344.65	2hrs48min
3	F_2	1.43	39min
4	F_2	1509.47	1hrs25min

The obtained process trends for the process response in Fig. 2 and Fig. 3 are similar to process responses described in the literature (Liteanu, 1972; Luca, 1983; Marinoiu and Paraschiv, 1992; Nenițescu, 1972; Pietrzyk, 1989; Skoog, 1988). As described in Table 3, there is a strong variation of the process gain (K_p) on the studied domain, which emphasize the strong nonlinearity of the process. Also, the transient time (T_{tr}) is about 2hrs respectively 3hrs and the dead time (τ) value is zero.

Further on, the process analysis on y-F_1 and y-F_2 channels (Fig. 4) shows the strong nonlinear behavior (high step changes in K_p), which emphasis the importance in dosage accuracy for the acid and the alkaline neutralizers ($Ca(OH)_2$ and H_2SO_4).

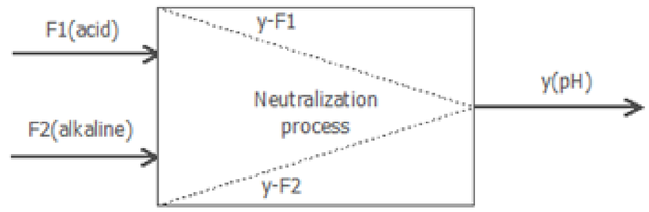

Fig. 4. pH neutralization process - channel analyses.

Table 4 shows the results of y-F_1 channel simulations, for different alkaline type pH starting points and with the same stop point (pH=7, neutral pH), using different step changes for F_1.

Table 4. Process parameters on y-F1 channel

No.	F_1 step change [liters/hr]	K_p	T_{tr} [hrs]	pH value
1	20.9	-5.75	8hrs23min	13.13 ↘ 7.00
2	10.9	-10.53	7hrs56min	12.85 ↘ 7.00
3	0.9	-103.87	6hrs14min	11.76 ↘ 7.00
4	0.1	-746.70	4hrs46min	10.81 ↘ 7.00
5	0.01	-5429.87	3hrs18min	9.77 ↘ 7.00
6	0.001	-20762.5	2hrs17min	8.06 ↘ 7.00

Fig. 5 presents the process responses for the simulations described in Table 4.

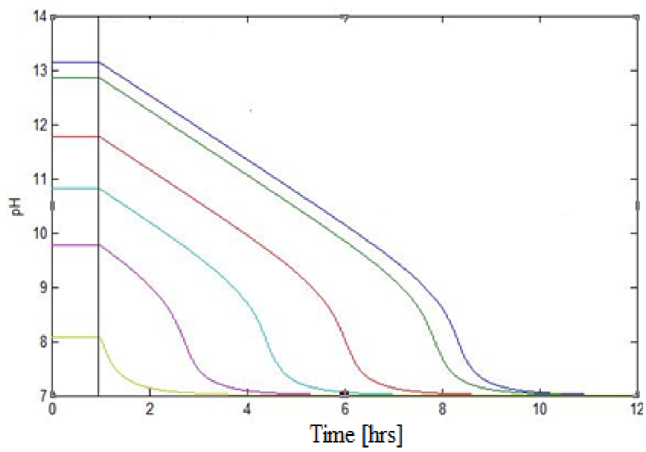

Fig. 5. Simulated process response at F_1 step change (simulations 1 to 6).

The strong process gain factor (K_p) can be easily extrapolated from Table 4 and Fig. 5, fact that confirms the high process nonlinearity. In order to adjust the pH from alkaline to neutral, a very precise dosage of F_1 is necessary. The obtained dead time τ value is 0 hrs.

Table 5 shows the y-F_2 channel simulations results for different pH starting points in acid pH area, with different step changes for F_2. The final pH target is neutral (pH=7).

Table 5. Process parameters on y-F2 channel

No.	F_2 step change [liters/hr]	K_p	T_{tr} [hrs]	pH value
1	445.84	1.37	7hrs4min	2.70↗7.00
2	149.84	3.60	6hrs27min	3.22↗7.00
3	19.84	20.82	5hrs21min	4.11↗7.00
4	1.84	144.52	4hrs10min	5.14↗7.00
5	0.14	821.50	3hrs6min	6.19↗7.00

The neutralization process response for each of those five simulations is presented in Fig. 6. The same strong process gain factor (K_p) can be observed from Table 5 and Fig. 6. Also, the same precision is required in dosing the alkaline neutralizer (F_2). Te obtained dead time value τ is also 0 hrs.

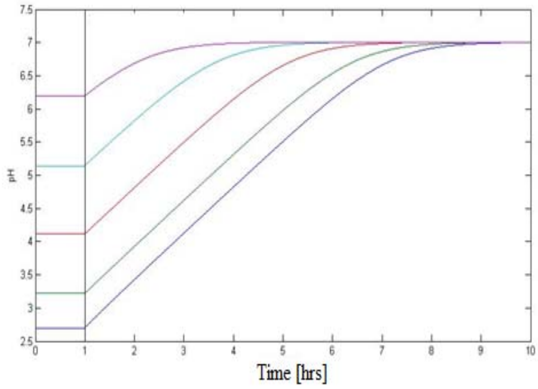

Fig. 6. Simulated process response at F_2 step change (simulations 1 to 5).

To verify the results from a chemical point of view - to determine the neutralization process CS - an additional set of experiments were performed (Cărbureanu and Gheorghe, 2014) by manually dosing the reactants in laboratory conditions. The same neutralizers with the same concentrations were used. The tests were performed on WWTP water samples with different pH values. The same step changes in pH value were recorded and the obtained CS's are similar to the simulations performed in MATLAB/Simulink (Fig. 7, Fig. 8) and to the CS's from literature (Liteanu, 1972; Luca, 1983; Marinoiu and Paraschiv, 1992; Nenițescu, 1972; Pietrzyk, 1989; Skoog, 1988).

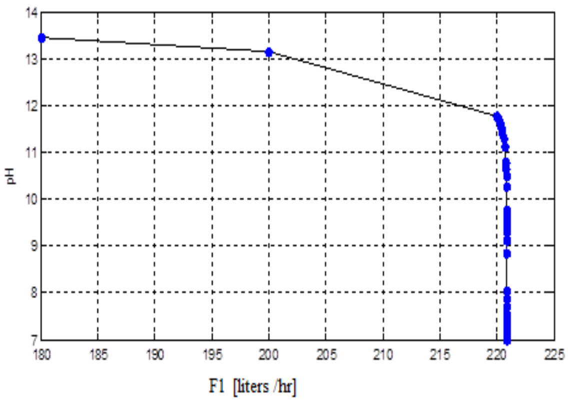

Fig. 7. Process CS in alkaline type pH neutralization area.

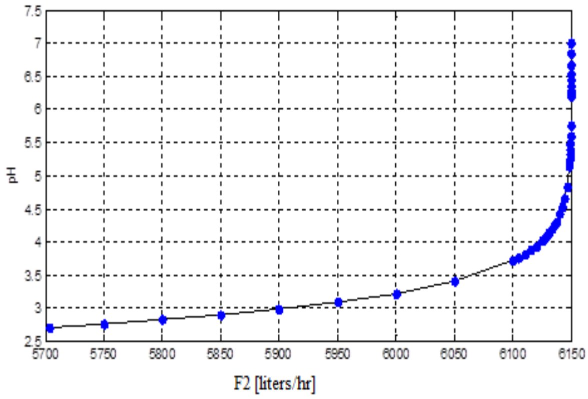

Fig. 8. Process CS in acid type pH neutralization area.

Following Fig. 7 and Fig. 8, the process' CS are similar to the literature (Liteanu, 1972; Luca, 1983; Marinoiu and Paraschiv, 1992; Nenițescu, 1972; Pietrzyk, 1989; Skoog, 1988).

To validate the neutralization process in industrial conditions, a set of tests and measurements were made under supervision in the considered refinery. The F_1 and F_2 step changes, as well as the transient time, are presented in Table 6.

Table 6. Parameters step changes – studied Romanian refinery tests

Test no.	F_1 step change [liters/hr]	F_2 step change [liters/hr]	V [liters]	pH	T_{tr} [hrs]
1	220.8... 220.9	5225	4000	10.8 ... 7	4hrs53min
2	260	6148 ... 6150	4000	5.1 ...7	4hrs5min
3	260	6130... 6150	4000	4.1 ...7	5hrs17min

The tests from Table 6 were performed using the simulated process model. Each simulated test is described in Table 7.

Table 7. Simulated process responses for the Romanian refinery tests

Test no.	Romanian Refinery (pH)	Simulated model		|Model error| (|e_{sim}-e_{real}|)	Error T_{tr}
		pH	T_{tr} [hrs]		
1	10.8 ... 7	10.8011... 7.0087	4hrs 45min	$1.1*10^{-3}$	8min
2	5.1 ... 7	5.1002... 7.0075	4hrs 9min	$0.2*10^{-3}$	4min
3	4.1 ... 7	4.1041... 7.0073	5hrs 20min	$4.1*10^{-3}$	3min

The model error in Table 7 is defined as the difference between the simulated error (e_{sim}) and the measured error (e_{real}). These values are between acceptable limits, their modulo values are smaller than 10^{-3} and the simulated transient time (T_{tr}) is acceptable compared to the measured transient time in the real process. By analyzing Table 6 and Table 7, similarities between the real and the simulated process responses can be observed.

A comparison with the traditional PID solution was performed by implementing a simulated PI controller in the process model (derivative T_d component value was set to zero). According to the results in Table 8 and Table 9, there is no set of tuning parameters (K_R, T_i) available for the entire pH domain - this is one of the many reasons for an AI approach.

Another more advanced PID-based solution is the Gain-Scheduled PI/PID, described in (Chan and Yu, 1995; Lin and Yu, 1993; Gnoth, 2010).

Table 8. Tuning parameters in the PI approach - alkaline pH domain

Simulation no.	pH domain	Adjusting parameters	
		K_R	T_i [min]
1	13.13 ... 12.85	-1.6169	60
2	12.85 ... 11.76	-0.6	78
3	11.76 ... 10.81	-0.05	76
4	10.81 ... 9.77	-0.005	78
5	9.77 ... 8.06	-0.0006	89
6	8.06 ... 7.00	-0.00005	46

Table 9. Tuning parameters in the PI approach - acid pH domains

Simulation no.	pH domain	Adjusting parameters	
		K_R	T_i [min]
1	2.70 ... 3.21	3.6246	48
2	3.22 ... 4.11	0.9192	54
3	4.11 ... 5.14	0.2	66
4	5.14 ... 6.19	0.02	65
5	6.19 ... 7.00	0.002	62

In this work, the chosen AI-based solution was ANFIS combined with ES to develop a pH controller capable to work on the entire pH domain.

4. THE NEURO-FUZZY CONTROLLER AND THE ANFISpHCONTROL DEVELOPMENT

Fig. 9 shows the ANFISpHControl control system architecture with the following components:

1. The pH set point (i_{pH}=7);

2. A neuro-fuzzy controller (R-ANFIS.fis), Sugeno-type, with one input - *error* ($e=i_{pH}-m_{pH}$) and one output - the pump opening degree (*EE_open_degree*) for hydrated lime $Ca(OH)_2$ dosage;

3. An actuator (EE) - the dosage pump for $Ca(OH)_2$, for adjustments of an acid or alkaline pH. The variation control in acid or alkaline pH is performed with step changes in the alkaline reactant ($Ca(OH)_2$) only;

4. The process mathematical model, described by the equations (1) and (2) and implemented in MATLAB as described in Fig. 1.

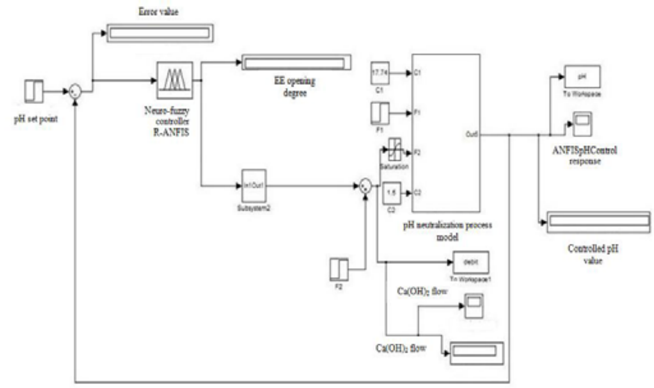

Fig. 9. The ANFISpHControl architecture.

The R-ANFIS.fis neuro-fuzzy controller (presented in Fig. 10) was developed in MATLAB 7.9 with the *anfisedit* command at MATLAB command prompt, which calls the ANFIS editor. The R-ANFIS controller was considered to be a zero order Sugeno-type system, which is a particular case of the Mamdami fuzzy system - each rule effect is formulated through a fuzzy singleton.

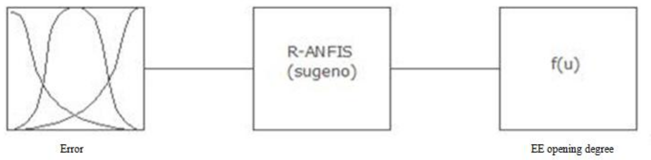

Fig. 10. The R-ANFIS arhitecture.

The MFs for the input *error* and the output *EE_opening_degree,* the associated rules and the output values translated in unified industrial signal (4...20 mA) are presented in Table 10. The rules were automatically generated through *Generate Fis* option. This option using a set of training data (data obtained through process analysis), generates the entire system, system described by Fig. 10.

Table 10. R-ANFIS MFs and rules

<table>
<tr><th rowspan="2">No.</th><th rowspan="2"></th><th rowspan="2">Input (error) MFs (trimf)</th><th rowspan="2"></th><th colspan="2">Output (EE_opening _degree)</th></tr>
<tr><th>constant</th><th>[4... 20 mA]</th></tr>
<tr><td>1</td><td rowspan="5">if</td><td>in1mf1
[-5.375 -4.476-3.782]</td><td rowspan="5">then</td><td>out1mf1
-0.0213</td><td>6.32</td></tr>
<tr><td>2</td><td>in1mf2
[-4.3 -3.485 -2.037]</td><td>out1mf2
-0.0142</td><td>8.21</td></tr>
<tr><td>3</td><td>in1mf3
[-2.877 -2.505-1.063]</td><td>out1mf3
-0.007158</td><td>10.10</td></tr>
<tr><td>4</td><td>in1mf4
[-2.181-1.48-0.0003946]</td><td>out1mf4
-0.006934</td><td>10.12</td></tr>
<tr><td>5</td><td>in1mf5
[-1.051-0.05361 -1.057]</td><td>out1mf5
0.00704</td><td>13.87</td></tr>
</table>

6		in1mf6 [0.008819 1.522 2.188]		out1mf6 0.01406	15.77
7		in1mf7 [1.057 2.502 2.879]		out1mf7 0.01431	15.78
8		in1mf8 [2.047 3.496 4.3]		out1mf8 0.0213	17.68
9		in1mf9 [3.782 4.47 5.375]		out1mf9 0.0284	19.57

Fig. 14 shows the generated model architecture for R-ANFIS.fis.

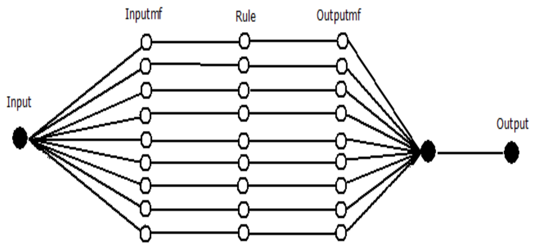

Fig. 14. The R-ANFIS model architecture.

The above model consists of one input (*error*), one output (*EE_opening_degree*) for $Ca(OH)_2$ dosage pump and the set of fuzzy rules. The sign of the membership functions output (negative or positive) represents the domain (alkaline or acid) for the input pH.

The R-ANFIS was trained using a hybrid training algorithm, and validated using a validation data set. The resulted Surface Viewer is presented in Fig. 15.

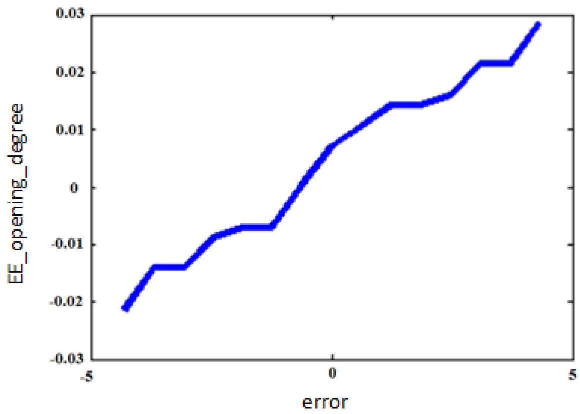

Fig. 15. The R-ANFIS Surface Viewer.

The R-ANFIS controller was developed to operate with values for flowrates and volume from the studied industrial plant (as presented in the previous section). Also in the surveyed WWTP, a constant F_2 ($Ca(OH)_2$) flowrate of 6000 liters/hr is maintained when recycling.

Table 11 shows the simulation results supplied by *ANFISpHControl* (presented in Fig. 9) based on the neuro-fuzzy controller *R-ANFIS.fis* (described by Fig.10), previously presented in this paper.

For an acid pH adjustment, the neutralizing agents' parameters are as following: constant F_1 - 260 liters/hr, F_2 starting point - 6150 liters/hr.

Table 11. ANFISpHControl simulations results for acid type pH

No.	pH domain	Transient timeT_{tr} [hrs]
1	2.70 $\nearrow$7	5hrs38min
2	3.22 $\nearrow$7	4hrs58min
3	4.11 $\nearrow$7	3hrs47min
4	5.14 $\nearrow$7	2hrs30min
5	6.19 $\nearrow$7	1hrs54min

As it can be observed from Table 11 and Fig. 16, our ANFISpHControl system ensures response times between 2 and 5 hours and null steady state error (e_{st}).

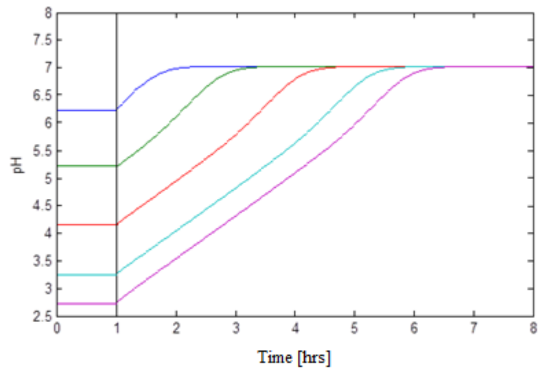

Fig. 16. ANFISpHControl simulations results for acid type pH.

Table 12 presents the ANFISpHControl simulations results for an alkaline type pH. The process parameters are: F_1 constant - 260 liters/hr, F_2 starting point - 6149 liters/h.

Table 12. ANFISpHControl simulations results for alkaline type pH

No.	pH domain	Transient timeT_{tr} [hrs]
1	8.06 $\searrow$7	25min
2	9.77 $\searrow$7	36min
3	10.81$\searrow$7	1hr30min
4	11.76 $\searrow$ 7	2hrs45min
5	12.85 $\searrow$ 7	4hrs16min
6	13.13 $\searrow$ 7	4hrs40min

According to Table 12 and Fig. 17, the ANFISpHControl system ensures response times between 25 minutes and 4 hours and null steady state error (e_{st}).

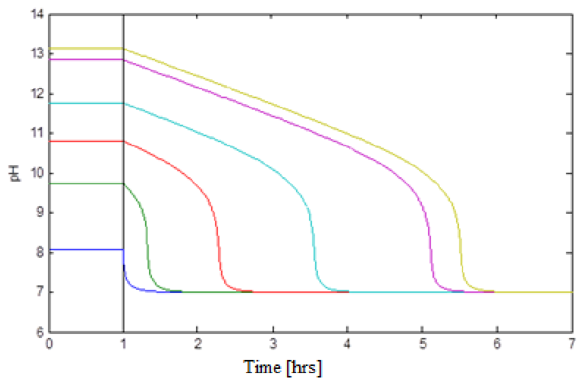

Fig. 17. ANFISpHControl simulations results for alkaline type pH.

By following the results presented in Table 11 and Table 12, and by analyzing Fig. 16 and Fig. 17, the ANFISpHControl system with the R-ANFIS neuro-fuzzy controller (which works on the entire pH domain) achieves the control of both acid and alkaline pH from any point of the pH domain, and also provides null steady state error.

For these reasons, the developed ANFIS (R-ANFIS) was chosen as the software component of our SENFpHCTRL prototype hardware system.

5. THE PROTOTYPE SYSTEM SENFpHCTRL DEVELOPMENT

Figure 18 describes the block diagram of our developed hardware-software SENFpHCTRL system for wastewater pH control.

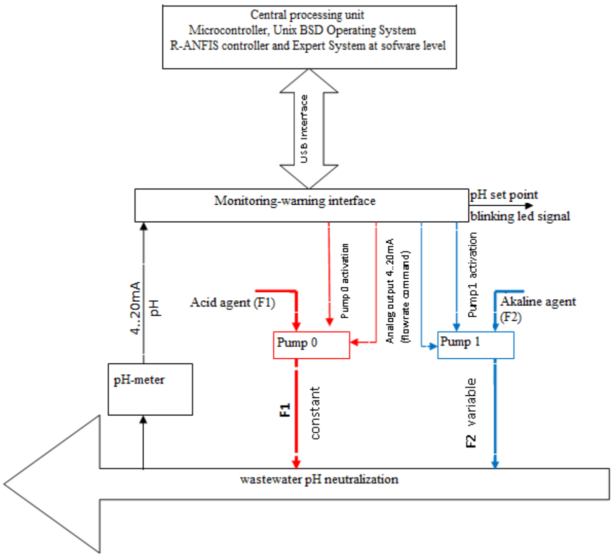

Fig. 18. SENFpHCTRL – block diagram.

The SENFpHCTRL hardware-sofware prototype system developed for the wastewater pH control has the following components (see Fig. 18):

1. *Central processing unit* - based on a Marvell Kirkwood 88F6281 microcontroller running the latest version of BSD Unix operating system, built and programmed according to (Buruiană, 2012). The POSIX standard allows the same implementation on a traditional PC;

2. The *monitoring-warning interface*, with both analog and digital inputs and outputs, measures the 4...20 mA pH value supplied by the pH meter. The output signals (generated by the central processing unit) are: pump commands, analog outputs for F_1 and F_2 flowrates control, and an optic warning signal (blinking led) to signal the final pH reached the initial set point;

3. The *pH-meter*, documented in (Transducer pH SBE-18 Operating Instruction Manual);

4. Two *actuators* (pump 0 and pump 1), both adjustable via 4..20mA analog signals. Pump 1 is adjusted by the R-ANFIS controller, while pump 0 flowrate is set to a constant value.

The ANFIS software component was obtained through a *core memory dump* procedure which was applied to a running MATLAB session with a running ANFIS editor (Buruiană, 2012). This method consists of dumping the entire RAM memory content into a file located on the hard drive. Later, the running MATLAB session and also the ANFIS function were extracted and disassembled (Buruiană, 2012) using the Ida PRO Disassembler tool. Later, the C program was reconstructed using the same tool, and the result was found to be similar with the files *fis.c* and *fismain.c* available in the MATLAB enterprise license *foolbox-fuzzy*. The fuzzy software component is able to load *.fis* files exported by MATLAB. Also, an additional expert system (ES containing KB and IE) was developed and programmed into *fismain.c*. The final software program was compiled using the gcc-4.2.1 Free Software Foundation C Compiler for both ARM (microcontroller) and x86-32 (PC) architectures.

The software component loads the R-ANFIS.fis (the neuro-fuzzy controller previously developed) and the training data file (training.dat), performs the ANFIS training and loads the measured pH value. According to the command *./fis training.dat R-ANFIS.fis* executed at system startup, the controller R-ANFIS.fis is executed as follows:

1. The compiled program (ANFIS, ES, analog I/O access functions) is loaded into the memory;

2. The controller configuration exported from MATLAB (R-ANFIS.fis) is loaded;

3. The controller loads the training data file (*training.dat*);

4. The ANFIS is configured according to the configuration (R-ANFIS.fis), trained with the training data (*training.dat*);

5. The pH data is acquired through the analog input (Cărbureanu and Buruiană, 2013), passed to the ES (see Fig. 19) which forks into a separate parallel process, and also compared with the default set point (*pHref*), and the difference (the *error*) is sent to the previously-configured ANFIS (R-ANFIS controller), which generates an output numeric value;

6. In parallel (see Fig. 19), the developed ES generates its own output by passing the measured pH value through its knowledge base and inference mechanism;

7. The two outputs are combined into the command processing block and the P1 flowrate is adjusted;

8. In parallel, the ES also controls the P0 pump.

The operating functions for the monitoring-warning interface were implemented according to (Buruiană, 2012) and are used to acquire the numerical values supplied by the pH sensor, to control the pumps and to signal the *pH_set point* reached in the process.

Our SENFpHCTRL is a hybrid intelligent system, obtained by combining the developed ANFIS (R-ANFIS.fis) with an ES (knowledge base – KB and inference engine - IE). Fig. 19 presents the SENFpHCTRL flow chart from the author point of view.

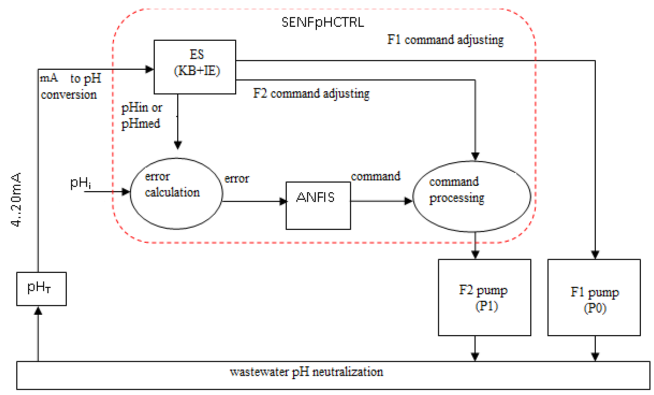

Fig. 19. The flow chart of the SENFpHCTRL completed with an ES (KB and IE).

As it can be observed from Fig. 19, the numeric pH value supplied by the pH meter (pH_T) is processed in the ES block by a smoothing function – which sends the *pHmed* (cleaned for unwanted signal spikes), or the raw *pHin* data (if no disturbances are detected) to the error calculation block.

According to the rules in the KB and the decisions in the IE, the F1 (P0) state and also a set of adjustments for the ANFIS F2 (P1 control) output are generated. Furthermore, the ES supplies a set of additional information regarding:

1. the estimated time until different pH points are reached, if the ES would be absent. These time intervals were recorded in the previously-made simulations and experiments, before the ES was implemented. The estimated time information is used to highlight the ES improvements;

2. the estimated neutralizing agents consumptions, as recorded under the same conditions previously described;

3. the ANFIS P1 command, P1 state, ES adjustment for ANFIS output, final variable flowrate command (for P1);

4. the P0 state, as decided by the ES (active or inactive);

5. The process time interval.

The SENFpHCTRL KB initially consisting of the R-ANFIS fuzzy rules (presented in Table 10) was completed with a set of deductive rules developed by the author using a set of heuristic knowledge obtained through the pH neutralization process analysis from the studied plant, simulations and experiments.

The new rules establish the estimated times for the process operating (process_estimated_time, hrs_estimated_time, min_estimated_time) until it reaches a certain pH value (next_pH). The rule base contains a number of thirty-two rules for acid and alkaline type pH, a selection of these being presented:

1. **if** ((*pH_value* > 5.47) **and** (*pH_value*<7)) **then begin**
process_estimated_time =2+8/60
hrs_estimated_time = 2
min_estimated_time = 8
next_pH = 7
F2=(6149.2+6149.7)/2 **end**

2. **if** ((*pH_value*>7) **and** (*pH_value*<=7.17)) **then begin**
process_estimated_time =0.48/60
hrs_estimated_time = 0
min_estimated_time = 0.48
next_pH = 7
F1=(220.8997+220.8998)/2 **end**

The SENFpHCTRL inference engine (IE) was developed by the author to improve the system performance (T_{tr} adjustment) and to solve the problems encountered during the experiments made with this system in the initial form (without IE). During the experiments achieved with the developed system in the initial form, made in the Mud Logging laboratory of a Romanian oil Drilling Company, the following aspects where observed:

1. The acquisition of pH data is influenced by surges and spikes, according to the well site conditions (diesel generators, poor power filtering, variable power consumption);

2. Some of the transient times recorded in pH neutralization processes are high, due to high volumes;

3. An extremely high consumption of neutralization agents occurs;

4. The special situations around equivalence point (pH [5..9]). The alkaline agent (F_2) having variable flowrate is used first of all to neutralize the acid type agent (having constant flowrate) and a small percentage of it is used for the wastewater pH neutralization. The same situation was noticed for the acid agent used in alkaline agent neutralization.

The proposed solutions to these problems are:

1. The smoothing of the pH-meter output signal is required, especially on [5...9] pH domain where precise measurements are needed;

2. The pH neutralization process acceleration on [13.13...9] pH domain should be done by disabling the alkaline agent (F_2) and by using only F_1 agent. On the [2.7...5] domain, it should be done by disabling the acid agent and by using only F2 agent;

3. Near the equivalence point (the [5...9] domain), the control is recommended to be handed to ANFIS. In parallel, the ES corrections are applied on the ANFIS output and also the pumps are enabled or disabled, according to the IE treated situations;

4. When the estimated completion time decreases to minutes, an increased process control is needed and a reduction in agent flowrates is decided, because the process follows its evolution by its own inertia.

The IE developed by the author is presented as follows:

if ((*pH*>2.7) **and** (*pH*<=7)) **then begin**
if *pH* < 5 **then begin**
ANFIS controls the alkaline agent pump - P1
IE increases the ANFIS initial command by 10%

IE requests deactivation for acid type agent pump P0 **end**

if *pH* between 5 **and** 7 **then begin**
ANFIS partially controls the process
IE executes adjustments (+/-10%) on ANFIS command (the pump P1)
The pump P0 with constant acid agent flowrate is on
Near the pH equivalence point, the IE deactivates the acid pump P0, the process works from inertia
end end

if ((*pH*>=7) **and** (*pH*<13.13)) **then begin**
if *pH* > 9 **then begin**
IE asks for acid pump P0 (acid flowrate constant) activation
IE suppress the ANFIS command for alkaline dosage **end**

if *pH* between 9 **and** 7 **then begin**
ANFIS partially controls the process
IE asks for pump P0 activation
IE performs adjustments on ANFIS command (the pump P1)
Near the equivalence point, IE successively reduces the ANFIS command (the pump P1)
Close to equivalence point, IE stops the pump P0, the process works from inertia **end end**

The conditions from IE were established after the following criteria:

1. The measured pH interval;

2. The estimated time in which the measured pH reaches a certain value;

3. The ANFIS supplied command.

The conditions related to the measured pH interval (selection) are the following (deactivate the acid pump; increase ANFIS command by 10%):

1. **if** ((*pH_value*>6.27) **and** (*pH_value*<6.66) **and** (*next_pH* = 7)) **then begin**
acid _command = 0
IE_command=1.1
end

The conditions related to the estimated time (selection) are the following (near to equivalence point, estimated time – tens of seconds; the alkaline dosage is reduced to 0, the pump P0 is turned off, the process works on its inertia; decrease ANFIS output to 50% but keep a small alkaline pressure in the alkaline tank; disable the acid pump):

1. **if** ((*next_pH*=7) **and** (*hrs_estimated_time*=0) **and** (pH_ *value*<=7.05) **then begin**
IE_command=0.5
acid_command=0
end

The condition related to the elaborated ANFIS command (selection) are the following (decrease ANFIS output to 50%; keep small alkaline pressure in the tank; enable the acid pump):

1. **if** ((*min_estimated_time*<=10) **and** (*pH_value*>=8.1) **and** (*pH_value*<=8.7)) **then begin**
IE_command=0.50
acid_command=1
end

The percentages associated to the *IE_command* were established by consulting the technical specifications of the dosage pumps P0 and P1, and by manually tuning the values according to the required pressures on the dosing pipes.

The hardware component of the system SENFpHCTRL is presented in Fig. 20.

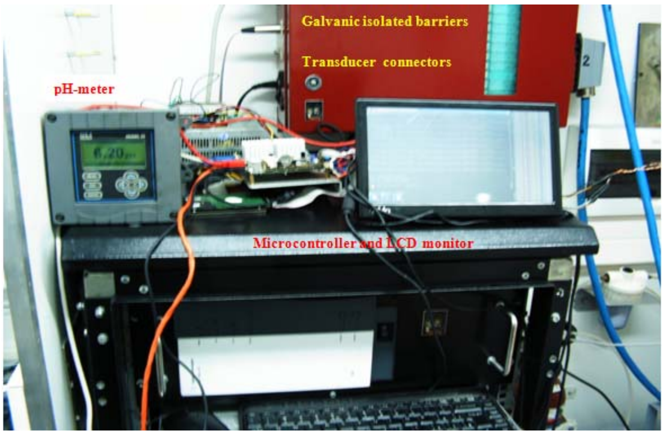

Fig. 20. Microcontroller-based SENFpHCTRL.

The hardware system is composed from the following elements:

1. A pH-meter, GLI-53 model;

2. The Marvell 88F6281 Microcontroller motherboard with a graphic LCD monitor;

3. A warning-monitoring interface connected to the process;

4. Two MOS-FET power transistors for controlling the dosage pumps;

5. An electrical panel with galvanic isolated barriers, to provide a degree of safety when interfacing the system with the process.

Table 13 and Table 14 present the results of the experiments made with SENFpHCRTL for both cases (without and with IE), as recorded within the Mud Logging mobile laboratory. The system final command for the P1 pump was defined according to relation (3).

$$Final\_command = ANFIS\_command * IE\_command \quad (3)$$

According to Table 13 and Table 14, the following aspects can be observed:

1. The steady state error (e_{st}) differences for pHin≈10.8 case are caused by power supply electrical disturbances due to the location conditions (in the case of the experiments with an implemented ES), disturbances partially compensated

through the application of the smooth function. For the other cases, the steady state error slowly decreases, although the exact reproduction for the initial pH value was not possible;

2. The transient times were reduced through the ES implementation. The ES intervention on the ANFIS generated command contributes to reduction in agents quantity when approaching to pH equivalence point (advantages of adding an ES to the software component). So, a reduction of T_{tr} leads to a reduction in agent costs;

3. The IE progressive intervention on ANFIS command (for the pumps P1 and P0) by adjusting the command, also contributes to the reduction in neutralizing agents' consumption.

Table 13. ANFISpHCTRL without IE simulations results

pHin	10.83	8.36	9.08	4.48	6.14
pHi	7	7	7	7	7
Final pH	7.02	7.19	7.17	6.91	6.97
Mediated pH	-	-	-	-	-
e_{st}	0.02	0.19	0.17	0.08	0.02
ANFIS command [V]	4.38	4.35	4.35	4.39	4.39
T_{tr}	1hr 18 min	28 min	30 min	3hrs 9min	1hr 24min
IE command [%]	-	-	-	-	-
Final command [V]	AN FIS	AN FIS	AN FIS	AN FIS	AN FIS

Table 14. ANFISpHCTRL with IE simulations results

pHin	10.86	8.31	9.08	4.48	6.15
pHi	7	7	7	7	7
Final pH	7.09	7.09	7.09	7.04	6.97
Mediated pH	10.83	8.31	9.08	4.46	6.15
e_{st}	0.09	0.09	0.09	0.04	0.02
ANFIS command [V]	4.37	4.36	4.36	4.37	4.38
T_{tr}	49min 32sec	21min 9sec	22min 16sec	2hrs 21min	54min 10sec
IE command [%]	0.96	0.80	0.96	0.50	0.90
Final command [V]	4.19	3.49	4.19	2.18	3.94

The pH neutralization process models from the literature (McAvoy, 1972; Gustafsson and Waller, 1983; Mwembeshi, 2001; Henson and Seborg, 1994; Ibrahim, 2008) assume the maintaining of F_1 flowrate constant and the successive addition of F_2, regardless of pH domain (out or near the pH equivalence point). The author also identified a set of problems, such as high transient time and high consumption of reagents. These problems were solved by developing the SENFpHCTRL prototype system that has, at software level, an ANFIS combined with an ES controller. The ES adjusts the ANFIS controller command, out and near the pH equivalence point, which leads to the reduction of the transient times, implicitly to the neutralizing agents flowrates reduction. These are very important aspects in terms of neutralizing process efficiency and operating costs.

6. CONCLUSIONS

The pH neutralization process is very complex because of its dynamic behavior and mostly due to its high non-linearity. The wastewater pH control can be made by means of conventional control (Proportional-Integral-Derivative – PID or Gain-Scheduling PID) or by using artificial intelligence (AI) techniques, such as adaptive neuro-fuzzy inference systems (ANFIS) and expert systems (ES).

In this paper the author main contributions are:

1. The validation of the wastewater pH neutralization process mathematical model for the flowrates and volume used in the studied plant from a Romanian refinery through a set of simulations and experiments. This validation implies a good knowledge of the pH neutralization process from the studied plant and the achievement of a considerable number of simulations and experiments. It was highlighted that the model has a strong non-linear behavior within the entire F_1 and F_2 domain, because the process gain (K_p) has a strong variation (the process gain gets higher as one is closer to pH≈7 (neutral pH)). Also, the reactants ($Ca(OH)_2$ and H_2SO_4) dosage precision is very high, which triggers problems regarding the actuators (P0 and P1 dosage pumps). Also, through a set of simulations and chemical experiments, the static characteristics (the titration curves) were determined for the neutralization process of an acid and alkaline pH, characteristics with a strong nonlinear behavior. The obtained titration curves correspond to those found in the literature (Skoog et al.,1988; Pietrzyk et al.,1989; Liteanu et al. 1972; Luca et al., 1983);

2. A neuro-fuzzy controller (R-ANFIS.fis) was developed, then tested on a pH control system named ANFISpHControl, developed in MATLAB/Simulink. It was established that this ANFIS controller (later combined with an ES - KB and IE also developed by the author), works on the entire pH domain and, as a component of the developed control system, it supplies quality control (the pH reaches the pH set point, the supplied error is small and the transient times T_{tr} correspond to those registered in the studied plant);

3. It was developed a hardware-software prototype system named SENFpHCTRL (a hybrid system using an adaptive neuro-fuzzy system and an expert system) for wastewater pH control. The software component is represented by R-ANFIS.fis (a neuro-fuzzy controller that works properly on the entire pH domain) combined with an ES (whose knowledge base and inference engine were also developed by the author). From the architectural point of view, the

developed system is portable, small sized and it can be attached to any industrial process that implies pH control. It requires only the technical data for the transducer and actuators (the dosage pumps) and the developing of an adequate ANFIS to be exported from MATLAB. Thus it is no longer needed to develop a software application singularized on the process; the set of programs – (fis.c+fismain.c), adapted by the author, represents a neuro-fuzzy setup controller with the help of the exported files from MATLAB). The SENFpHCTRL system is hybrid due to the following elements:

- It contains a knowledge base initially represented by the fuzzy rules developed within the neuro-fuzzy controller (R-ANFIS.fis), completed with a set of heuristic rules deduced by the author from process analysis, simulations and experiments;

- It contains an inference engine (IE) used to adjust the ANFIS command;

- The developed ANFIS is combined with another AI technique, such as ES (also developed by the author). The parallel operation of ANFIS with ES proves its usefulness through the transient times decreasing and the reagent consumption reduction. Also, the ES comes to adjust the ANFIS command and to supply information regarding the process evolution (times, consumption of reagents).

- The controller (ANFIS with ES) was developed around a microcontroller supported by industrially certificated UNIX-based operating systems. Industrial pH-meters and pumps were used, with adjustable flowrates for the neutralizing agents.

- The software component (ANFIS with ES, the set of programs – fis.c+fismain.c) was implemented on both microcontroller and PC architecture.

The main advantages of the developed system SENFpHCTRL are the following:

1. The ANFIS functioning improving with the help of a set of heuristic knowledge transposed into an ES;

2. The transient time and neutralizing agent consumption reduction (it is effective in terms of costs);

3. The functionality under disturbances conditions caused by variations in supply voltage or electromagnetic influences;

4. The system usability in real conditions for high flowrates.

In our future work, the SENFpHCTRL system will be improved to acquire and process other wastewater parameters such as: chemical oxygen demand (COD), biological oxygen demand (BOD), phenols, chlorides, extractibles and total suspended solids (TSS). This implies the KB and IE completion with a set of heuristics for these parameters and also a number of additional transducers to measure this parameters. Currently, the system is tested for the pH neutralization of oil drilling mud at different Romanian well sites.

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