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Fuzzy logic-PLC-based controller for water treatment simulator system

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Abstract

The constant demand for clean water is critical for both consumption and daily activities. A water pH control system is essential for regulating and determining the concentration of acid and base values in water. Research projects often employ a Programmable Logic Controller (PLC) control system with various control methods. This serves as the backdrop for the design of a water treatment simulator, which utilizes a fuzzy logic control system. Fuzzy logic control is a reliable method that produces effective and accurate output values. Experiments conducted on the designed water treatment simulator demonstrate this. Factors influencing the relationship between the solution pump response time and the normalized water pH results are the concentrations of the pH-UP and pH-DOWN solutions. The water treatment simulator is a lab-scale water pH control system simulation tool using a fuzzy logic control mode. It uses an Outseal PLC microcontroller, a pH sensor to measure pH, a DC pump, and a solenoid valve to control the output flow. The experimental results show a significant relationship between the initial pH value of the water measured and the response time of the solution pump. Data analysis shows a positive correlation where the further the pH concentration value of the water is from the normal pH state, the higher the response time value. Factors influencing the relationship between the solution pump response time and the normalized water pH results are the concentration of the pH UP and pH DOWN solutions. The concentration of the solution is set for a pH UP of 12.2 and a pH DOWN solution of 2.2.

Keywords:
Fuzzy logic, water pH, programmable logic control, water treatment simulator, blending.

1 Introduction

Clean water is one of the most important needs in human life because clean water is always needed continuously, both for consumption and daily needs. The water, called clean or pure, is tasteless, odorless, and colorless water made up of hydrogen and oxygen because water is a solution in which almost all natural and artificial substances can be dissolved [1]. Clean water can be consumed and used in daily life when clean water meets physical quality standards, chemical quality standards, and biological quality standards [2].

In the modern industrial age, industrial control systems usually refer to the automation control systems used. Industrial control systems, where humans still play a very dominant role, have been shifted and replaced by automatic control systems as they relate to factors affecting the efficiency and productivity of the industry itself, such as the human error factor and what is provided by the industry. The most common is the Programmable Logic Controller (PLC) [3].

The potential of Hydrogen (pH) is an indicator that determines the acidity and alkalinity of a solution. A solution is acidic when the number of H+ ionic charges is greater, whereas the solution is basic when the number of H- ionic charges is greater [4]. For pH values, a scale of 0-7 is an acidic category, 7 is a neutral or saline category, and 7-14 is an alkaline category [5].

A prerequisite for clean water is water with a pH value of 6 to 7. There are various techniques for achieving an ideal pH value. One of the techniques used is the mixing technique, in which mixing techniques work through the combination or union of materials with a predetermined amount. It is a solution that raises and lowers the pH of the water so that the pH returns to normal [6]. The pH control system is essential to determine the acidity and alkali levels of the water so that it conforms to the provisions of the water pH standards [7].

Water treatment unit that supports production activities such as meeting the need for clean and potable water. Water treatment in oil and gas refineries (water treatment plants) is a process. Water is aimed at purifying water until it can be used for refinery process needs, as cooling water is used for cooling water supply of oil refining equipment such as turbine generators, production lubricants, compressors, and others. Steam is used in boiler machines as process water for clean rooms, toilet water, and drinking water to meet potable water needs [8][9].

The development of science is directly proportional to the problems that often arise in this field. This has led to the emergence of control methods for dynamic systems ranging from the simple to the complex [10]. Fuzzy Logic Control (FLC) is a control method commonly used in complex systems [11]. The advantage of FLC is that no mathematical model of the plant to be controlled is used. The FLC system schemes use the concept of fuzzy set theory to find out how this fuzzy algorithm works on the system [12][13].

Limited research on designing modular systems that allow easy reconfiguration or scaling for different water treatment scenarios aims to implement the fuzzy logic controller on a physical PLC for a water treatment simulator system.

2 Materials and Methods

The hardware devices to build this system are a water pH sensor, a water pump, a solenoid valve, a DC motor, a relay, and an Outseal PLC, which are the major components used in the construction of this water treatment simulator.

The prototype initiates the process by pumping the input from the acid and base reservoirs into the process tank, followed by the DC motor carrying out the blending process. If the pH value is less than 6, the base solution pump adds the base solution to the main/process tank to bring the pH concentration back to normal. If the detected pH value exceeds 7, the acid solution pump injects the acid solution into the process tank to bring the pH concentration back to normal. After adding the acid or base solution to the tank, we blend it for 1 minute, and then the pH sensor measures the pH concentration in the tank again. If the pH value falls between 6-7, we classify the liquid's pH concentration as normal. If the pH read is normal, then the output pump and solenoid valve on the output part of the process tank will turn on and flow water into the reservoir/output tank until the process tank is empty. Furthermore, the process will continue to run according to the initial input specified and the pH value read. The Haiwel HMI facilitates control and monitoring systems.

A water pH sensor is a pH measurement range of 0.0 to 14.0 pH. The pH meter transmitter is a sensor used to detect pH that is installed within the process tank. Fig. 1 shows the pH meter transmitter. The Modbus RS-485 communication protocol is utilized [14].

Fig. 1. pH meter transmitter.

An electrical device known as a Programmable Logic Controller (PLC) is used to control the logic state, or ON and OFF status, of a device that is attached to it. This allows the PLC to make changes to the regulatory scheme. A PLC is composed of three basic parts: input, controller, and output. Hardware with the standard features found in PLCs is known as an external PLC. Outseal Studio software is used to program this Outseal PLC. To program Outseal Studio, a ladder diagram and visual programming are used [15][16][17]. PLC is shown in Fig. 2.

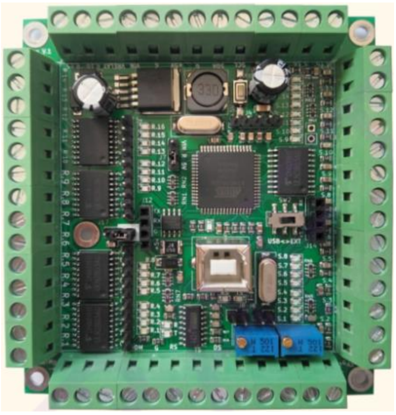
Fig. 2. PLC Outseal.

Relays are electronic components that serve as switches by using electromagnetic forces to link and disconnect electrical signals or activate and deactivate switch contacts. The mechanical and coil components make up the two primary portions of the relay. The relay's coil's job is to produce a contact magnetic field that is both ordinarily closed and normally open [18].

2.1 Fuzzy Logic

The study employs fuzzy logic to control and monitor water pH. Fuzzy is a technique or algorithm that uses fuzzy principles for modeling and decision-making [19]. Fuzzy logic consists of three approaches, namely, fuzzification with membership functions, an inference system to calculate fuzzy output, and defuzzification to create crisp output [20].

Determination of the membership function is carried out using membership triangle curves and trapezium curves. Fig. 3 and Fig. 4 are the shapes of a triangular curve and a trapezoidal curve [21].

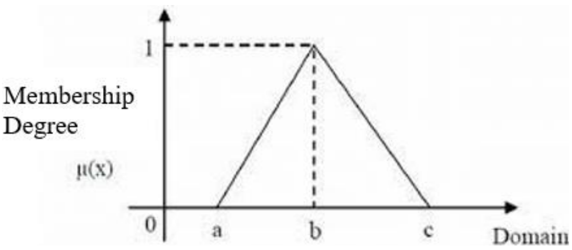

Fig. 3. Triangular curve.

In the form of a triangular curve, there is an equation for determining the membership function, namely Eq. 1.

$$\mu[x,a,b,c] = \begin{cases} 0\,, & x < a \text{ atau } x > c \\ (x-a)/(b-a), & a \leq x \leq b \\ (c-x)/(c-b), & b \leq x \leq c \end{cases} \quad (1)$$

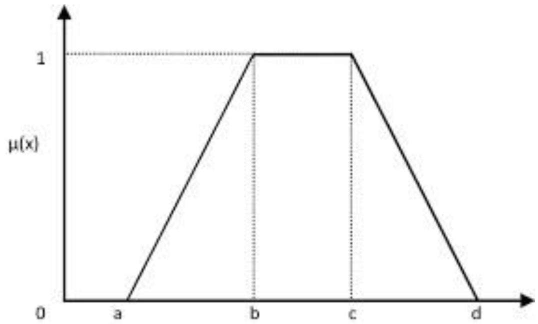

Fig. 4. Trapezoidal curve.

In the form of a trapezoidal curve, there is an equation for determining the membership function, namely Eq. 2.

$$\mu[x,a,b,c] = \begin{cases} 0\,, & x < a \text{ atau } x > c \\ (x-a)/(b-a), & a \leq x \leq b \\ 1\,, & b \leq x \leq c \\ (c-x)/(c-b), & b \leq x \leq c \end{cases} \quad (2)$$

After system fuzzification, then for system inference using the zero-order Sugeno method and defuzzification is carried out using the weight average method [5]. Eq. 3 is a zero-order Sugeno equation that works based on the if-and-then rules, while Eq. 4 is a Weight Average (WA) calculation.

$$IF\ (x_1 \text{ is } A_1)\ x\ \ldots\ x\ (x_n \text{ is } A_n)\ THEN\ z = P_1 \text{ is } x_1 + \ldots + P_n \text{ is } X_n) + q \quad (3)$$

$$WA = \frac{\alpha_1 z_1 + \alpha_2 Z_2 + \alpha_3 Z_3 + \cdots + \alpha_n Z_n}{\alpha_1 + \alpha_2 + \alpha_3 + \cdots + \alpha_n} \quad (4)$$

2.2 System Design

In this research, a fuzzy system was designed using the Sugeno method to control the water treatment simulator. Designing a fuzzy system is carried out using stages, namely fuzzification, rule base, inference system, and defuzzification [12].

1. System fuzzification

The FIS model of this study is shown in Fig. 5. In the water pH control system, the range of sensors used to measure pH values is 0–14, so in the design of the prototype, the membership function was designed with a trapezium-type triangle. The linguistic variables for the input and outputs are:

a. Water pH: {very small, small, normal, big, very large}
b. pH UP: {shut up, currently, fast}
c. pH DOWN: {shut up, currently, fast}.

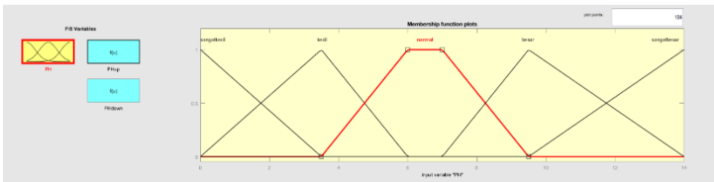
Fig. 5. Fuzzy inference model for water pH.

Table 1 is the membership function input for measuring water pH.

Table 1. Membership function input

Name	Type	Parameter
Very small	trimf	0, 0, 3.5
Small	trimf	0, 3.5, 6
Normal	trimf	3.5, 6, 7, 9.5
Big	trimf	7, 9.5, 14
Very large	trimf	9.5, 14, 14

Then, after designing the membership function input, the membership output will be designed. pH UP and pH DOWN are output variables; the designed output value is used for the pump start-up time based on the measured pH value; the pH UP and pH

DOWN outputs are each grouped into 3 membership functions. The parameter selection is based on results from the trial and error experiment. The selection of the numbers, where the unit is time, is based on the experiment's results, namely how long it takes to produce the desired pH value. This grouping as shown in Table 2.

Table 2. Membership function output

	pH UP	
Name	Type	Parameter
Shut up	Constant	0
Currently	Constant	60
Fast	Constant	120
	pH DOWN	
Name	Type	Parameter
Shut up	Constant	0
Currently	Constant	70
Fast	Constant	150

2. Design rule base

The fuzzy rule base is the core part of the designed fuzzy system, which functions to obtain a value based on the level of truth. The design of the fuzzy logic controller rule base is:

a. If (pH is very small) Then (pH UP is long) (pH DOWN is still)
b. If (pH is small) Then (pH UP is medium) (pH Down is still)
c. If (pH is normal) Then (pH UP is still) (pH DOWN is still)
d. If (pH is large) Then (pH UP is still) (pH DOWN is medium)
e. If (pH is very large) Then (pH UP is still) (pH DOWN is long)

Setting the system rule base is done using Matlab in the rule editor menu to be able to see the output variables from the rule base.

3. System inference

After designing the fuzzy rule base, the next stage is to carry out calculations manually using the zero-order Sugeno method with if-then rules. Examples of calculations carried out with pH values (1, 3, 6.5, 10.5, 13) for the calculations:

[R1]: *If* (pH is very small) *Then* (pH UP = 120) (pH DOWN = 0)

$\alpha predikat1 = \mu\ very\ small(1)$
$= \min\ (\ \mu\ very\ small(1))$
$= \min\ (0.71; 0.28)$
$\mu 1 = 0.28$
$Z1 = 120$

[R2]: *If* (pH is Small) *Then* (pH UP = 60) (pH DOWN = 0)

$\alpha predikat2 = \mu\ Small(3)$
$= \min\ (\ \mu\ kecil(3))$
$= \min\ (0.14; 0.85)$
$\alpha 2 = 0.14$
$Z2 = 60$

[R3]: *If* (pH is normal) *Then* (pH UP = 0) (pH DOWN = 0)

$\alpha predikat3 = \mu\ normal(6.5)$
$= \min\ (\ \mu\ normal\ (6.5))$
$= \min\ (1)$
$\alpha 3 = 1$
$Z3 = 0$

[R4]: *If* (pH is big) *Then* (pH UP = 0) (pH DOWN = 70)

$\alpha\ predikat4 = \mu\ big\ (10.5)$
$= \min\ (\ \mu\ big\ (10.5))$
$= \min\ (0.2; 0.7)$
$\alpha 4 = 0.2$
$Z4 = 70$

[R5]: *If* (pH is very large) *Then* (pH UP = 0) (pH DOWN = 150)

$\alpha predikat5 = \mu\ very\ large(13)$
$= \min\ (\ \mu\ very\ large\ (13))$
$= \min\ (0.2; 0.7)$
$\alpha 5 = 0.2$
$Z5 = 150$

4. Defuzzifikasi

At the defuzzification stage, calculations are carried out using the average formula (weight average) so that the defuzzification value is obtained:

$$Z = \frac{\sum_i^n \alpha Predikat\ i\ \times\ zi}{\sum_i^n \alpha\ Predikat\ i}$$

$$Z = \frac{(0.28 \times 120) + (0.14 \times 60) + (1 \times 0) + (0.2 \times 70) + (0.2 \times 150)}{(0.28 + 0.14 + 1 + 0.2 + 0.2}$$

$$Z = 47.252$$

2.2.1 Water Treatment Simulator Design

The water treatment simulator design contains an explanation of the Piping and Instrument Diagram (P&ID) as well as the wiring of the design shown in Fig. 6. Where Fig. 6 depicts the instruments used in the water pH control process, in the figure there are 4 pumps, one pH element (pHe) as a water pH sensor, a blending element (be) that functions as a mixer in the solution mixing process, and a flow solenoid valve (fsv). Where these elements are controlled by a pH controller element (pHce) with an electrical output signal of 1-5VDC.

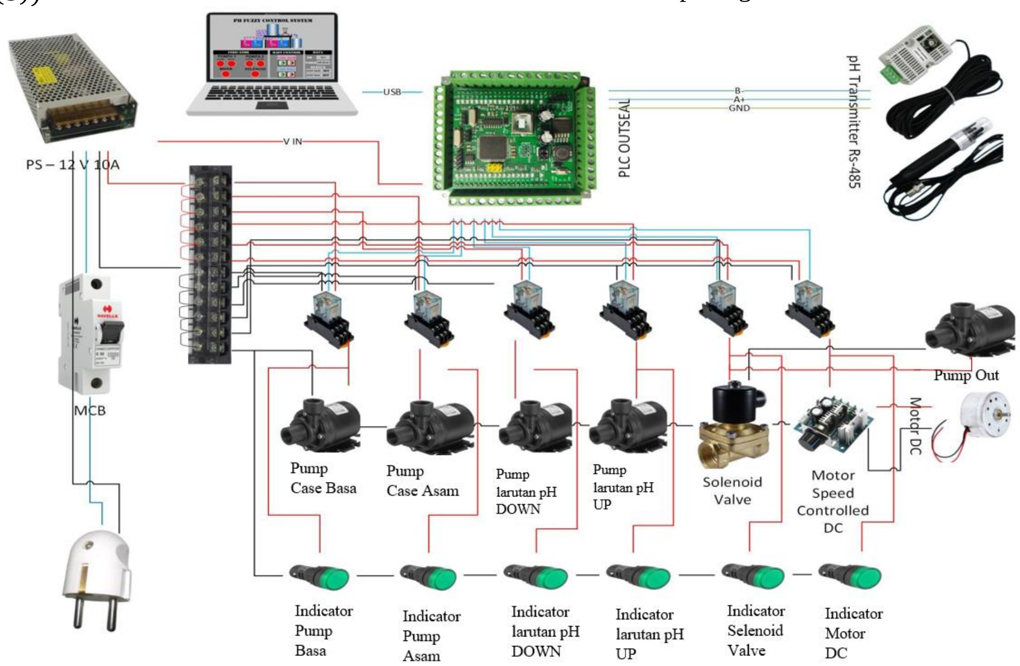

Fig. 6.Wiring design control system.

The system wiring design explains the connections from the PLC controller to the system supporting components. Fig. 6 is the hardware wiring for the water treatment simulator design, with the type of controller used being the Outseal Mega V 1.2 PLC.

Fig. 6 demonstrates the wiring design that uses 1 water pH sensor to measure the pH of the water in the process tank. Apart from that, a Main Circuit Breaker (MCB) is also used as an automatic circuit breaker if an overload or electrical short occurs. There is also a terminal block that functions to reduce the use of too many cables in the installation and to act as a connector, then the DC water pump functions to pump solution and water (acid case and base case), the solenoid valve as the final control element, the relay which functions as a switch and safety, the 12VDC motor which functions as a mixer for the solution-blending process, and pH case, which is controlled using a speed-controlled DC motor, a power supply for the voltage source, and Haiwell HMI hardware as a SCADA system and HMI for the system.

2.2.2 Human Machine Interface Design

The ladder diagram programmed in Outseal Studio is a ladder diagram of the components used in the water pH control and monitoring system. These components are the pH sensor, pump, solenoid valve, DC motor, LEDs, and push buttons. Fig.7 is the water pH control system program with Outseal Studio.

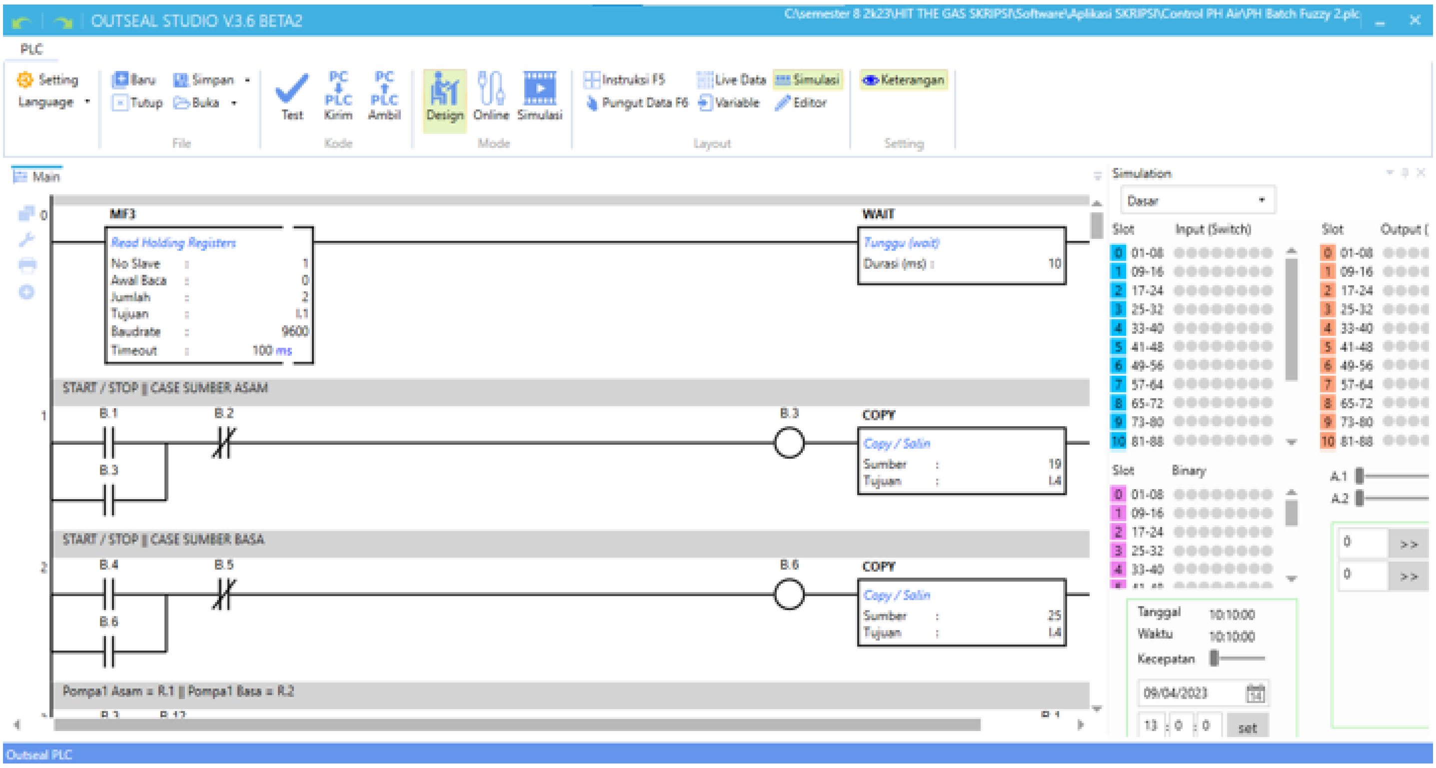

Fig. 7. Program control system water pH.

The use of Outseal PLC and SCADA-HMI has been used in various research projects [22]. The HMI design is then carried out. The HMI design on the Haiwel Cloud Scada begins with designing the components that will be displayed on the HMI, namely push buttons, LEDs, solenoid valves, and other hardware components that can be seen more clearly in Fig. 8 of the Haiwell Cloud Scada Software can be communicated using a USB port cable so that it can be connected to Outseal PLC Hardware. After designing new components, the components displayed on the HMI are addressed so that the addressing is in accordance with the addressing variables of the Outseal PLC.

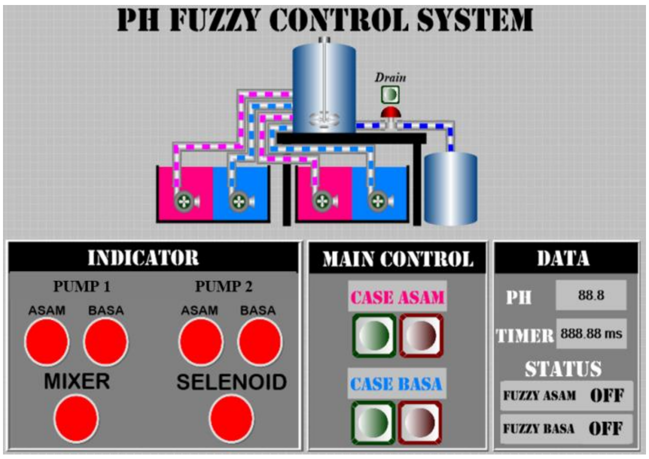

Fig. 8. Human machine interface.

3 Results and Discussion

3.1 Results

The process in the water treatment simulator starts from the input obtained from the acid and base storage tank, which will be pumped into the process tank, and then the DC motor will carry out the blending process. After that, the analog pH sensor installed on the tank wall will read the concentration of the pH value of the water inside tank. If the pH value is less than 6, then the alkaline solution pump will add an alkaline solution into the main/process tank, which aims to increase the concentration of the pH value to a normal state, but if the detected pH value is more than 7, then the acid solution pump will inject the acid solution into the process tank so that the pH concentration drops to normal. The acid or base solution is added to the tank and then blended for 1 minute, and then the pH sensor will read the pH value concentration in the tank again. If the pH value read is in the range of 6-7 then the pH concentration of the liquid in the tank is classified as normal. If the pH reading is normal, the output pump and solenoid valve at the output of the process tank will turn on and flow water into the reservoir/output tank until the process tank is empty. Next, the process will continue according to the initial input specified and the pH value read. The control and monitoring system can be done using the Haiwell cloud. In Fig. 9 is a water treatment simulator that has been designed and made.

Fig. 9 can be explained: sequentially, number 1 is the process tank, which is a container for processing and mixing pH solutions and water; in this tank, the blending process occurs. Number 2 is the control box, a place to put the PLC Outseal, relay, Haiwel HMI, and connecting cables. Numbers 3 and 4 are tanks for alkaline water and acidic water, while number 5 is a tank to hold water as input.

Fig. 9. Water treatment simulator.

3.2 Simulation Results

Testing the control system on a prototype that has been made with a batch control type where the control process is carried out sequentially. For testing on the prototype, it consists of water being input into the process tank as acid and base in the water pH control system, then measuring the pH concentration of the water. If the pH value of the water is less or more than neutral, then the pH UP and pH DOWN solution pumps will flow the solution in the process tank to re-neutralize the pH of the water.

3.2.1 First Scenario Simulation

Testing was carried out using the trial and error method. In carrying out trials, there were 30 trials with 3 prototype simulations. The first simulation in Table 3 was carried out with a solution concentration of pH UP = 9.1 and pH DOWN = 3.9, where the experimental results show that the pH concentration is acidic with the response time of the pH UP solution pump resulting in a pH value that is in a neutral state. Meanwhile, for alkaline pH concentration, the response time of the pH DOWN solution pump produces a pH value that cannot be said to be stable; this is because the pH value of the water is still more than a neutral concentration (6-7 pH). For more clarity is shown in Table 3.

Table 3. First simulation experiment results

Try to	Initial pH water	Pump response time (ms) pH UP = 9.1 and pH Down = 3.9	Measured pH
1	2.1	82.3	6
2	11	94.9	7.1
3	4.3	43.2	6.2
4	11.7	109	7.4
5	4.8	28.8	6
6	11.9	113	7.1
7	5	21.6	6
8	11.9	113	7.1
9	5.5	12	6.3
10	12.3	118	7.6

3.2.2 The Second Scenario Simulation

In the second simulation, the process of controlling water pH at acid and base concentrations was carried out with a total of 10 trials. For the acid concentration experiment, the range of measured acid pH values was 2.7-5.3 pH, while the base concentration for alkaline pH values was 9.2-11.4 pH. When the pH concentration of the water is measured at 2.7, the pH concentration of the water is classified as an acidic concentration because it is less than 6, so the UP pH solution pump flows the solution into the process tank with a time of 72 ms (milliseconds) in accordance with the fuzzy design that has been implemented to increase the concentration of the water pH so that it returns to its normal state (6-7 pH). As a result, the pH concentration of the water, which was previously acidic, was successfully returned to a neutral state with a value of (6.5 pH). Likewise, with the base concentration tested when the pH value of the water was 10.4, the solution pump response time was 86 ms (milliseconds). With this response time, the pH of the water with the base concentration could be neutralized again with a measured pH value of 6.3 pH. For more clarity is shown in Table 4.

Table 4. The second simulation experiment results

Try to	Initial pH water	Pump response time (ms) pH UP = 12.2 and pH Down = 2	Measured pH
1	2.7	72	6.5
2	9.2	56	6.4
3	2.7	73.7	6
4	9.8	50.4	6.2
5	2.8	72	6.3
6	10.1	78.9	6.3
7	5.1	48	6.1
8	10.4	86	6.3
9	5.3	16.8	6.1
10	10.9	93.1	6.3

3.2.3 The Third Simulation Scenario

Trials in the third simulation were carried out with 10 trials for the concentration of the pH UP solution = 13.1 pH and the pH DOWN solution = 1.3 pH. The acid concentration of the pH of the water tested was measured at 1.7-5.2 pH, while the alkaline concentration of the water pH was 9.7-12.8 pH. In the 7th experiment, the pH value of the blending results exceeded the normal value of water pH 7.6 with a solution pump response time of 80.6 milliseconds, which means that the pH of the water in the 7th experiment was not successfully neutralized, whereas the base concentration with the pH DOWN solution was blended with concentrated water. The base succeeded in reducing the pH concentration of the water to a neutral pH state, namely 6-7 pH. For more clarity is shown in Table 5.

Table 5.The third simulation experiment results

Try to	Initial pH water	Pump response time (ms) pH UP = 13.1 and pH Down = 1.3	Measured pH
1	1.7	90.9	6.7
2	9.7	71.8	6.5
3	1.8	89.1	6.7
4	11.9	113	6.5
5	2.1	84	7
6	12.3	120	7
7	2.3	80.6	7.6
8	12.7	86	7
9	5.2	14.4	6.2
10	12.8	127	7

3.3 Discussion

Based on information from test results from simulations I, II, and III, analysis is carried out in this discussion.

3.3.1 Effect of the Measured pH Concentration Value on the Response Time of the Solution Pump

The analysis obtained is observing the response time of the pH UP and pH DOWN solution pumps to the measured pH value concentration based on the fuzzy logic that has been designed. Apart from that, an analysis was also carried out on the pump response time and pH value, which reached normal conditions, and a calculation analysis was performed using a fuzzy system. This analysis aims to determine the type of control with efficient and effective fuzzy logic control to be applied to the prototype that has been created. Fig. 10 is a graph of the experimental results of the pump response time to the initial measured water pH value.

Fig. 10 is a graph of the effect of pH on the time the pump is turned on to drain the solution into the tank, where the pH is down to neutralize the pH of the water. For the pH solution pump, the UP range is time (0-120 ms), while the pH solution pump is down; the time range is (0-150 ms). The graph describes that if the pH concentration of water is smaller or greater than neutral, the response time of the solution pump will be longer. When the water flows into the process tank with a pH concentration of 2.1 (acid), the response time of the pump to flow the UP pH solution into the process tank is 82.3 ms. Likewise, when the pH concentration of the water is 12.3 (alkaline), the response time of the pH-down solution pump is 118 ms.

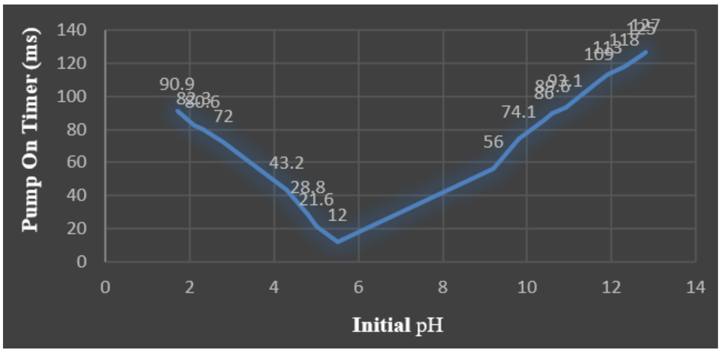

Fig. 10. Graph of the water treatment simulator experiment results.

3.3.2 Effect of Solution Pump Response Time on Water pH Value

The response time of the pH UP and pH DOWN solution pumps greatly influences the process of raising and lowering the pH concentration of the water back to a neutral state because the solution pump will flow the solution according to the normal concentration value (6-7). In the second simulation carried out, the concentration of the pH UP solution was at a value of 12.3, while the concentration of the pH DOWN solution had a value of 2.2; with this concentration value, the pH of the water, which was previously not in a neutral condition, could be normalized again. Fig. 11 is a presentation of the pH value measured based on the time the pump is on to flow the solution into the process tank.

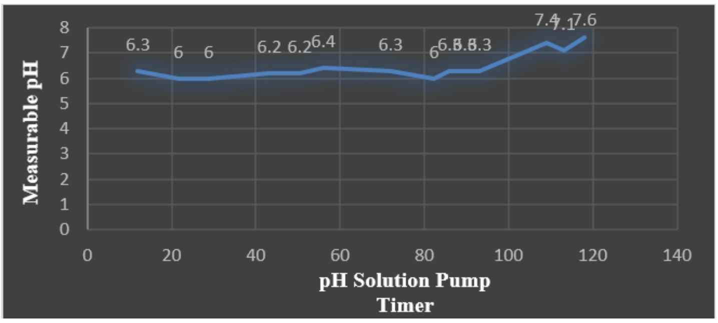

Fig. 11. Graph of the effect of pump time response on water pH values.

Based on Fig. 11, it is revealed that the longer the time the solution pump is on to flow the solution into the tank, the more stable the concentration of the pH value of the water. With a pump response time ranging from 12 ms to 118 ms and a pH solution concentration, both pH UP (12.2) and pH DOWN (2.2) can re-neutralize the pH of the water with an average pH value of 6.4. In this case, the concentration of the pH solution also affects the stability of the pH of the water, where the higher the concentration of the pH solution, the more stable the pH value of the water being neutralized.

4 Conclusion

From the design, the water treatment simulator created is a lab-scale water pH control system simulation tool with a fuzzy logic control mode using an Outseal PLC microcontroller, a pH sensor to measure pH, a DC pump, and a solenoid valve to control the output flow. From the graph of the experimental results, it can be seen that there is a significant relationship between the initial value of the pH of the water measured and the response time of the solution pump. This is supported by data analysis, which shows a positive correlation where the further the pH concentration value of the water is from the normal pH state, the higher the response time value pump the pH UP or pH DOWN solution. The research results show that factors influence the relationship between the solution pump response time and the normalized water pH results, where these factors are the concentration of the pH UP and pH DOWN solutions. The concentration of the solution is set for a pH UP of 12.2 and a pH DOWN solution of 2.2. Real research is carried out in the refinery to get the desired results by installing sensors and other equipment in the water basin.

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