Mathematical Modeling and Development of a Low Cost Fuzzy Gain Schedule Neutralization Control System

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***Abstract*— This paper has focused on the development of a Low-Cost Fuzzy Gain Schedule Neutralization Control System. The system dynamics has been identified for different operational conditions and the empirical models parameters were calculated. The implementation and instrumentation of a typical Neutralization System using low cost elements, with an appropriate monitoring, control and data acquisition of the process variables has been successfully implemented, as well as the Fuzzy Gain Schedule pH neutralization controller. As inputs it has been used the Auxiliary Variable, defined with the linguist terms as Acid, Neutral and Alkaline by three trapezoidal membership functions, as well as the control error and the change in the control error, both defined by five triangular membership functions. The controller outputs were defined for the Acid and Alkali pumps by 18 triangular membership functions and it was defined a set of 50 fuzzy rules. The development of the control system considered in this paper reveals an attractive industrial application perspective, representing a potential application for water consumption reduction in industry, based on low cost elements.**

***Index Terms*— Fuzzy Control, Mathematical Modeling, Neutralization, Water Consumption Reduction**

I. INTRODUCTION

Water is an essential natural resource for any human activity and, for that reason, there is a need to minimize its consumption, as well as return it to the environment with minimal contamination due to its limited capacity for self-purification [1]. Thus, there is a need of balance between the increase of production without depleting natural resources, thus generating smaller amount of waste as well as recovering and reusing water as much as possible.

The pH neutralization process is used in different industrial processes such as wastewater treatment, chemical and biotechnological processes. This process make it possible to reuse the water for wide range of applications in the production, such as the first rinse for cleaning equipment in the food industry, or any need that allows the application of recycled water.

Since any system has an inherent cost, with financial advantages in reducing the cost in industry, the aim of this paper is the development of a low cost prototype neutralization system using a Fuzzy Gain Schedule Controller and an Arduino board based on the system's dynamic behavior.

II. THEORETICAL FRAMEWORK

Different processes in industry use the pH neutralization process, such as wastewater treatment and chemical process. A large amount of research projects has been conducted regarding the pH neutralization process, which is justified by the high non-linearity and dead time inherent in the process. That reinforces the need of studies regarding modeling and control strategies [8].

Directly related to the wastewater neutralization control, there is a need of balance, not exhausting the natural resources with the production increase, generating less waste, as well as recovering and reusing water as much as possible, which strengthens the idea of the control strategy studies.

The above mentioned is complemented by [3], describing that climate change, the limits of water supply and the continued growth of the population have intensified efforts to reduce water consumption, as well as the amount of water wasted.

Searching for different control strategies, the development of Artificial Intelligence (AI) techniques in recent years increasingly occupies a prominent position in research of industrial processes control and gradually used in industrial plants successfully, which is the case of the fuzzy control [5].

One important step for the fuzzy control system project is the system behavior response knowledge, which can be based in several methods such as the process knowledge (based on experience) or obtained from the step response curves, where it is possible to extract low order approximate models, which describes the dynamic behavior of the process [6].

A typical fuzzy is described by [4], where the controller is composed by: i) the input signal fuzzyfication (converting the sensor signal in fuzzy values); ii) a fuzzy engine, which handles the rule inference (based on input-output relations

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conditions); and iii) defuzzyfication, generating a continuous output signal for the actuators.

There are different possibilities of implementing fuzzy controllers, such as the fuzzy controller presented by [7], where the authors simulate the fuzzy controller with one input and two outputs.

A different fuzzy controller structure has been developed and simulated by [4] using an auxiliary variable to detect in which region the process is operating, with the objective of compensating the gain process non-linearity; this system has been implemented by [9] using low-cost instrumentation.

III. Material And Methods

A. Experimental system

The prototype developed for the experimental tests was mounted on the Laboratory E209-B of the Department of Automation Science and Engineering of the Tampere University of Technology.

A simplified general diagram of the studied system is presented on the Fig. 1, where AE1 represents the pH measured sensor (Haoshi - FIT0348 low cost glass electrode pH meter). The signal converter (and AT1) consists on a motor shield (L298N chip and two output channels - to amplify the analog output signal) and a pH-Voltage converter (to convert the pH meter signal into Volts).

For the acid and alkaline solution injection, it has been used 2 pumps (Drift - 12VDC/2A).

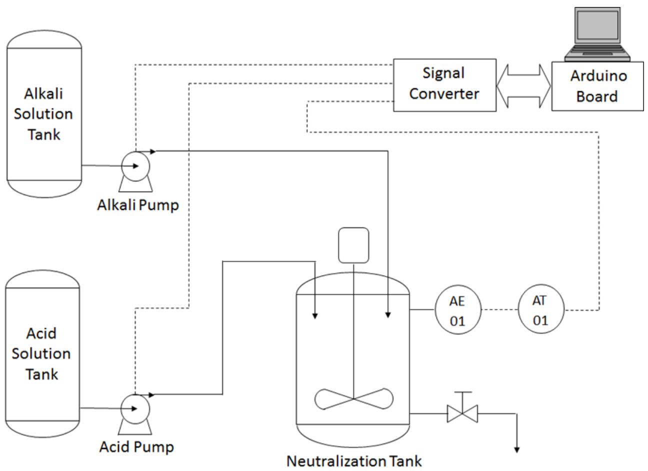

Fig. 1. Simplified general diagram for the studied system.

The system works as described in the sequence (referring to the Fig. 2). The Neutralization Tank (2) collects the water that is going to be neutralized. The pH meter sends the pH value for the Arduino board and this signal is sent to the computer. Based on the control system, the acid pump (5) or the alkali pump (6) controls the acid and alkali solution injection from the tanks - acid (1) and alkali (3) – to the Neutralization Tank (2). The mixer (4) constantly homogenizes the neutralization tank solution.

The electronic system used to collect data is composed by a computer, an Arduino Mega board and the Labview® tool used to monitor, acquire data and control the process in real time.

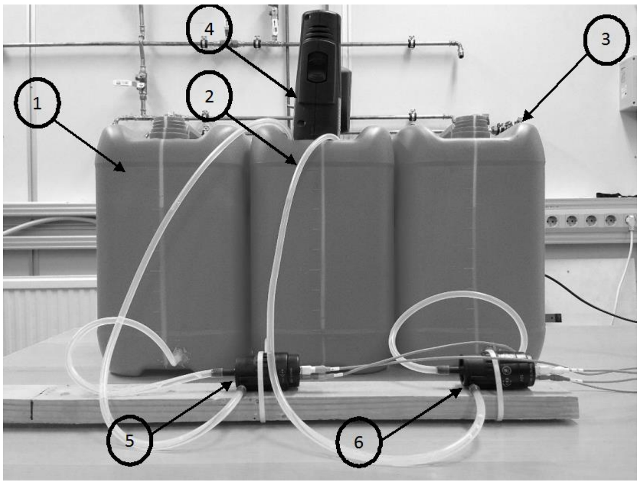

Fig. 2. Neutralization System prototype for the studied system.

Also, it has been developed an application using Labview® dedicated to collect data for the proceeded experiments, from which the data for the system behavior study and the control of the system has been developed.

To make it possible the integration between the Arduino board and the Labview tool it was installed the Arduino Toolkit, then the Interface for Arduino Firmware was loaded in the Arduino board. After that, it was possible to develop the application.

B. Open Loop Tests

In order to know the system behavior for the instrumentation used, mainly the low-cost pumps and pH meter, it has been developed an application using the Labview tool.

Then, after calibrating the pH meter, it has been proceeded open-loop tests applying step disturbances on the acid and alkali pumps separately, making it possible to acquire the pH system response for each different step on the pumps.

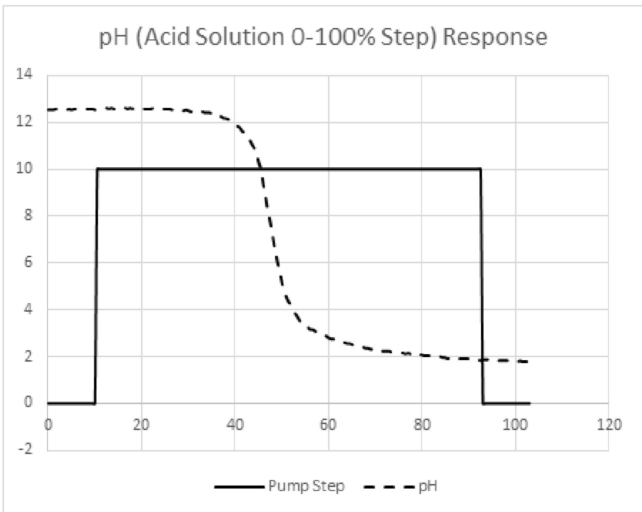

Fig. 3. Acid pump Step Response 0 to 100%.

The first step tests applied on the input were from 0 to 60%, 0 to 80% and 0 to 100% on the acid pump with the alkali pump closed. Then, the same step tests were applied to the alkali pump (0 to 60%, 0 to 80% and 0 to 100%) with the acid pump closed. The system response for the step from 0 to 100% is presented on Fig. 3 to illustrate the open loop tests response.

C. FOPDT Model Development

After obtaining the open loop test responses, the process models were calculated using the FOPDT (first order plus dead time) approach, which is largely used to represent industrial processes dynamics [2].

The non-parametric identification employs the response curves of the process when excited by input signals as step changes. From the curves obtained, it is possible to extract low order approximate models, which describes the dynamic behavior of the process [6].

Since the process is non-linear, it has been defined three regions for the acid and three regions for the alkaline step, and calculated the transfer functions using the Smith Method in order to develop the rules and the membership functions.

The process parameters, K_P (process gain), τ_P (process time constant) and θ_P (process transport delay) were calculated using the process response curve method (for the pH response) to a step change in the pump voltage.

The empirical models parameters are presented on Table I (acid pump) and Table II (Alkali pump).

TABLE I
EMPIRICAL MODELS PARAMETERS - ACID PUMP

Step Change (%)	Gain K_p (pH/%)	Transport Delay θ_p (s)	Time constant τ_p (s)
0-60	1.45	311.5	8.25
0-80	1.075	184.5	13.5
0-100	0.76	297.25	8.25

TABLE II
EMPIRICAL MODELS PARAMETERS - ALKALI PUMP

Step Change (%)	Gain K_p (pH/%)	Transport Delay θ_p (s)	Time constant τ_p (s)
0-60	1.31	49.5	13.5
0-80	0.99	35	9.75
0-100	0.71	28	7.5

Based on the obtained pH responses and the models presented, it was possible to identify the system behavior response. This information was used for the Fuzzy Controller development.

D. Fuzzy Controller Membership Functions Development

Once known the system behavior, the next step was the Fuzzy Controller Development. After a research on the Neutralization System Controller and after testing some different techniques, the fuzzy controller structure proposed by [7] was used as a starting point for the development of the Low Cost pH Neutralization System proposed in this paper.

The process has been divided into three regions of non-linear gains: pH Acid, pH Neutral and pH Alkali. The process gain, as [7] states, is low in the pH Acid and pH Alkali regions (i.e. considerable changes have to be made in the acid/alkali pump, to make appreciable changes in the pH value); and the process gain is high in the pH Neutral region (i.e. a small change in the acid/alkali pump, results in a large change in the pH value).

This division was used for the Auxiliary Variable (AV) definition as an input for the Fuzzy Gain Schedule Controller. The three trapezoidal fuzzy membership functions for this variable (based on the process knowledge and after practical tests) were defined with the linguist terms as Acid, Neutral and Alkaline and the discourse universe between [1, 14] (presented on Fig. 4).

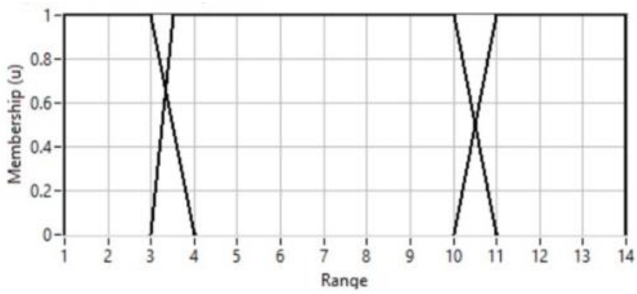

Fig. 4. Membership Function for the Auxiliary Variable.

The next step was to define the other fuzzy membership functions related to the controller inputs. The control error has been defined by five triangular membership functions and the linguist terms defined were NL (negative large), NS (negative small), Z (zero), PS (positive small) and PL (positive large) with the discourse universe between [-7, 7] - since pH range is 14; and the change in the control error has the same membership functions but with discourse universe between [-2, 2] – based on practical tests.

Finally it has been defined the fuzzy membership functions related to the controller outputs for the Acid and Alkali pumps (18 triangular membership functions) and the linguist terms defined were: Z0Alkali, AlkaliPumpOff, SlowAlkali, AverageAlkali, FastAlkali, zz0Alkali, zSlowAlkali, zAverageAlkali, zFastAlkali, Z0Acid, AcidPumpOff, SlowAcid, AverageAcid, FastAcid, zz0Acid, zSlowAcid, zAverageAcid and zFastAcid. The discourse universe has been defined between [0, 90] – using the pump range from 0 to 90%.

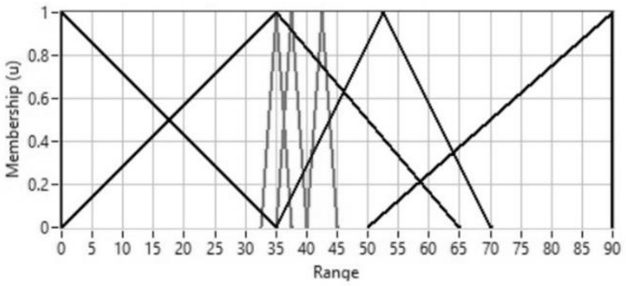

Fig. 5. Membership Function for the Controller Output.

The membership function for the controller outputs are presented on Fig. 5.

E. Fuzzy Controller Rules Development

The next and final step for the Fuzzy Gain Schedule Controller development was the definition of the rules. The defuzzification method defined was Center of Area.

It was defined the rules for each process region. As [5] presented, by means of the Auxiliary Variable (AV), it was possible to simplify the rules, and it was defined a set of 25 fuzzy rules for the AV = neutral and 25 rules for AV = not-neutral. The tool for the rules implemented on the Labview® is presented on Fig. 6.

Fig. 6. Tool for the rules implementation on Labview®.

The rules are divided in two different kinds, one group for AV = neutral and the other for AV = not-neutral. Two rules examples (from the set of 50 rules) are presented below, to illustrate the rules defined:

1) ***IF*** *'AV'* ***IS NOT*** *'Neutral'* ***AND*** *'Error'* ***IS*** *'NL'* ***AND*** *'DeltaError'* ***IS*** *'NL'* ***THEN*** *'Acid Pump'* ***IS*** *'FastAcid'* ***ALSO*** *'AlkaliPump'* ***IS*** *'AlkaliPumpOff'*
2) ***IF*** *'AV'* ***IS*** *'Neutral'* ***AND*** *'Error'* ***IS*** *'NS'* ***AND*** *'DeltaError'* ***IS*** *'NS'* ***THEN*** *'Acid Pump'* ***IS*** *'zFastAcid'* ***ALSO*** *'AlkaliPump'* ***IS*** *'AlkaliPumpOff'*

F. Fuzzy Gain Schedule Controller Implementation and Application

After defining and implementing the Fuzzy Gain Schedule pH Neutralization Controller using the Labview tool, the block diagram is presented on Fig. 7 and the data acquisition system front panel with all the variables defined is presented on Fig. 8.

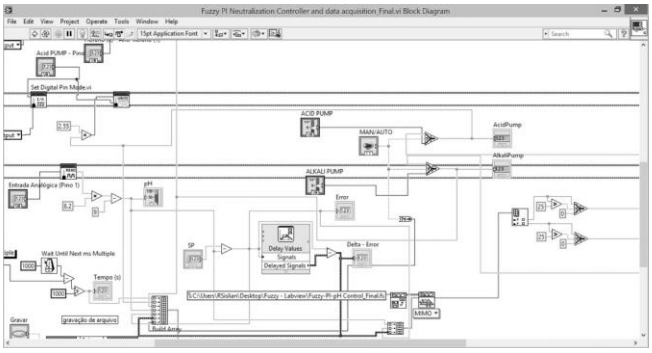

Fig. 7. Block Diagram of the Fuzzy Gain Schedule pH Neutralization Control.

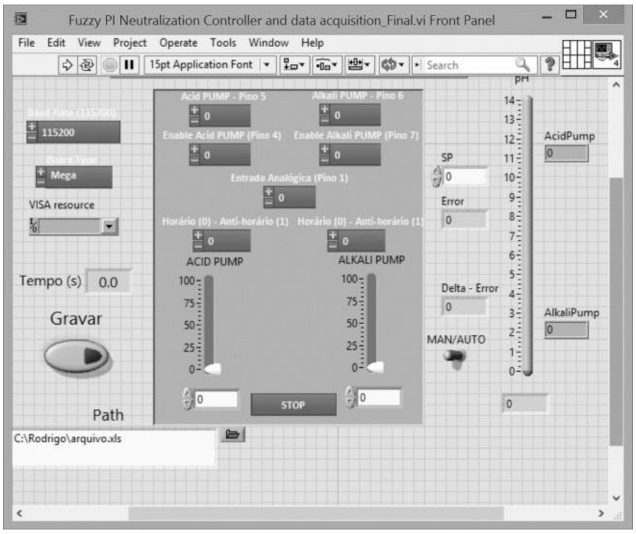

Fig. 8. Front Panel of the Fuzzy Gain Schedule pH Neutralization Control System.

To evaluate the control performance, it has been set-up the pH set-point to 7 (for pH neutralization) and inserted a alkali solution (pH 6) in the Neutralization Tank.

After the water inside the tank was neutralized, it was inserted pure acid, waiting for the system to neutralize the water and then pure alkaline solution, simulating system disturbances. It is possible to see in Fig. 9 - where it is presented the percentage of voltage sent to the pump, the pH and pH set point – the system neutralizing the pH of the water inside the Neutralization tank, showing that the

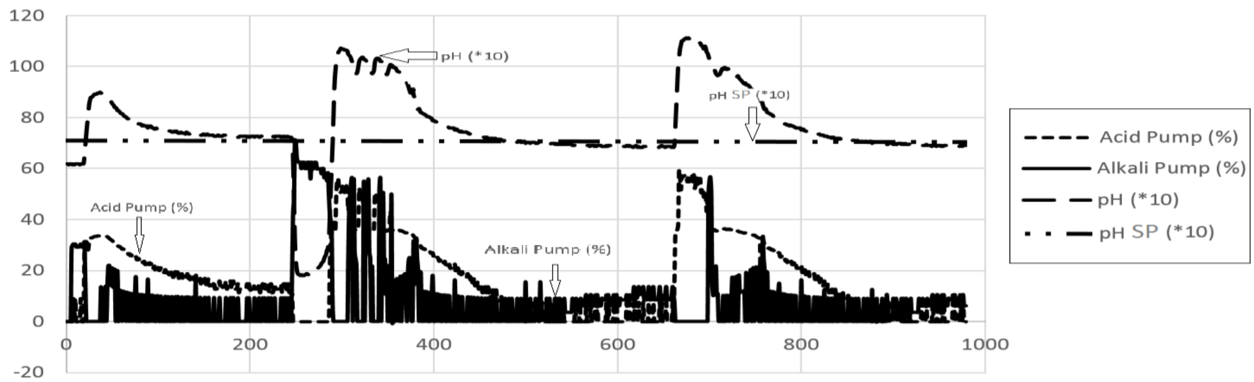

Fig. 9. pH Neutralization System Response.

neutralization control system is functional.

IV. Conclusions

The implementation and instrumentation of a typical pH Neutralization System, with an appropriate monitoring, control and data acquisition of the process variables has been successfully implemented, as well as the Fuzzy Gain Schedule pH neutralization controller.

The fuzzy controller implementation was based on the process models calculated using the FOPDT (first order plus dead time) approach, making it possible to describe the dynamic behavior of the process.

The development of the control system considered in this paper reveals an application of the non-parametric identification (mathematical modeling) and the Fuzzy Gain Schedule Control, and an attractive industrial application perspective, representing a potential application for water consumption reduction in industry, based on low cost elements, whit a rapid return on investment.

Acknowledgment

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