UNIVERSIDAD AUTÓNOMA DE QUERÉTARO

13° CONGRESO INTERNACIONAL DE INGENIERÍA

15th-19th MAY 2017

A pH Process Control Embedded on a PLC Using Fuzzy Logic

R. Velázquez-González, T. Gómez-Lemus
Querétaro Institute of Technology
Querétaro, México
rvelazquez.siac@gmail.com,
tgomezlemus@yahoo.com.mx

J. Rodríguez-Reséndiz
Enginnering Faculty
Querétaro State University
Querétaro, México
juvenal@uaq.edu.mx

***Abstract*— The present work shows the design and implementation of a controller based on Fuzzy Logic for pH regulation using an S7-1200 Programmable Logic Controller (PLC) as a processing element. The inputs of the controller are the current error (desired pH - current pH) and the rate of change in error (current error - previous error). On the other hand, the output is given by the activation time of an on-off dosing pump, which was adjusted to a constant flow of 2.5 liters per hour. The controller calculates the time that the pumps must be on or off so that the process variable reaches the desired value. A Delta Human Machine Interface (HMI) are used to acquisition data and process parameters configuration.**

Keywords—Fuzzy Logic, Potential of Hydrogen, Programmable Logic Controller, Human Machine Interface.

I. Introduction

pH is the measure of how acidic or alkaline is a substance, and is defined as the negative logarithm of the hydrogen ion concentration (in mol/L) [1]:

$$pH = -\log(H^+) \tag{1}$$

The pH regulation is very useful in wastewater treatment processes, for example, for the precipitation of heavy metals, the conditioning of electrochemical reactors, etc. [2], [3]. In this experiment, the pH control was used for an experimental design in which it is desired to know what are the best performance parameters of an electrocoagulation reactor, used for water treatment of laundries. For this purpose, a prototype was built where the tests were carried out. The parameters to be varied are shown in Table 1. As can be seen, each variable has three levels.

The goal is to combine the values of the variables and then perform the treatment to see which parameters offer better performance in the removal of pollutants and energy use. Then, the experiment has 27 possible combinations, and according to the Design of Experiment theory (DOE), it is necessary to repeat the complete design at least twice [4]. So theoretically we would need 54 runs, however, because perform all the tests requires a lot of time and economic resource, we chose only 18 representative combinations according to the design theory of fractional experiments [5], this in order to perform a statistical analysis at the end of the experiment.

TABLE I. EXPERIMENTAL DESIGN FOR ELECTROCOAGULATION PROCESS

Values of Variables		
pH	***Voltage (Volts)***	***Time of contact (Minutes)***
4	1	10
7	2.5	15
10	3.5	25

TABLE II. COMBINATIONS OF PARAMETERS FOR FRACTIONAL EXPERIMENTAL DESIGN

Values of Variables			
Run	***pH***	***Voltage (Volts)***	***Time of contact (Minutes)***
1	4	1.0	10
2	4	3.5	15
3	10	2.5	15
4	7	3.5	25
5	4	2.5	25
6	7	1.0	15
7	4	3.5	15
8	4	2.5	25
9	10	2.5	25
10	10	2.5	10
11	4	1.0	10
12	7	1.0	15
13	7	3.5	25
14	10	2.5	15
15	10	2.5	25
16	7	2.5	10
17	7	2.5	10
18	10	2.5	10

Regulating the pH manually for each run is a heavy task and requires a lot of time, also, the same pH definition tells us that the process is non-linear [6] (see eq. 1), so manual regulation is not a good option, since too many over-passes are raised due to the inertia of the system, resulting in wasted time and money.

Fuzzy logic-based controllers have taken a big leap in system applications that present nonlinearities such as delayed systems and higher order systems, which represent a challenge for classical control (e.g. PI controllers, PID controllers, etc.) [7].

The purpose of this work is to implement a fuzzy controller for automatic pH regulation in each run of the mentioned experiment. The project was divided into three stages: Design of

978-1-5386-1694-9/17/$31.00 ©2017 IEEE

the controller, programming of the algorithm in the PLC and start-up.

II. Fuzzy Logic Controllers

The origins of fuzzy logic go back to 1965 when Lotfi A. Zadeh posed the theoretical basis for this concept and with it new alternatives in control engineering [8]. Fuzzy systems are based on human knowledge and experience, using a set of rules of the form *IF-THEN* to determine the output of the given controller a set of inputs. One of the great advantages of controllers based on fuzzy logic is that, for its application, it does not require a rigorous mathematical knowledge of the system to control. However, it requires a knowledge base which is obtained from an expert in the process [9]. In general, a fuzzy controller works as follows: one or more crisp inputs are entered into the controller and it *Fuzzified*, that is, child mapped in the fuzzy membership domain. The inference engine then applies the *Diffuse rule base* to the inputs to determine how the controller should react and obtain a set of fuzzy outputs. Finally, the fuzzy outputs are "Defuzzied" to get a crisp value. A typical scheme of the structure of a fuzzy controller is shown in Fig. 1.

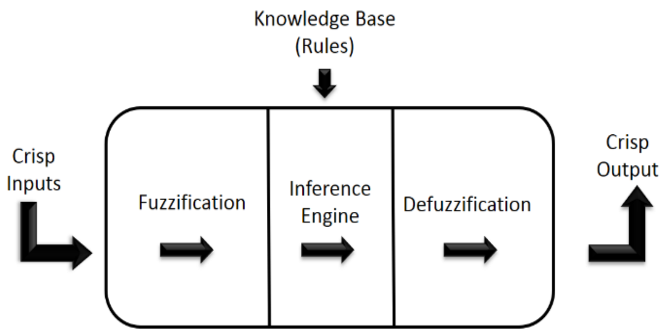

Fig. 1. Typical Fuzzy Control Structure.

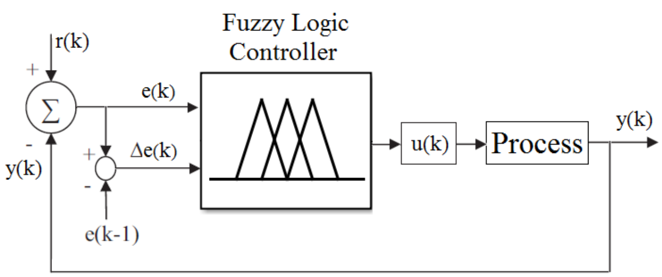

Fig. 2. General scheme of control using a fuzzy controller.

III. Process to Control

The process to be controlled consists of a 20-liter equalizing tank where the contaminated water is deposited, a mixer, 2 Blackstone 5 l/h dosing pumps for acid reagent (HCl) and alkaline reagent (NaOH). The pH is measured with a sensor model D0020043 Hanna Instruments. The signal is sent to the PLC of the brand SIEMENS S7-1200 CPU 1214-C model 6ES72344HE32QXBQ. Also, a Delta Electronics Model DOP-B03E211 HMI was integrated for Set-Point configuration and process parameters (see Fig. 2).

Fig. 3 shows the general scheme of control for the process, the output calculated by the fuzzy controller will be the dosing time of the acid and alkaline reagents.

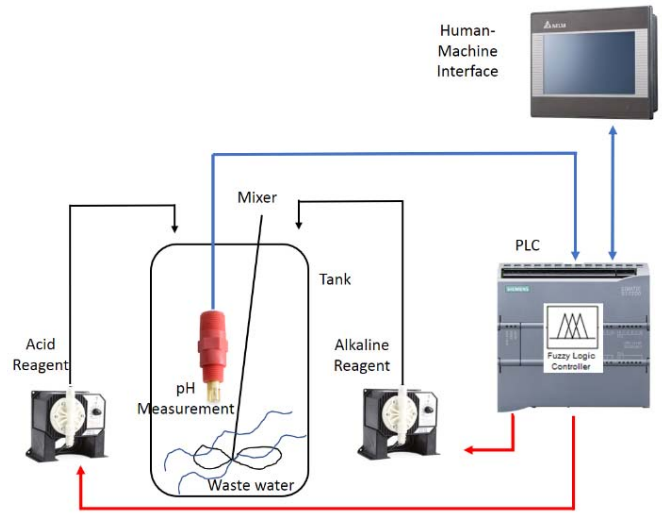

Fig. 3. Process to control.

IV. Design of PH Regulation Controller

A. Definition of inputs and outputs

The first step consisted in the definition of the inputs and outputs of the controller:

Input 1: $Error \ = \ pH\ Desired \ - \ Current\ pH$
Input 2: $Change\ of\ error \ = \ Current\ Error - Past\ Error$
Output 1: $Acid\ reagent\ activation\ time\ (Seconds)$
Output 2: $Alkaline\ reagent\ activation\ time\ (Seconds)$

B. Membership functions for inputs and outputs

Then, the linguistic variables were established for each input, as well as their membership functions. For the *error* and *change of error* inputs, the same membership functions were established (as triangular): NL (Negative Large), NM (Negative Medium), Z (Zero), PM (Positive Medium) and PL (Positive Large). The *error* input can vary in a maximum range of 14 to -14 pH (for example, if pH desired is pH = 5, and current pH is pH = 8, then, error = 5 - 8 = -3 units.), likewise, *change of error* input can vary in a range of 5 to -5 units, depending on the pH of the waste water and the desired setting value. Fig. 4(a) and 4(b) shows the membership functions and universe of discourse for the inputs.

Regarding the outputs, the activation time of the dosing pumps was established by the membership functions: TZ (Time Zero), TS (Time Small), TM (Time Medium) and TL (Time Large). This time can vary in a range of 0 to 10 seconds, for example, if the controller calculates an activation time of 1 second, then the pump will remain off 9 seconds, that is to say, the activation/deactivation times are complementary to 10 seconds since the pumps are on-off.

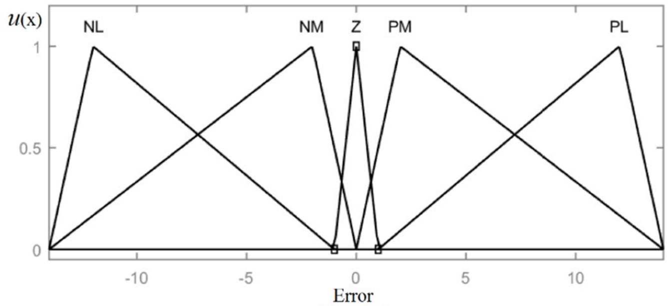

Fig. 4(*a*).

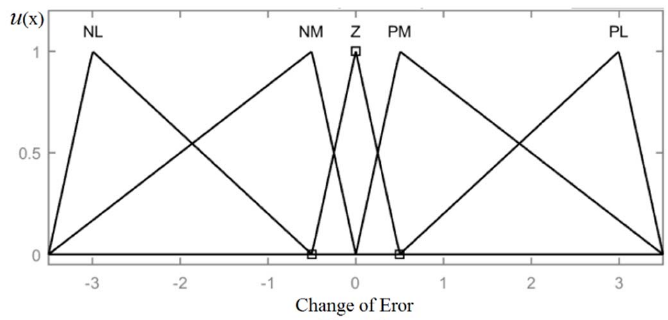

Fig. 4(*b*).

Fig. 4. Membership Functions for inputs *Error* (*a*) and *Change of Error* (*b*).

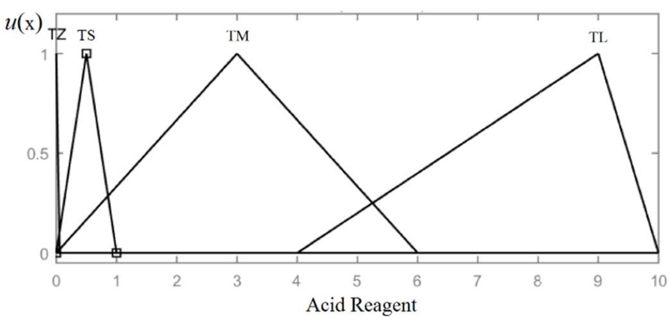

Fig. 5(*a*).

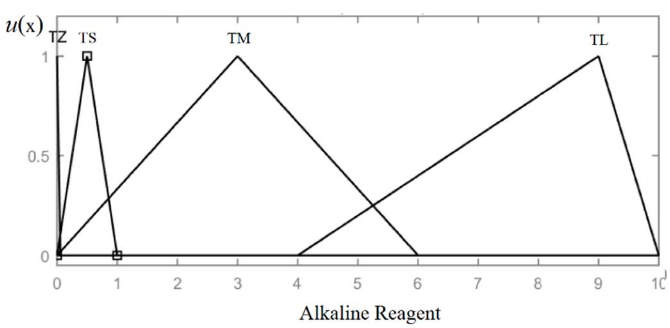

Fig. 5(*b*).

Fig. 5. Membership Functions for outputs *Time Dosification Acid Reagent* (*a*), and *Time Dosification Alkaline Reagent* (*b*).

C. Rules of control

The control rules were established as follows:

1. If (Error is PL) and (Change_Error is PL) then (Pump_Acid is TZ) and (Pump_Alkaline is TL).
2. If (Error is PL) and (Change_Error is PM) then (Pump_Acid is TZ) and (Pump_Alkaline is TM).
3. If (Error is PL) and (Change_Error is Z) then (Pump_Acid is TZ) and (Pump_Alkaline is TM).
4. If (Error is PM) and (Change_Error is PL) then (Pump_Acid is TZ) and (Pump_Alkaline is TM).
5. If (Error is PM) and (Change_Error is PM) then (Pump_Acid is TZ) and (Pump_Alkaline is TS).
6. If (Error is PM) and (Change_Error is Z) then (Pump_Acid is TZ) and (Pump_Alkaline is TM).
7. If (Error is Z) and (Change_Error is PM) then (Pump_Acid is TZ) and (Pump_Alkaline is TS).
8. If (Error is Z) and (Change_Error is Z) then (Pump_Acid is TZ) and (Pump_Alkaline is TZ).
9. If (Error is Z) and (Change_Error is NM) then (Pump_Acid is TS) and (Pump_Alkaline is TZ).
10. If (Error is NM) and (Change_Error is Z) then (Pump_Acid is TM) and (Pump_Alkaline is TZ).
11. If (Error is NM) and (Change_Error is NM) then (Pump_Acid is TS) and (Pump_Alkaline is TZ).
12. If (Error is NM) and (Change_Error is NL) then (Pump_Acid is TM) and (Pump_Alkaline is TZ).
13. If (Error is NL) and (Change_Error is Z) then (Pump_Acid is TM) and (Pump_Alkaline is TZ).
14. If (Error is NL) and (Change_Error is NM) then (Pump_Acid is TM) and (Pump_Alkaline is TZ).
15. If (Error is NL) and (Change_Error is NL) then (Pump_Acid is TL) and (Pump_Alkaline is TZ).

Finally, is displayed the response surface for the outputs depending on the value of the inputs. The general design of the controller was done using the Mathworks Matlab software and the Fuzzy Logic Designer toolkit. The control rules were raised according to the experience of a chemical engineer who is skilled in wastewater treatment.

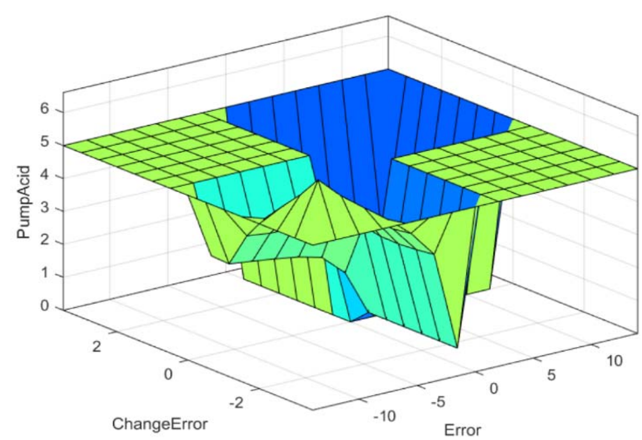

Fig. 6. Response surface for output *Time Dosification Acid Reagent.*

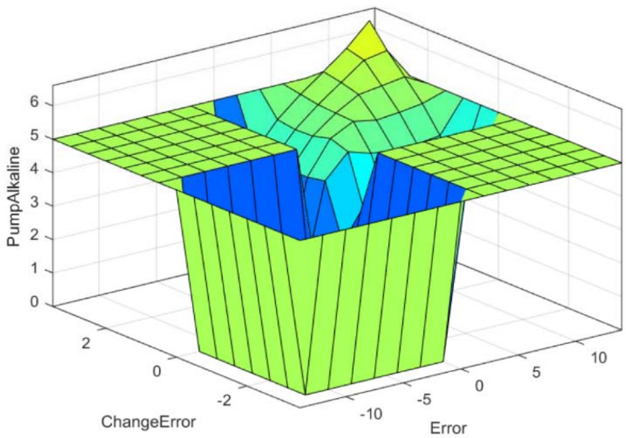

Fig. 7. Response surface for and *Time Dosification Alkaline Reagent*

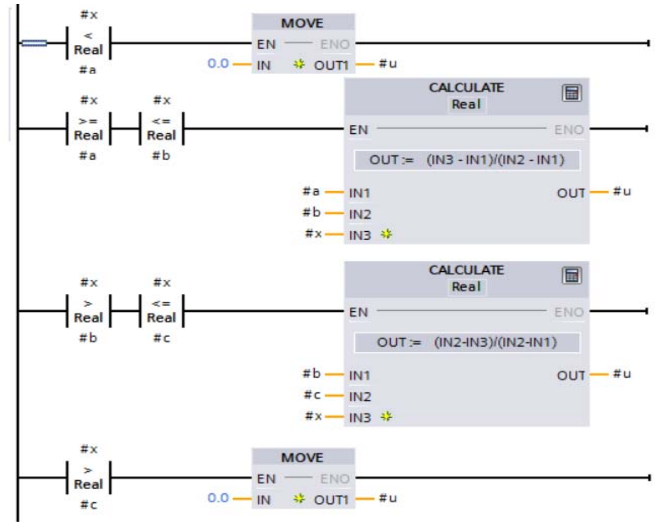

Fig. 9. Function block to calculate the degree of membership of the inputs implemented in the PLC.

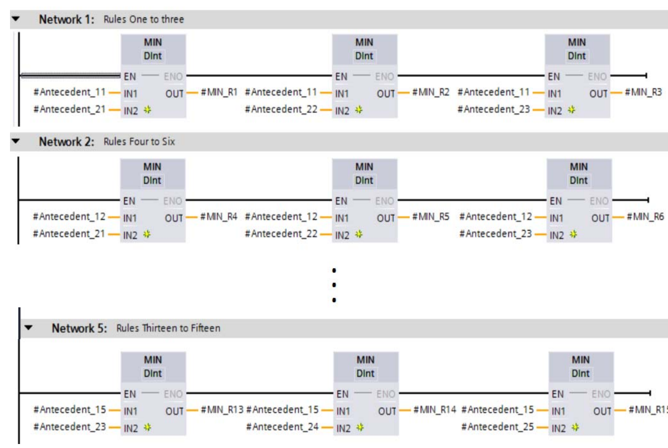

Fig. 10. Inference of the control rules.

V. IMPLEMENTATION OF FUZZY CONTROLLER IN THE PLC

The next step was to *empty* the information regarding the controller design in the PLC. For this, the following methodology was established:

A. *Fuzzification*

This step consists in obtaining a membership value *μ(x)* of the inputs. As it was observed in the previous section, the domain of the linguistic variables of inputs is formed by triangular functions, whose mathematical expression is:

$$\mu(x)=\begin{cases} 0 & if \quad x\le a \\ \dfrac{x-a}{m-a} & if \quad x\in(a,m] \\ \dfrac{b-x}{b-m} & if \quad x\in(m,b) \\ 0 & if \quad x\ge b \end{cases} \qquad (2)$$

Where:

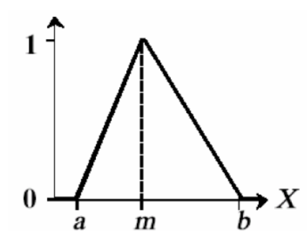

Fig. 8. Triangular membership functions for inputs.

Fig. 9 shows the function implemented in the PLC to calculate the degree of membership of the inputs.

B. *Inference*

Mamdani inference [10] method was used to establish the direct relation between the inputs and the outputs according to the 15 rules that were raised in the previous section. In the PLC, this method of inference was applied by calculating the minimum between the membership values involved in each rule (see Fig. 10).

C. *Defuzzification*

After calculating the minimum values of each rule, we proceed to calculate the output of the controller, for this, we used the method of the defuzzifier of the centers, which is given by the expression:

$$z^*=\frac{\sum_{i=1}^{M}\overline{z_l}\,w_i}{\sum_{i=1}^{M}w_i} \qquad (3)$$

Where:

$$w_i=\mu_i(M_i)=min\{\mu_1,\mu_2,\ldots,\mu_k\} \qquad (4)$$

$\overline{z_l}$ (equation 3) represents the geometric center of the *i-th* diffuse set, μ_k represents the number of fuzzy sets involved in the antecedent of the *i-th* rule. The value of the output variable *z** is determined by the average of the centers of the fuzzy output sets *M* with the weights *w* being equal to the height of the corresponding fuzzy sets. For the calculation of the crisp output in the PLC, a new function block was created:

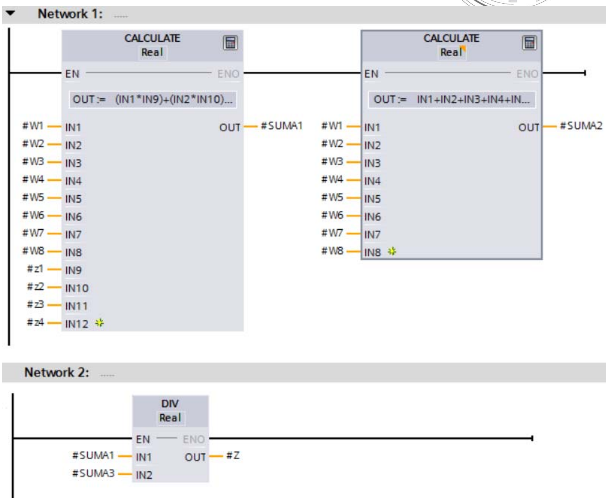

Fig. 11. Function block for calculating the output of the fuzzy controller.

VI. Results

In the first run, a sample of water was taken which had a pH = 6.99. However, the aim is to adjust it to pH = 10. The operation of the controller was very satisfactory, since reached the desired value, in the end, the error was set at pH = 0.03 units, as shown in Fig. 12(*a*).

A second adjustment test shows the efficiency of the controller, as the process pH reached the desired value, in this experiment, the initial pH of the water was pH = 7.5, and the desired value was pH = 4. In this test the steady-state error was pH = 0.04 units (Fig. 12(*b*)).

A third test was performed, the waste water had an initial pH = 7.79, now, again it is desired to set the final value at pH = 10. The behavior of the process variable as a function of the controller's action is observed in Fig. 12(*c*). process variable approaches the desired value, the time is getting shorter.

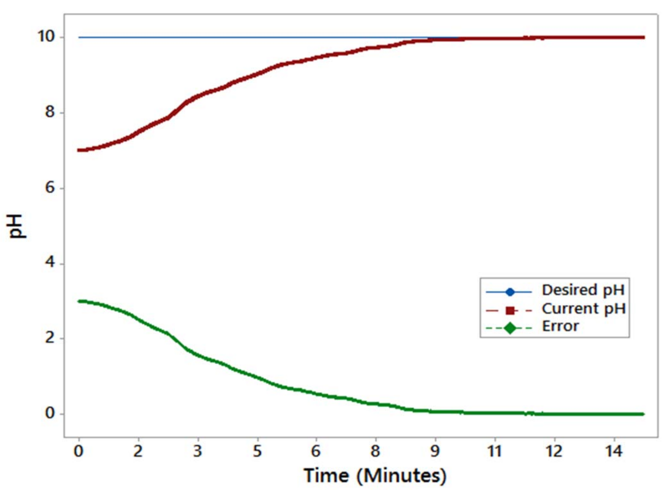

Fig. 12(*a*).

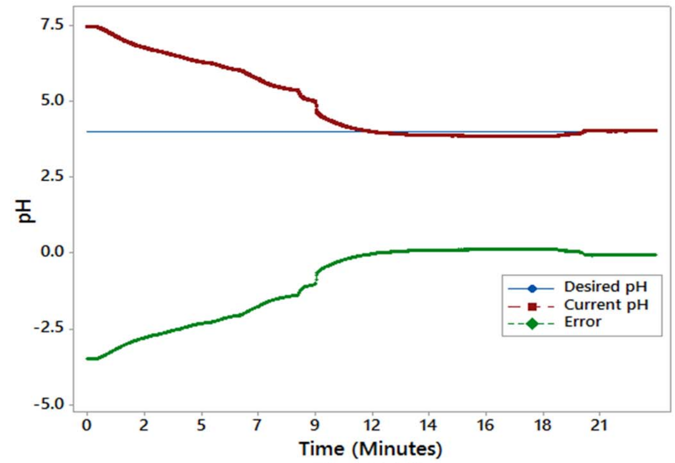

Fig. 12(*b*).

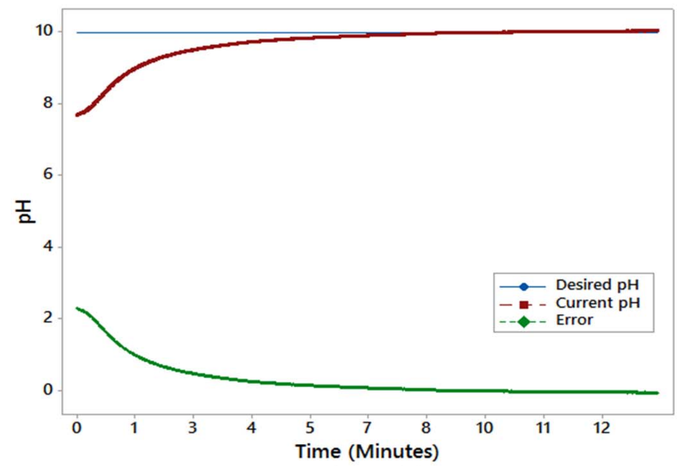

Fig. 12(*c*).

Fig. 12. Behavior of pH variable during the first, second, and third test, 12(*a*), 12(*b*), 12(*c*), respectively.

The behavior of the dosing alkaline pump in the first run is observed in Fig 13(*a*). It should be noted that the chemical reagents were diluted in concentrations of 0.25 liters of reagent per 4.75 liters of water, in order to decrease the inertia when dosing the reagents.

The control signal for dosing pump acid reagent in the second run is shown in Fig. 13(*b*), Although a slight over-pass occurs, the controller corrected the dosage of the acid reagent and turned on the alkaline reagent pump.

Also, the activation of the alkaline reagent dosing pump in the third run is shown in Fig. 13(*c*), note that due to the excellent performance of the controller, acid reagent dosage was not necessary.

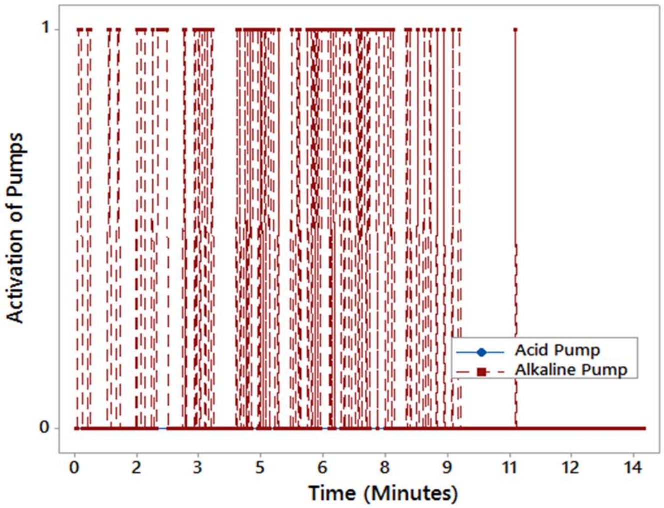

Fig. 13(a).

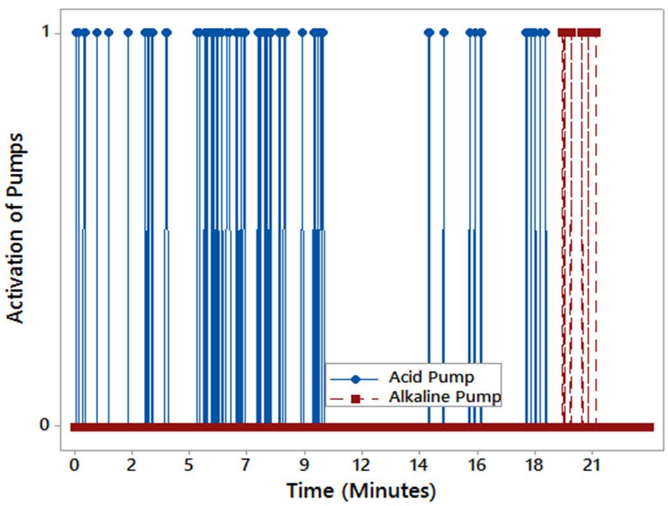

Fig. 13(b).

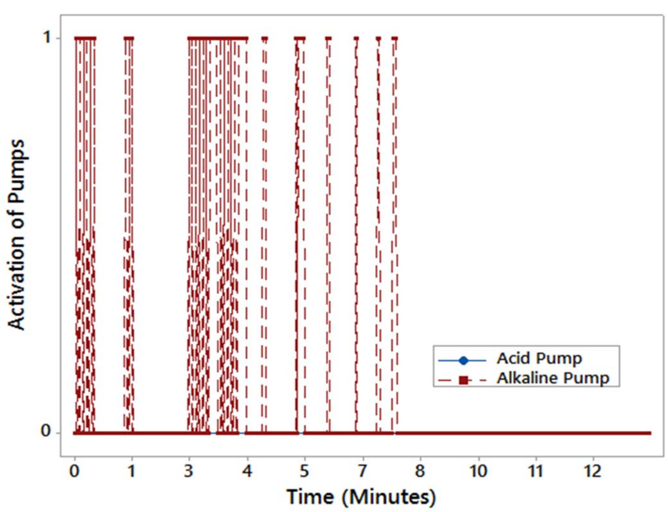

Fig. 13(c).

Fig. 13. Controller performance for pH adjustment during first (13(a)), second (13(b)) and third (13(c)) test.

VII. Conclusions

Although the mathematical model of the system to be controlled was not deduced, it was not necessary since the controller's performance for pH regulation was very good. The final error was established, on average, at pH = 0.035 units. The implementation of the fuzzy controller in the PLC was easy and practical since the selected model has the necessary tools for its application. The performed tests demonstrate that the operation of the controller meets the purpose for which it was designed, also, it is documented that the fuzzy logic is an excellent choice for complex systems requiring simple solutions.

VIII. References

[1] R. Chang, Chemistry, New York: McGraw-Hill, 2010.

[2] M. Mohd, "A Fuzzy Logic Controller of Two-Position Pump with Time-Delay in Heavy Metal Precipitation Process", *International Conference on Pattern Analysis and Intelligent Robotics,* vol. I, nº 6, pp. 171-176, 2011.

[3] T. Gustafsson and K. Waller, “Dynamic modeling and reaction invariant control of pH”, *Chemical Engineering Science,* vol. 38, pp. 389-398, 1983.

[4] R. Kuehl, Statistical Design Principles and Research Analysis, California, U. S.: THOMSON LEARNING, 2001.

[5] D. Montgomery, Design and Analysis of Experiments, New York: WILEY, 2013.

[6] Abdullah and Brahim, “A review of pH neutralization process”, *IEEE Trans. On Intelligent and Advanced Systems,* vol. 2, pp. 594-598, 2012.

[7] B. Kelkar and B. Postlethwaite, “Study of pH control process using fuzzy modeling”, *International Conference On Control, Coventury, U.K.,* nº 1, pp. 272-275, 1999.

[8] P. Ponce, Inteligencia artificial con aplicaciones a la ingeniería, Primera ed., México D.F.: Alfaomega, 2010.

[9] H. Adeli and S.L. Hung, Machine Learning, Neural Networks, Genetic Algorithms and Fuzzy Systems, New York: WILEY, 1995.

[10] J. Jantzen, Foundations of Fuzzy Control, Sussex, England: WILEY, 2007.