# AUTOMATED ELECTRICAL CONDUCTIVITY AND PH CONTROL OF NUTRIENT SOLUTION IN HYDROPONIC SYSTEM USING MODIFIED FUZZY LOGIC CONTROL

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| By | Thanavin Mansakul |
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| Thesis Advisor | Dr. Kanticha Kittipeerachon |

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The Graduate School of Thai-Nichi Institute of Technology has been approved and accepted as partial fulfillment of the requirement for the Master's Degree

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THANAVIN MANSAKUL: AUTOMATED ELECTRICAL CONDUCTIVITY AND PH CONTROL OF NUTRIENT SOLUTION IN HYDROPONIC SYSTEM USING MODIFIED FUZZY LOGIC CONTROL. ADVISOR: DR. KANTICHA KITTIPEERACHON, 82 PP.

The hydroponic system is one of the most techniques that farmers have usually applied growing some vegetables, herbs, and fruits. Water and nutrient solutions have been mixed and then flowed through the roots or soaked the roots to provide minerals and water for plant growth. However, the technique needs a human resource to control mixed solutions frequently, namely electrical conductivity and pH, because these factors endanger the plant's roots directly, such as acidity toxic, high concentration, and low concentration. Hence, automatic methods have been necessary for controlling solutions to reach a target interval and take excellent response time to achieve goals. This thesis presents a fuzzy logic control and its application to control electrical conductivity and pH in nutrient solution automatically. The fuzzy logic controller is designed by referring to experienced human adjustment. Then, an electronic control box consisting of Arduino, sensors, and pumps is built. The designed algorithm of the fuzzy logic controller is uploaded and ready for a prototype. According to the experimental results, the system can operate automatically following the designed control algorithm and can reach the determined target. Furthermore, the system can save human costs, and also a farmer can prepare inventory well.

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| Graduate School | Student’s Signature……………………. |
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Finally, I praise my parents and my friends, who always support every role of my life.

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# Chapter 1
# Introduction

This chapter describes the background of research titled automated electrical conductivity (EC) and pH control of nutrient solution in the hydroponic system using modified fuzzy logic control. In a hydroponic system, EC and pH of the nutrient solution are usually maintained in order. The nutrient solution will conform to the plant type because the nutrient solution is one of the main factors that will affect the plant, such as damaged root and some minerals absorption problem.

## 1.1 Background

The world's population has increased gradually and will be 9.3 billion in 2050. Therefore, high-yield crop production has been expected to provide food for humans adequately. However, many factors, such as unusual weather, water shortages, and insufficient available land, have threatened crop production [1]. Hydroponics is a method to cultivate plants by using nutrient solution and water without soil. Scientists primarily use this method as a research tool to study plant nutrient and root function. Scientific achievements have received and developed to a commercial-stage. Now many types of soilless systems have been applied for growing vegetables and ornaments in greenhouses. Since greenhouses have been modified by using plastic screen cover and climate control system to protect the cultivation system, soilless cultivation has offered high quality and out-of-season products [2]. For leafy vegetables, several hydroponics techniques have been presented. Water and fertilizer are mixed in a nutrient solution tank, and then the nutrient solution goes through plant roots to supply minerals and come back to the tank. This process is called a recirculated system. Therefore, unabsorbed nutrients and water can be approximately known by measuring the nutrient solution tank [3].

The volume of fertilizer dispensed into a nutrient solution tank depends on the type of plant, and the quantity of electrical conductivity (EC) needed. The EC value, which indicates the concentration of the nutrient solution in a mixing tank, is usually measured to check whether the nutrient quantity is appropriate [4]. In the Japanese standard nutrient solution, the EC of about 1200-1600 µS/cm is suitable for lettuce. An excess and a lack of nutrients influence plant growth; therefore, the system that can continuously control and keep nutrient levels in the target range is necessary. Furthermore, the nutrient solution's pH value is monitored and controlled because over acid and over alkaline result in the damaged cell membrane of the plant's root, and some minerals absorption problems. Generally, pH should be 5.0-6.0 for leafy plants [5].

An EC and pH control in a hydroponic system requires a lot of and experienced employees because of a large area and many agricultural processes. Moreover, monitoring EC and pH values in nutrient solutions all the time is tedious for humans, so using an automatic monitoring system instead will be very helpful. Nowadays, technologies are essential to support human activities to be more comfortable and faster. Similarly, control techniques can support farmers to reduce workforce and complicated processes.

This research presents a fuzzy logic control technique whose defuzzification method is modified for automatically controlling EC and pH of nutrient solution in a hydroponic system.

## 1.2 Objectives

1.2.1 To present a modified fuzzy logic control method for EC and pH control of the nutrient solution.

1.2.2 To create a prototype for verifying the design method.

## 1.3 Scope of the study

1.3.1 Study hydroponic systems and fuzzy logic controls.

1.3.2 Create a prototype system.

1.3.2.1 The deep flow technique (DFT) is used in this research.

1.3.2.2 The size of the nutrient solution tank is 6 liters.

1.3.2.3 Nitric and Phosphoric acid are used as acid, tap water is used instead of alkaline.

1.3.3 Design nutrient solution control systems:

1.3.3.1 EC control

1.3.3.2 pH control

1.3.3.3 EC and pH control

1.3.4 Verify the designed control systems with the prototype.

The prototype of this research is shown in Figure 1.1

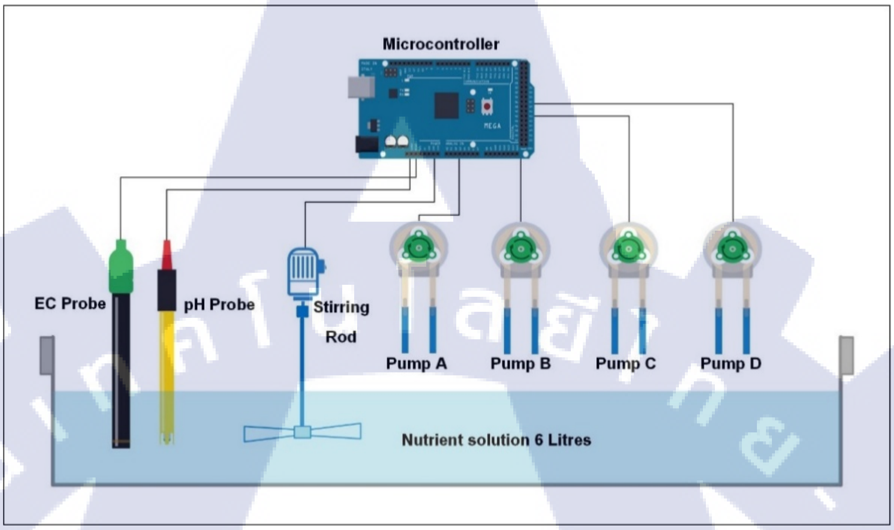



Figure 1.1 The prototype of this research

## 1.4 Expected results

1.4.1 The system can operate all day automatically without human.

1.4.2 The system can maintain EC and pH values within target ranges.

## 1.5 Research plan

The research schedules are from January 2019 to April 2020.

Table 1.1 Research plan

| **Research Methodology** | **2019** | | | | | | | | | | | | **2020** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** |
| 1. Hydroponic system practice and learning | | | | | | | | | | | | | | | | | |
| 2. Literature review | | | | | | | | | | | | | | | | | |
| 3. Equipment study and design | | | | | | | | | | | | | | | | | |
| 4. Controller design and programming | | | | | | | | | | | | | | | | | |
| 5. Test and tuning | | | | | | | | | | | | | | | | | |
| 6. Experiment analysis | | | | | | | | | | | | | | | | | |
| 7. Thesis summary | | | | | | | | | | | | | | | | | |

# Chapter 2
# Related theories and literature reviews

In this chapter, theories and other researches are reviewed because the purpose of the study is not only to control systems but also to know some basic agricultural techniques. The control system will be adequately designed when the system is acquainted comprehensively. Many reviews provide ideas to apply and to improve this research.

## 2.1 Related theories

Agriculture has many factors that affect the plant's properties and growth. Technologies and techniques are applied to the cultivation process to control and modify the factors appropriate for plant growth. The conditions which provide abundant environment are useful because the plant's quality and crop period will be as expected. On the other hand, if conditions are improper for the plants, the plants will try to survive instead of growing. The hydroponic system is a practical method to control nutrients and eliminate defects from the soil. Moreover, the plant factory is an efficient way to control the environment because the operation is in the building caused the quality and predictable results. Hence, studying factors and providing sufficient resources are significant for cultivation and also an investment [3].

### 2.1.1 Hydroponic technique

Growing plants in water culture without the use of any solid substrates has been known as hydroponics. A mineral nutrient is given to plants by using solvent water. There are several techniques in a hydroponic system, for example, the dynamic root floating technique, nutrient film technique, ebb, and flow technique. This research will focus on deep flow technique. Neil Mattson and J. Heinrich Lieth define the meaning of the deep flow technique (DFT) system as one of the categories of cultivation hydroponic, which involves a large amount of water in the roots that have soaked. The plant is held above the dissolved fertilizer nutrients water. To ensure proper mixing of nutrients and dissolved oxygen, both air pumps (or injecting oxygen from tanks) and water pumps are essential to install. The grower can adjust the flow rate and water movement if oxygen and nutrient become deficient.

Deep flow systems can have the plants mounted by the cap of the box that holds the plants above the water so that only the roots and the end of the stems are soaked in the solvent water. Another method is to mount the plants on floating boards (often insulation boards), which have appropriate buoyancy to keep the plant above water at all times. The size of systems can range from buckets to ponds [6].

### 2.1.2 Nutrient solution

The nutrient solution [7] is liquid fertilizer dissolved in water and supplied to the substrate for plant consumption. The nutrient solution should contain all essential elements. All elements should be in ion form. The concentrations of each ion and total ions that are measured as EC should be in proper ranges for the plant. The EC of nutrient solution is around 1200-1600 for lettuce or dependent on plant type. Pathogenic microorganisms and harmful substances must not be included. The nutrient solution's pH is around 5.5-6.5 stably. The EC and pH do not fluctuate exceedingly during the cultivation period. Besides, dissolved oxygen should be enough for root respiration. Table 2.1 shows the example of EC and pH values that each plant requires.

Table 2.1 Example of EC and pH required by each plant

| **Plant type** | **EC (µS/cm)** | **pH** |
|---|---|---|
| Lettuce | 1200-1600 | 5.0-6.0 |
| Strawberry | 1800-2200 | 6.0-6.8 |
| Parsley | 800-1800 | 5.5-6.0 |
| Cucumber | 1700-2500 | 5.5 |

### 2.1.3 Control methods

#### 2.1.3.1 Linear regression

Linear regression is a method to approximate a system whose mathematical model is unknown by creating a linear model that approaches the real system with an acceptable error. From the linear model, control values can be estimated with the predicted relation [8] as

$$u(t) = f(e(t)) \tag{2.1}$$

where $u(t)$ is the control signal,
$f(e(t))$ is the linear function derived by a linear regression method,
$e(t)$ is the error given by

$$e(t) = |r(t) - y(t)| \tag{2.2}$$

When $r(t)$ and $y(t)$ are the reference input and the output, respectively. A linear regression control system can be expressed using the block diagram shown in Figure 2.1

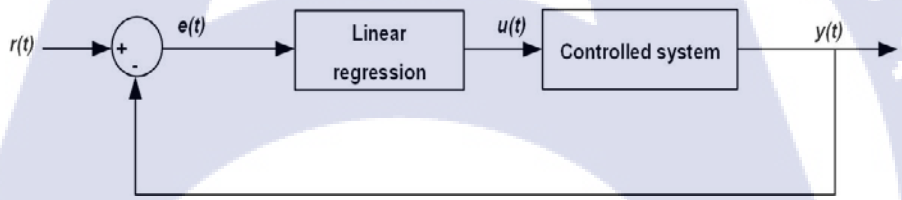



Figure 2.1 Linear regression control system

2.1.3.2 PID control

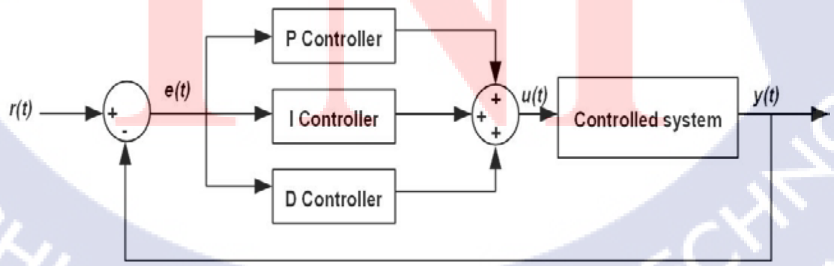



Figure 2.2 PID control system

PID control is a classical closed-loop control, and its block diagram is shown in Figure 2.2. The PID control combines three parts that are the proportional (P) term, integral (I) term, and derivative (D) term. $u(t)$ is the control signal calculated from the PID controller to control the controlled system. $e(t)$ is an error obtained by comparing the output $y(t)$ with the reference input $r(t)$. The obtained error will be moved to the controller and used to compute an adequate control signal to the error through the following equation

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{2.3}$$

Where $K_p$ is the proportional gain, $K_i$ is an integral gain, and $K_d$ is *a* derivative gain. These gains will be designed and adjusted correctly to get the desired output performance. Each gain will affect output response differently; therefore, the controller gains can be adjusted, or some gains can be selected, and the unselected gains are set to be zero in order to get the desired output performance [9].

Designing a PID controller is no need for a mathematical model of a controlled system. The PID controller is mostly used in the industry because a mathematical model of an industrial process is sometimes hard to find, and PID controller gains can be adjusted on site. There are many techniques to adjust PID controller gains, and some techniques provide adjusting gain precisely [10].

2.1.3.3 Fuzzy logic control

Fuzzy logic control [11] is a methodology for carrying out human problems about how to control a system. Figure 2.3 shows a fuzzy logic controller embedded in a closed-loop control system. The system output is $y(t)$, the reference input is $r(t)$, the error is $e(t)$, and the control signal is $u(t)$. The fuzzy logic controller has four principal components as follows:

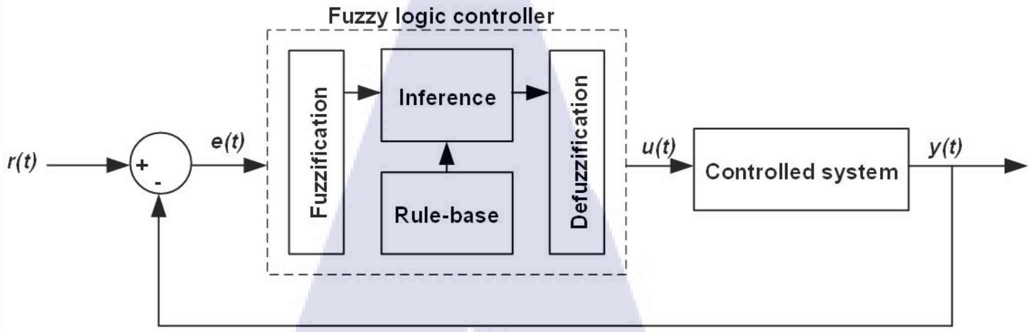



Figure 2.3 Fuzzy logic control system

(1) Fuzzification

The fuzzification process converts inputs of the controller into fuzzy set membership levels. This step consists of linguistic variables that are represented by membership functions. Received input value will be calculated to be fuzzy value following the membership function and evaluated to be degree or level of membership $\mu$. Examples of membership functions are shown in Figure 2.4, and Figure 2.5 where Low, Ideal, High, OFF, and ON are linguistic variables. Degree of membership for membership functions in Figure 2.4, and Figure 2.5 are given by equations (2.4) to (2.8).

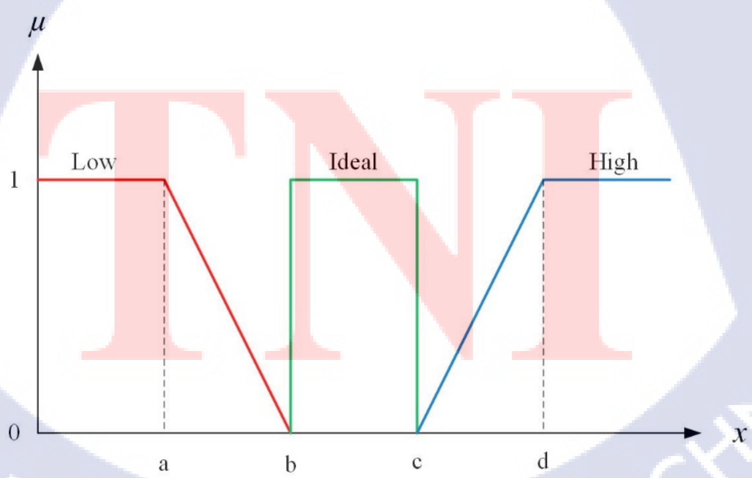



Figure 2.4 Example of input membership functions

$$\mu_{Low}(x) = \begin{cases} 1, & x \le a \\ \dfrac{b-x}{b-a}, & a \le x \le b \\ 0, & x \ge b \end{cases} \tag{2.4}$$

$$\mu_{Ideal}(x) = \begin{cases} 0, & x \le a \ and \ x \ge d \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases} \tag{2.5}$$

$$\mu_{High}(x) = \begin{cases} 1, & x \ge d \\ \dfrac{d-c}{d-c}, & c \le x \le d \\ 0, & x \ge c \end{cases} \tag{2.6}$$

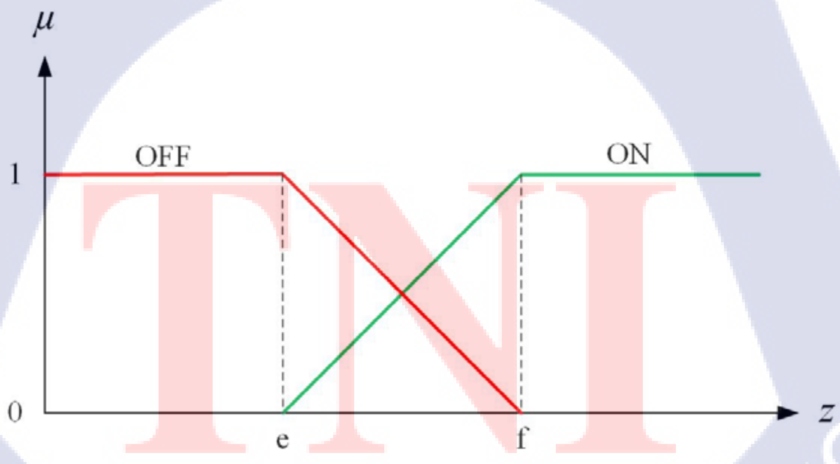



Figure 2.5 Example of output membership functions

$$\mu_{OFF}(z)=\begin{cases}1, & z\le e\\ \dfrac{f-z}{f-e}, & e\le z\le f\\ 0, & z\ge f\end{cases} \tag{2.7}$$

$$\mu_{ON}(z)=\begin{cases}1, & z\ge f\\ \dfrac{z-e}{f-e}, & e\le z\le f\\ 0, & z\ge e\end{cases} \tag{2.8}$$

(2) Rule-base

The rule-base is a set of rules that provide how to control the system efficiently. Information used to design a rule is from a human who works in a control task. "Rules" basically say, "If the system output and the reference input are behaving in a certain manner, then the system input/control signal should be some value." A set of "If-Then" rules is used as the rule-base.

(3) Fuzzy Inference

Based on the designed rule, variable value will follow this rule base. The inference mechanism evaluates which rules are appropriate for the present time then determines fuzzy control signals according to the inference strategy selected.

(4) Defuzzification

The defuzzification process transfers the conclusions into the input of the system. This step will convert fuzzy control signals into a crisp (non-fuzzy) control signal. One of the typical defuzzification methods is the weighted average method described by

$$Control\ signal\ u(t)=\frac{\sum_{i=1}^{n}\mu_{x_n}z_n}{\sum_{i=1}^{n}\mu_{x_n}} \tag{2.9}$$

2.1.4 System performance

2.1.4.1 Stability

The stability is criteria that consider whether the system is stable or not. The output response of the system converges to the final value or diverges. The criteria can examine the output response in a transient state and steady-state.

2.1.4.2 Maximum overshoot

The maximum overshoot is the highest value of the response curve that is measured from the steady-state value. The maximum overshoot presents the stability of the system.

2.1.4.3 Settling time

The settling time is required time for the response curve to approach and stay within 2% or 5% of the steady-state value. The settling time affects the time constant of the system.

2.1.4.4 Steady-state error

The steady-state error is an error that occurred when the system is in a steady-state. The error is around the final value firmly, but that is not equal.

### 2.2 Literature reviews

Table 2.2 Literature reviews

| Author | Year | Title |
|---|---|---|
| T.Kaewwiset and T.Yooyativing [8] | 2017 | Electrical conductivity and pH adjusting system for hydroponics by using linear regression |
| D. Yolanda et al. [12] | 2018 | Control of electrical conductivity for NFT hydroponic systems using fuzzy logic and android environment |
| M. Fuangthong et al. [4] | 2018 | Automatic control of electrical conductivity and pH using fuzzy logic for hydroponic system |
| S. Mashumah et al. [13] | 2018 | Nutrient film technique based hydroponic system using fuzzy logic control |

T.Kaewwiset and T.Yooyativing [8] implemented automatic control EC and pH in reservoir with linear regression because adding A&B solution or nitric acid were similar direction as EC or pH. The results showed that EC adjusting equation had accuracy more than 80.8%, and pH adjusting equation had accuracy more than 95% from the experiment.

D. Yolanda et al. [12] was to control EC in ideal conditions for NFT method by using fuzzy logic and Android-based application. The EC in ideal conditions were 1.0 mS/cm to 1.5 mS/cm. The results showed that the system restored the lowest EC to be ideal within 101 seconds and the highest EC to be ideal within 89 seconds.

M. Fuangthong et al. [4] applied fuzzy logic to control EC and pH in a hydroponic system, which was DRFT method for growing green oaks. The decision-making process was applied to adjust the optimum range for the plant the results shown that the system could adjust EC and pH efficiently and reduce waste of resources.

Furthermore, S. Mashumah et al. [13] designed fuzzy logic to control EC in the nutrient solution of NFT method in the hydroponic system. The EC was estimated by image processing of the HSV histogram of Pak Choy mustard plant. The results showed that the system provided nutrients with an error rate of 8.9%.

# Chapter 3
# Methodology

The research methodology has classified to four parts which are hydroponic system, equipment design for prototype, control design, and programming to command microcontroller. This methodology is significant to reach purposes of this research. The detail of each part will be described below.

## 3.1 Hydroponic system

In a hydroponic system there are many types of hydroponics to operate such as nutrient film technique (NFT), deep flow technique (DFT), dynamic root floating technique (DRFT), Ebb and flow, and so on. The kind of hydroponic system will be selected by conditions because every technique has advantages depending on plants, location, personal skills, and others. This research uses deep flow technique, firstly, because Thailand is located in tropical zone that the weather is hot therefore, water will evaporate easily leading to damaged roots and dried roots; secondly, because this technique is simple and uses common equipment convenient to find; and lastly, because this method uses small area which can be installed in a laboratory and the experiment can be carried out expediently. The example of a deep flow technique is shown below in Figure 3.1.

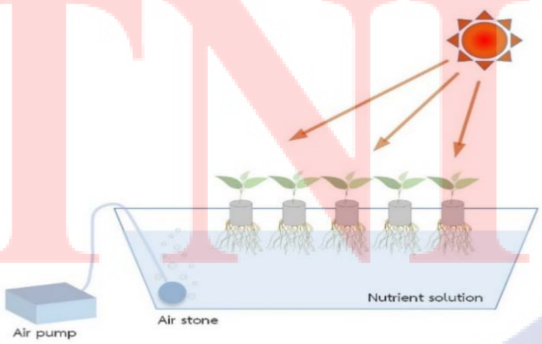



Figure 3.1 Deep flow technique (DFT)

## 3.2 Equipment design

3.2.1 Sensors

The laboratory-grade sensors, which are EC probe and pH probe, were selected because of the electrode of probes made from high-quality material such as graphite and silver that appropriate for experimenting to get correct data without noise from the sensor. Even, reliability of product influences the accuracy of the results. The product warranty is also essential to ensure that the product can be used throughout life expectancy. The specifications of pH probe are as follows: range 0-14, resolution 0.001, accuracy 0.002, response time 1 second, temperature range -5 to 99 degrees Celsius, and maximum pressure 100 PSI. The specifications of EC probe are range 5 to 200,000 µS/cm, accuracy 2%, response time 1 second, temperature range 1 to 110 degrees Celsius, and maximum pressure 500 PSI.

Figure 3.2 EC probe and pH probe

3.2.2 Pumps

The laboratory-grade peristaltic pumps with high precision were selected for this research. The pumps have an appropriate flow rate, size, and connection with the test prototype. The specifications of pump are as follows: flow rate 0.5 ml/min to 105 ml/min, pump head 2 meters, and operating voltage is 12 to 24 volts. The nutrient solution tank is 6 liters and distance from stock solution tank to nutrient tank is within 50 centimeters including height and length. Therefore, the pump can be used and the system is not necessary to use a high flow rate pump because of high budget and required low dispensing volume.

Figure 3.3 Peristaltic pump

3.2.3 Microcontroller

Microcontroller is Arduino because it is an open-source electronics platform which is widely used in many projects and based on easy-to-use hardware and software. Moreover, a lot of libraries can be used and developed to be fit to the project.

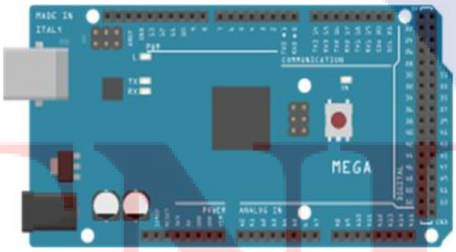



Figure 3.4 Microcontroller

3.2.4 Stirring rod

Stirring rod was specifically designed for this experiment. This equipment was modified from a cordless drill motor and house paint's stirring rod. After the pump dispenses fertilizer, acid, and water, the system will take a time to make the nutrient solution circulating and homogeneous. To eliminate this problem, the stirring rod is indispensable because sensors will get exact value from the overall nutrient solution rather than a specific point in the nutrient solution.

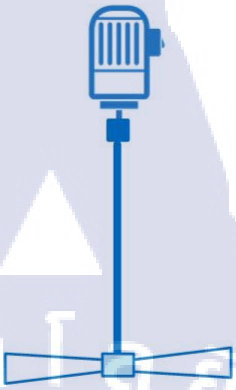
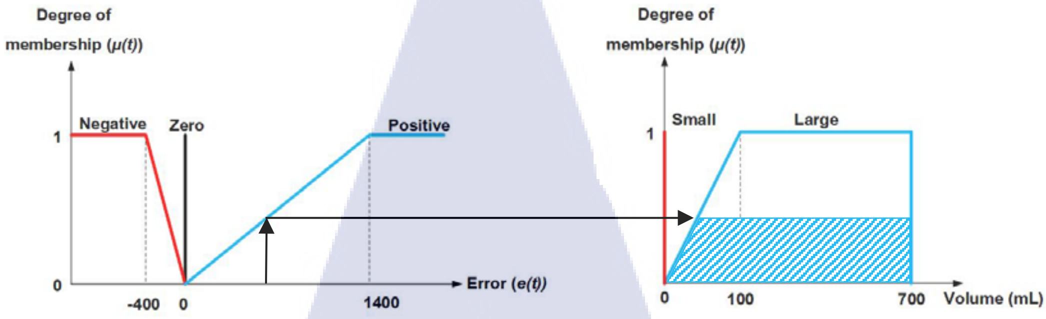


Figure 3.5 Stirring rod

**3.3 Control design**

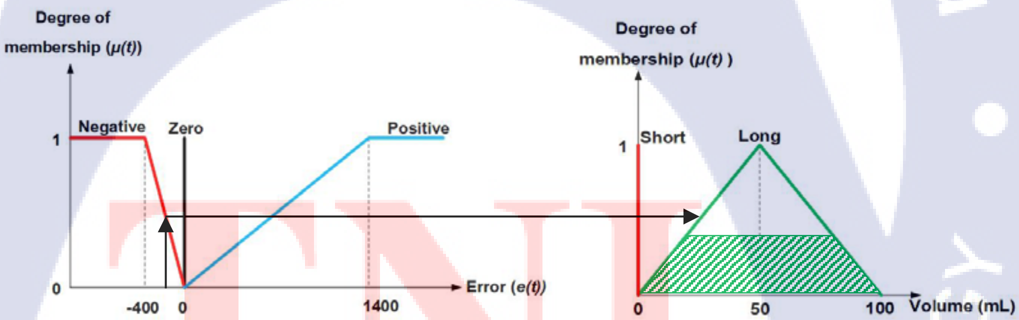
A fuzzy logic control is a control method that has been used around the world because this method can provide not only 0 or 1 but also provide 0.1 or value between 0 and 1. That is the reason why this control method offers great control in some systems. Generally, a fuzzy logic controller uses Mamdani and Sugeno inference systems that allow own advantages depending on system. However, used in this research is similar to Mamdani inference system but defuzzification has been modified. Basically, methods mostly used in defuzzification in Mamdani inference system are weighted average method and centroid method. Although these two methods are widely practical, they may not be suitable for every system. In the modified fuzzy logic control, a weighted average method has been changed to area under a designed shape because that is a straightforwardly simple technique and supplies excellent control results to nutrient solution control systems. The example of this technique can be expressed as Figure 3.6.




(a) Input membership functions (b) Output membership functions

Figure 3.6 Defuzzification in modified fuzzy logic control.

Figure 3.6 shows how to get value of control signal in defuzzification process of the modified fuzzy logic controller. A crisp (nonfuzzy) value of the control signal will be obtained from a shading area of output membership functions. Therefore, the required large control signal means area under a designed shape has to be huge consequently. Nevertheless, if the required control signal is not much in high error, the area under a designed shape will be small as shown in Figure 3.7.




(a) Input membership functions (b) Output membership functions

Figure 3.7 Defuzzification in modified fuzzy logic control for other shape example.

<u>3.3.1 Electrical conductivity control in nutrient solution</u>

This experiment is to control EC in nutrient solution. The EC target is set to 1600 dS/cm because this value is appropriate for general plant that can be cultivated in a hydroponic system. The equipment of the experiment is shown below in Figure 3.8.

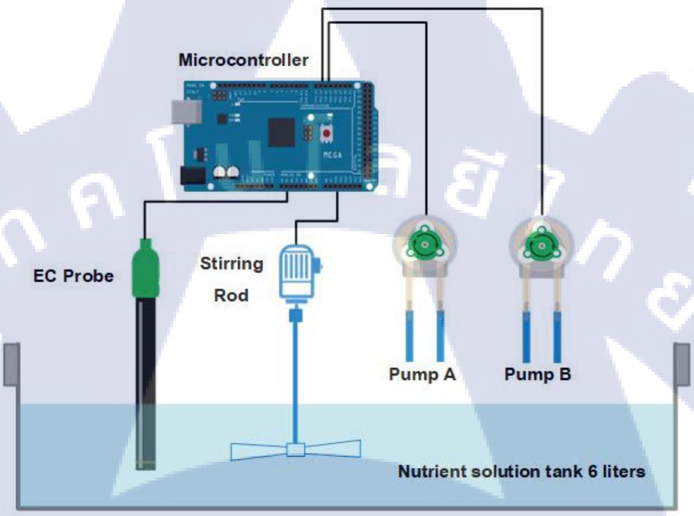



Figure 3.8 EC control equipment

3.3.1.1 Linear regression method

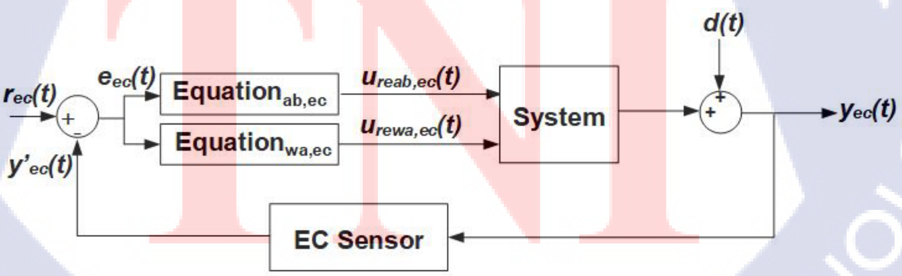



Figure 3.9 Linear regression block diagram for EC control

The block diagram for EC control using the linear regression method is shown in Figure 3.9. The EC target is represented by $r_{ec}(t)$. The error $e_{ec}(t)$ is the value derived from comparison between the EC target and the output value read from EC sensor called $y'_{ec}(t)$. The actual output is $y_{ec}(t)$, which is measured from nutrient solution tank and is equal to $y'_{ec}(t)$ because EC sensor's gain is 1. $u_{reab,ec}(t)$ and $u_{rewa,ec}(t)$ are control signals for activation of pump A and pump B, which are fertilizer stock's pump and water stock's pump respectively, to increase or decrease EC converging to target. Disturbance $d(t)$ denotes undesirable input from environment that may perturb the system and may increase or decrease EC unavoidably. For example, the hot weather will heat the nutrient solution and water will evaporate, resulting in high concentration in nutrient solution (high EC). Otherwise, rain will fill the water in the nutrient solution tank, causing low concentration in nutrient solution (low EC).

The control signals of fertilizer dispensing volume and water dispensing volume are

Equation$_{ab,ec}$;
$$u_{reab,ec}(t) = 0.11 * e_{ec}(t) + 18.59 \tag{3.1}$$

where the r-squared is 0.995, and

Equation$_{wa,ec}$;
$$u_{rewa,ec}(t) = -3.22 * e_{ec}(t) + 1227 \tag{3.2}$$

where the r-squared is 0.927.

The r-squared value is calculated from manual data by human. The minimum was not set because the method was following manual data and the experiment was proving how linear regression method works.

3.3.1.2 P control method

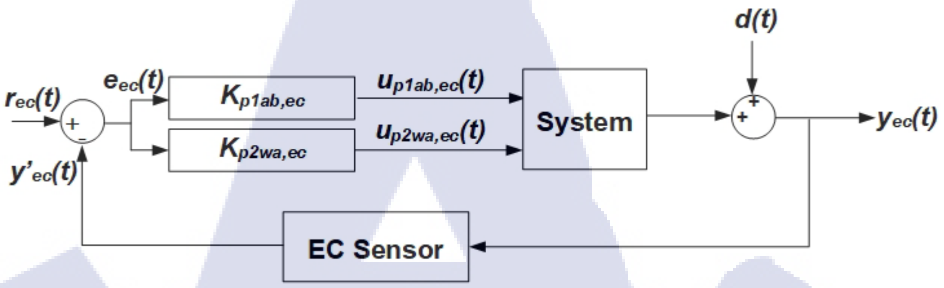



Figure 3.10 P control block diagram for EC control

The block diagram for EC control using the P control method is shown in Figure 3.10. The block diagram can be described in the same way as the linear regression block diagram. The control signals of fertilizer dispensing volume and water dispensing volume are

$$u_{p1ab,ec}(t) = K_{p1ab,ec} * e_{ec}(t) \tag{3.3}$$

where $K_{p1ab,ec}$ is 0.12, and

$$u_{p2wa,ec}(t) = K_{p2wa,ec} * e_{ec}(t) \tag{3.4}$$

where $K_{p2wa,ec}$ is -7.84.

The $K_p$ was set from the highest volume dispensed by manual data divided by error which was calculated by comparing target and actual value.

3.3.1.3 Modified fuzzy logic control method

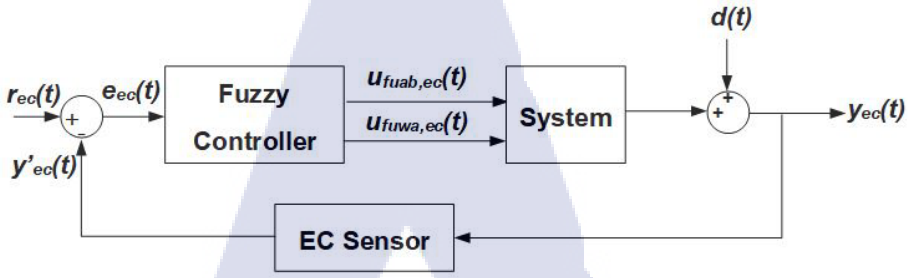



Figure 3.11 Modified fuzzy logic control block diagram for EC control

The block diagram for EC control using the modified logic control method is shown in Figure 3.11. Fuzzification process in the fuzzy controller is divided to three parts. Firstly, negative membership function will provide degree of membership by linear interpolation for high EC. Secondly, positive membership function will give degree of membership by linear interpolation for low EC. Lastly, zero membership function is error equal to zero or EC is in the target hence, in this part the system does nothing. The graph is shown in Figure 3.12.

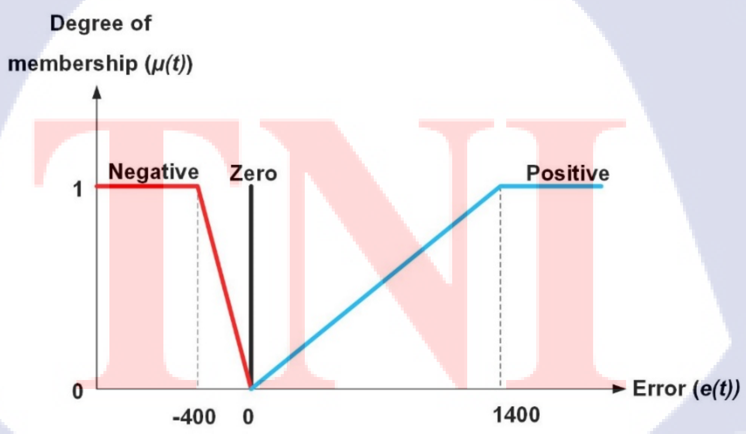



Figure 3.12 EC fuzzification

Rules are designed from experience of user. The sensor reads EC value from nutrient solution and then the EC value will be regulated following the designed rules (Table 3.1) and defined degree of membership.

Table 3.1 Rule base for EC control

| Rules | | |
|---|---|---|
| **Negative** | **Zero** | **Positive** |
| **IF** Error is Negative, **THEN** fertilizer stock dispensing volume is Large and Water dispensing volume is Small | **IF** Error is Zero, **THEN** fertilizer stock dispensing volume is Small and Water dispensing volume is Small | **IF** Error is Positive, **THEN** fertilizer stock dispensing volume is Small and Water dispensing volume is Large |

The defuzzification has two graphs. The first graph (Figure 3.13) is for decreasing EC by dispensing water stock into nutrient solution. The Small membership function is used when no need to decrease EC and the Large membership function is used when the system needs dropping off EC. Required volume in dispensing water depends on degree of membership and rules to indicate value of area under graph to activate pump.

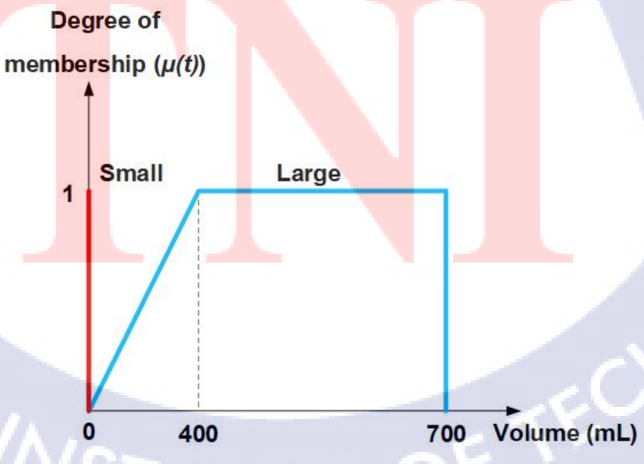



Figure 3.13 Water of EC defuzzification

The second graph is for increasing EC by dispensing AB stock into nutrient solution. The Small membership function is used when no need to increase EC and the Large membership function is used when the system needs more EC. Required volume in dispensing AB stock or fertilizer depends on degree of membership and rules.

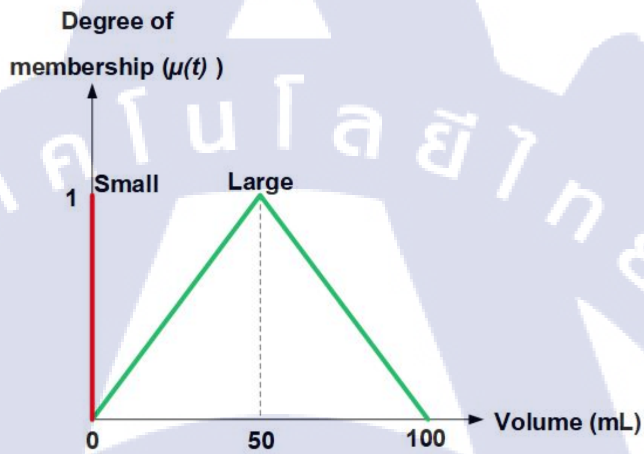



Figure 3.14 Fertilizer defuzzification

3.3.2 pH control in nutrient solution

This test is pH control in nutrient solution. The reference value of pH is selected as 6.0 to determine common value for general plant. The standpoint is similar to EC control in nutrient solution. The device of the experiment is shown in Figure 3.15.

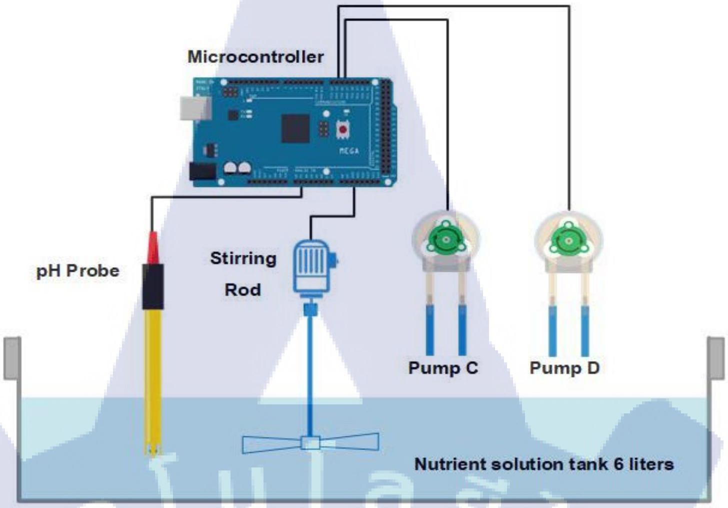



Figure 3.15 pH control equipment

3.3.2.1 Linear regression method

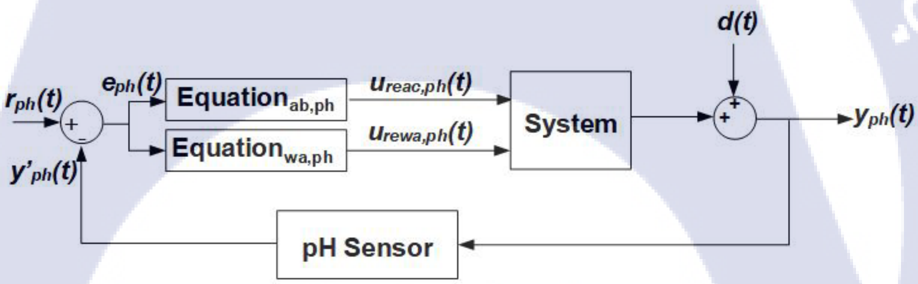



Figure 3.16 Linear regression block diagram for pH control

The block diagram for pH control using the linear regression method is shown in Figure 3.16. The reference value is represented by $r_{ph}(t)$. And the error is represented by $e_{ph}(t)$ obtained from comparison between the pH reference value and the value read from pH sensor called $y'_{ph}(t)$. The actual output is $y_{ph}(t)$ which is measured from nutrient solution tank and is equal to $y'_{ph}(t)$ because pH sensor's gain is 1. The control signals are $u_{reac,ph}(t)$ and $u_{rewa,ph}(t)$ to dispense acid stock (pump C) and water stock (pump D) to decrease or increase acidity in nutrient solution. $d(t)$ is disturbance to the system, for example, rain will fill the nutrient solution tank with the water then pH in nutrient solution will vary according to the rainfall. The control signals of acid dispensing volume and water dispensing volume are

Equation$_{ab,ph}$; $$u_{reac,ph}(t) = -9.39 * e_{ph}(t) + 6.12 \tag{3.5}$$

where the r-squared is 0.802, and

Equation$_{wa,ph}$; $$u_{rewa,ph}(t) = 831.06 * e_{ph}(t) - 14.57 \tag{3.6}$$

where the r-squared is 0.971.

The r-squared is calculated from manual data by human. The minimum was not set because the method was following manual data and the experiment was proving how linear regression method works.

3.3.2.2 P control method

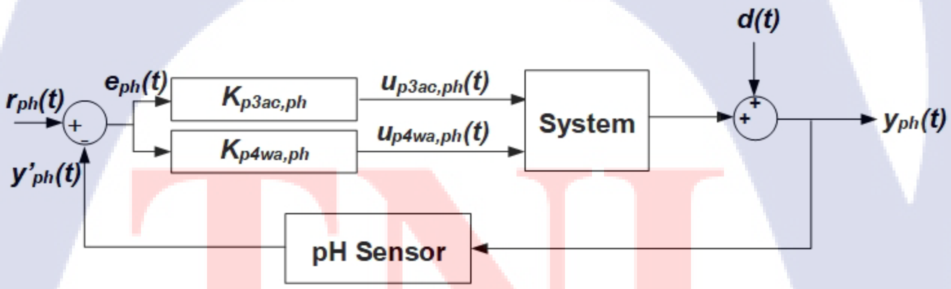



Figure 3.17 P control block diagram for pH control

The block diagram for pH control using the P control method is shown in Figure 3.17. The control signals of acid dispensing volume and water dispensing volume are

$$u_{p3ac,ph}(t) = K_{p3ac,ph} * e_{ph}(t) \tag{3.7}$$

$$u_{p3ac,ph}(t) = K_{p3ac,ph} * e_{ph}(t) \tag{3.7}$$

where $K_{p3ac,ph}$ is -10, and

$$u_{p4wa,ph}(t) = K_{p4wa,ph} * e_{ph}(t) \tag{3.8}$$

where $K_{p4wa,ph}$ is 900.

The $K_p$ was set from the highest volume dispensed by manual data divided by error which was calculated by comparing target and actual value.

3.3.2.3 Modified fuzzy logic control method

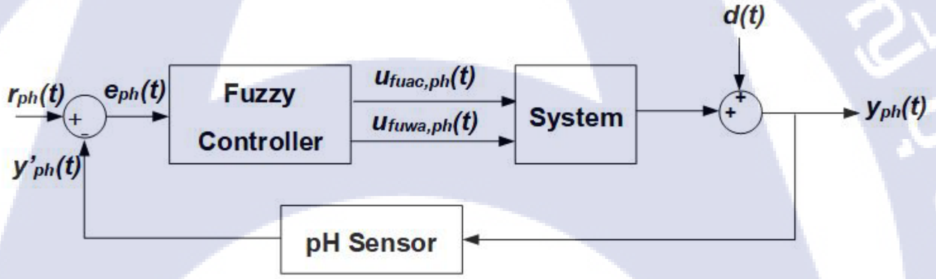



Figure 3.18 Modified fuzzy logic control block diagram for pH control

In pH control, fuzzification is the same process as that of EC control in nutrient solution, but each system has specific relation therefore shape of area is changed to fit the system. The membership functions of the error are shown in Figure 3.19. The error is negative when pH is high, and the error is positive when pH is low. The zero means the system is in target. The rules for pH control are shown in Table 3.2.

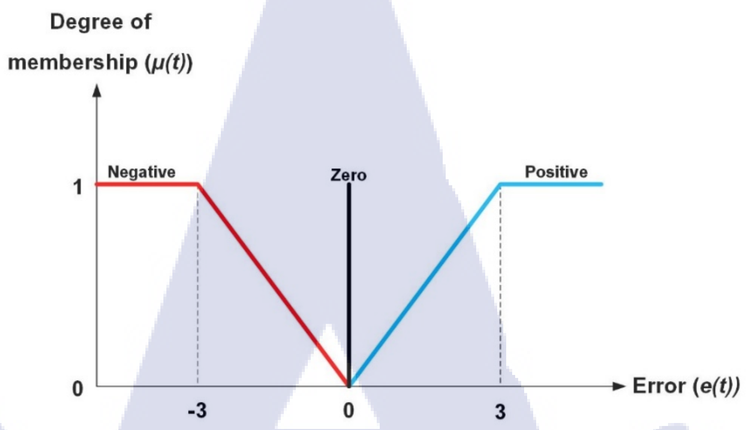



Figure 3.19 pH fuzzification

Table 3.2 Rule base for pH control

| Rules | | |
|---|---|---|
| Negative | Zero | Positive |
| **IF** Error is Negative, **THEN** Acid dispensing volume is Large and Water dispensing volume is Small | **IF** Error is Zero, **THEN** Acid dispensing volume is Small and Water dispensing volume is Small | **IF** Error is Positive, **THEN** Acid dispensing volume is Small and Water dispensing volume is Large |

The defuzzification has acid dispensation and water dispensation membership functions. These membership functions are shown in Figure 3.20 and Figure 3.21. The Small membership function is for doing nothing because the system output is in target, but if the system output is not in target the Large membership function will be active.

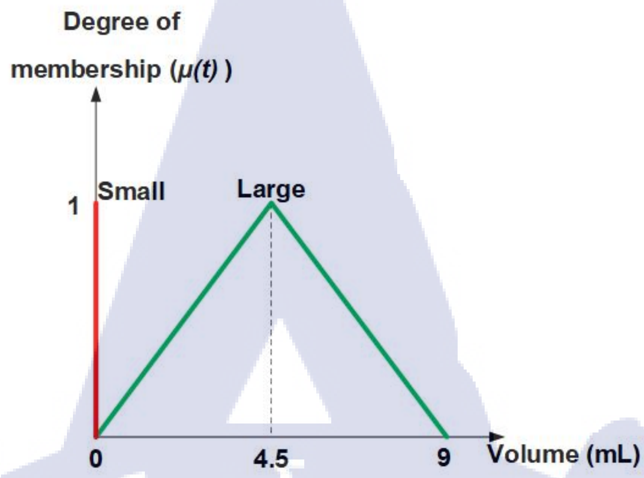



Figure 3.20 Acid defuzzification

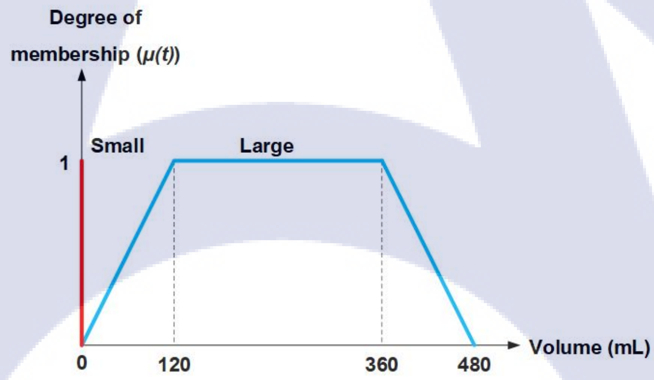



Figure 3.21 Water of pH defuzzification

3.3.3 EC and pH control in nutrient solution

This is combination between EC and pH controls, but this operation is more complicated because injecting some stocks into nutrient solution affects others. For example, if the system wants to decrease pH, the system will inject acid stock to nutrient solution then EC will increase accordingly. The system has four actuators. Pump A is acid stock, Pump B is fertilizer stock, Pump C is water stock of pH, and Pump D is water stock of EC. The system will operate through the implement as shown in Figure 3.22.

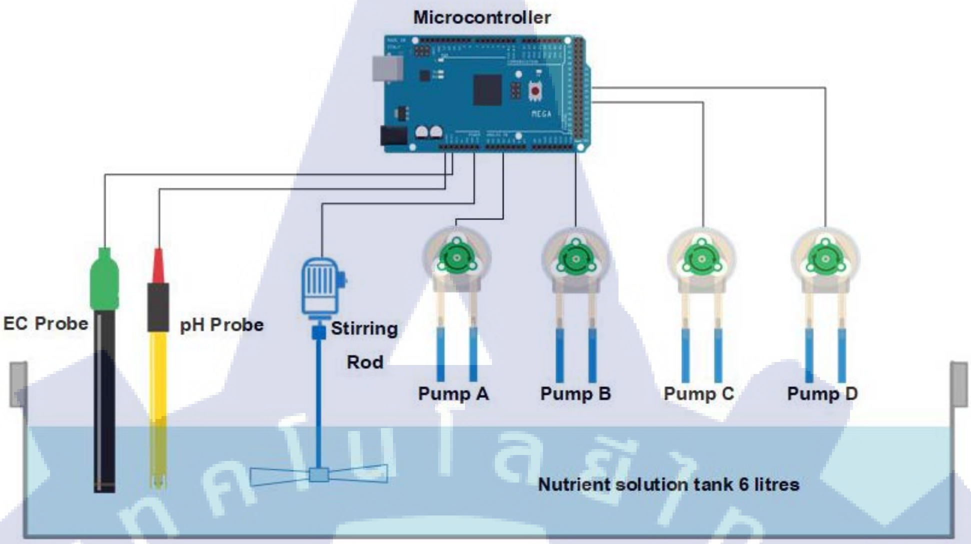



Figure 3.22 EC and pH control equipment

3.3.3.1 Linear regression method

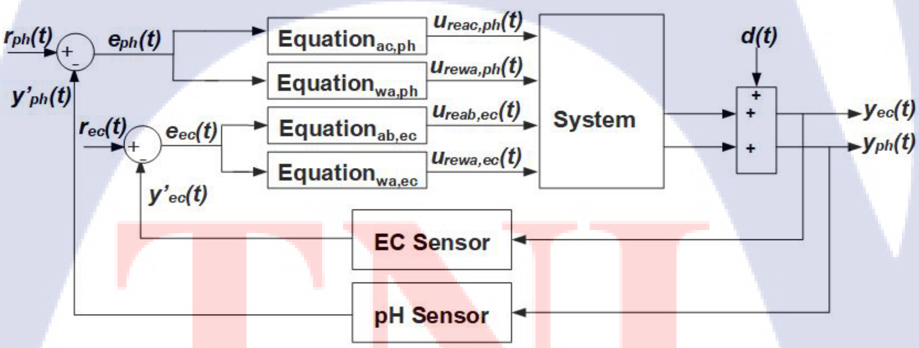



Figure 3.23 Linear regression for EC and pH control block diagram

The block diagram is shown in Figure 3.23. The equations are from EC control and pH control then each system was combined. The system will be tested to get results of the linear regression method.

3.3.3.2 P control method

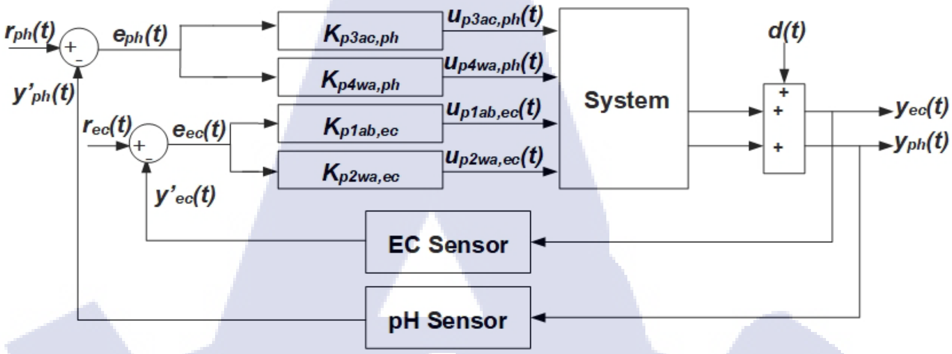



Figure 3.24 P control for EC and pH control block diagram

Figure 3.24 shows the block diagram of EC and pH control using P control. The gains are from EC control and pH control then the system was integrated. The system will be tested to get results of P control method.

3.3.3.3 Modified fuzzy logic control method

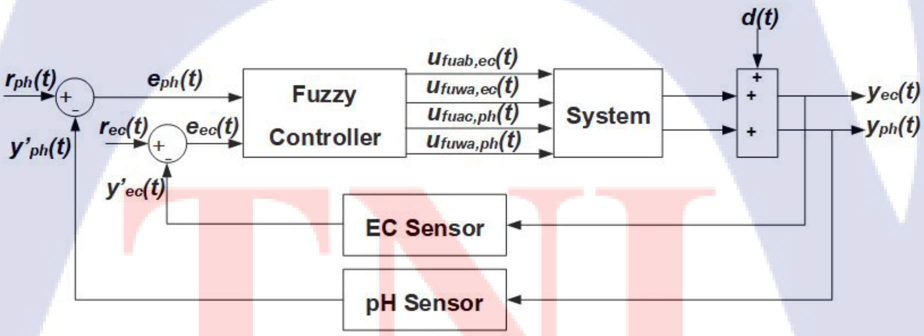



Figure 3.25 Modified fuzzy logic control for EC and pH control block diagram

The block diagram is shown in Figure 3.25. The fuzzification is similar to EC control and pH control because targets are very close.

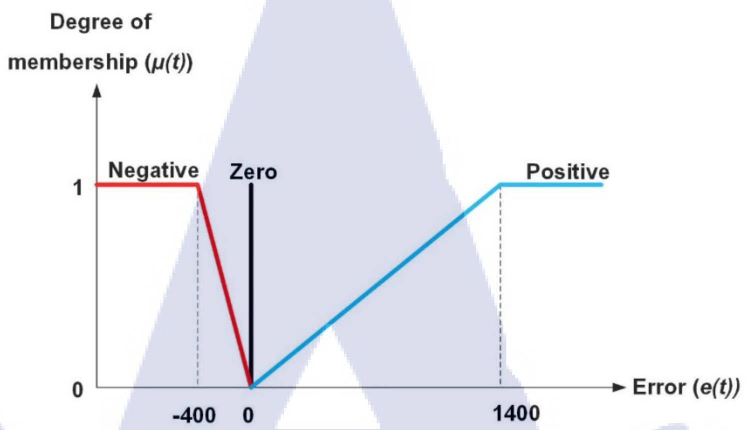



Figure 3.26 pH fuzzification in combination system

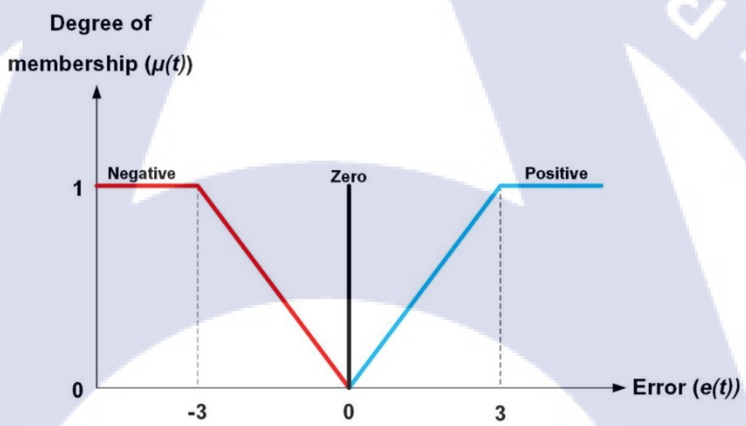



Figure 3.27 EC fuzzification in combination system

The combination control of EC control and pH is much more complicated than a single control because of co-factor. The system will follow the regulation shown in Table 3.3 to control the system properly.

Table 3.3 Rule base for EC and pH control

| **Rules** | | | | |
|---|---|---|---|---|
| | | **pH** | | |
| | | Negative | Zero | Positive |
| **EC** | Negative | IF EC Error is Negative and pH Error is Negative THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Large and Acid dispensing volume is Large and Water$_{pH}$ is Small | IF EC Error is Negative and pH Error is Zero THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Large and Acid dispensing volume is Small and Water$_{pH}$ is Small | IF EC Error is Negative and pH Error is Positive THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Large and Acid dispensing volume is Small and Water$_{pH}$ is Large |
| | Zero | IF EC Error is Zero and pH Error is Negative THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Small and Acid dispensing volume is Large and Water$_{pH}$ is Small | IF EC Error is Zero and pH Error is Zero THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Small and Acid dispensing volume is Small and Water$_{pH}$ is Small | IF EC Error is Zero and pH Error is Positive THEN Fertilizer dispensing volume is Small and Water$_{EC}$ is Small and Acid dispensing volume is Small and Water$_{pH}$ is Large |

Table 3.3 Rule base for EC and pH control (Cont.)

<table>
<tr><th colspan="5">Rules</th></tr>
<tr><td rowspan="3">EC</td><td colspan="4">pH</td></tr>
<tr><td></td><td>Negative</td><td>Zero</td><td>Positive</td></tr>
<tr><td>Positive</td><td>IF EC Error is Positive and pH Error is Negative THEN Fertilizer dispensing volume is Large and Water$_{EC}$ is Small and Acid dispensing volume is Large and Water$_{pH}$ is Small</td><td>IF EC Error is Positive and pH Error is Zero THEN Fertilizer dispensing volume is Large and Water$_{EC}$ is Small and Acid dispensing volume is Small and Water$_{pH}$ is Small</td><td>IF EC Error is Positive and pH Error is Positive THEN Fertilizer dispensing volume is Large and Water$_{EC}$ is Small and Acid dispensing volume is Small and Water$_{pH}$ is Large</td></tr>
</table>

The defuzzification is four graphs according to number of pumps. The principle is Large membership function will be active when the system needs, and Small membership function will be active when the system does not need. However, the system can activate two of pumps at the same time because the rules have been designed already to adjust EC and pH to target together. For instance, EC was high, and pH was low that mean the nutrient solution has high concentration and high acid which is dangerous situation hence, the water of EC and pH will work jointly to decrease EC and increase pH. The design of 4 graphs are shown below in Figure 3.28-3.31

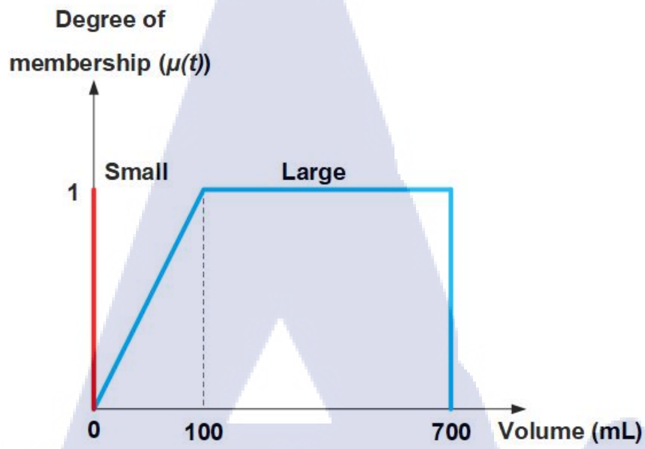



Figure 3.28 Water of EC defuzzification in combination system

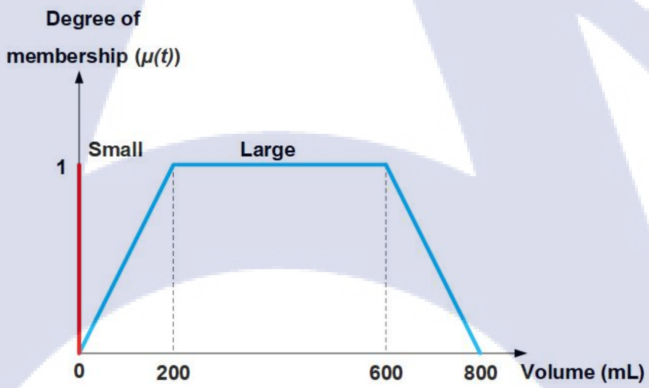



Figure 3.29 Water of pH defuzzification in combination system

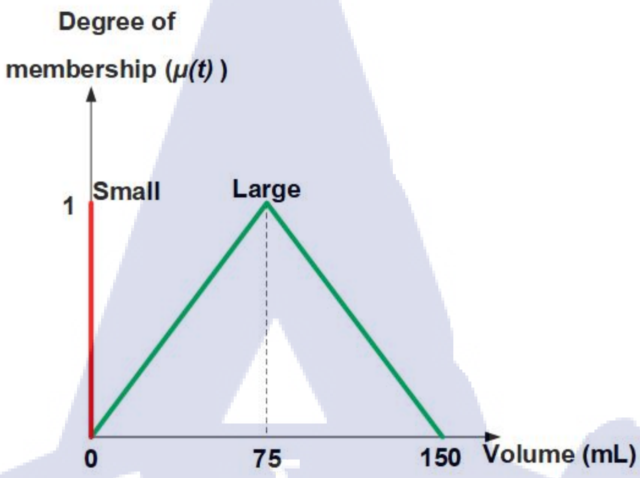



Figure 3.30 Fertilizer defuzzification in combination system

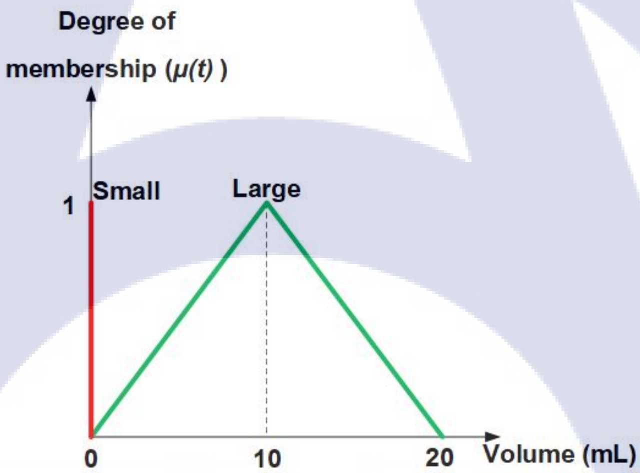



Figure 3.31 Acid defuzzification in combination system

**3.4 Programming**

The programming is based on C to comply and run in Arduino microcontroller. This research is used flowchart in Figure 3.32 to flow the code until getting result. This flowchart can control the system greatly.

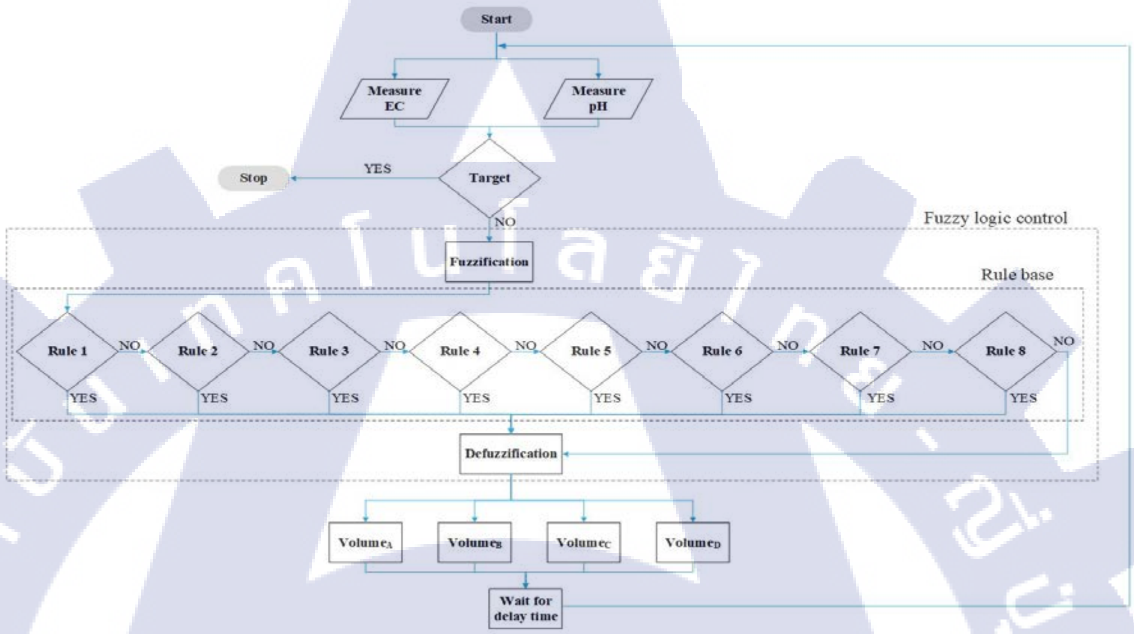



Figure 3.32 Programming flowchart

Primarily, the nutrient solution was measured by EC sensor and pH sensor. Then, EC value and pH value were compared with the target and error will go to fuzzification, which was designed as Negative, Positive and Zero following the determined shape equations. After that, the conditions will be decided by rule base, which has three rules for EC control and pH control, but EC and pH control has nine rules. The decided conditions will move into defuzzification that was designed by determined shape equations as Small and Large. The control signal will activate the volume dispense of pumps that will be added into the nutrient solution tank. The delay time was set into 30 seconds for waiting pump to operate and stirring rod was also active in this time. The program will be operated to measure EC and pH again in this loop until EC and pH are in the target range.

# Chapter 4
# Experimental results

The prototype has been completed following the equipment design and the control design and is ready to verify the system, as shown in Figure 4.1.

Figure 4.1 The prototype model

## 4.1 EC control in nutrient solution

Firstly, the experiment was conducted by human power to collect technical data. Then, the data were analyzed and divided into linear regression, P control, and fuzzy logic control.

### 4.1.1 EC control in the nutrient solution using linear regression method

Linear regression was designed following the technical data from human control by plotting the graph between EC changed and an amount of fertilizer injection. After that, the trend line function estimates the electrical conductivity control model. The linear regression equation has been used in the system as the proportion of electrical conductivity and amount of liquid dispense.

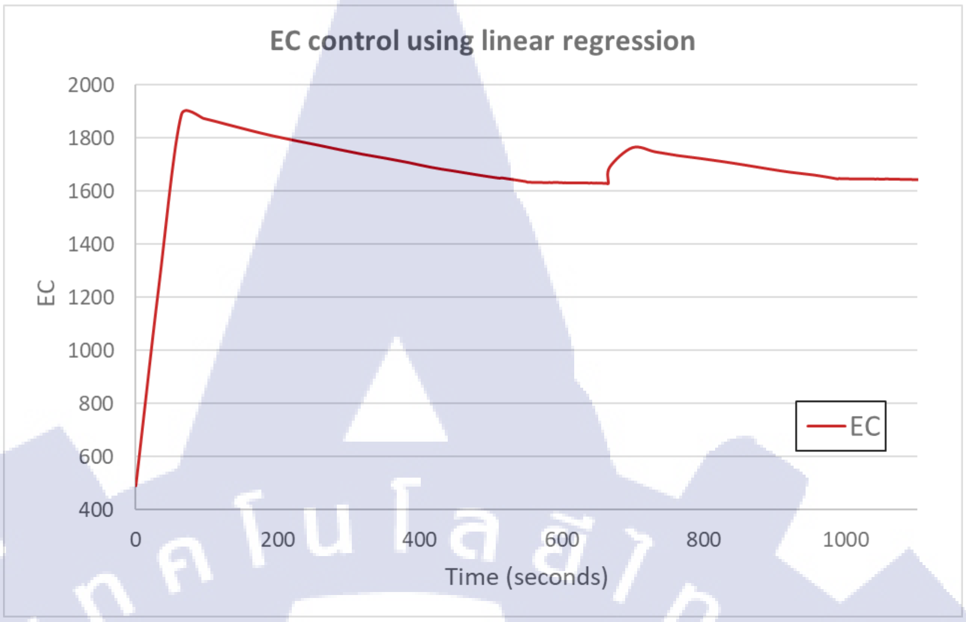



Figure 4.2 EC response of EC control using linear regression

From Figure 4.2, initially, tap water was adjusted by the linear regression method. The EC was started at nearly 600 µS/cm, and the target was 1600 µS/cm. The overshoot has occurred, and the steady-state error happened; then, the system was disturbed by 20 ml of fertilizer at 700 seconds. The system can eliminate disturbance, and all the response times were recorded. Moreover, the control signals conformed to the change of error that is shown in Figure 4.3.

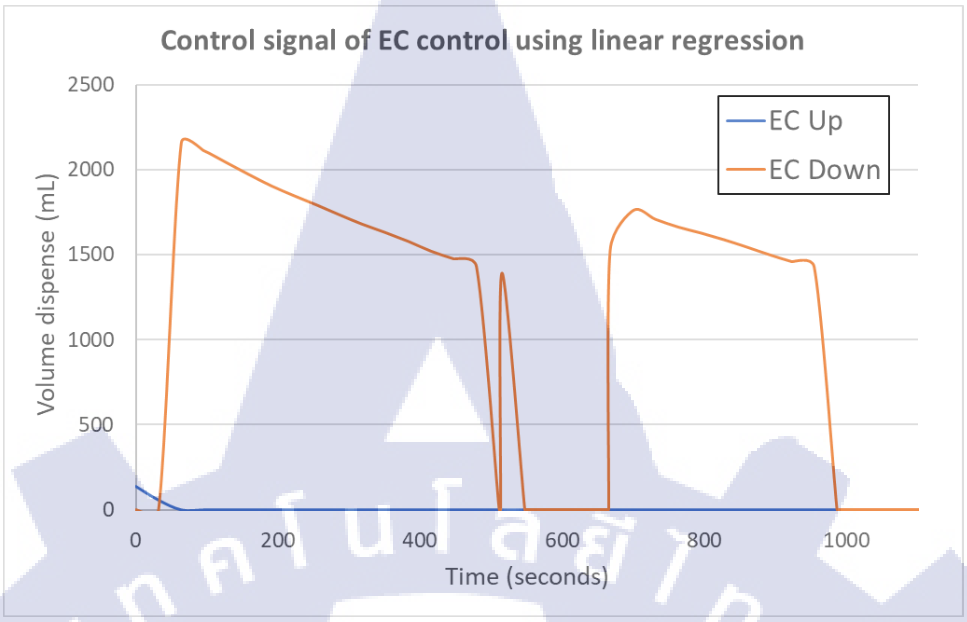



Figure 4.3 Control signals of EC control using linear regression

4.1.2 EC control in the nutrient solution using P control method

P control was designed primarily from the coefficient of an error on the linear regression equation, and then the gain was fine-tuned to match the system.

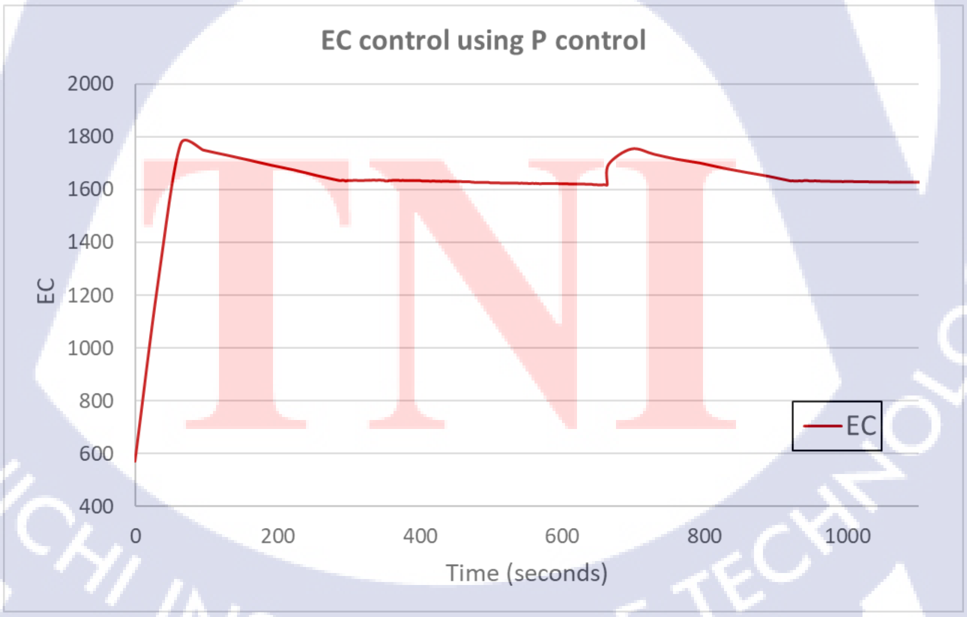



Figure 4.4 EC response of EC control using P control

From Figure 4.4, EC was adjusted from 600 µS/cm to 1600 µS/cm by tap water as a designed target when the system was steady for a while. At 700 seconds, the operation was interrupted by 20 ml of fertilizer to test disturbance elimination. And Figure 4.5 expressed that the control signals conformed to error.

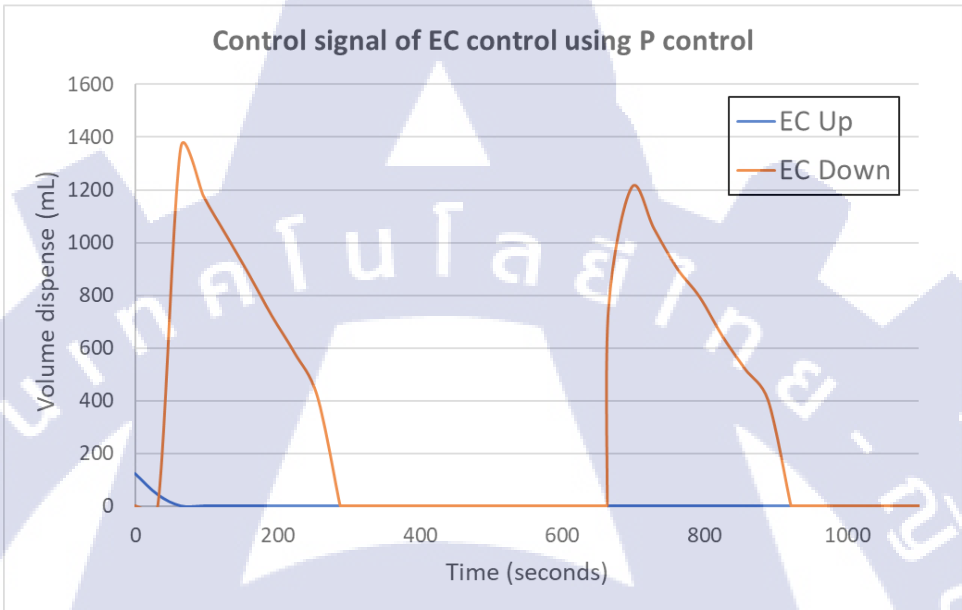



Figure 4.5 Control signals of EC control using P control

4.1.3 EC control in the nutrient solution using modified fuzzy logic control method

Fuzzy logic control was designed following the fuzzy logic theory and applied technical data to obtain the appropriate amount of fertilizer dispense correctly. The EC target determined the input membership function; then, the output membership function was established by the amount of fertilizer injection by human control that received minimum and maximum quantity and also some trends.

This method is generated as a single-input and multiple-output (SIMO) control system. The range of error of electrical conductivity is defined as Negative, Positive, and Zero, depending on the design. The output is a fertilizer volume and dilution volume, which were designed in the output of fuzzy. The maximum and minimum dispensing volumes base on manual operation, and the output graph shapes depend on design.

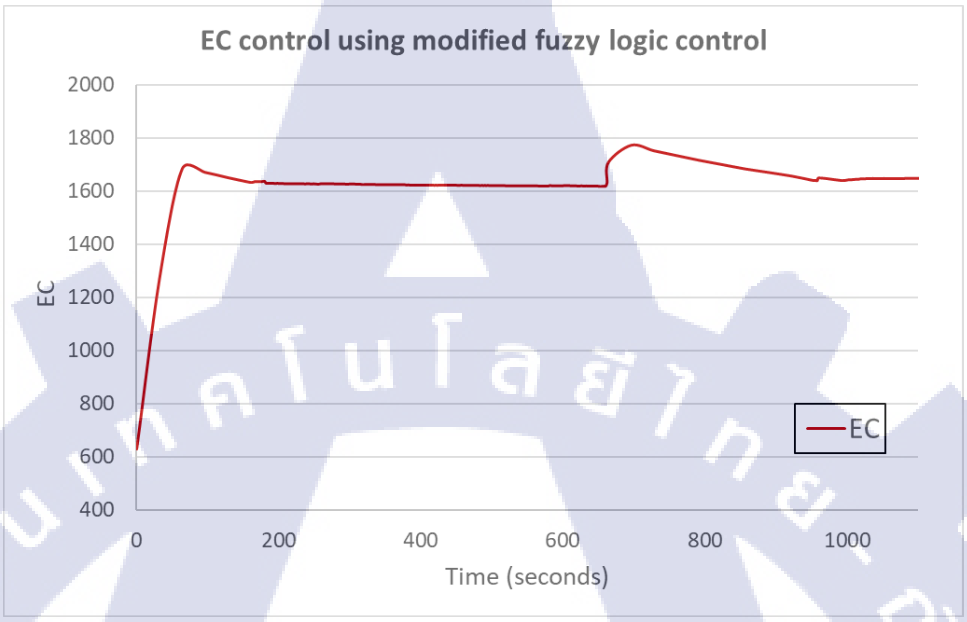



Figure 4.6 EC response of EC control using modified fuzzy logic control

From Figure 4.6, the experiment was the same process as the linear regression and P control method. The first process was adjusted EC of tap water to be in target. The system can keep EC value in the target, even when the 20 ml of fertilizer was applied at 700 seconds. Figure 4.7 is the control signals that respond to a change of error. The control signals can control the system converged to target.

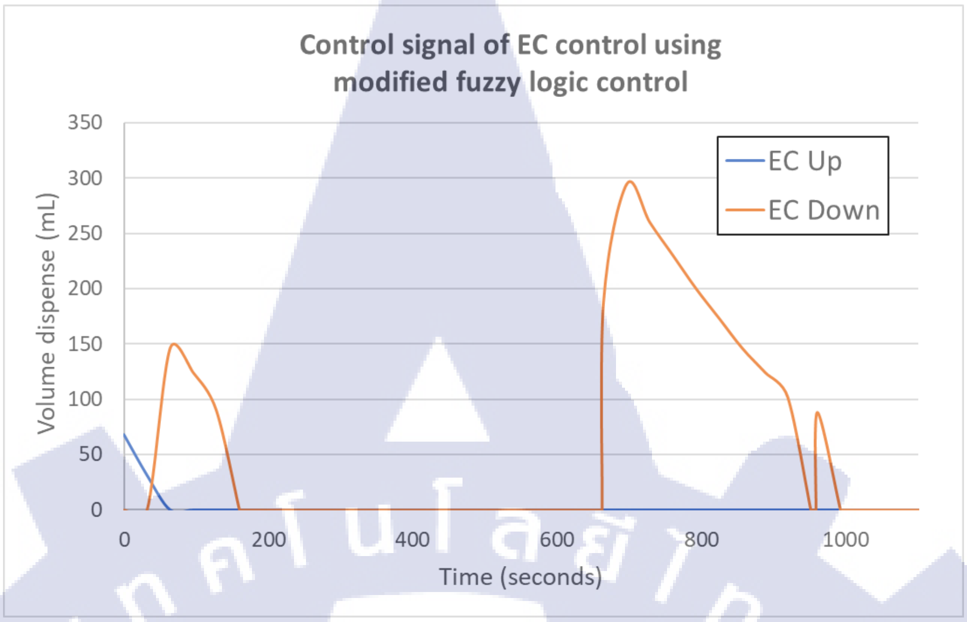



Figure 4.7 Control signals of EC control using modified fuzzy logic control

## 4.2 pH control in nutrient solution

Secondly, the experiment was conducted by human control, and technical data was collected, which was similar to EC control. Furthermore, the experiment was conducted by three tests that are linear regression, P control, and fuzzy logic control.

### 4.2.1 pH control in the nutrient solution using linear regression method.

The experiment was operated by manual operation with experienced humans as a simple record. Then, the data was plotted as a graph that was shown the linear regression equation. The linear regression equation has been used in the system as the proportion of pH and amount of liquid dispense.

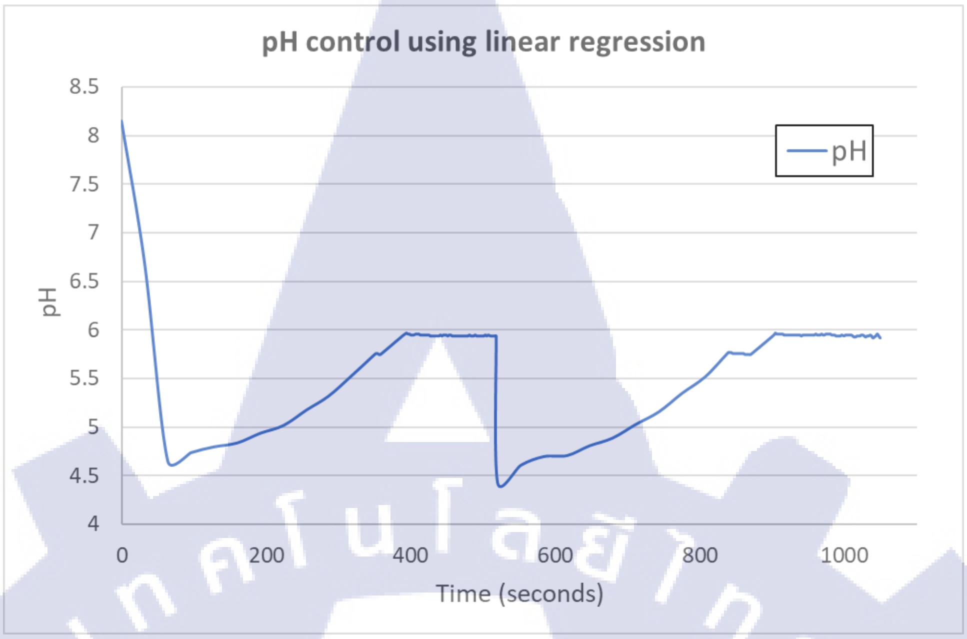



Figure 4.8 pH response of pH control using linear regression

From Figure 4.8, the target was 6.0, and the pH of the system has begun nearly 8.0 by tap water, which was high for the nutrient solution. The system can be in target and respond to a disturbance at 500 seconds, which is an acid of 5 ml, but the overshoot and steady-state error have occurred. The control signals responded to the change of error, as shown in Figure 4.9.

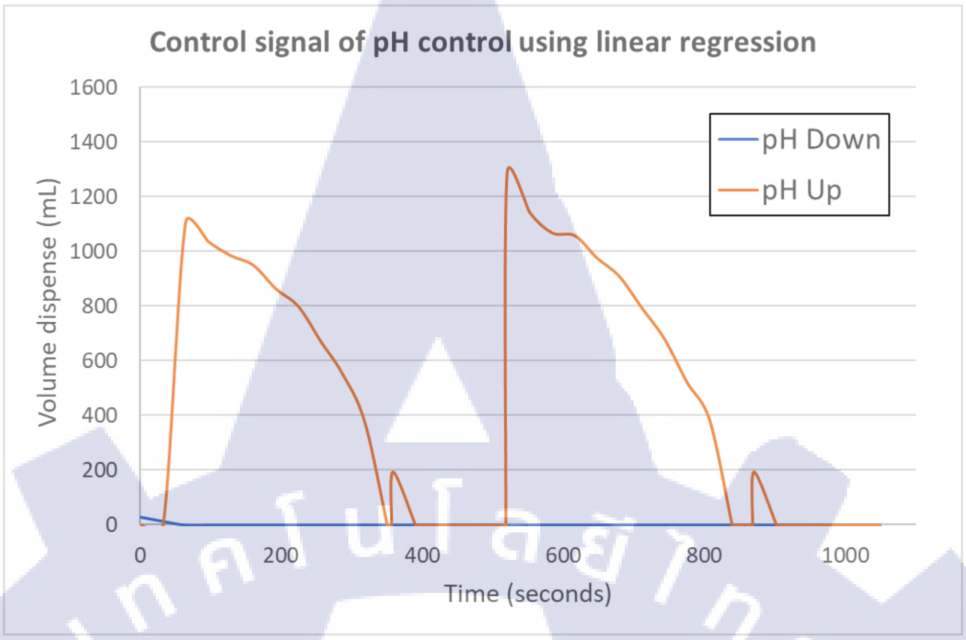



Figure 4.9 Control signals of pH control using linear regression

4.2.2 pH control in the nutrient solution using P control method

P control was designed firstly from the coefficient of an error on the linear regression equation, and then the gain was fine-tuned matching the system.

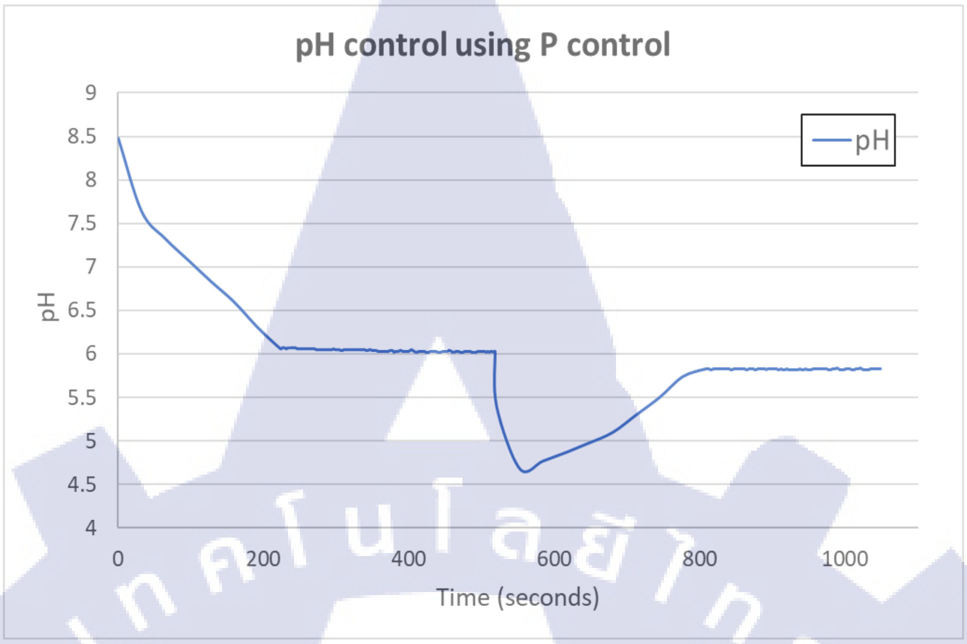



Figure 4.10 pH response of pH control using P control

From Figure 4.10, the pH value of the system was started at 8.5 by tap water and went to a target of 6.0. Then at 500 seconds, the system was interfered with by 5 ml of acid. The system can remove disturbance, yet the steady-state error has occurred. Although, the control signals also conformed to the change of error well, which was shown in Figure 4.11.

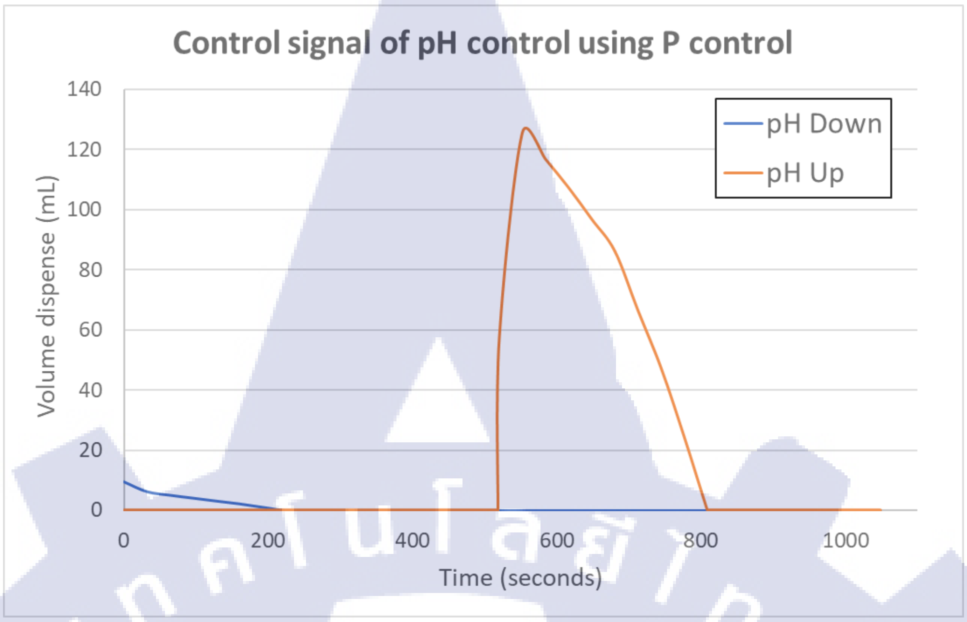



Figure 4.11 Control signals of pH control using P control

4.2.3 pH control in the nutrient solution using modified fuzzy logic control

The principle is the same as mentioned in EC control based on fuzzy logic control. However, defuzzification is modified to the area under a designed graph instead of a weighted average method or centroid method. The benefits are flexible in picking up the graph shape and easy to tune when the control signal is over or underestimation.

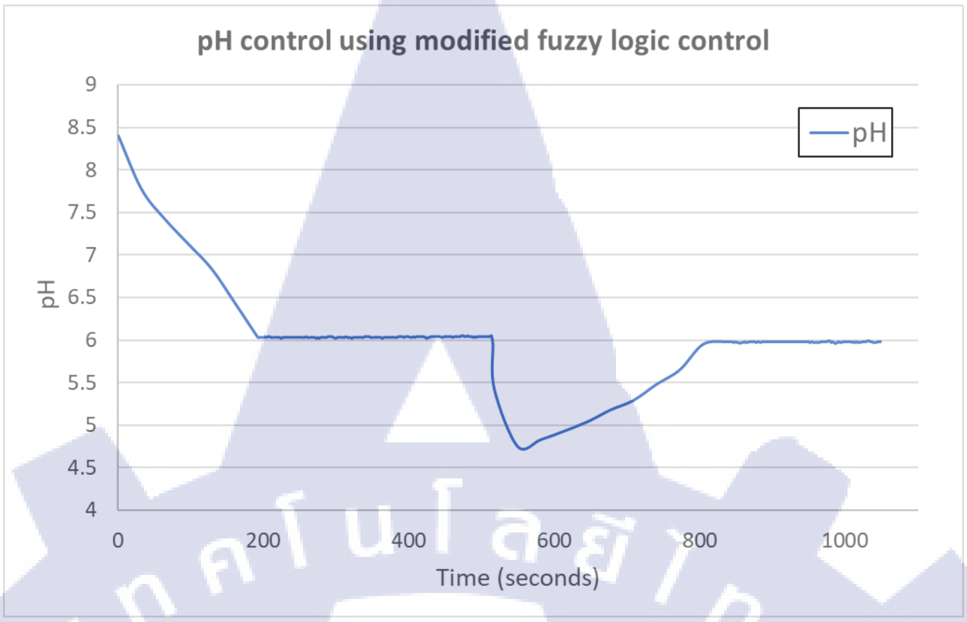



Figure 4.12 pH response of pH control using modified fuzzy logic control

From Figure 4.12, in the beginning, tap water was adjusted, and the pH of the system can reach to target within 200 seconds without overshoot, and steady-state error was almost gone. At 500 seconds, the system was interrupted. The system can keep the target. Moreover, the control signals conformed to change of error substantially, which can be seen in Figure 4.13

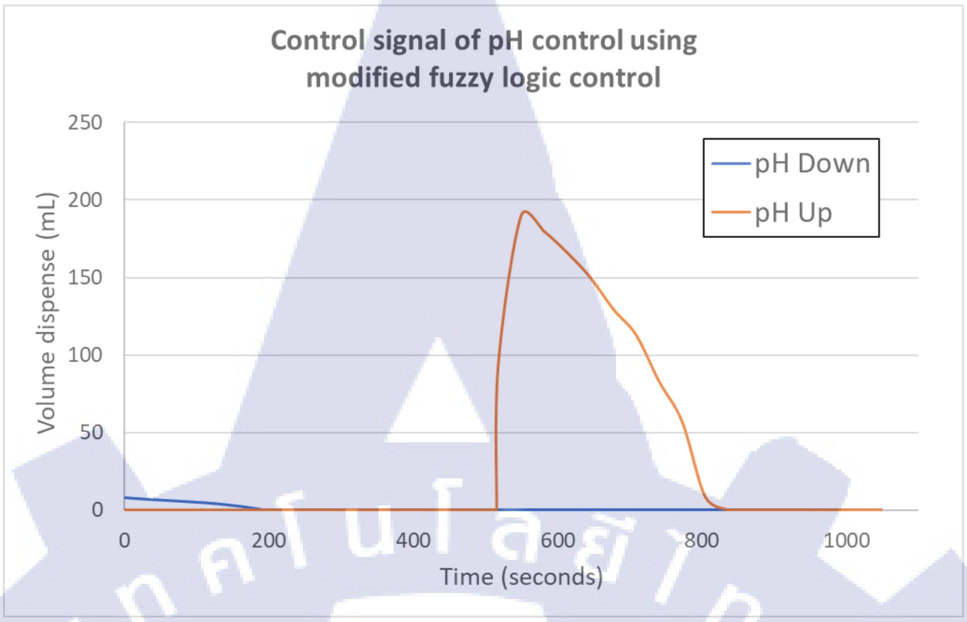



Figure 4.13 Control signals of pH control using modified fuzzy logic control

**4.3 EC and pH control in nutrient solution**

Lastly, the experiment was also conducted by three tests that are linear regression, P control, and fuzzy logic control. Each method has been tested by adjusting tap water, interrupting the system with an acid of 5 ml, and interrupting with water of 1000 ml. Furthermore, the experiment has been tested by varying targets to see the robustness of the system.

4.3.1 EC and pH control in nutrient solution using linear regression method

EC and pH control using linear regression combined EC control using linear regression and pH control using linear regression because the equations were the same. The rule base in modified fuzzy logic control was used in programming because the patterns of both programmings are identical. However, equations for dispensing each liquid solution were changed following the designed method.

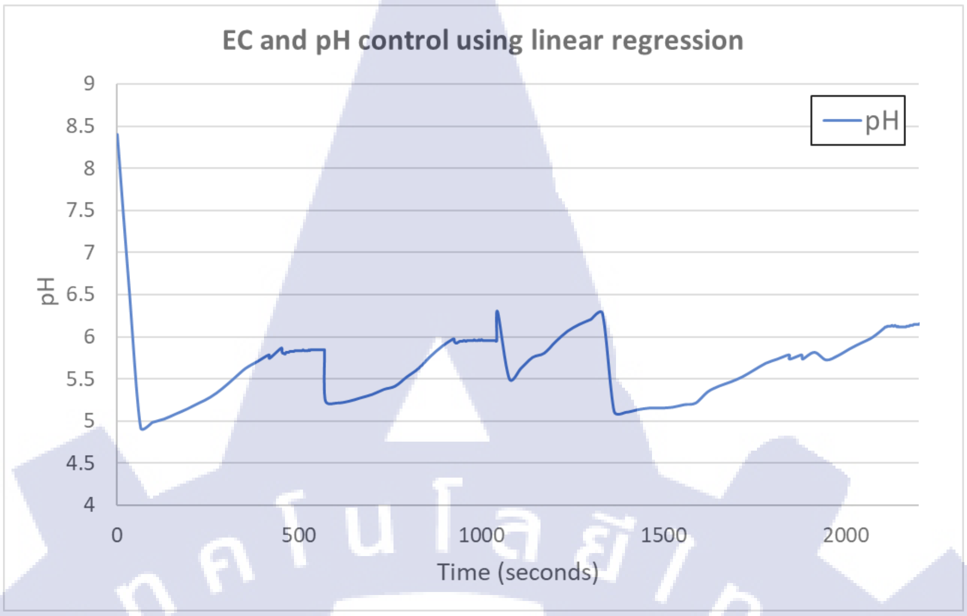



Figure 4.14 pH response of EC and pH control using linear regression

From Figure 4.14, the system adjusted pH of tap water from nearly 8.5 to 6.0, and then at near 600 seconds, the system tried to maintain pH in target from disturbance, which was acid of 5 ml. After that, at around 1100 seconds, the system tried to keep pH again from adding water of 1000 ml. The overshoot and steady-state error happened tendentiously.

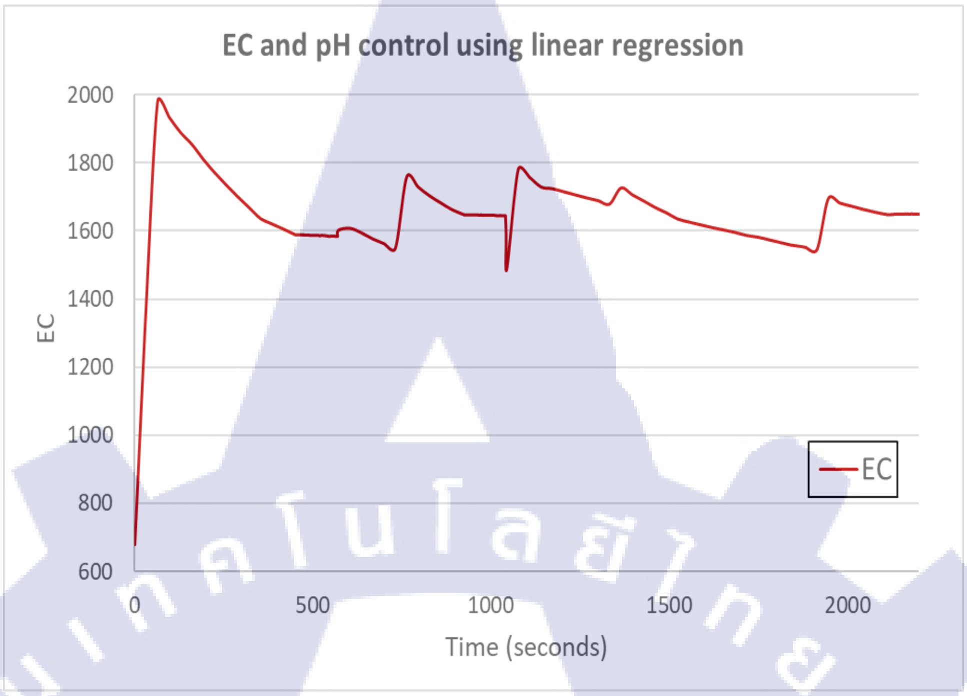



Figure 4.15 EC response of EC and pH control using linear regression

From Figure 4.15, in the view of EC, the system response has high overshoot in the beginning, and around 750 seconds, adding 5 ml of acid influenced EC by adding higher electrical conductivity in the nutrient solution. Then, around 1000 seconds, the system was interrupted by adding 1000 ml of water that affected to decrease EC in the nutrient solution. Although the system can handle disturbance, overshoot, and steady-state error have occurred. The control signals were shown in Figure 4.16.

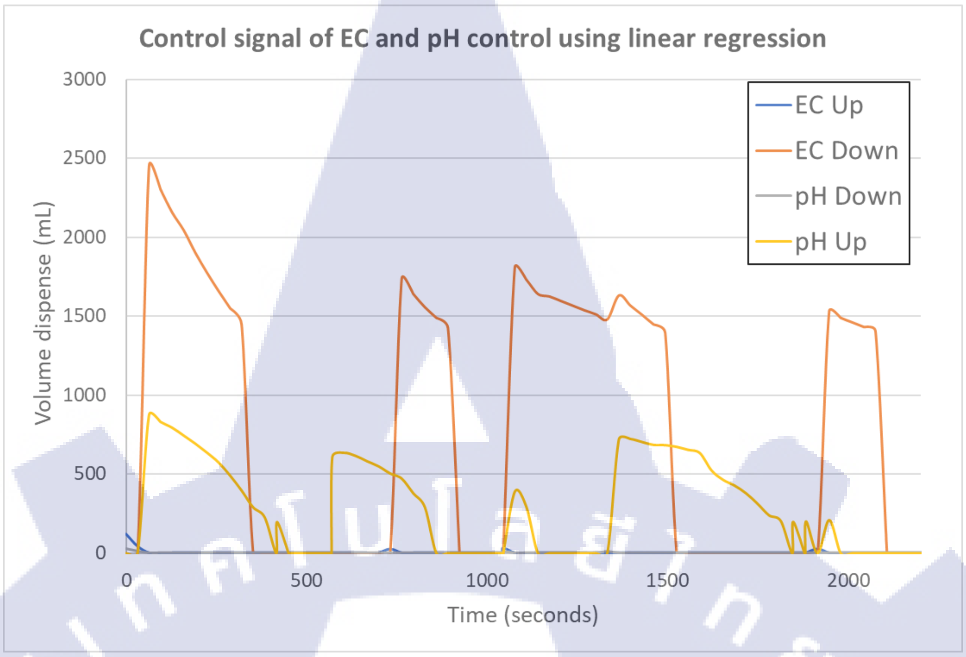



Figure 4.16 Control signals of EC and pH control using linear regression

4.3.2 EC and pH control in nutrient solution using P control method

EC and pH control using P control integrated EC control using P control and pH control using P control. However, operation in programming used the rule base in modified fuzzy logic control because the methods were especially compared to designed equations to control EC and pH in the target.

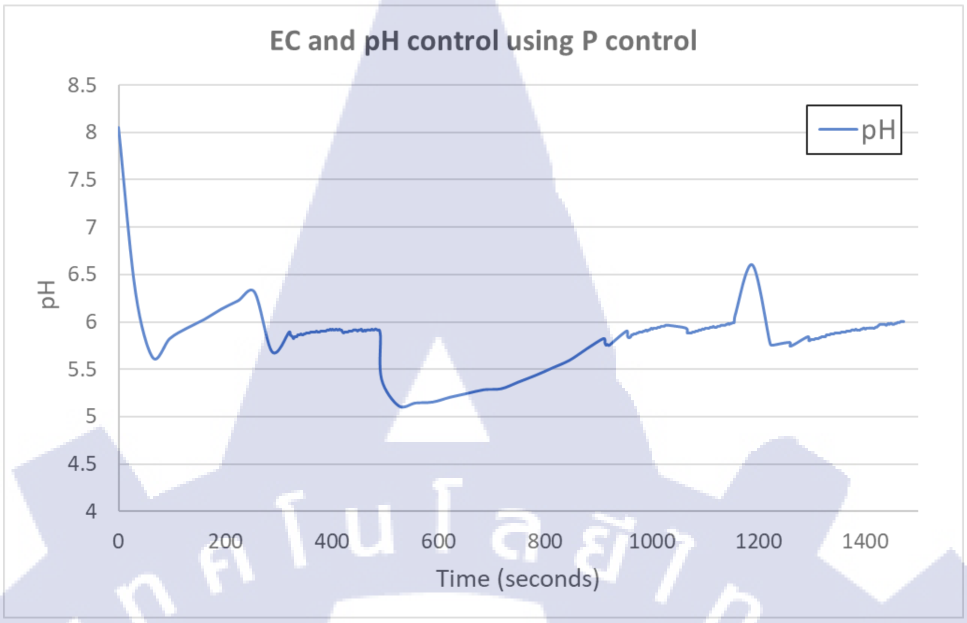



Figure 4.17 pH response of EC and pH control using P control

From Figure 4.17, in the beginning, the overshoot has occurred a little for adjusting tap water in target, but around 100-250 seconds, the impact of high EC resulted in dispensing more water; therefore, pH was going up again. After that, at near 500 seconds, the system was interfered with 5 ml of acid. The graph went down suddenly, and the system tried to move up. At near 1200 seconds, the system was interfered again with 1000 ml of water that was resulted in increased pH in the nutrient solution. On the other hand, the system can keep pH in target along the process. The overshoot and steady-state error have occurred lightly.

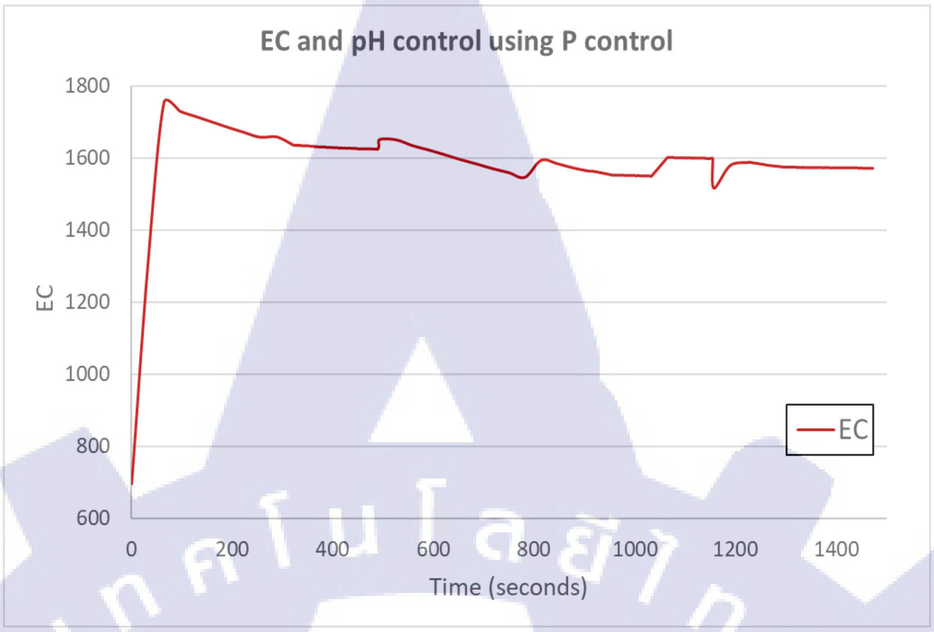



Figure 4.18 EC response of EC and pH control using P control

From Figure 4.18, at the initial period, the system adjusted tap water to be in target. The overshoot was high a bit which impacted on pH because if EC is not in target, pH will be changed accordingly. At about 500 seconds, the acid 5 ml was added to disturb the system, so EC moved up a little. At about 1200 seconds, 1000 ml of water was added to disturb again that has resulted in decreased EC in the nutrient solution. However, the system can maintain EC and pH within the target, and its response has some overshoot and steady-state error. The control signals of the system were displayed in Figure 4.19.

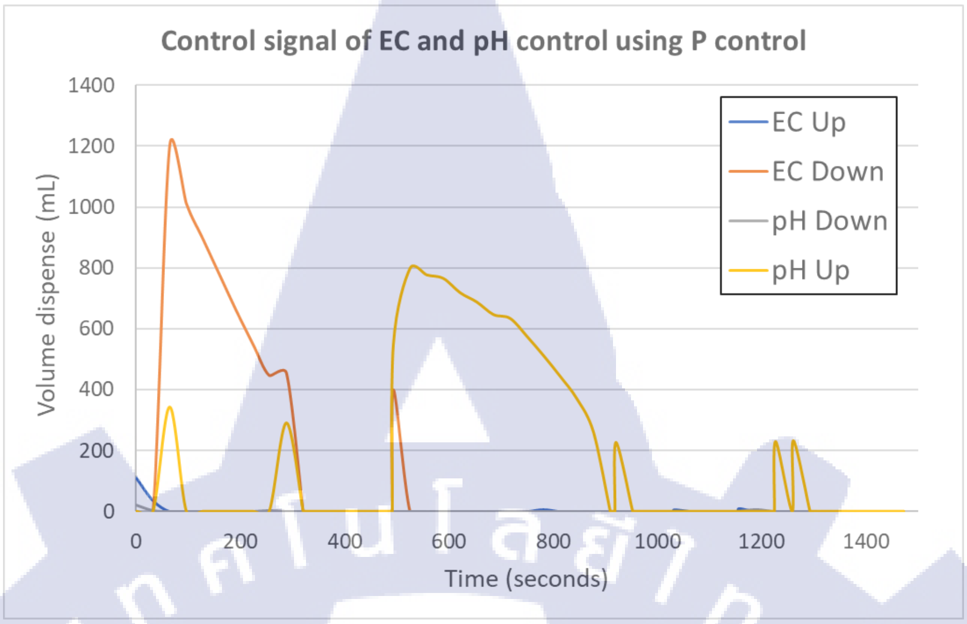



Figure 4.19 Control signals of EC and pH control using P control

4.3.3 EC and pH control in nutrient solution using modified fuzzy logic control method

EC and pH control using modified fuzzy logic control was based on EC control using modified fuzzy logic control and pH control using modified fuzzy logic control. However, the rule base was increased corresponding to the membership functions of fuzzification and defuzzification. The rule base was increased from three rules to nine rules. The defuzzification was tuned slightly from individual control because EC and pH were related.

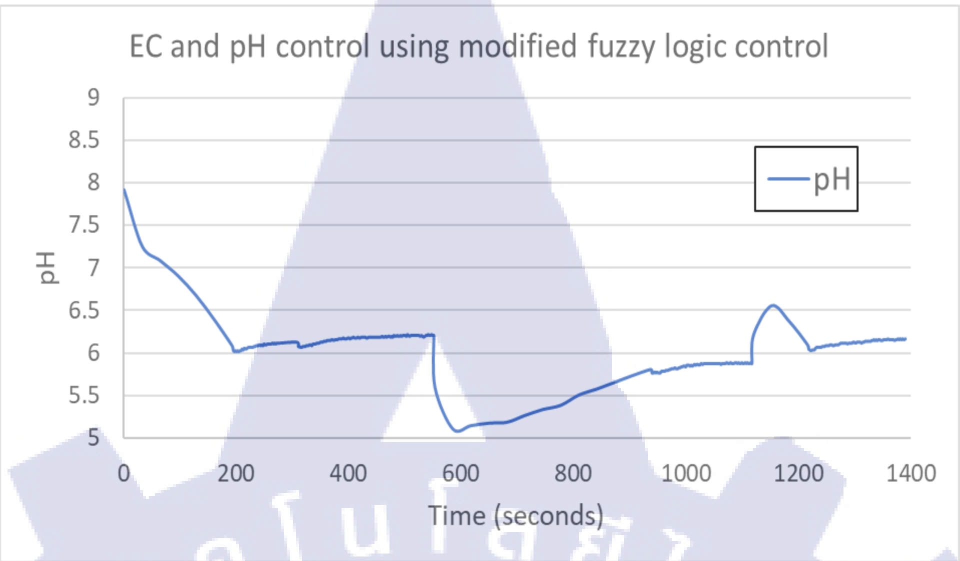



Figure 4.20 pH response of EC and pH control using modified fuzzy logic control

From Figure 4.20, the experiment started with the nutrient solution tank containing 6 liters of tap water that pH was nearly 8.5. Next, the system has begun to adjust pH to target, namely pH target is 6.0 for growing lettuce. Then, at around 600 seconds, the system was perturbed by 5 ml of acid. The system tried to keep pH in the target. Unfortunately, perturbing the system with acid influenced EC that was going up a bit; therefore, concentration in nutrient solution will be decreased proportionally to decreased EC too. After EC and pH were in target again, at near 1150 seconds, the system was perturbed by 1000 ml of water. These resulted in decreasing EC and increasing pH in the nutrient solution.

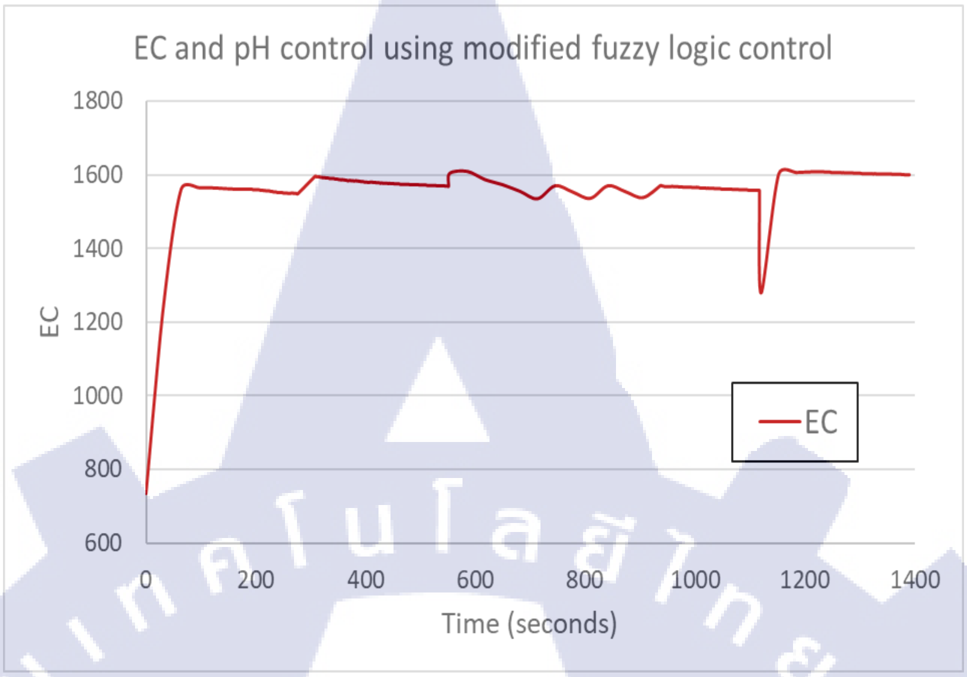



Figure 4.21 EC response of EC and pH control using modified fuzzy logic control

From Figure 4.21, Tap water started at 700 µS/cm of EC, and the system was running to adjust EC in the target, which is 1600 µS/cm. At around 600 seconds, the system was perturbed by 5 ml of acid. The relation between EC and pH impacted both values, but the system can be in target. At near 1150 seconds, the system was perturbed by 1000 ml of water that decreased EC in the nutrient solution sharply. Finally, the system still maintained its target.

The control signal for EC Down was not active because the EC value was in the target range and not high enough when the system was interfered with. The control signals correspond to a change of error, and the system can keep EC and pH in target with these control signals. The control signals follow the modified fuzzy logic control and can activate together in determining the case correctly. The system can keep the EC and pH of the nutrient solution in target despite disturbance occurred.

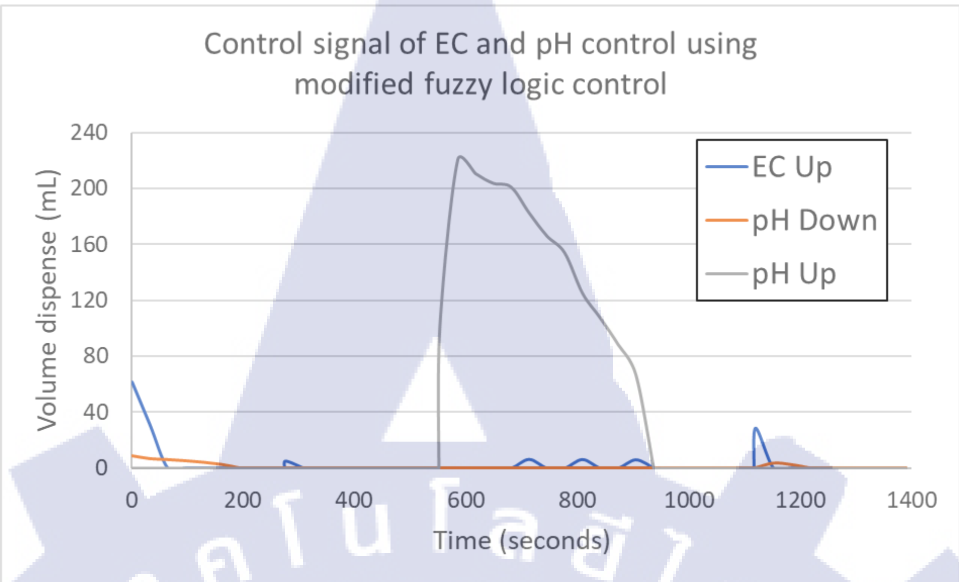



Figure 4.22 Control signals of EC and pH control using modified fuzzy logic control

4.3.4 EC and pH control in nutrient solution with variations of targets

4.3.4.1 EC and pH control using linear regression for parsley

Although linear regression can move EC and pH to the target, the results were not good enough. The settling time was so long despite without any disturbances. This designed method is not appropriate to grow parsley, and the varied target does not work for this method.

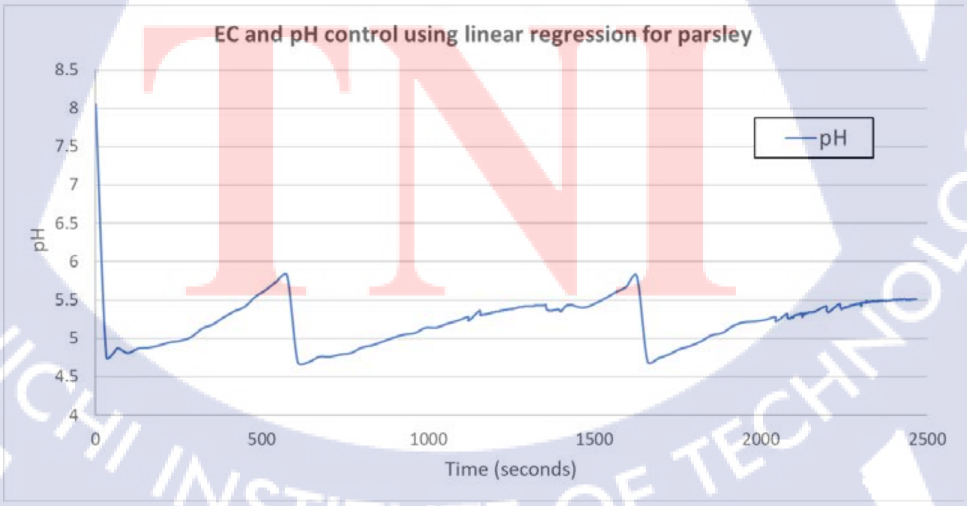



Figure 4.23 pH response of EC and pH control using linear regression for parsley

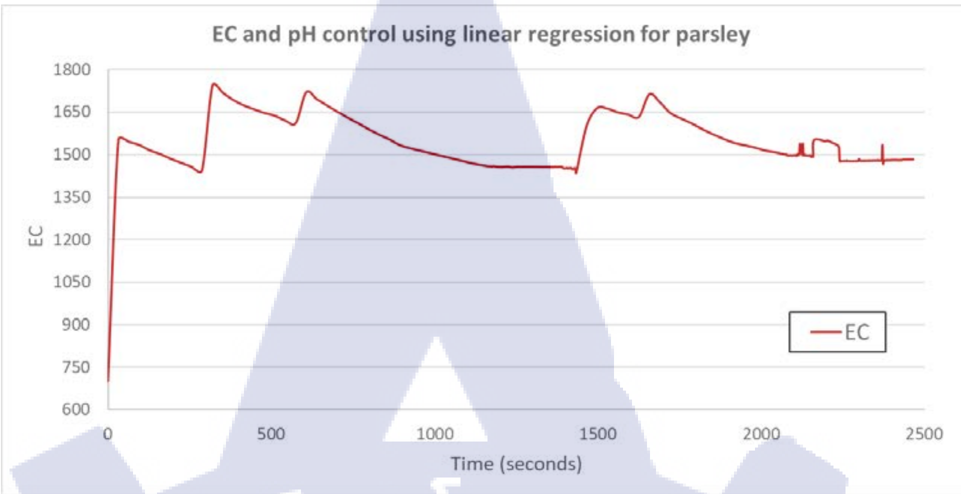



Figure 4.24 EC response of EC and pH control using linear regression for parsley

The control signals did not suit to system needs. The unnecessary amount of liquid dispense is waste because the system must add other dispenses to compensate for the system for the target.

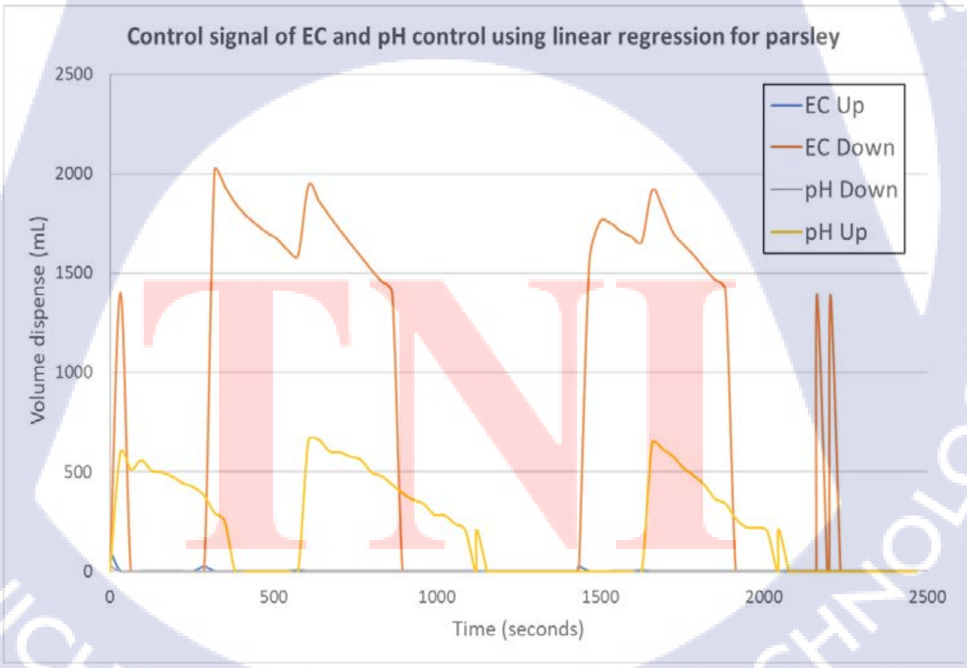



Figure 4.25 Control signals of EC and pH control using linear regression for parsley

4.3.4.2 EC and pH control using linear regression for strawberry

According to 4.3.4.1, the linear regression was still not proper for the varied target. The settling time was too slow without disturbance. This method also did not work for growing strawberry.

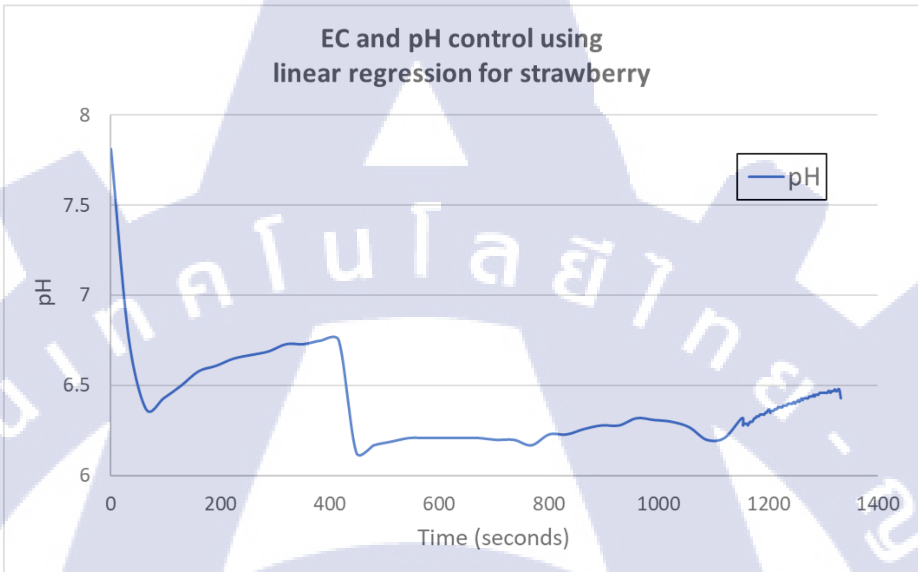



Figure 4.26 pH response of EC and pH control using linear regression for strawberry

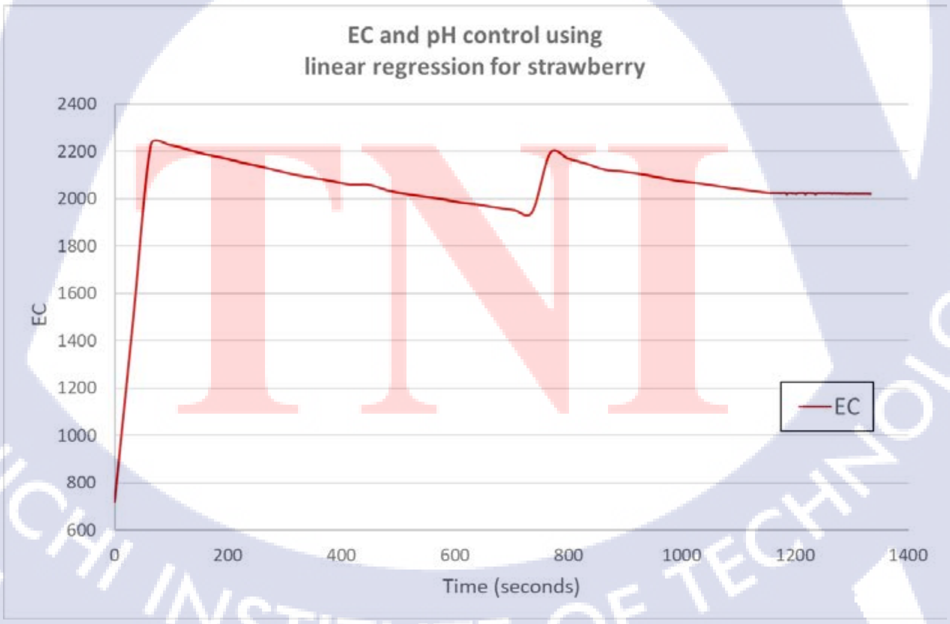



Figure 4.27 EC response of EC and pH control using linear regression for strawberry

The control signals did not conform to change of error, resulting in over dispensing liquid and much water required for compensation.

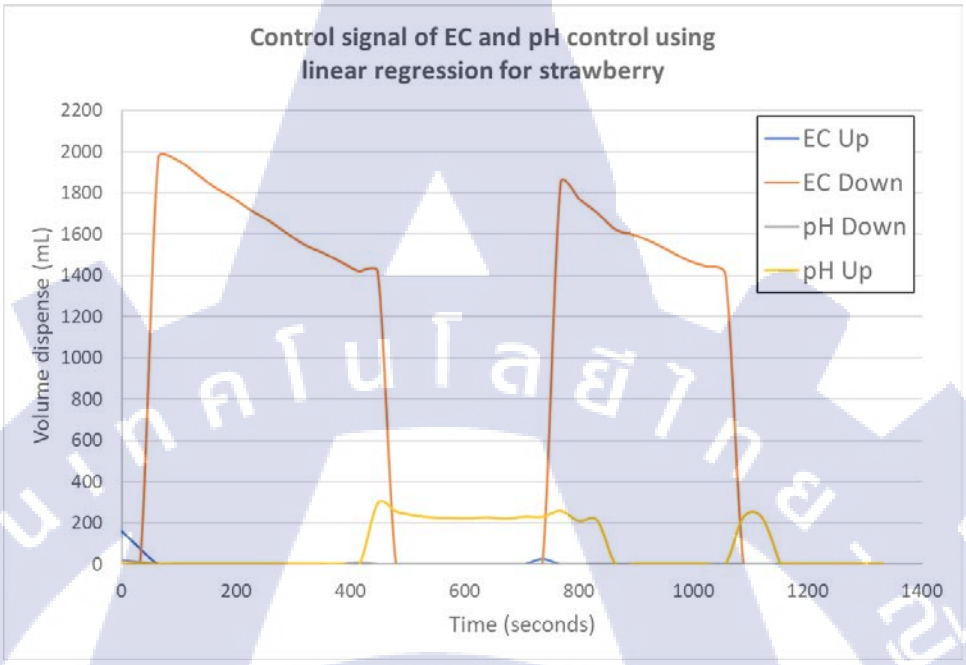



Figure 4.28 Control signals of EC and pH control using linear regression for strawberry

4.3.4.3 EC and pH control using P control for parsley

The parsley requires EC of 1500 µS/cm and pH of 5.5; therefore, the target was set following the requirement. In terms of pH, the first state was adjusting tap water to be in target. The first state indicated that the overshoot was high, and steady-state error has occurred. At around 750 seconds, the system was disturbed by 5 ml of acid and can cope with disturbance. At near 1400 seconds, the system was disturbed by 1000 ml of water and can also respond to disturbance.

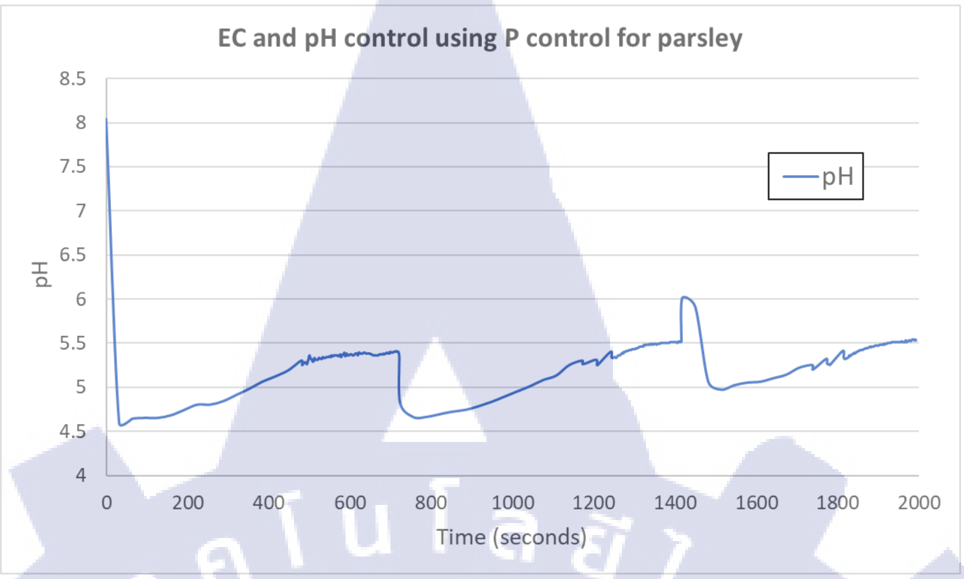



Figure 4.29 pH response of EC and pH control using P control for parsley

In terms of EC, in the first state was adjusting tap water. The EC got the impact of low pH, so the graph had oscillated because the system has to regulate EC up when the water was added to decrease acidity in the nutrient solution but also decrease EC in the nutrient solution. At around 750 seconds, the system was disturbed by 5 ml of acid; therefore, EC was increased a little. At near 1400 seconds, the system was disturbed by 1000 ml of water, which affected to decrease EC in the nutrient solution immediately, but the system can respond to disturbance. In this view, the system can control EC and pH for growing parsley.

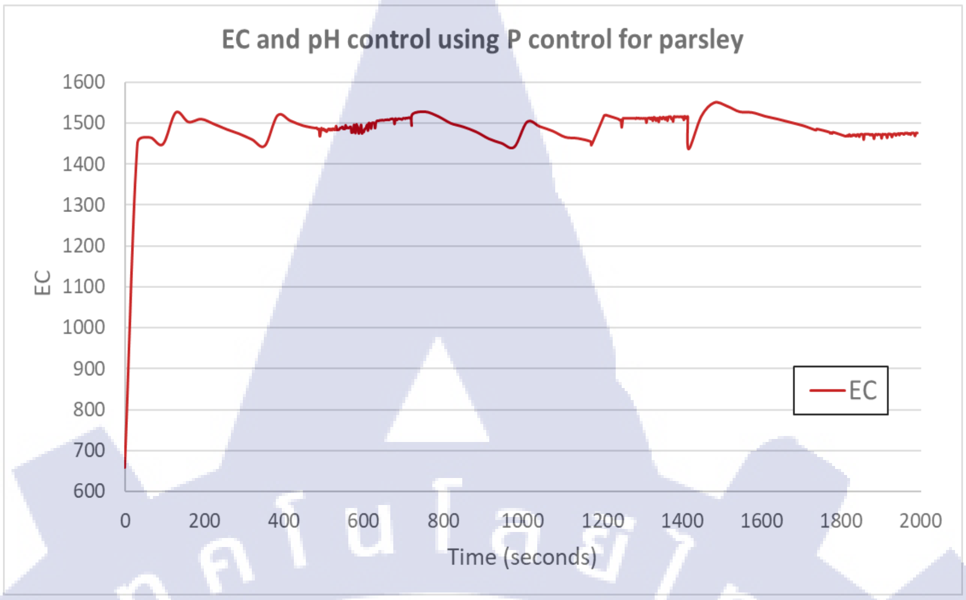



Figure 4.30 EC response of EC and pH control using P control for parsley

The control signals conformed to the change of error, but the control signal of pH was higher than the system required.

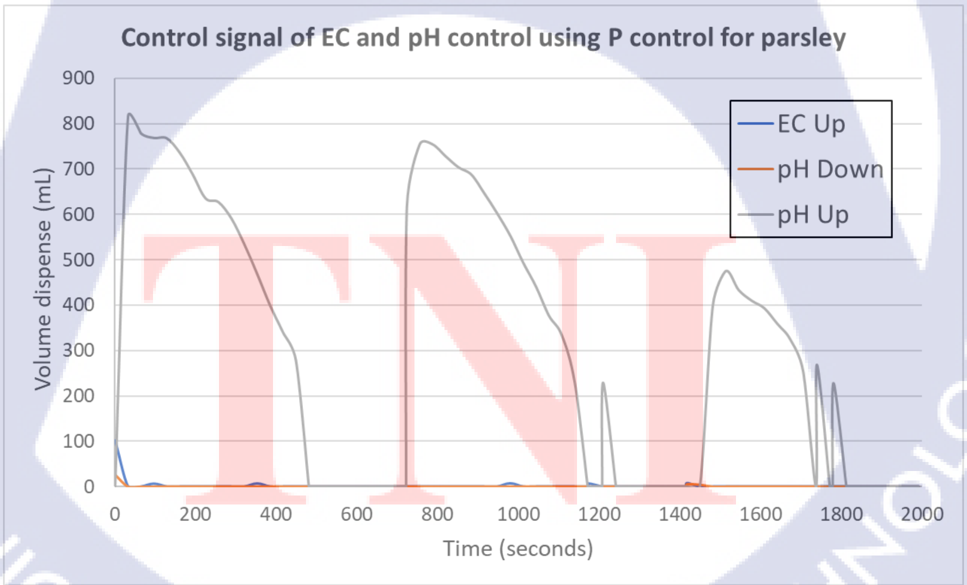



Figure 4.31 Control signals of EC and pH control using P control for parsley

4.3.4.4 EC and pH control using P control for strawberry

The strawberry requires EC of 2000 µS/cm and a pH of 6.5. Firstly, the system started with adjusting the pH of tap water from nearly 7.4 to be in the target until steady for a while. Then, at around 400 seconds, the system was interfered with 5 ml of acid, but the system can come back to the target again. After that, at around 650 seconds, then 1000 ml of water was filled in the tank to interfere with the system, but the system still comes back to the target.

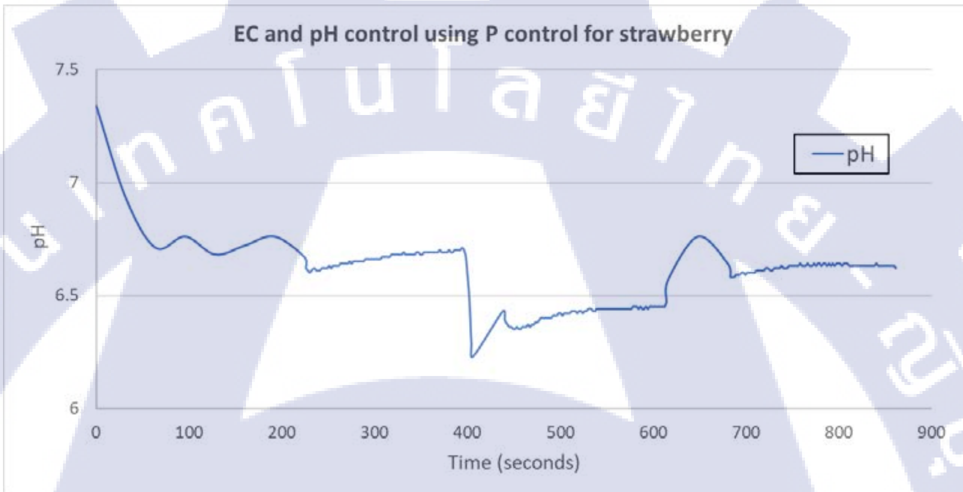



Figure 4.32 pH response of EC and pH control using P control for strawberry

In the beginning, EC of tap water was adjusted from 600 µS/cm to be in the target. Then, at around 400 seconds, the system was interfered with 5 ml of acid, but that did not change EC apparently. At around 650 seconds, 1000 ml of water was added to disturb the system that changed EC in the nutrient solution definitely. Notwithstanding, the system can keep the EC considerably. P control can work significantly in terms of EC, but in terms of pH, the response has overshoot and steady-state error visually. However, the system can control both EC and pH for growing strawberry against disturbance.

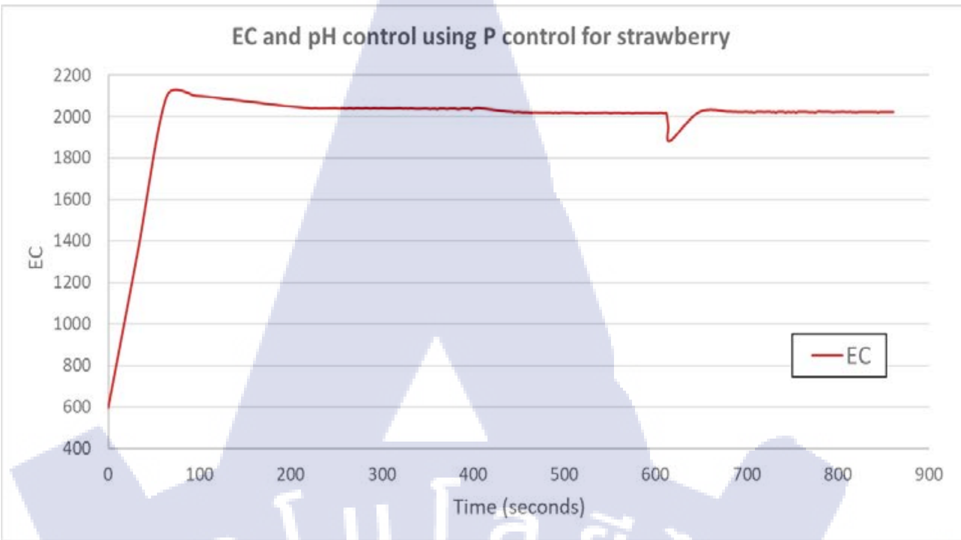



Figure 4.33 EC response of EC and pH control using P control for strawberry

The control signals of EC and pH control using P control for strawberry conformed to change of error and control signals of EC are excellent.

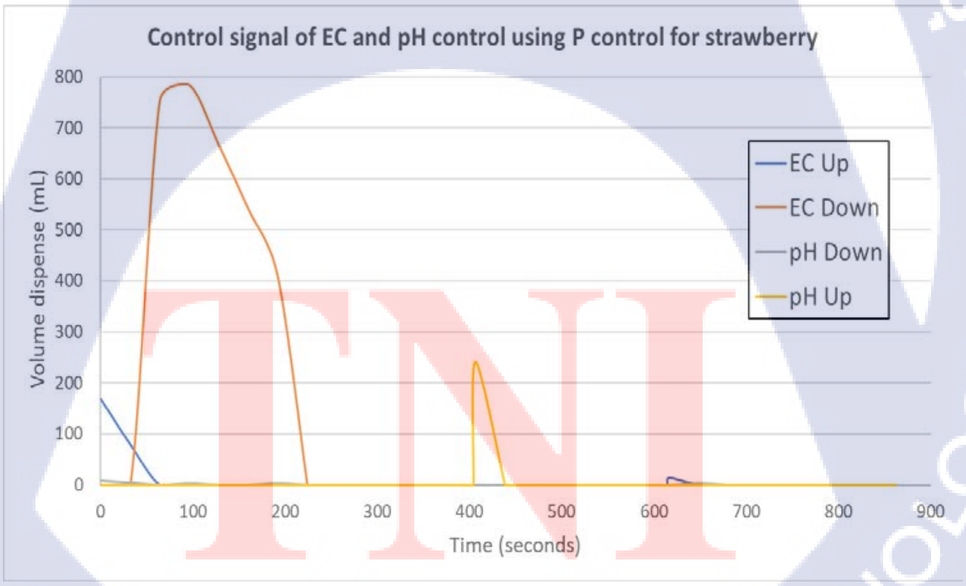



Figure 4.34 Control signals of EC and pH control using P control for strawberry

4.3.4.5 EC and pH control using modified fuzzy logic control for parsley

The target is changed in this experiment to see the robustness of the system. The target referred to EC and pH for growing parsley; namely, pH is 5.5, and EC is 1500 µS/cm. Primarily, the system can adjust the pH of tap water, which was nearly 8.0 to target. At 750 seconds, the system can keep pH in the target when the system was interfered with by adding 5 ml of acid. At 1300 seconds, the system was interfered again with by adding water 1,000 ml, but the system can also keep pH the target.

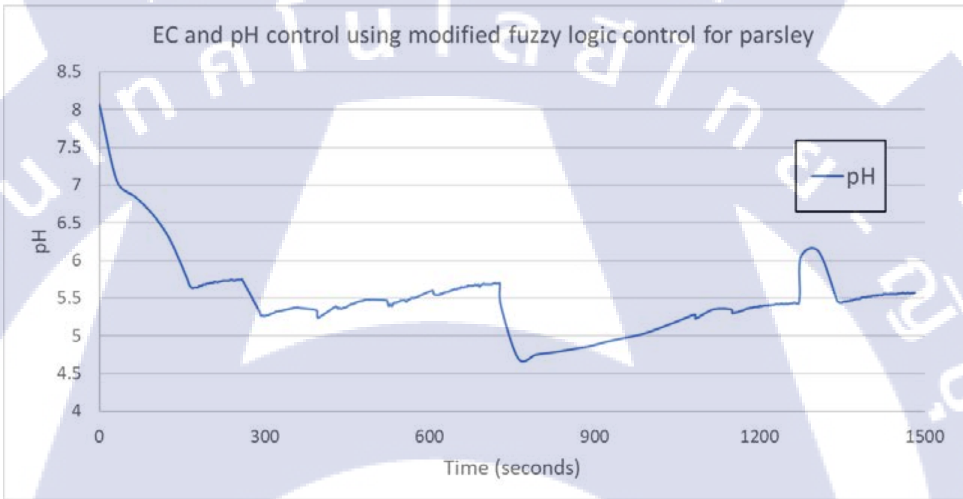



Figure 4.35 pH response of EC and pH control using modified fuzzy logic control for Parsley

Initially, tap water had EC nearly 700 µS/cm and was adjusted to 1500 µS/cm. At 750 seconds, 5 ml of acid was injected that was not significant to change EC in the nutrient solution. At 1300 seconds, 1000 ml of water was filled in the nutrient solution tank that was abruptly changed EC to be lower than the target. However, the system can eliminate disturbance and maintain the target for growing parsley decent.

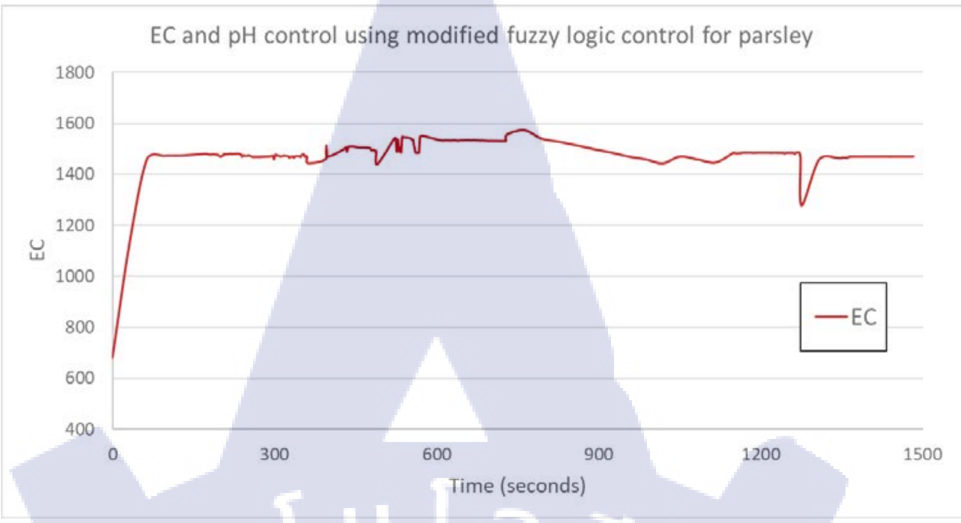



Figure 4.36 EC response of EC and pH control using modified fuzzy logic control for parsley

The control signals referred to change of error, and the system can keep EC and pH in target with these control signals. Although The target was varied, the system can keep the EC and pH of the nutrient solution in the target.

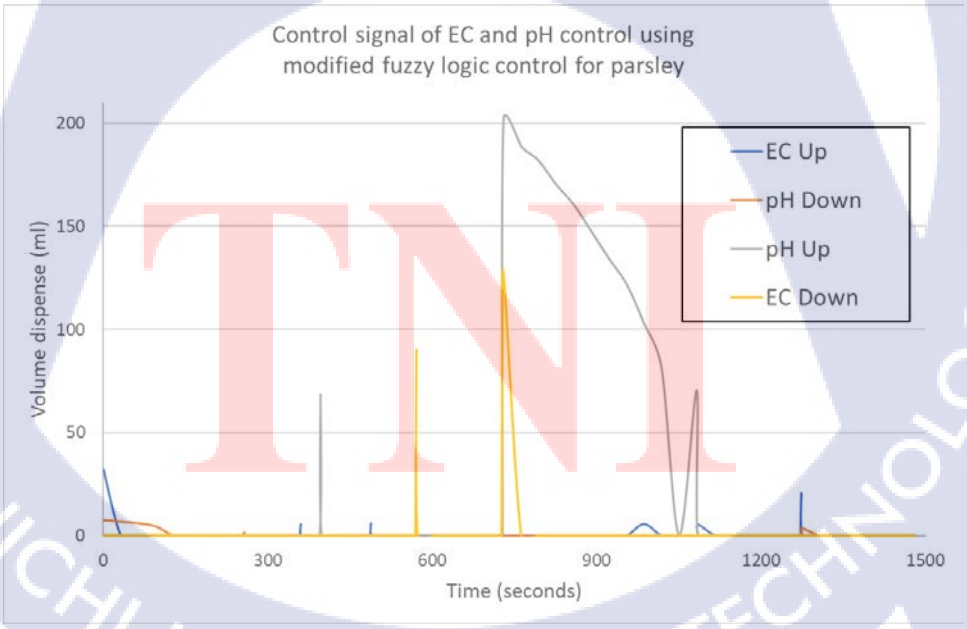



Figure 4.37 Control signals of EC and pH control using modified fuzzy logic control for parsley

4.3.4.6 EC and pH control using modified fuzzy logic control for strawberry.

This experiment is also a different target to see the robustness of the system. The target quoted from EC and pH for growing strawberry; namely, pH is 6.5 and EC 2000 µS/cm. The system can modulate the pH of tap water from nearly 8.25 to the target for starting. At about 400 seconds, the system can keep the target when the system was interfered with by adding 5 ml of acid. At near 750 seconds, 1000 ml of water was added to interfere with the system, but the system can deal with disturbance and be in the target.

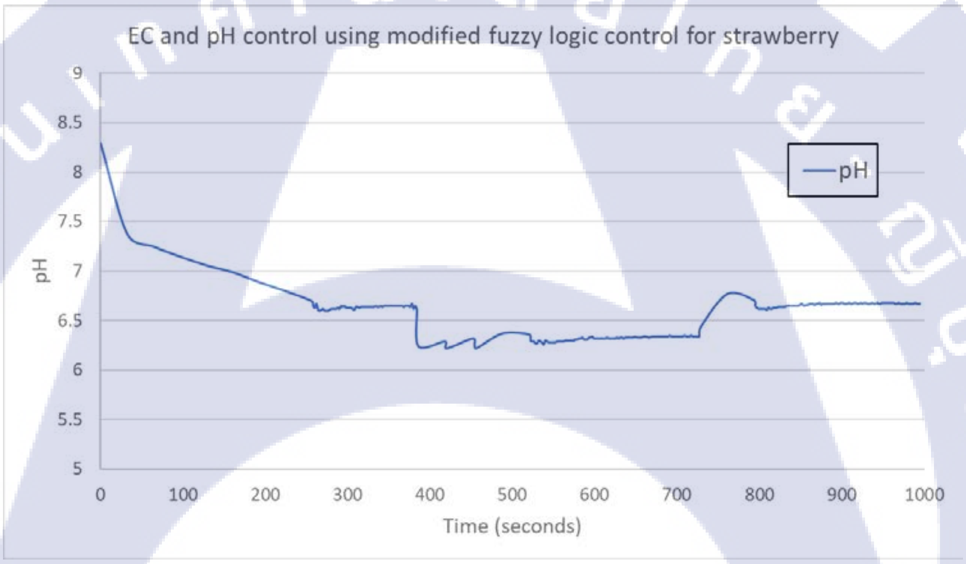



Figure 4.38 pH response of EC and pH control using modified fuzzy logic control for strawberry

At first, the system adjusted EC of tap water from about 400 µS/cm to the target. At about 400 seconds, the system was interfered with by adding 5 ml of acid, but that did not affect to EC in the nutrient solution clearly. At near 750 seconds, 1000 ml of water was filled in the nutrient solution tank that affected to decrease EC in nutrient solution obviously. However, the system was in the target nicely, and that can show the robustness of the system for growing strawberry.

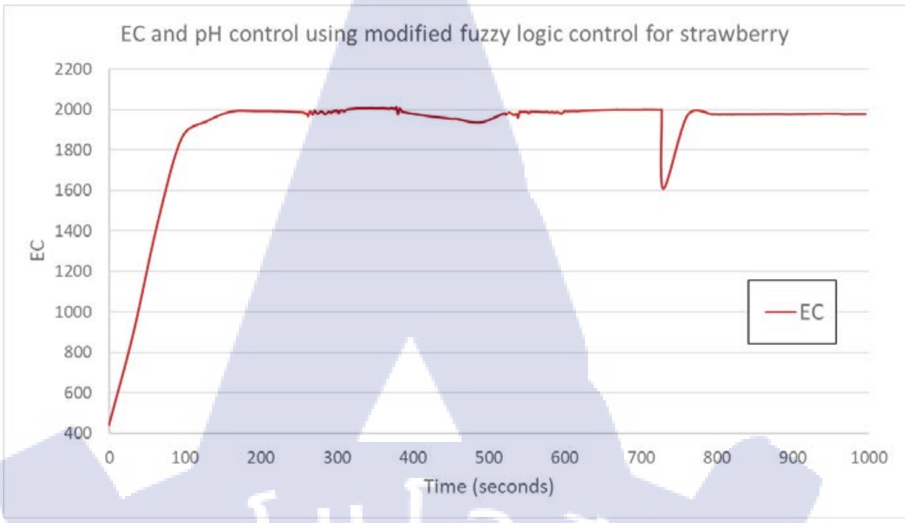



Figure 4.39 EC response of EC and pH control using modified fuzzy logic control for strawberry

The control signals are from a change of error. This experiment confirmed that the system could keep the EC and pH of the nutrient solution in target even though the target was changed.

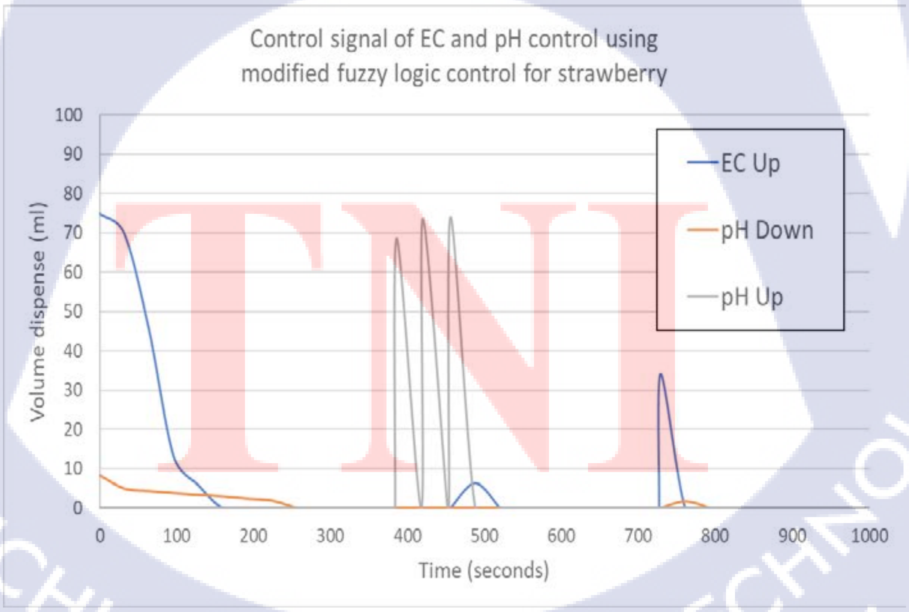



Figure 4.40 Control signals of EC and pH control using modified fuzzy logic control for strawberry

# Chapter 5
# Conclusion

## 5.1 EC control in nutrient solution

According to experimental results, the stability of each process is considered, and the modified fuzzy logic control method shows that maximum overshoot, settling time, and steady-state error are better than linear regression method and P control method following the Figure 5.1. The dilution process in the nutrient solution of each method was perturbed by adding 20 ml of fertilizer; likewise, but the diffusion rate was not equivalent; therefore, the sensor could read different values. However, the experiment could be improved to be such an Internet of Things to be more convenient, and other control methods could be used to compare.

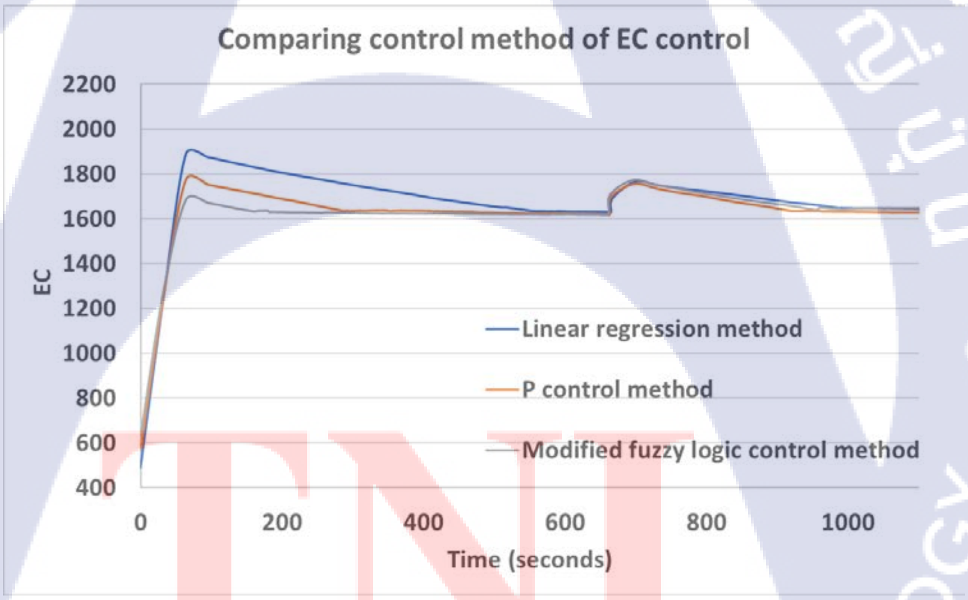



Figure 5.1 Comparing control methods of EC control

## 5.2 pH control in nutrient solution

A suitable pH in the nutrient solution is right for plants because roots can absorb some minerals better, such as iron and manganese in pH between 6.0 – 6.5, and if pH is lower than 5.0 or more than 9.0, the root will be damaged. The experiment is tested by comparing the linear regression method, P control, and modified fuzzy logic control method. All methods can control pH in the nutrient solution in target and eliminate disturbance well. However, modified fuzzy logic control can provide faster response, lower overshoot, and less steady-state error than linear regression and P control methods following Figure 5.2. This pH control can also combine with other factors to control nutrient solution, such as electrical conductivity control.

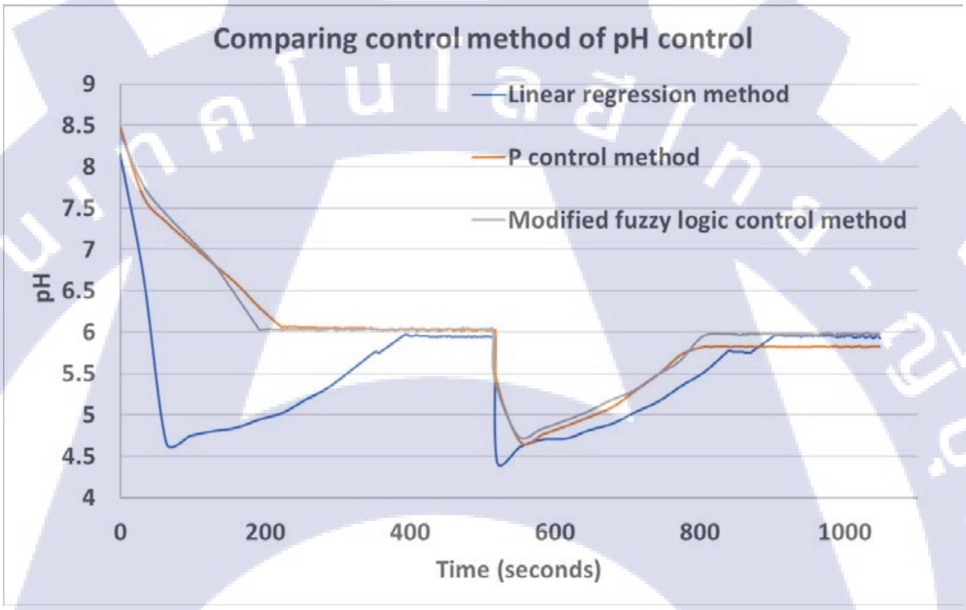



Figure 5.2 Comparing control methods of pH control

**5.3 EC and pH control in nutrient solution**

All methods can control EC and pH to be in the target ranges, which are set not greater than 5% of error. However, in case of increasing pH, the system has a slow response because the designed solution is water, not an alkaline solution, to avoid turbulence in nutrient solution and to compensate gradually. On the other hand, the system can keep the nutrient solution in the target and remove disturbance correctly. Moreover, the system was tested by different targets for other plants to see the system's robustness. The linear regression method cannot work well in a different target because control signals were not appropriate for changes of error. Nevertheless, P control method and modified fuzzy logic control can maintain EC and pH and handle disturbance.

Surprisingly, P control can work significantly for the strawberry condition. Nevertheless, modified fuzzy logic control has robustness in all conditions, and the results are acceptable because the EC and pH converge to target within 5% of determined error and satisfy stability.

The results of EC and pH control using modified fuzzy logic control is acceptable. If the system is normalized to 1 liter of nutrient solution tank, the settling time of the EC response is 10.67 seconds for the starting process, and the settling time of the pH response is 32 seconds for the beginning process. Comparing to the results reviewed in the automatic control of electrical conductivity and pH using fuzzy logic for the hydroponic system from Table 2.2, if the tank is normalized to 1 liter, the settling time of the EC response is 50 seconds and the settling time of the pH response is 30 seconds.

In this research, the experiments are tested in the lab and can be used in a real situation. The system can reach the point of the automatic system control, and the prototype is practically used to verify many experiments. The research can support farmers and can reduce the complicated process. However, the system can be improved to have a better response or can be adapted to other conditions. Furthermore, there is an essential substance inside the nutrient solution that can also be controlled. However, the obstacle is a high investment as sensors are expensive, and chemical processes become necessary to classify substance.

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# Appendix

**Appendix A.**

**Variables definition**

Table A.1 Variables definition

| **Variable** | **Definition** |
|---|---|
| EC | Electrical conductivity |
| pH | Power of hydrogen |
| $e(t)$ | Error |
| $f(e(t)$ | Function of error |
| $e_{ec}(t)$ | Error of electrical conductivity |
| $e_{ph}(t)$ | Error of power of hydrogen |
| $r(t)$ | Reference point |
| $r_{ec}(t)$ | Reference point of electrical conductivity |
| $r_{ph}(t)$ | Reference point of power of hydrogen |
| $y(t)$ | Output |
| $y_{ec}(t)$ | Output of electrical conductivity |
| $y_{ph}(t)$ | Output of power of hydrogen |
| $y'_{ec}(t)$ | Electrical conductivity read from sensor |
| $y'_{ph}(t)$ | Power of hydrogen read from sensor |
| $u(t)$ | Control signal |
| $u_{reab,ec}(t)$ | Control signal of dispensing stock AB for adjusting electrical conductivity using linear regression |
| $u_{rewa,ec}(t)$ | Control signal of dispensing water for adjusting electrical conductivity using linear regression |
| $u_{reac,ph}(t)$ | Control signal of dispensing acid for adjusting power of hydrogen using linear regression |
| $u_{rewa,ph}(t)$ | Control signal of dispensing water for adjusting power of hydrogen using linear regression |
| $u_{p1ab,ec}(t)$ | Control signal of dispensing stock AB for adjusting electrical conductivity using P control |
| $u_{p2wa,ec}(t)$ | Control signal of dispensing water for adjusting electrical conductivity using P control |

Table A.1 Variables definition (Cont.)

| Variable | Definition |
|---|---|
| $u_{p3ac,ph}(t)$ | Control signal of dispensing acid for adjusting power of hydrogen using P control |
| $u_{p4wa,ph}(t)$ | Control signal of dispensing water for adjusting power of hydrogen using P control |
| $u_{fuab,ec}(t)$ | Control signal of dispensing stock AB for adjusting electrical conductivity using modified fuzzy logic control |
| $u_{fuwa,ec}(t)$ | Control signal of dispensing water for adjusting electrical conductivity using modified fuzzy logic control |
| $u_{fuac,ph}(t)$ | Control signal of dispensing acid for adjusting power of hydrogen using modified fuzzy logic control |
| $u_{fuwa,ph}(t)$ | Control signal of dispensing water for adjusting power of hydrogen using modified fuzzy logic control |
| $\mu$ | Degree of membership |
| $\mu_{Low}(x)$ | Degree of input membership of Low function |
| $\mu_{Ideal}(x)$ | Degree of input membership of Ideal function |
| $\mu_{High}(x)$ | Degree of input membership of High function |
| $\mu_{ON}(z)$ | Degree of output membership of ON function |
| $\mu_{OFF}(z)$ | Degree of output membership of OFF function |
| $K_p$ | Proportional gain |
| $K_i$ | Integral gain |
| $K_d$ | Differential gain |
| $K_{p1ab,ec}$ | Proportional gain of dispensing stock AB for adjusting electrical conductivity using P control |
| $K_{p2wa,ec}$ | Proportional gain of dispensing water for adjusting electrical conductivity using P control |
| $K_{p3ac,ph}$ | Proportional gain of dispensing acid for adjusting power of hydrogen using P control |

Table A.1 Variables definition (Cont.)

| Variable | Definition |
|---|---|
| $K_{p4wa,ph}$ | Proportional gain of dispensing stock AB for adjusting power of hydrogen using P control |