Development of Fuzzy Logic pH controller for pH Neutralization in Waste Water Treatment Plant (WWTP)

By

Nor Mohd Hafiz Bin Johar

Dissertation submitted

in partial fulfillment of

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NOR MOHD HAFIZ BIN JOHAR

ABSTRACT

pH neutralization is one of the important processes in Wastewater Treatment Plant (WWTP). As WWTP used to treat effluent and discharged water to public sewage, the right pH is important to save the environment, safety, fulfill the rules and regulations and keep the plant equipment in safe condition. pH neutralization is well known for highly non-linear characteristic with high sensitivity at the neutral region. Thus, pH neutralization is of the hardest parameter to be controlled in WWTP. From the literature review, current and most popular control strategy like PI controller produces certain range of errors. This is due to PI controller unable to compensate the non-linear characteristic of pH neutralization process. Advanced control strategy is believed to be the solution to control pH neutralization process in WWTP. Therefore, the objective of this project is to investigate and design advanced control strategy. A mathematical modeling is used to develop a plant model based on McAvoy Model. The plant model is obtained from previous researcher. From the validation of the model, the plant is accepted to be used throughout the project. Both conventional and advanced control strategy is developed. The development of controller is carried out in SIMULINK environment. Evaluation of the controller performance is based on few parameters such as settling time, rise time and integral of absolute error. Based on the simulation results, Fuzzy Logic has given a excellent control performance compared to PI controller. Fuzzy logic is able to compensate any changes in high sensitivity in neutral region. In conclusion, advanced control strategy of Fuzzy Logic able to deal with high non-linearity of pH neutralization process compared to conventional control strategy which is PI controller. The findings in this project will encourage other researcher to implement it for other non-linear processes and being implemented in real time industry.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

WWTP	Waste Water Treatment Plant
DOE	Department of Environment
PID	Proportional Integral Derivatives
PI	Proportional Integral
PD	Proportional Derivatives
FLC	Fuzzy Logic Controller
FIS	Fuzzy Inference System
PV	Process Variable
SP	Set Point
MF	Membership Function
CSTR	Controlled Stirrer Tank Reactor

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Wastewater Treatment Plant (WWTP) is related to the process of removing contaminants from wastewater or effluent and disposed it to environment such as river, lake or sea. In WWTP, there are many type of process such as physical, chemical and biological processes to clarify the effluent. The objective of this WWTP is to produce environmentally safe water and can be use for human being daily routine.

In industrial plant, WWTP is one of the major concerns for industrial safety [27]. pH is one of the waste water parameters need to be controlled. The level of neutrality of the discharged water is important to avoid catastrophic life to human being. Not only that, the right pH of discharged water is important for survival of the aquatic life. Too acidic or alkaline discharged water may kill the aquatic life. Therefore, it will affect the protein source to the human being. pH control is not only focusing to save the environment. It is related to the rules and regulations and for the plant itself. For rules and regulations, Department of Environmental (DOE), in Environmental Act 1974 required any discharged water to be in between of pH value of 6 and pH value of 9. As per discussed earlier, the rules and regulations try to make sure the plant is totally following the requirement to save the environment. Failing to fulfill this act, serious punishment can be considered.

Moreover, by controlling the right pH, plant equipment such as control valve, tank or pipe can be protected. If the process of the fluid is too acidic or alkaline, it will lead to big disaster to the plant as it will make the equipment corroded and damaged. In conclusion, controlling the right pH in the WWTP is important and crucial to save the environment, to fulfill the rules and regulations and to save the plant equipment from damage.

1.2 Problem Statement

pH neutralization is of the most challenging processes in WWTP process control. Based on the literature review, pH neutralization process is well known for their high non-linear with high sensitivity in the range of neutral point. Neutral point is considered between pH values of 6 to pH value of 8. pH neutralization is related to the titration curve. Each characteristic of acid will give different reaction to different alkaline such as reaction of strong acid and strong alkaline is different from the reaction of strong acid and weak alkaline. The pH neutralization is related to the flow of acid and alkaline. A minimum flow of acid or alkaline into the mixture will cause a significant change in pH value. The most popular control strategy, PI controller produces certain range of errors [8]. PI controller is unable to conduct neutralization with precision and accuracy. From the literature review, advanced control strategy such as fuzzy logic, neural network is believed to deal with the high non-linearity of pH neutralization control system and obtain a better control strategy.

1.3 Objective

- To investigate, design and develop a Fuzzy Logic controller for pH neutralization plant.
- To compare the existence control strategy with the developed advanced control strategy.
- To analyze the controller performance between the conventional PI controller and the advanced Fuzzy Logic controller.

1.4 Significance of the Research

As discussed earlier, pH neutralization is well known for high non-linearity characteristic. This pH neutralization process represents other non-linear process control. pH neutralization can be the representative or benchmark to other non-linear process. The successfulness of this finding for the right method of controlling the pH neutralization will encourage other researcher to implement the same method or control strategy for other non-linear process especially for chemical processes.

CHAPTER 2

LITERATURE REVIEW

2.1 pH

The concept of pH was discovered by Danish chemist, Soren Sorenson (1868-1939) in 1909. pH is defined as the negative logarithm of the concentration of hydrogen ion (H^+) in a solution [8].

$$\mathbf{pH = -\log [H^+]} \quad (1)$$

The equation above shows the single ion quantity which is immeasurable by any thermodynamically valid method [9].

In other way round, pH can be defined in very specific as:

$$\mathbf{pH = -lg}\ a_H = -\mathbf{lg}\ (m_H\gamma_H / m^\circ) \quad (2)$$

a_H is the relative (molal basis) activity and γ_H is the molal activity coefficient of the hydrogen ion H^+ at the molality m_H and m° is the standard molality. Hence, pH only measured the activity of hydrogen ions in solution [9].

pH scale is a logarithmic and runs from 0.0 to 14.0. From the range itself, it is divided to three regions which is acidic, neutral and alkaline. If the solution has pH of 7, the solution is neutral while if the solution is below than 7, it is acidic solution. The solution become more acidic if it is reaches to pH 1.

For alkaline, the solution must be more than 7. As the same thing as acidic generally, the solution will become more alkaline if it is reaches pH of 14. Both acidic and alkaline become weaker solution for both characteristic if it is reaches the neutral point which pH of 7.

2.2 Titration Curve

Titration is a technique used in chemical analysis to determine the concentration of unknown acid or alkaline. Titration method deals with the slow addition of one known concentration solution to unknown concentration solution. Titration will stop until reaction reaches some level [8]. For both strong acid – strong base reaction, titration curve is illustrated as shown below:

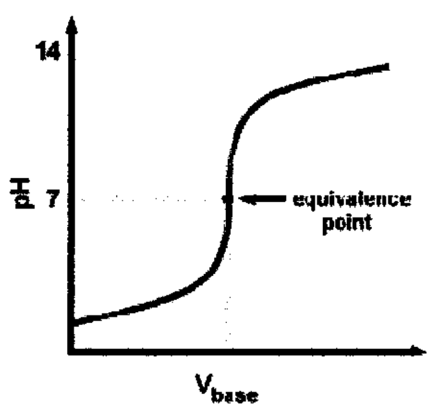

***Figure 1**: Strong acid and Strong base Titration Curve.*

Based on Figure 1, there is the initial slow rise in pH until the reaction nears the point where just enough alkaline is added to neutralize all the initial acid. This point is called the equivalence point. For a strong acid/alkaline reaction, this occurs at pH is equal 7. As the solution passes the equivalence point, the pH slows its increase where the solution approaches the pH of the titration solution.

The 'S' shape of the titration curve shows the high non-linearity neutralization process. The curve begins at low pH which is in strong acid side, and ends at high alkalinity. There is a large rapid change in pH near the equivalence point [10],[11]. The titration curve is differing from different strength of acid and alkaline. Each reaction e.g. Strong acid-weak base will give changes in 'S' shape in titration curve [8]. Figure below shows the different reaction of different strength of acid and alkaline (base).

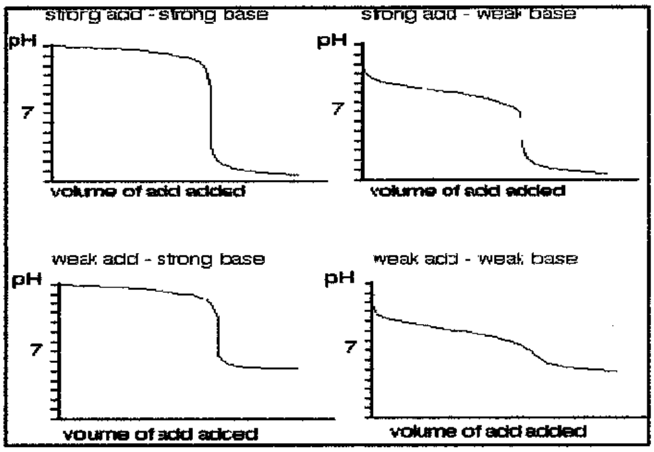

***Figure 2:** Types of Titration Curve*

2.3 Controlled Stir Tank Reactor (CSTR)

The operation of pH neutralization process is based on the concept of Controlled Stirred Tank Reactor (CSTR). Figure 3 shows the pH neutralization process in stirred tank. A mixer in the tank is used to ensure proper reaction between acid and alkaline. Moreover, it is use enhance the reaction time of both solutions.

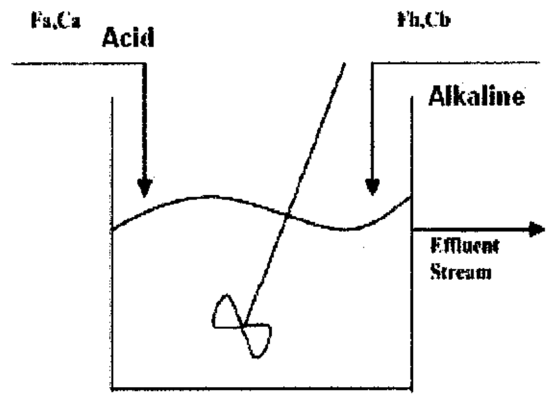

***Figure 3**: Controlled Stirred Tank Reactor (CSTR)*

From Figure 3, both acid and alkaline with certain concentration is pumped into the tank. The flow of acid and alkaline will represent by F_a and F_b respectively. Meanwhile, concentration of acid and alkaline represents C_a and C_b. Somehow, there is control valve in both stream to control the flow of both solutions. According to [20], the volume of reactor tank, V, concentration of acid C_a and alkaline C_b and the flow rate, F_a and F_b essential in order to determine the mathematical model of single acid-single base process. Most of the researches on pH neutralization process used this model to develop their own pH neutralization model.

Based on the CSTR, previous researcher [20] developed two equations to express pH process. The two equations are shown below:

$$V\frac{d\alpha}{dt} = F_1C_1 - (F_1 + F_2)\,\alpha \quad (3)$$

$$V\frac{d\beta}{dt} = F_2C_2 - (F_1 + F_2)\,\beta \quad (4)$$

From the equations, F_1 and F_2 represents flow rate of acid and alkaline respectively. The concentration of acid and alkaline represented by C_1 and C_2. The volume of the tank represents by V.

The symbol in Equation 3 and Equation 4, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ is represents the non-reactant component for acid and alkaline. As an example, Sulphuric Acid (H_2SO_4) reacts with Sodium Hydroxide (NaOH) will represents $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ to be shown as equations below:

$$\alpha = [H_2SO_4^{+}] + [H_2SO_4^{-}] + [SO_4^{2-}] \quad (5)$$

$$\beta = [Na^{+}] \quad (6)$$

Based on the electro neutrality concept, all solutions are neutral. Hence, for acid-alkaline reaction, the last solution should be in neutral in terms of its electron. There is no excess positive or negative charge since the sum of positive charges and negative charges are the same or produced zero. Take same example as in Equation 5 and Equation 6, the total electro neutrality condition is shown below:

$$[Na^{+}] + [H^{+}] = [OH^{-}] + [H_2SO_4^{-}] + 2[SO_4^{2-}] \quad (7)$$

The pH value is depends on the hydrogen ion as shown in Equation 1. The composition of hydrogen ion can lead to Ph equation which knows as:

$$[H^{+}]^4 + \alpha_1[H^{+}]^3 + \alpha_2[H^{+}]^2 + \alpha_3[H^{+}]^1 + \alpha_4 \quad (8)$$

The coefficients of α_1 to α_4 can be represented as shown below:

$$\alpha_1 = K_1 + \beta \quad (9)$$

$$\alpha_2 = \beta K_1 + K_1K_2 - K_w - K_1 \alpha \quad (10)$$

$$\alpha_3 = \beta K_1 K_2 - K_1 K_w - 2 K_1K_2 \alpha \quad (11)$$

$$\alpha_4 = - K_1 K_2 K_w \quad (12)$$

The Equation 9 to Equation 12 represents the sub equation in Equation 8. K_1 and K_2 represents the two acid dissociation constants which are to be $1.0\text{x}10^{3}$ and $1.2\text{x}10^{-2}$. K_w is represents the constant value for the ionic product of water which equal to $1.0\text{x}10^{14}$.

Based on the CSTR and equations developed by previous researcher [20], a mathematical modeling approach of designing a pH plant process can be developed. This mathematical modeling involves the dynamic parts of the process and the calculations of pH value of the system.

2.4 pH Controller : Past, Present and Future

pH control is one of the high non-linear systems [5]. pH control is a difficult process since its non-linear characteristic, time varying properties and high sensibility of small disturbances [6]. Furthermore, neutralization process face another challenge since it needs to deal with more than one product, change over grade and varying points of transition regimes [6]. Nonlinear characteristic is hard to be modeled and being controlled by a mathematical approach [11]. Large time delay of pH characteristic which related to the physical part of the system such as large container and circulating pipe, that lead to the large time delay of the system [11]. Large time delay of the system takes place make the more difficult to have an accurate control and use high amount of neutralizing agent. All this examples are the common problem of controlling pH in industrial plant.

pH controller has been implemented such as Linear Adaptive, Model Based, Non-linear Adaptive, Neural Network and Robust controller. Based on [6], previous pH controller approaches as listed above have some weaknesses like quite complex, difficult to be implemented in distributed control system. Apart from that, the usual approach of pH neutralization is using Proportional, Integrative and Derivative (PID) controller and Proportional Integral (PI) controller [3]. Conventional method like PID Controller difficult in achieving a good and desired control result in the wastewater treatment plant [11]. Not only that, another way to control pH is to use predictive system [12].

Fuzzy logic is a control system method which uses problem solving-making method [7]. This approach provides a simple way to give conclusion based upon ambiguous, imprecise, and noisy information [7]. In pH controller, fuzzy logic is believed to overcome is high non-linear system [4]. Fuzzy logic allows simpler approach since the method does not need mathematical model as in the case of conventional control design method. Based on [4], Fuzzy logic approach is much better for the pH neutralization process in terms of its regulatory and servo-response compared to PI controller.

The technology of pH controller, there are many researches goes on the Fuzzy logic itself. Moreover, the existence of Fuzzy logic is being combined with other method like Fuzzy PD Controller which helps to achieve better closed control loop performances [13]. Fuzzy logic use fuzzy back propagation algorithm which is called as Fuzzy Neural Network Controller [14].

2.5 Foundations of Fuzzy Logic

Fuzzy theory begins with the idea of fuzzy sets [28]. A fuzzy set is defined to be those sets whose boundary is not clear [31] such as a set of weekend days or a set of tall men. It depends on the human being to set the boundary of the weekend days or how tall a man. Usually, the fuzzy set is compared with the classical set. A classical set is a set that wholly includes or excludes any given element. For fuzzy set, is a set containing elements that have different degree of membership in the set [29]. This fuzzy is very important in human reasoning for pattern recognition. It is just how the human interpret and defined the elements [32].

For fuzzy logic, it is just a matter of how truth the statement. Definitely, this is the major advantage of fuzzy as it defined any element to be 'true' or 'false' instead of partially true or partially false.

Membership function (MF) can be defined as a curve that defines how each point in the input is fall to a degree of membership. Usually for fuzzy logic, the degree of membership is between 0 and 1. The numbers 0 and 1 here can represents to be true or false or inversely. There are many ways to assign membership value to the fuzzy set. According to [29], there are six possible ways to assign membership value of functions to fuzzy variables. The six ways are by intuition, inference, rank ordering, neural networks, genetic algorithms and inductive reasoning.

In fuzzy logic system, there are many types of membership function. The most commonly used is the triangular membership function. There is no proper rules or ways to select or determine types of membership function is most suitable for a given system or application [30]. The typical types of membership function of fuzzy logic systems are shown below:

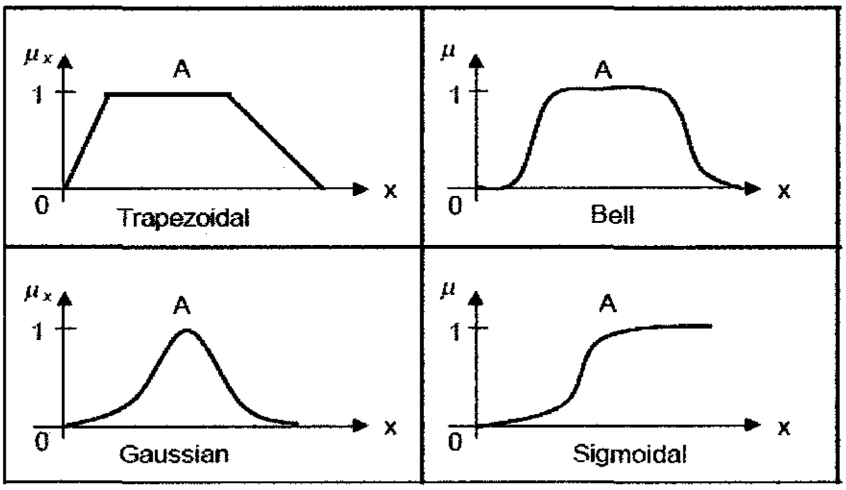

***Figure 4** : Types of Membership Function*

From the fuzzy sets and membership function, a fuzzy logic system can be developed. In general, there are three steps that involve the development of fuzzy logic system as shown in Figure 5 below. The first step is the fuzzification process. Fuzzification involves the converting the system inputs into the fuzzy set inputs.

As an example for pH neutralization process, the system will measure the current plant pH value. The current plant pH value will be converting to the fuzzy set inputs. The new fuzzy set input of pH value of the plant is transformed into its group and membership function.

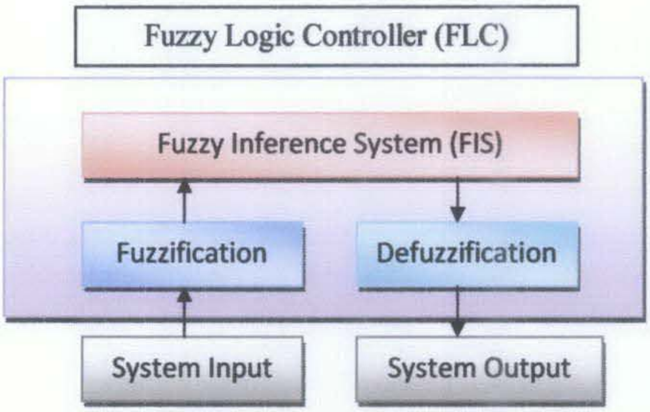

***Figure 5** : Common Architecture of Fuzzy Logic Control*

After the fuzzification process, the fuzzy inference system (FIS) will take place. In this step, the rule of fuzzy is so important. The rules will be developed to mapping the fuzzy inputs and output sets. It is known as 'IF-THEN' rules. The 'IF-THEN' rules are used to allocate these inputs for the outputs. IF-THEN rules provide conditions for certain input to set the outputs. The IF-THEN rules is depends on the designer on how to assign the fuzzy set input to produce the outputs.

Defuzzification is the last steps in Fuzzy Logic Controller (FLC). This step it is just an inverse process of fuzzification. As discussed earlier, fuzzification used to convert system input into the fuzzy set inputs. For defuzzification, this step will convert fuzzy output into the system output. As an example, the defuzzification will transform the fuzzy output to actuate final elements such as control valve.

Throughout the literature review, fuzzy logic gives a lot of advantages. Fuzzy logic theory is not only used in engineering but also in social science [28]. The advantages of fuzzy logic are listed below:

a. Fuzzy logic is able to control non-linear process. It deals with the uncertainty in non-linear process characteristic.
b. Fuzzy logic is able to resemble human decision of making processes. Fuzzy logic will help to produce accurate and reliable solutions.
c. Fuzzy logic is much easier to understand compared to other advanced control strategy. This is because fuzzy logic uses a linguistic approach rather than a complex mathematical form of description.

2.6 Fuzzy Logic and PID Controller

Fuzzy logic is a system that evaluates inputs as true or false [15]. It will generate inputs based on the state of inputs. This fuzzy logic uses the concept of a flexible set of if-then rules.

PID stands for Proportional, Integral and Derivatives which deal with the error from between the set point and process variable to initiate an action [15][18]. The action taken will be based on the magnitude of error (proportional mode), the persistence of error (integral mode) and the rate of change in error (derivative mode) [15]. It is based on the final element that being controlled by the controller in PID mode. This control approach depends on the final element if it is non-linear, linear response from proportioning action will take less acceptable control [16].

When it comes to the reverse acting control loop, large positive error calls for a large negative output change. Small positive error calls for a small negative output change. It is the same thing if large change in error calls for large change in direction of the output, while a small change in error calls for a small change in direction [15]. When it comes there is no error or no change in error, there is no change in output. This kind of set of rules help for fuzzy logic to be more general in almost any process compared to the PID approach [15].

pH of waste water plant can be controlled by fuzzy logic approach. With its more general characteristic, fuzzy logic used to control the addition of chemical based on the pH and how the pH changes over time. With if-then set of rules to be play around in fuzzy logic, amount of acid or alkaline will based on the pH itself. The addition of acidic or alkaline will be drop if the pH reaches the target [16][17].

Fuzzy logic is a good technique for the engineers to do control system. Fuzzy logic can replace PID approach especially when it comes to the process which has unacceptable overshoot [15]. Fuzzy logic offers faster set point recovery with less overshoot compared to PID control. Fuzzy logic give 'zero' noise since it develops a nonlinear response analogous to an error squared PID controller. Fuzzy logic is definitely suitable for large time constant (no dead time) which overshoot and slow recovery is both undesirable. Hence, fuzzy logic can comprehend PID loops in many situations.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

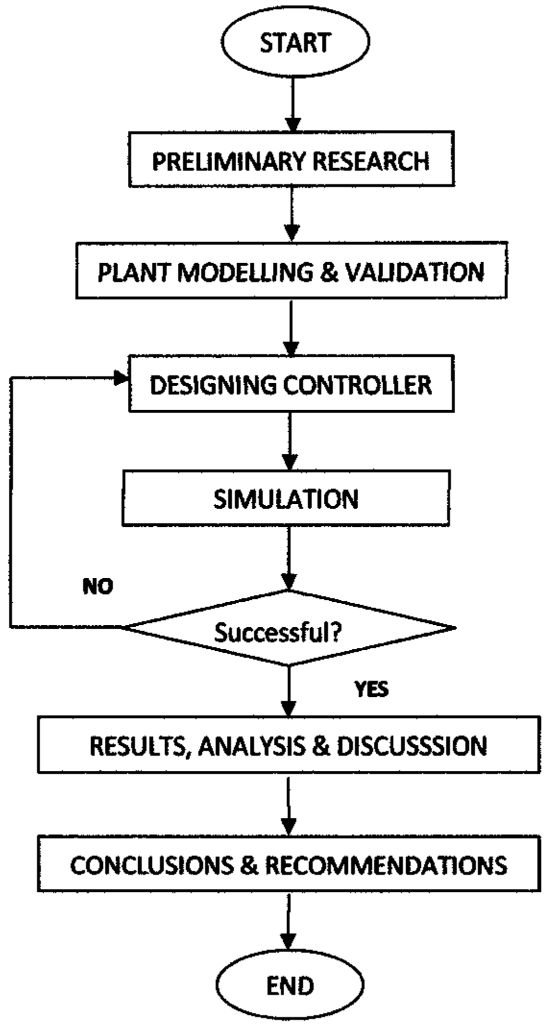

***Figure 6** : Procedure Identification*

3.2 Project Activities

Table 1: *Elaboration on Each Step of Flow Chart*

Activity	Description
Preliminary Research	Initial ground work in getting information regarding the project. Covers literature review to enhance knowledge on the subject and any research that has been done for this topic such as conventional and advanced pH neutralization control strategy.
Plant Modeling & Validation	Plant modeling is developed by using mathematical modeling. The plant is almost similar to the previous researcher [3]. Thus, validations of the plant model need to be considered.
Designing Controller	Conventional and advanced controller is developed in the same plant model. For conventional method, PI controller is chosen while for advanced method, fuzzy logic approach is chosen.
Simulation	The simulation involves both PI controller and Fuzzy Logic controller. The simulation used to understand the behavior of the PI and Fuzzy Logic and how it controls the plant model.
Results, Analysis & Discussion	After simulation, results of the both controller performance will be analyzed and discussed. Each controller performance is measured for same performance parameters such as settling time, rise time, integral absolute of error and overshoot.
Conclusions and Recommendations	From the results, the best controller will be chose based on the controller performance and state any improvement or suggestion for the whole project itself.

3.3 Gantt Chart

The Gantt chart is provided together with the report in the Appendices section. Noted that the Gantt chart as a guideline for the project timeline. There can be any changes on the project scope based on the circumstances.

3.4 Tools and Equipments Required

For the project, Modeling and Simulation process for the design is done using MATLAB software. Simulation of the plant model will be carried out based on SIMULINK in MATLAB. SIMULINK is an environment for multi-domain simulation and model-based design. SIMULINK provides an interactive graphical environment which involves drag in any function block into the simulation interface. The embedded function block helps for the user to design any mathematical equation for their designated system. The developed system in SIMULINK environment can be simulated to obtain their dynamic behavior and the results can viewed lively. For this project, SIMULINK will be fully utilized. With the embedded Fuzzy logic toolbox and PID block, the control strategy for both method of conventional and advanced can be carried out throughout this project.

CHAPTER 4
RESULT & DISCUSSION

4.1 Model Validation

The simulation model of pH neutralization pilot plant is obtained from a researcher [3]. According to [3], the model is built based on the fundamental principles applied by [20]. The description of the model is shown in Appendix 3. Although the researcher has done on proving the functionality of the model, validation should be re-executed to verify the model. One experiment has been performed to validate the model. The experiments executed are shown in Table 1.

Simulation	Concentration	Flow Rate
Experiment 1	*Acid*: 0.0485M *Alkaline:* 0.0489M	*Acid:* Step change from 80L/h to 0 at 500 second. *Alkaline*:Step change from 0L/h to 135.92L/h at 1150 second.

***Table 2** : Experiment setup of prediction model validation*

This experiment is done by doing simulation based on the prediction model. Based on Figure 5, the experimental result obtained [6] is used as reference in this research. It is believed that the result obtained represents the dynamic response of the prediction model.

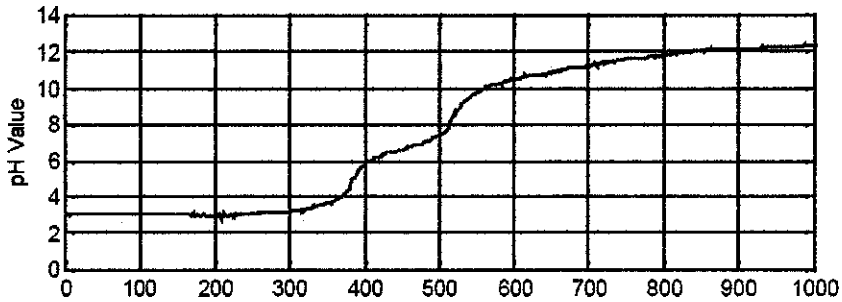

Figure 7: Dynamic Response of the prediction model

Simulation dynamic response of prediction model:

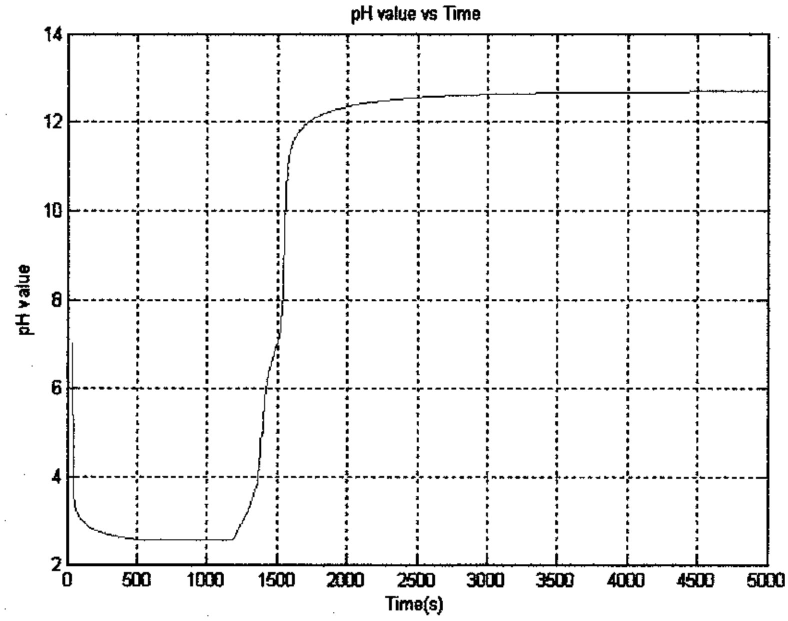

Figure 8: Simulated dynamic response of prediction model.

Simulated dynamic response as shown in Figure 8, is carried out to the prediction model. Based on Figure 7 and Figure 8, the simulation result is similar apart from the reaction rate. Although, based on Figure 8, there is an initial value of pH value below 200 seconds, but the model is still accepted. Hence, this model is being used throughout the simulation of the research.

4.2 Control Strategy

4.2.1 Proportional Integral Controller

Before advanced control strategy is used, the classical approach of control should be investigated. In this case, a PI (Proportional + Integral) Controller is designed to control pH neutralization process. The controller is simulated based on the equation below.

$$MV(t) = \text{Kp}\,\text{E(t)} + \text{Ki} \int E(t) \qquad (13)$$

Based on Figure 6, the PI controller parameters are obtained based on trial and error. The value of Kp used in this simulation is 20 while for the value of Ki is 0.05. The single order of transfer function represents the acid control valve characteristic.

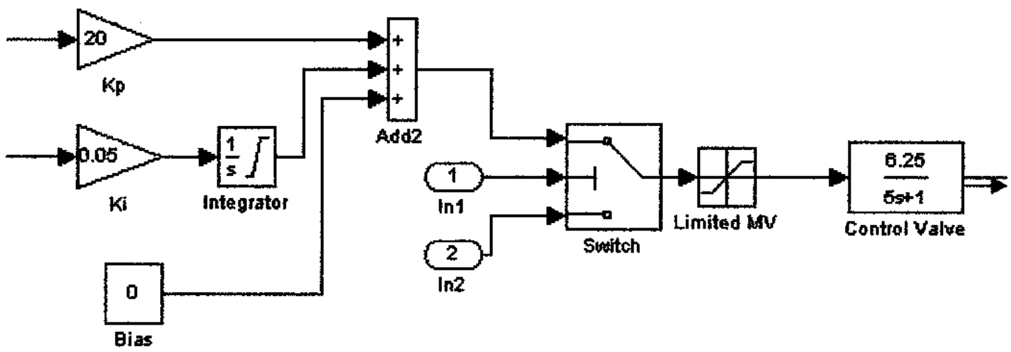

Figure 9: SIMULINK representation of PI Controller

4.2.1.2 Simulation Results of PI Controller

Experiment 1: Step Change from 5 to 7

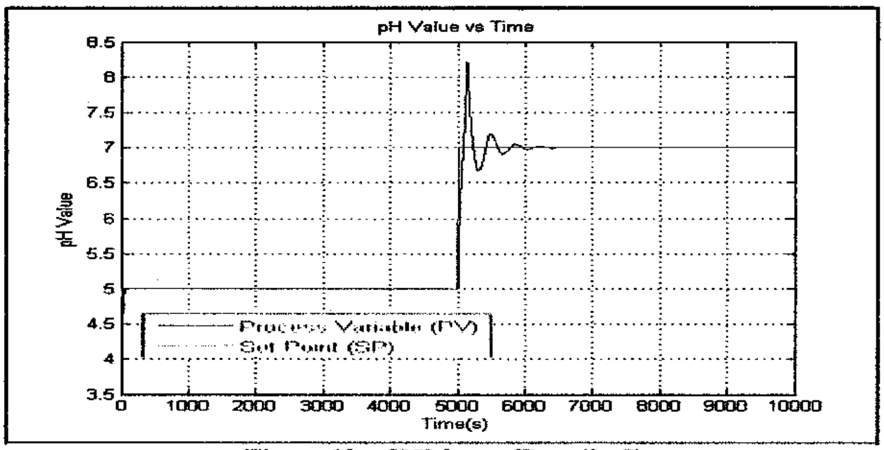

***Figure 10:** pH Value vs Time (5to7)*

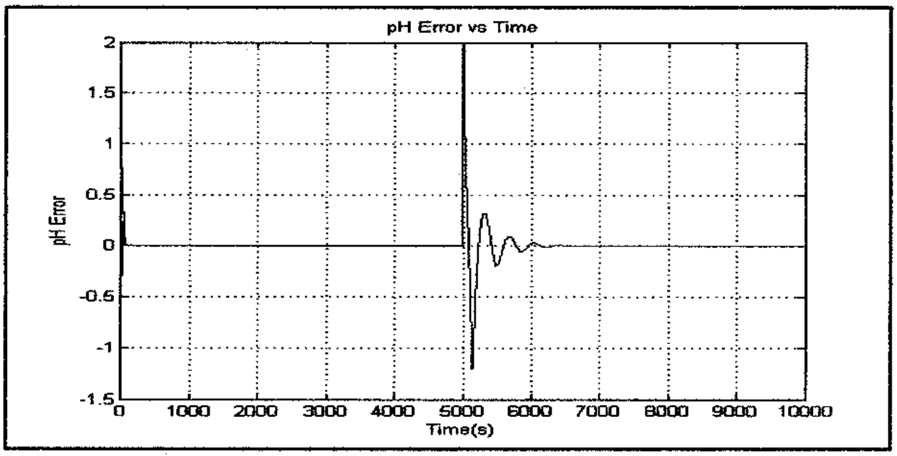

***Figure 11:** pH Error vs Time(5to7)*

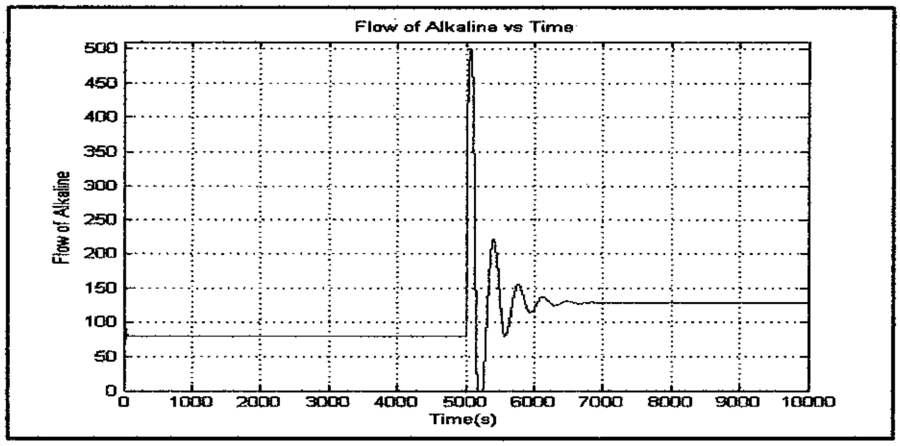

***Figure 12:** Flow of Alkaline vs Time(5to7)*

Experiment 2: Step Change from 7 to 5

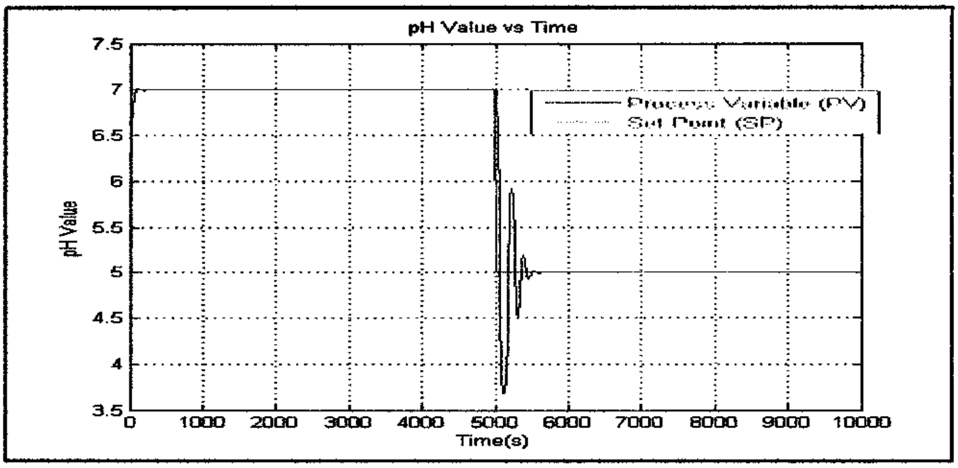

***Figure 13:** pH Value vs Time (7to5)*

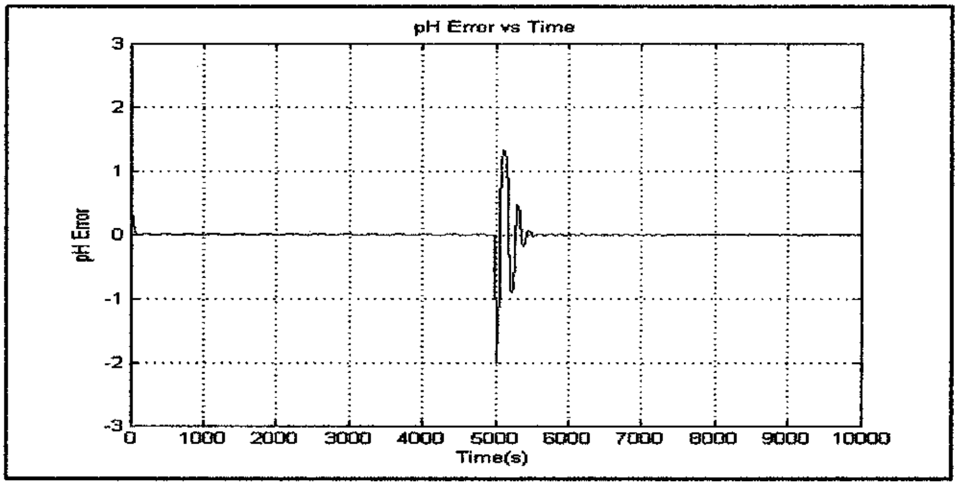

***Figure 14:** pH Error vs Time(7to5)*

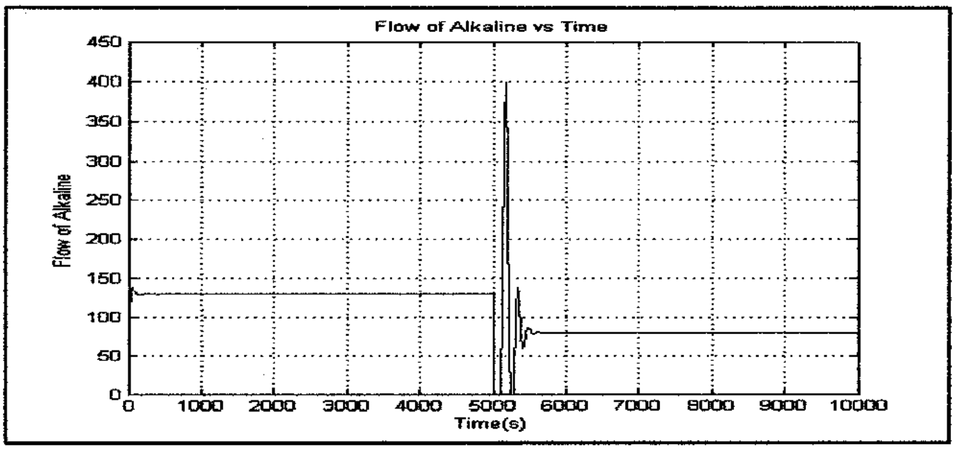

***Figure 15:** Flow of Alkaline vs Time(7to5)*

4.2.1.2 PI Controller Performance

Two experiments are carried out to test the performance of PI controller for neutralization processes. First, the PI Controller tested with step change from pH 5 to Ph 7 while the second one, the controller is tested with step change from pH 7 to Ph 5. For both experiments, the performance of PI controller is judged by looking at the pH value, pH error and flow of alkaline into the plant. The flow of acid is set to be constant at 80 L/h. For the neutralization of this plant model, two moles of alkaline is required to react with one mole of acid. Hence, the flow rate of alkaline should be 160 L/h.

The performance of PI controller looks similar for both experiments. When there is step change from one condition to other condition, the PI controller takes time to settle down. There is overshoot for the PI controller to adjust the pH plant to be the same as setpoint. Both experiments are tested on the high sensitivity region of pH neutralization which is between pH 6 and pH 7. The main objective to carry out this performance test is to ensure either the PI controller is able to control pH at the critical region or not. Based on the both results, it shows that PI Controller is unable to adjust the pH value according to the set point. There is oscillation of very small value in first 100s with certain offset. When fall in the region of the step changing, there is a few oscillation between the regions. It shows that when it falls in the critical region, increasing volume of alkaline causes very small change in the pH. From the literature review, linear controller like PI controller is poor to do controlling on non-linear processes.

The performance of the controller also related to the plant equipment. When there is an oscillation of the process, it will definitely affect the final element in the process. The final element here is referring to the control valve. The control valve needs to adjust opening and closing to adjust the flow rate of alkaline. Oscillation of the process will make the valve to open and close and repeat the same action in short time. Thus, it gives bad physical result on the control valve for long term. It can reduce control valve performance and damaged.

The performance of PI controller is measured based on few parameters. After certain time, PI controller shows a good response of controlling pH process as it achieves the pH value according to the set point. The settling time is quite short with overshoot and oscillation.

In conclusion, there are still rooms for improvements for PI controller in pH neutralization process. Consistency of the control performance is needed to shows that the controller is able to control the process in any circumstances. Non-linear characteristic of pH neutralization is not suitable for linear control such as PI controller. A good controller must able to adjust or make decision to make the plant running as the same as set point. Good controller must show the performance parameters such as settling time or rise time in very minimum level. Fine tuning of PI controller is recommended for this stage to improve the result in controlling non-linear process of pH neutralization process.

4.2.2 Fuzzy Logic Controller

Once the prediction model is validate, a controller need to be design to control the pH value of the overall plant. Fuzzy logic approach is chosen since it has much capability towards PI Controller especially in high-non linear process such this pH neutralization process [4].

Based on the prediction model and Figure 2, there is two flow stream into the tank which are the acid and alkaline. The alkaline will be injected stream to neutralize the pH to be neutral. From this statement, the alkaline flow will be control to do the neutralization process.

Before develop the controller itself, the reaction between the acid and base need to define first. According to [3], the plant model is used for strong acid and strong base reaction. In this model, Sulphuric Acid (H_2SO4) and Sodium Hydroxide (NaOH) is used for acid and alkaline stream. The different types of acid and alkaline reaction may lead to different titration curve as per discussed in Chapter 2.2.

Next, the reaction of acid and base need to be considered. As Sulphuric acid and sodium hydroxide is chose in the neutralization process, the mole ratio of the between the streams must taken into consideration. Two moles of alkaline is required to neutralize 1 mole of acid. In other words, the volume of acid required for neutralize process is half of the volume of acid. The relationship of the mole shown in the Equation 15 below:

$$V_b = (C_a \times V_a \times 2) / C_b \quad (15)$$

The Fuzzy Inference System (FIS) designed is based on Mamdani approach. Based on the literature review, most of advanced controller developed for pH neutralization process is using Mamdani.

Fuzzy Logic Controller (FLC) is developed to control the flow of acid stream in the prediction model. The FLC developed consists of two inputs (error and set point) and one output (Valve). For input 1, the error will represent the difference between the set point and the current plant pH. Figure 16 below shows the details of the input 1.

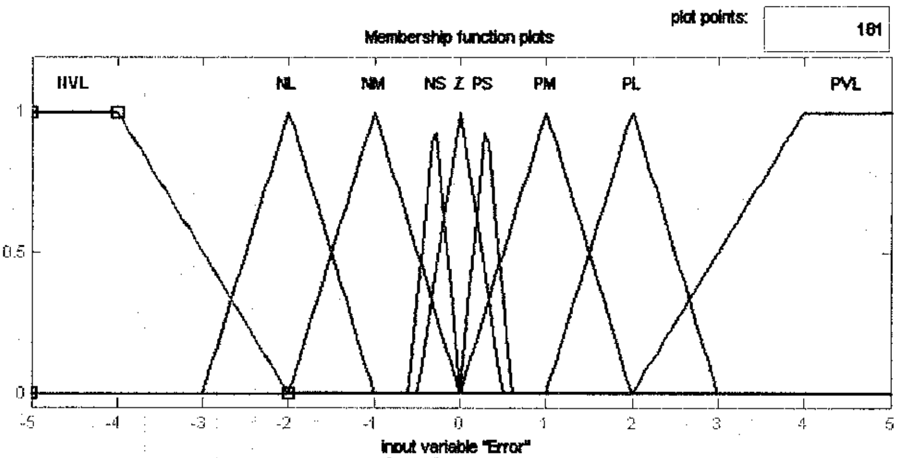

Figure 16: Membership Function of 'Error

The error block is configured with 9 membership functions correspond to the difference to the set point. The range of error is selected to be between -5 and 5. This is because the typical pH is active between pH value of 2 and pH value of 12 while pH value of 7 is assumed to be neutral point. The error block is represents for both positive and negative. The actual parameters of this error block are shown in Table 3.

Symbol	Description	Type	Parameters			
PVL	Positive Very Large	Trapezoidal	2	4	5	5
PL	Positive Large	Triangle	1	2	3	
PM	Positive Medium	Triangle	0	1	2	
PS	Positive Small	Triangle	0	0.3	0.6	
Z	Zero	Triangle	-0.5	0	0.5	
NS	Negative Small	Triangle	-0.6	-0.3	0	
NM	Negative Small	Triangle	-2	-1	0	
NL	Negative Large	Triangle	-3	-2	-1	
NVL	Negative Very Large	Trapezoid	-5	-5	-4	-2

***Table 3**: Parameters for Input 1(Error Block)*

Input 2 (Set point) block is developed to specify the control process regions which fall in between of pH value of 6 and pH value of 8. Figure 17 below shows the details of the set point block. This set point block is configured to the range of 0 to 10.

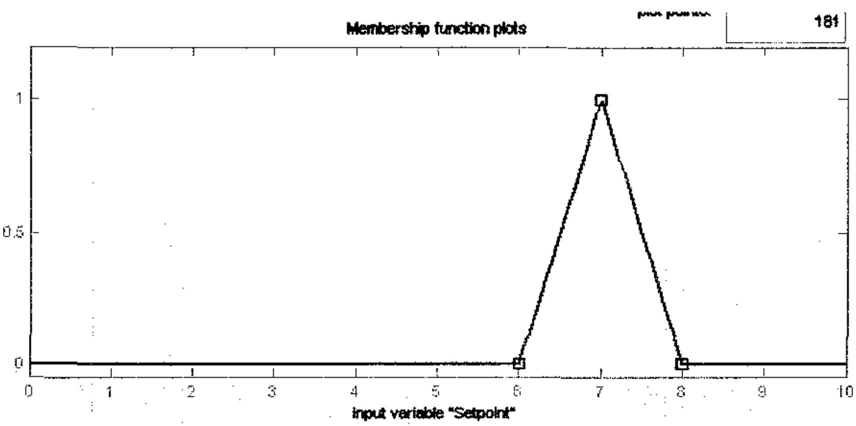

***Figure 17**: Membership Function of 'Special'*

The output of this FIS represents the opening and closing of the valve. The opening and closing of the valve indicates the flow of acid into the tank. For the output, there are eleven membership functions which represent the flow rate of acid required to deal with change in pH process. The range of membership is between -50L/h to 50L/h. The positive region is to increase the flow rate while for negative region, the flow rate is reduced. Control valve operations react to these changes by open or close the valve.

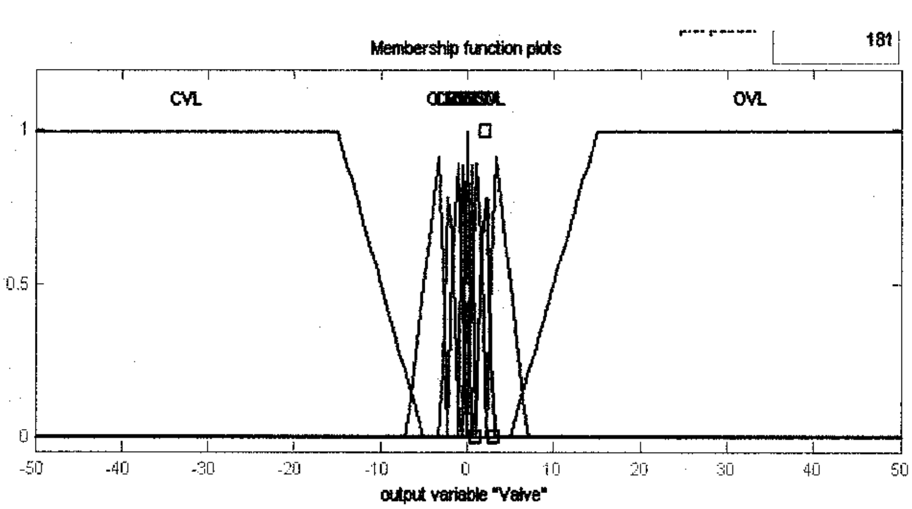

***Figure 18**: Membership Function of 'Output*

Table 4 below shows the actual parameters of Output (Valve):

Symbol	Description	Type	Parameters			
OVL	Open Very Large	Trapezoidal	5	15	50	50
OL	Open Large	Triangle	2.5	3	7	
OM	Open Medium	Triangle	1	2	3	
OS	Open Small	Triangle	0	1.25	2.2	
OVS	Open Very Small	Triangle	0	0.5	1	
Z	Zero	Triangle	-0.05	0	0.05	
CVS	Close Very Small	Triangle	-1	-0.5	0	
CS	Close Small	Triangle	-2.2	-1.25	0	
CM	Close Medium	Triangle	-3	-2	-1	
CL	Close Large	Triangle	-7	-3	-2.5	
CVL	Close Very Large	Trapezoidal	-50	-50	-15	-5

***Table 4**: Parameters of Output (Valve)*

After all the inputs and output is configured, the rules between the inputs and output are determined. Fuzzy logic related to the IF/ THEN rules. The mapping of FLC designed shown in Table 5.

Error - Setpoint	Output	Special
Z	Z	-
PVL	OVL	-
NVL	CVL	-
PL	OL	OM
NL	CL	CM
PM	CS	-
NM	OS	-
PS	-	OVS
NS	-	CVS

***Table 5**: IF-THEN rules statements for FLC*

The parameters configurations are important to determine the output response of FLC. Proper selection of parameters may affect the control performance of FLC. Parameter must parallel to the control objectives. Once the input and output is determine the IF/THEN rules is essential to determine the FLC's output response. Different mappings of input and output relationship will produce different output response.

Designated FLC into the prediction model as shown in Figure 19 below:

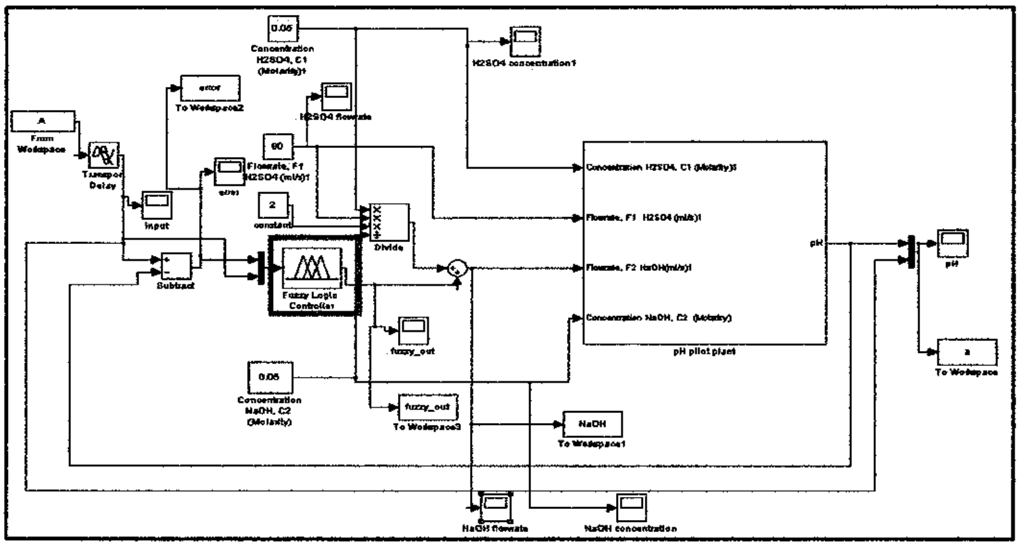

Figure 19: Embedded FLC to the plant model

Based on Figure 19 above, the red box shows the designated FLC to control the flow of the alkaline into the plant model. Meanwhile, for the orange box shows the 'Divide' blocks which derive from Equation 1.

4.2.2.1 Simulation Results of Fuzzy Logic Controller

Experiment 1: Step Change from pH 5 to pH 7

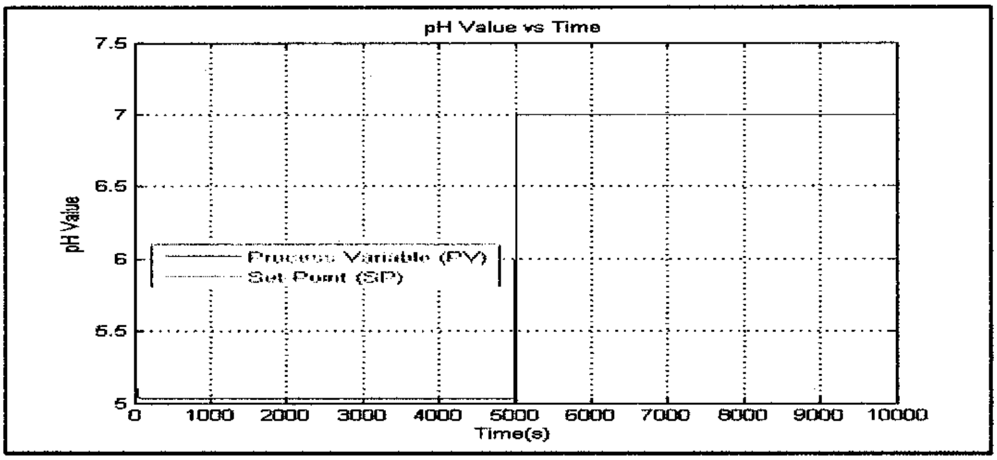

***Figure 20**: pH Value vs Time (Fz5to7)*

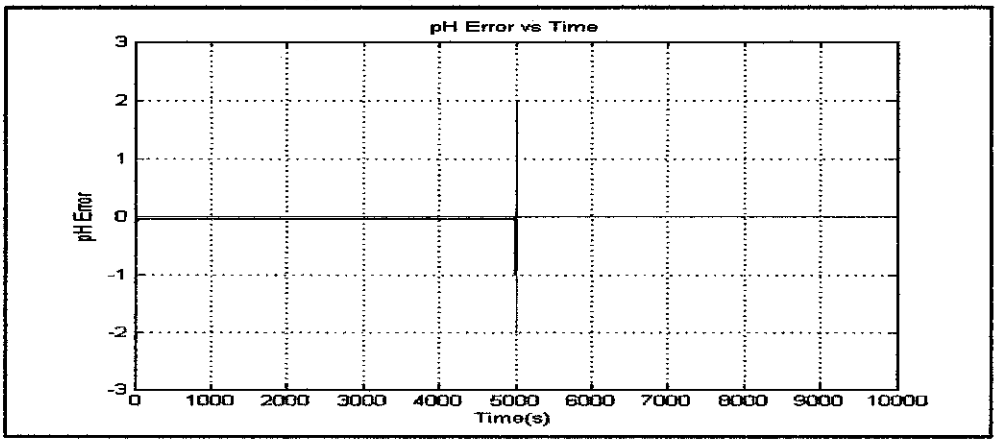

***Figure 21:** pH Error vs Time (Fz5to7)*

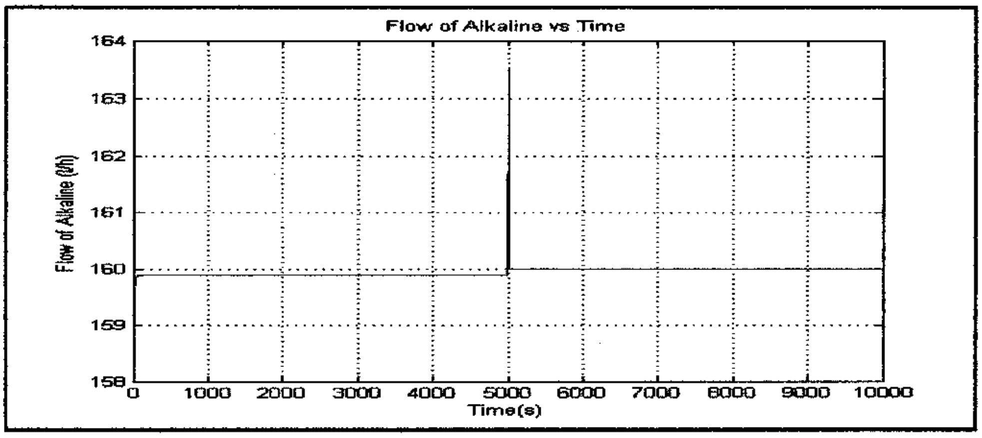

***Figure 22**: Flow of Alkaline vs Time (Fz5to7)*

Experiment 2: Step Change from pH 7 to pH 5

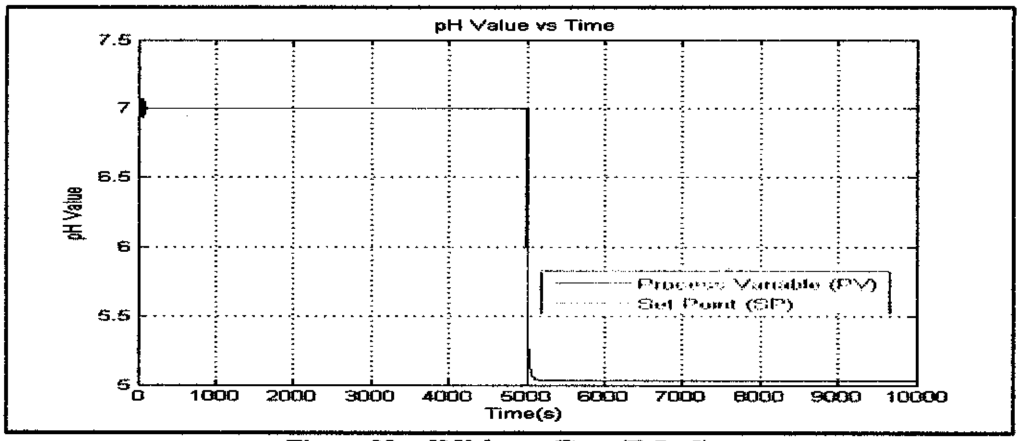

***Figure 23**: pH Value vs Time (Fz7to5)*

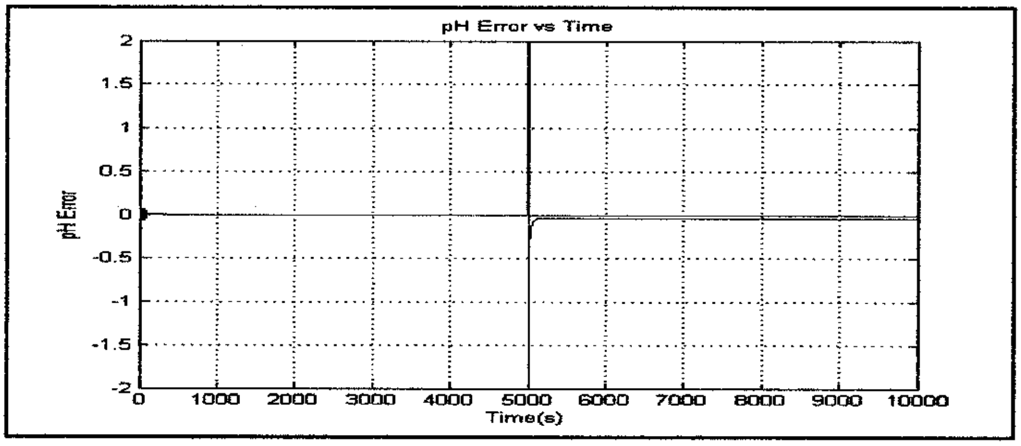

***Figure 24**: pH Error vs Time(Fz7to5)*

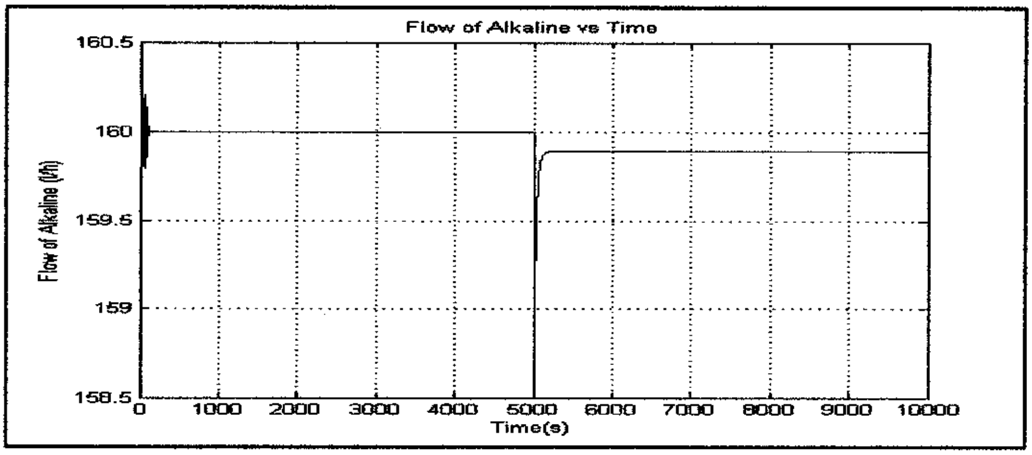

***Figure 25**: Flow of Alkaline vs Time(Fz7to5)*

Experiment 3: Set Point Tracking

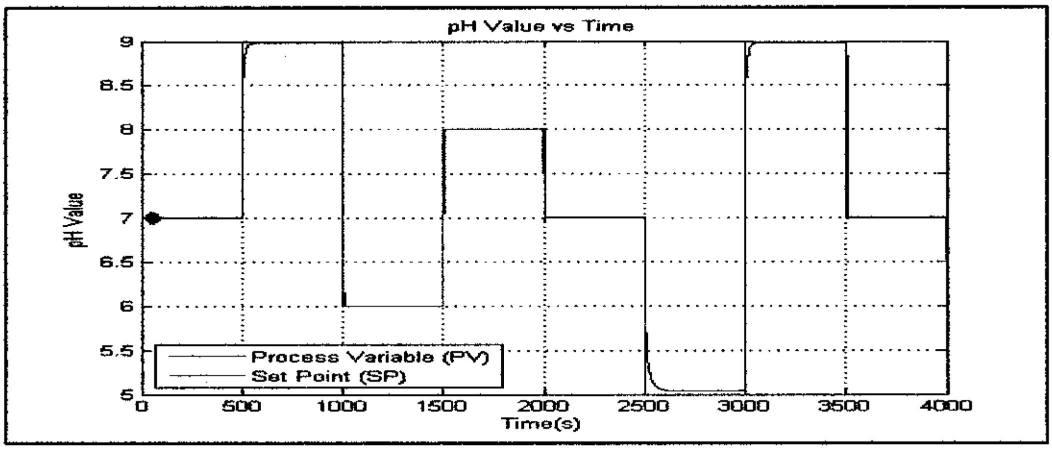

***Figure 25:** pH Value vs Time (FzSet)*

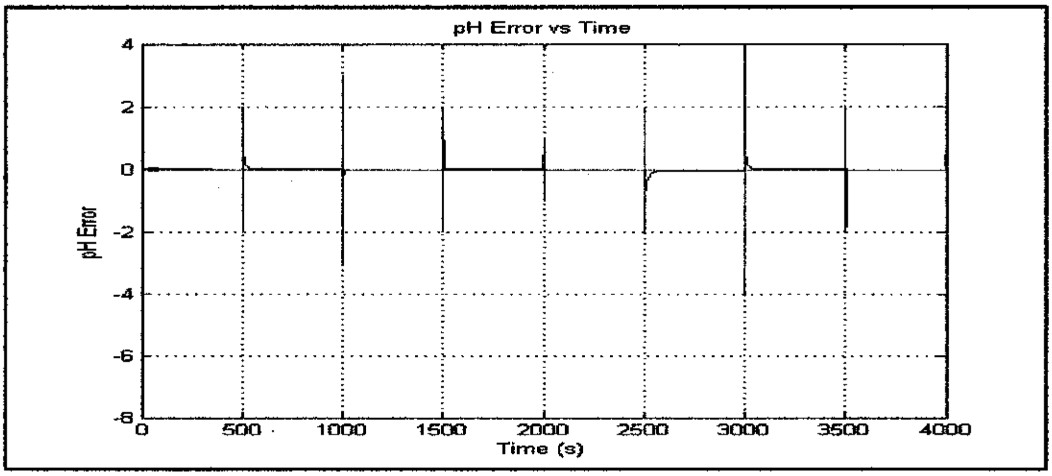

***Figure 26**: pH Error vs Time(FzSet)*

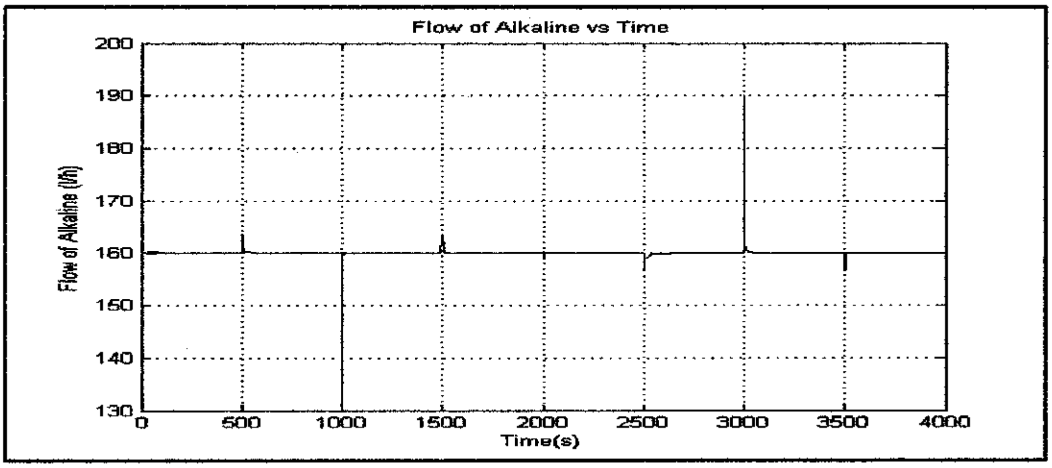

***Figure 27**: Flow of Alkaline vs Time (FzSet)*

4.2.2.2 Fuzzy Logic Performance

The performance of Fuzzy logic is tested on three different experiments. First, the controller is tested with step change from pH 5 to pH 7. Then, step change of pH 7 to pH 5 followed by set point tracking experiments to test the robustness of the fuzzy logic controller. In the simulation, the concentration of acid and alkaline is set constant to be 0.05 mol/cm^3. The flow of acid is maintained at value of 80 L/h. The performance of this advanced control approach is judged by looking on the pH value of the process, pH error and the how much the flow of alkaline into the plant.

Based on the three experiments, the performance of Fuzzy logic is successful. The controller managed to deal with changes in the set point as indicates in set point tracking experiment. As for step change experiments, the fuzzy logic shows a good response towards the most sensitivity region of pH. The fuzzy logic managed to make sure the plant pH is the same as the same point. There no tremendous oscillation or overshoot as shown in the conventional method, PI controller. Hence, fuzzy logic controller is able to compensate any changes of pH in the sensitivity region. The process controlled by the fuzzy logic managed to reach its steady state without any overshoot and offset value. Furthermore, the settling time of fuzzy logic controller of the response much faster compared to the PI controller.

4.3 Discussion

All the simulation successfully carried out to measure the performance of the conventional control (PI controller) and advanced control (Fuzzy Logic). Based on the results, it shows that FLC has proved that it is much better than PI controller to deal with non-linear process. FLC managed to produce high accuracy and very satisfying control performances. FLC is much flexible to adjust pH value in the sensitivity region which falls between pH 6 to pH 8. FLC not causing any oscillation or overshoot in the process which directly avoid final elements like control valve from damaged. From the results, the limitations of PI controller can be compensated by FLC. The overall performance for both control strategy is shown in Table 6 below.

	PI	**FLC**
Integral of Absolute Area (IAE)	Intermediate	Very Small
Rise Time	1005	20
Settling Time	1508	30
Decay Ratio	0.876	0
Steady State Error	Acceptable	0.00%
Overshoot	17.3%	0.02%

***Table 6**: Performance Comparison of PI and FLC Controller*

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

pH neutralization is one of the most important parameters to be controlled in WWTP. Proper control of pH in WWTP will save the environments from water pollutant, fulfill rules and regulations by DOE and keep the plant equipment in safe condition. pH neutralization is well known for high non-linearity with high sensitivity in neutral region. pH neutralization process can be benchmarking to other non-linear processes. From the literature review, there are many methods or control strategy to deal with pH neutralization process. Conventional method such as PI controller produces range of errors. Advanced control strategy is believed can compensate or improve the performance on controlling pH neutralization process. A mathematical modeling is used to develop a neutralization plant. A similar plant model is obtained from previous researcher. The plant is validated and can be used throughout the project. Both conventional and advanced control strategy has been developed. From the simulations results, Fuzzy Logic is able to control and deal with high non-linearity of pH neutralization characteristic. Fuzzy Logic excellently compensate in high sensitivity region compared to PI controller. As a conclusion, the objectives of the research have been achieved.

5.2 Recommendations

pH neutralization consists of many types of reaction which is related to the strength of acid and alkaline. For this project, it is focus on the reaction of strong acid and strong alkaline. For further research, the project can investigate the consequences of different strength in the reaction. Besides that, this project focusing on the Mamdani approach in designing fuzzy logic controller. Therefore, other type of fuzzy such as Sugeno approach can be used in order to determine different inference system on the control performance. This finding also can be used for combination with other control approach such as Fuzzy-PI or Fuzzy PID.

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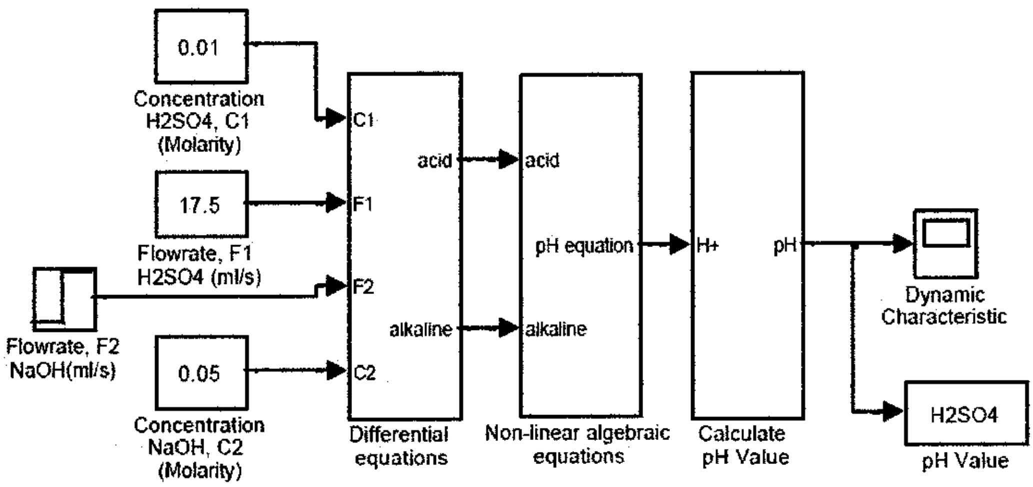
APPENDIX 1: GANTT CHART FYP I

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Selection and Confirmation of Project Title	■							MID SEMESTER BREAK								STUDY WEEK		EXAM WEEK		
2	Gathering information on pH controller	■	■	■	■																
3	Submission of Preliminary Report				●																
4	Study on Fuzzy Logic principles and Matlab for Fuzz Logic modelling.					■	■	■													
5	Submission of Progress Report									●											
6	Design modelling and simulation in MATLAB										■	■	■	■							
7	Seminar										●										
8	Finalize project work												■	■							
9	Submission of Interim Draft Report													●							
10	Submission of Interim Final Report															●					
11	Oral Presentation																				●

APPENDIX 1I: GANTT CHART FYP II

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Project Continue																				
									M												
2	Submission of Progress Report I				●				I												
									D								S		E		
3	Project Continue																T		X		
									S								U		A		
4	Submission of Progress Report II								E	●							D		M		
									M								Y				
5	Design modelling and simulation in MATLAB								E												
									S								W		W		
6	Poster Presentation								T		●						E		E		
									E								E		E		
7	Finalize project work								R								K		K		
8	Submission of Dissertation Final Draft								B					●							
									R												
9	Oral Presentation								E							●					
									A												
10	Submission of Project Dissertation								K												●

APPENDIX III: MATHEMATICAL MODEL OF THE PH PLANT



Model used throughout the research