INVESTIGATION OF ADVANCED CONTROL STRATEGY FOR A pH NEUTRALIZATION PROCESS PLANT

By

LEE WAI LUN

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
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JUNE 2009

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.

LEE WAI LUN

ABSTRACT

pH neutralization is one of the crucial processes to all industries with various functions range from food processing industry to wastewater treatment. Hence, the process must be maintained at optimum performance to fulfill its functionality. However, pH neutralization is a highly nonlinear process with high sensitivity at the neutralization point. The complexity of the process has challenged the conventional control strategy's performance. Currently, the control strategy used in the pilot plant (PI controller) is adequate with certain range of error. Thus, the objective of this project is to investigate, design and implement advanced control strategy which can improve the overall performance of the conventional control strategy. The calibration results show that the pilot plant's measuring meters have poor accuracy and repeatability. Due to this, no practical experiments have been performed throughout this research. Prior to simulation works, the pilot plant's model obtained from other researcher has been validated. The simulation results show that the model has faster dynamic response compare to the pilot plant. Nevertheless, the model is still being used for simulation. Through this research, the limitation of PI control strategy in controlling nonlinear process has been observed. Fuzzy logic controller (FLC) has been developed to improve the control performance of PI controller. According to the simulation results, FLC has produced excellent control performance with the ability of controlling process' nonlinear region. As a conclusion, advanced control strategy such as FLC is more superior to PI controller in nonlinear process control. For further research, perhaps the advanced control strategy developed can be implemented in the pilot plant to examine its real time performance.

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LIST OF ABBREVIATIONS

PID	Proportional plus Integral plus Derivative
PI	Proportional plus Integral
FLC	Fuzzy Logic Controller
FIS	Fuzzy Inference System
ULN	Universal Learning Network
CSTR	Continuous Stir Tank Reactor
SISO	Single Input Single Output
AIMC	Adaptive Internal Model Control
FYP	Final Year Project
UTP	Universiti Teknologi PETRONAS
NaOH	Sodium Hydroxide
GUI	Graphics User Interface

CHAPTER 1
INTRODUCTION

1.1 Background Of Study

In the 21st century, the fascinating advanced technology has conquered every field of industry from agriculture to aerospace. Technology has gained so much till it turns anything impossible to become possible. In the process industry, technology is inevitable in order to fulfil high consumers' demand. Some of the processes have become more complicated compare to the processes ten years ago. As a result, further improvement to the current technology is required to maintain the system's condition and the quality of the product.

pH neutralization is one of the common and crucial processes in all industries. It can be defined as the process of pH adjustment of acid or alkaline in order to obtain neutral mixture. Generally, the neutral mixture contains of pH 7 solutions. However, the desired pH depends on the requirement of the operation. Although wastewater discharged is not exactly at neutral point (pH 7), yet it is legal as long as the discharge obeys the environmental acts and regulations. pH neutralization process is so crucial that it may cause damages to the environment. In some extent, certain types of product could not be produced without this neutralization process. The usage of pH neutralization process can be different from one industry to another industry as shown below:

- In wastewater treatment process, pH neutralization is essential to neutralize the wastewater before being discharge to the environment because extreme acidic or extreme alkaline wastewater is harmful to the nature [21]. In terms of Environmental and Legislation concerns, this process is essential to protect aquatic life and human by providing "good" quality of neutral wastewater. Besides, pH neutralization can prevent corrosion and damage to other construction materials. [17]

- pH neutralization process is highly used in control of pH in food and beverage production. During the production of bread, liquor, beer, soy sauce, cheese, and milk production, certain enzymes are used to increase process reaction rate. Each enzyme has its optimum pH critical to the yield [11]. The enzymatic reactions are affected by the pH value of the process.
- In oil and gas industry, acidic solution is required to clean up the well for maintenance purposes. The left over acidic solution in the well is corrosive to the metal. Therefore, neutralization process will be performed to neutralize the acidic solution in the well.

1.2 Problem Statement

pH neutralization is one of the challenging processes in process control. This process has drawn so much attention due to its importance in several industries and difficulty to be controlled. Based on literature review, pH neutralization process is highly nonlinear with high sensitivity at the neutral point. This can be seen from pH titration curve. From the titration curve, minimum flow rate of acid or alkaline will cause significant change in pH as the process approaching neutral point. Significant change in pH has caused difficulties in process control. Besides, time varying is one of the problems in pH process control. The parameters of the titration curve may be varied due to uncertainties in flows and concentration of acid or alkaline [27]. Meanwhile, time delay in the process' reaction has increased the complexity of pH process control. Current control action is not affecting the current process output until the time delay elapsed [18]. The time delay is proportional to difficulty in pH process control. Therefore, the controller must be able to recognize the time delay and produce appropriate output to the final elements. Nevertheless, the conventional control strategy (PI or PID) produces certain range of errors. The control strategy is unable to conduct neutralization with high precision and accuracy. This could be due to the characteristic of PI or PID as a linear controller which is not optimal in controlling nonlinear processes. Therefore, the conventional control strategy must be improved in order to obtain better control of the process.

1.3 Objective

- To investigate, design and develop advanced control strategy for pH neutralization pilot plant.
- To compare the current control strategy in the pilot plant with the developed advanced control strategy.
- To implement the advanced control strategy in the pH neutralization pilot plant.

1.4 Significance Of The Research

The research is executed based on the pilot plant at UTP. This pilot plant is a small-scale of the actual system in the industry. The dynamic characteristics such as measurement noise, time delays and control valve characteristics of full-scale industrial plant are well captured in this pilot plant. The difference between the pilot plant at UTP and the industry pH neutralization plant is the size and the capacity of the plant. Thus, the pilot plant can be deduced as the representation of the pH neutralization plant in the industry [6]. Any problems found in the pilot plant can reflect potential problems in the actual industry system. This may be helpful to other researcher in understand, investigate and design pH neutralization process plant in the future.

As mentioned earlier, pH neutralization has been taken as a representative benchmark problem of nonlinear chemical process control [10]. In other words, pH neutralization is used as the starter for investigation of nonlinear chemical process. This includes investigation of the control strategy. The stability, robustness, accuracy and dynamic responses of the system will be evaluated upon the implementation of new control strategy. Success implementation of the control strategy in pH neutralization process will encourage researchers to implement the same control strategy in other nonlinear chemical processes.

CHAPTER 2
LITERATURE REVIEW

2.1 pH Neutralization Process

pH neutralization is the pH adjustment of acid or alkaline to obtain neutral mixture. Technically, neutral mixture means the mixture with pH 7. Usually, the pH of acid will be mixed by alkaline or versa vice to achieve neutral mixture. As mentioned in Chapter 1, pH neutralization process is important for wastewater treatment, food production and oil and gas industry. Meanwhile, it is useful for variety of operations including pharmaceutical, biotechnology and chemical processes.

In the past, pH neutralization process is carried out by using the method of diluting. However, this method is no longer accepted because the volume of alkaline to dilute the acid is calculated based on estimation. Inconsistency will occur in the estimation of the alkaline volume which will result error in the mixture solution's pH. Today, a typical neutralization process requires a system which is capable of handling acid and alkaline at different concentrations and varying flow rates. Such system must be able to measure and control the mixture solution's pH accurately. Some of these systems are using feedback and feedforward control structure in order to obtain satisfying results. Feedforward controller will compensate the disturbance before the process being affected while feedback controller will regulate the pH difference back to desired pH value. For example, a pH neutralization process is required to neutralize acidic effluent from chemical process, feedforward controller will reduce the flow rate of acid when transmitter detected more acid (pH less than 7) flowing into reaction tank. On the other hand, if the mixed solution is detected to be alkaline (pH more than 7), feedback controller will reduce the alkaline flow rate and increases the flow rate of acid.

The control valve for each solution must be able to control the flow rate accurately to ensure the concentration of the mixture is enough to achieve pH 7. Again, the desired pH of the mixture solution is depending on the operator's requirement. Nevertheless, pH 7 is assumed as neutral point throughout this research.

In chemical term, pH is defined as a measure of acidity and alkalinity of a solution by measuring the hydrogen ion $[H_+]$ activity. In simplified, pH of a solution can be measured by:

$$pH = -\log_{10}[H_+] \quad (1)$$

The typical pH range is between 0- 14. Any solutions with pH range less than 7 will be categorized as acidic solution [16]. In acidic solution, concentration of hydrogen ion (H_+) will be greater than concentration of hydroxide ion (OH_-). Any solutions with pH range higher than 7 will be categorized as alkaline solution [16]. Concentration of hydrogen ion (H_+) will be lesser than concentration of hydroxide ion (OH_-) in alkaline solution. Solution with pH 7 is considered as neutral solution. In neutral solution, the concentration of hydrogen ion (H_+) will be same as hydroxide ion (OH_-).

The basic concept of pH neutralization is to obtain neutral solution by mixing appropriate amount of acid with appropriate amount of alkaline. The process can be represented as below:

$$\text{Acid} + \text{Alkaline} \longrightarrow \text{Salt} + \text{Water} \quad (2)$$

In the pilot plant at UTP, the acid solution used is Sulphuric Acid (H_2SO_4) while Sodium Hydroxide ($NaOH$) is used as alkaline solution. Both solutions are strong acid and strong alkaline with 18M morality. Due to experimental purposes, both acid and alkaline will be diluted with water in order to obtain the specific concentration. According to Equation 3, the chemical reaction of Sulphuric Acid with Sodium Hydroxide will produce water and salt.

$$H_2SO_4 + 2NaOH = 2H_2O + Na_2SO_4 \quad (3)$$

From Equation 3, the ratio of acid to alkaline in pH neutralization process is 1:2. It means that 2 moles of alkaline will react with 1 mole of acid to obtain neutralization. A titration curve would be the best to explain the characteristic of acid- alkaline neutralization process. Titration curve is dependent on the types of acid and alkaline used (strong or weak, and whether monoprotic or polyprotic). This curve can provide useful information such as equilibrium point and the complexity of neutralization process especially in terms of nonlinearity and time varying of neutralization process.

Figure 1 shows the titration curves of different types of acid and alkaline [22]. From Figure 1, neutralization process has S- shape titration curve. This shows that neutralization process is highly nonlinear although different combination of acid- alkaline is used. From titration curve of strong acid- strong base, the most sensitive point in the curve is at the region of pH 7. At the region of pH 7, very small changes of acid or alkaline volume can cause significant changes in the output pH. This is due to dynamic characteristic of pH neutralization process which contains high gain at pH 7. This significant pH change is difficult to control by conventional control strategy perfectly.

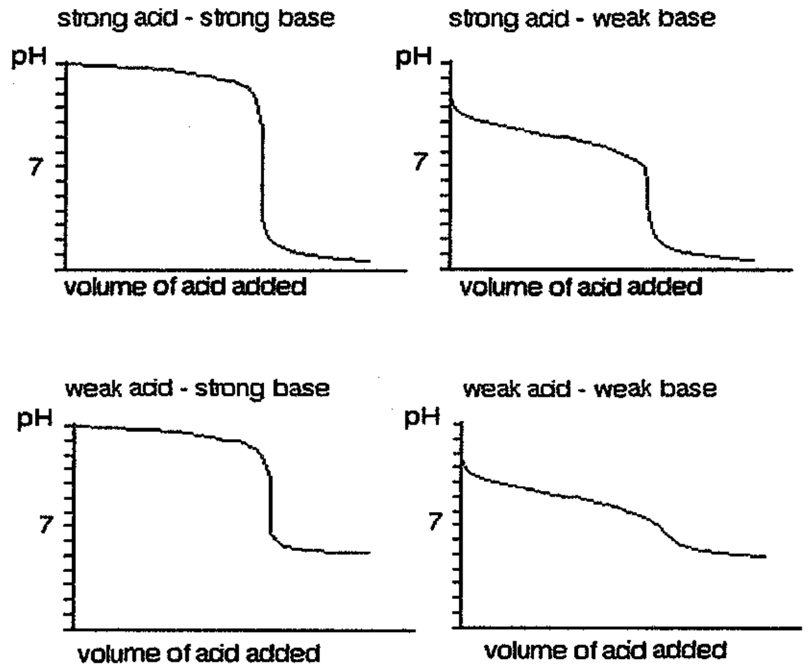


Figure 1: Types of titration curve

Besides, the titration curve also depends on the types of acid used in the experiment. There are few types of acid such as monoprotic acids and polyprotic acids [6]. Monoprotic acid means acid solution with one stage of ionization since it has one hydrogen ion to donate. Example of monoprotic acid is hydrochloric acid (HCL). On the other hand, polyprotic acid ionises in two stages because this type of acid has two hydrogen ions to donate. Example of polyprotic acid is sulphuric acid (H_2SO_4).

2.1.1 Controlled Stir Tank Reactor (CSTR)

The operation of pH neutralization process is based on the concept of Controlled Stirred Tank Reactor (CSTR). Figure 2 shows the pH neutralization process in a stirred tank. The mixture of both solutions is usually stirred by using a mixer to ensure proper reaction between acid and alkaline. Besides, the stirring process can enhance the reaction time of both solutions.

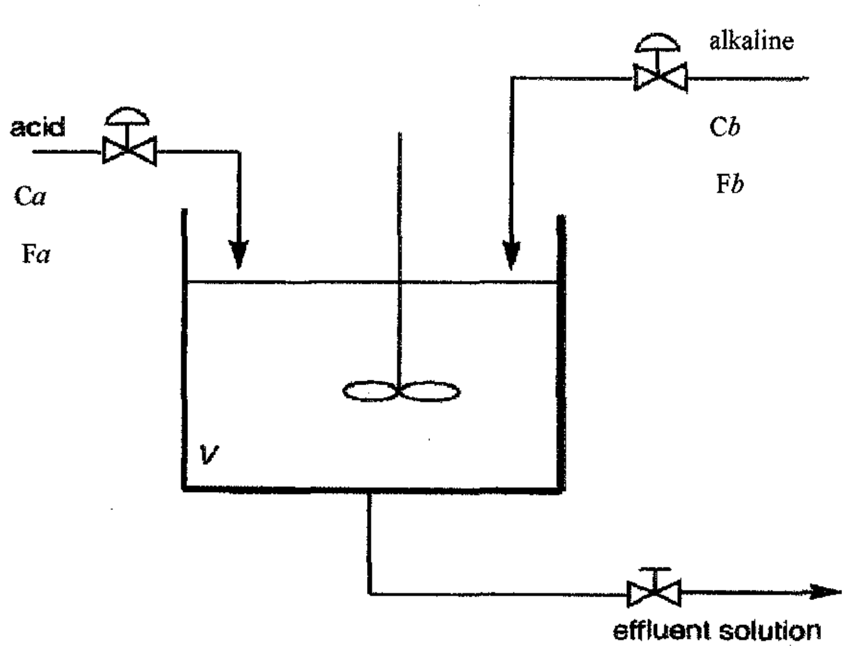


Figure 2: Controlled Stirred Tank Reactor (CSTR)

From Figure 2, acid is pump into the tank with certain concentration (C*a*) and flow rate (F*a*). The same process happens to the alkaline. Usually, acid is being pump into the reactor tank first. The control valve of the alkaline will be manipulated depending on the volume of alkaline required to neutralize the acid in the reactor tank. The opening percentage of the control valve will determine the flow rate (L/h) of the alkaline. According to [22], the volume of the reactor tank, V, concentration of acid, C*a* and alkaline, C*b* and the flow rate, F*a* and F*b* are essential in order to determine the mathematical model of single acid- single base process. CSTRs are typically assumed to be well-mixed with instantaneous reaction. For the past 30 years, many mathematical models have been developed by researchers. Most of the models produced are based on McAvoy's model [22].

This model is achieved through applying conservation of fundamental variables (mass, energy and momentum) [17]. Based on the principle of conservation, the component balances in the CSTR is taking consideration of chemical reactants' variation. The overall component balances can be shown below. Based on the equation below, the quantity of neutralize product (salt) produced in CSTR is varying according to difference of reactant flow and the process reaction rate. If the process reaction rate can be increased then the mixture solution will achieve neutral point faster.

$$\begin{pmatrix}\text{Rate of}\\\text{reactant}\\\text{accumulation}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\\text{reactant}\\\text{inflow}\end{pmatrix} - \begin{pmatrix}\text{Rate of}\\\text{reactant}\\\text{outflow}\end{pmatrix} + \begin{pmatrix}\text{Rate of reactant}\\\text{generation due to}\\\text{chemical reaction}\end{pmatrix} \quad \ldots\ldots\ldots (4)$$

Throughout the modeling of pH neutralization process, many considerations must be included apart from the reaction rate. Errors, unwanted substance reaction in the raw material tanks and process dead time are among the critical considerations faced by the researchers. Some researchers came out with several assumptions to deal with these process' uncertainties although they will reduce the accuracy of the model. However, the model is accepted as long as it obeys the modeling rule of thumb- maximum 25% of model error.

2.2 Control Strategies

2.2.1 Conventional Control Strategy

In the past, various control strategies have been applied to pH neutralization process. They range from linear controller to nonlinear model based controllers. The conventional control strategy which is PID has been practicing by most of the industries. The PID algorithm has been successfully used in the process industries since 1940s and remains the most often used algorithm today [25]. It may seem surprising that this old control strategy can be successful in many applications including oil refinery, steam generation, polymer processing and etc. This success is a result of the many advantages of the algorithm. One of the main reasons is that PID algorithm is easy to understand and easy to implement in the field.

The process industries which operate equipments at high temperature and pressure require reliable process control to minimize hazardous situations in the plant. Decades before digital computer came available, the control strategies developed were developed by using limited computing equipments. Analogue computing was the main method of automated computing at that time [25]. Due to lacking of computing equipments, the computing systems must be simple and should have easy ways to alter the parameters. At that time, most of the analogue controllers in process industries use pneumatic principles to control PID algorithm. After 1990, when computer starts to appear to the world, digital computing starts to immerse into process control industries. Yet, digital computing didn't overtake analogue computing as the main control structure in the industry.

PID algorithm or PID controller is used for single-loop systems which are also termed as single input- single output (SISO) systems. Typically, SISO systems have one controlled variable (CV) and one manipulated variable (MV). However, many single-loop systems may be implemented simultaneously on a process through feedforward or cascade control. The performance of each control system can be affected through interaction with other loops [25]. Overall, the performance of PID controller is acceptable in most of the industries. PID algorithm is a linear controller which usually performs well only in the range which they have been tuned. Therefore, linear controller is not suitable to control nonlinear process.

In order to fully utilise PID controller, engineers must understand the working mechanism of PID controller. As the controller's name goes, PID controller has three modes: Proportional (P), Integral (I) and Derivatives (D). Each mode has own roles in process control. The overall equation of PID controller is shown below.

$$MV(t) = K_c \left[E(t) + \frac{1}{T_i} \int_0^{\infty} E(t) + T_D \frac{dE(t)}{dt} \right] + I \quad \text{.....................} (5)$$

Proportional controller mode (P) is a simple gain which will cause proportional adjustment to the manipulated variable. Proportional mode is known as controller gain (*Kc*). As the error increases, the adjustment of manipulated variable will be increased. Proportional mode has significant effect on the controller performance especially on the overshoot and rise time of output response. Proper tuning of proportional mode can reduce the offset error but it fails to provide zero offset in the process. As the gain value increases, rise time of the output will be shorter. However, extremely large *Kc* will cause the controller to be unstable with large oscillation. The equation of proportional mode is shown below.

$$MV_p(t) = K_c \left[E(t) \right] + I \quad \text{...} (6)$$

Integral controller mode (I) can compensate the disadvantage of Proportional mode by achieving zero offset. Integral mode's parameter is termed as integral time (*Ti*) which has the unit of time. This mode will adjust the manipulated variable in a slower manner than pure proportional action [6]. According to Equation 5, manipulated variable is inversely proportional to integral time. Zero error offset can be achieved by reducing the integral time which will increase the manipulated variable change. High manipulated variable change will induce shorter settling time while guiding process output to desired set point. In some plants, integral mode also known as integral gain (*Ki*) which has the unit repeats of time. Mathematically, integral gain is inverse of *Ti* value. The equation of integral mode is shown below.

$$MV_i(t) = K_c \left[\frac{1}{T_i} \int_0^{\infty} E(t) \right] + I \quad \text{.......................................} (7)$$

One of the common issues of integral mode encountered in the plant is integral windup. In ideal situation, the integral mode should stop when control valve reaches its maximum limit. Integral windup happens when controller keep calculating (integrating) errors over a long period of time although the control valve has reached its maximum limit (0-100% opening). If the control valve has been operating at maximum limit for a period of time, integral windup will delay the valve operation due to sudden input change.

The last mode of PID controller is Derivatives mode (D). This mode does not have effect on the offset value. However, it can increase the initial kick of manipulated variable towards input change. As a result, the rise time of the output response has reduced. The equation for derivatives mode is shown below.

$$MV_D(t) = K_c\left[T_D\frac{dE(t)}{dt}\right] + I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

In certain process control, derivatives mode can be eliminated. Usually, derivatives mode is useful for slow process such as temperature. For fast process such as flow, derivatives mode is not being used because it has the tendency of amplifying noise in the measurement. When derivatives mode is being eliminated from PID controller, the controller becomes Proportional and Integral (PI) controller.

In order to put PID controller into work, engineers must insert parameters for each mode into the controller. These parameters can be obtained by using several tuning methods. Overall, tuning methods can be divided into two categories: open loop tuning and closed loop tuning. Open loop tuning methods include Ziegler Nichols open loop tuning and cohen-coon tuning. Ziegler Nichols closed loop tuning is one of the closed loop tuning methods. Each method has own mathematical calculations to determine the parameter of P, I and D. Open loop tuning is different from closed loop because it uses information such as dead time and time constant from process reaction curve. On the other hand, closed loop tuning methods require additional experimental test such as ultimate sensitivity test to calculate the controller's parameters.

2.2.2 Advanced Control Strategy

Based on literature review, conventional control strategy, PID controller is unable to control nonlinear process with high accuracy. In pH neutralization process, high gain near the neutral region is difficult to be controlled by PID controller. The pH neutralization process pilot plant used throughout the research is implemented with PID controller. Some experimental works in the pilot plant show that there is room of improvement for PID controller [4], [5], [6]. For this research, high priority is given to the investigation of better control strategy which can improve the performance of PID controller. Types of the possible control strategy are shown as below:

a) Neural PID controller

Neural network is the core of the neural control method. It is one of the adaptive algorithms used to optimize the performance of PID controller. In neural control systems, neural networks are used to update process model involved or to tune control parameters. It has the ability to self- organizing after some "learning" and "thinking" by large number of neurons [7]. Researchers got the inspiration and motivation to develop neural network from biological neuron control mechanisms [1]. For example baby walking mechanism. A few months old baby only can crawl before starts walking. Then, the baby learns how to walk slowly. After few falls, the baby can walk stably eventually. This mechanism is applied in neural network where desired results can be obtained through learning process. In simulation, the network is trained by several epochs. Most of the time, the error will be reduced and stabilize as epoch's number increases. The learning process will update neuron's parameter after every epoch of learning. In application, neurons of the model can be updated while the process is running continuously.

b) Fuzzy Logic Control

Based on literature review, Fuzzy logic controller (FLC) is very common among researchers. It allows for a simpler human like approach to control system design. FLCs provide reasonable and effective alternatives to conventional controllers through linguistic approach. The main advantage of FLCs is the usage of mimicking human's brain reasoning ability by using fuzzy reasoning. For instance, rain is a common natural phenomenon that is difficult to describe precisely. It might be classified as "light rain", "moderate rain" and "heavy rain" but it is difficult to determine the degree of rain. However, human brain has the incredible ability to process this type of judgments by looking at the volume of rain. In FLCs, operators can categorize rain as mentioned earlier. The controller will determine the rain condition by evaluating certain judgment criteria provided by the operators. Besides, the usage of IF {condition} THEN {action} rules base in fuzzy inference system has eased the understanding on how to evaluate the judgment criteria. Overall, FLCs are easier to understand compare to other types of advanced controller. Due to this reason, it is becoming one of the hot topics for research [26].

c) Dynamic Fuzzy Neural Network

Dynamic fuzzy neural network is the integration of neural network, fuzzy logic and conventional control ideas. Fuzzy logic and neural network are used to determine the controller gain (*Kc*), integral time (*Ti*) and derivatives time (*Td*) of PID controller instead of using conventional tuning method. Theoretically, this control strategy is very powerful after combining two main intelligent control strategies. On paper, Fuzzy Neural consists of all Fuzzy logic and neural network advantages in order to provide better dynamic quality and stronger robustness controller. In Fuzzy Neural controller, neural network architecture will alter the membership functions of Fuzzy logic depending on the network training. Learning process with sufficient quality data is required to train up neural network. The quantity of training is directly proportional to the performance of the process [1].

d) Adaptive algorithm of universal learning network (ULN)

This method is specifically dealing with the time delay of the system. The recent research showed that the key point to control the process with long time delay is to predict the output in the future time so the effect of the long time delay can be eliminated in advanced. ULN can be used in model predictive control for stabilizing nonlinear system with long time delay. The general architecture and adaptive learning algorithm give ULN more representing abilities to model and control the nonlinear black box system. Once the time delay of the plant has been identified, it will be acknowledged and applied by ULN model. Therefore, ULN model has the same time delay as the plant through specific sampling time. The trained model can be used as predictor to provide future outputs while the controller is adjusting the valve according to sampling time of the model. [18].

e) Model Predictive Control (MPC)

A Model Predictive Control controller adjusts the required manipulated variable in a target system (the plant) by combining a prediction and a control strategy. A plant model is required to provide the prediction while the control strategy will compare the output from the plant and predict the future output of the plant. From this prediction, the control strategy will adjust the particular actuator to achieve the target while respecting the plant's constraints [19].

f) Fuzzy PID controller

Fuzzy PID controller is another type of adaptive controllers. It can optimize the functionality of ordinary PID controller. Fuzzy logic is used to determine the controller gain (*Kc*), integral time (*Ti*) and derivatives time (*Td*) of PID controller instead of using conventional tuning method. Based on the research performed by [24], a fuzzy PI controller has successfully maintained the pH value around set point despite of the high gain neutral region. However, the controller is unable to perfectly deal with acid concentration change. Changes in acid concentration has deviated pH from set point. Nevertheless, Fuzzy PID has intensively improved the performance of conventional PID control strategy.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

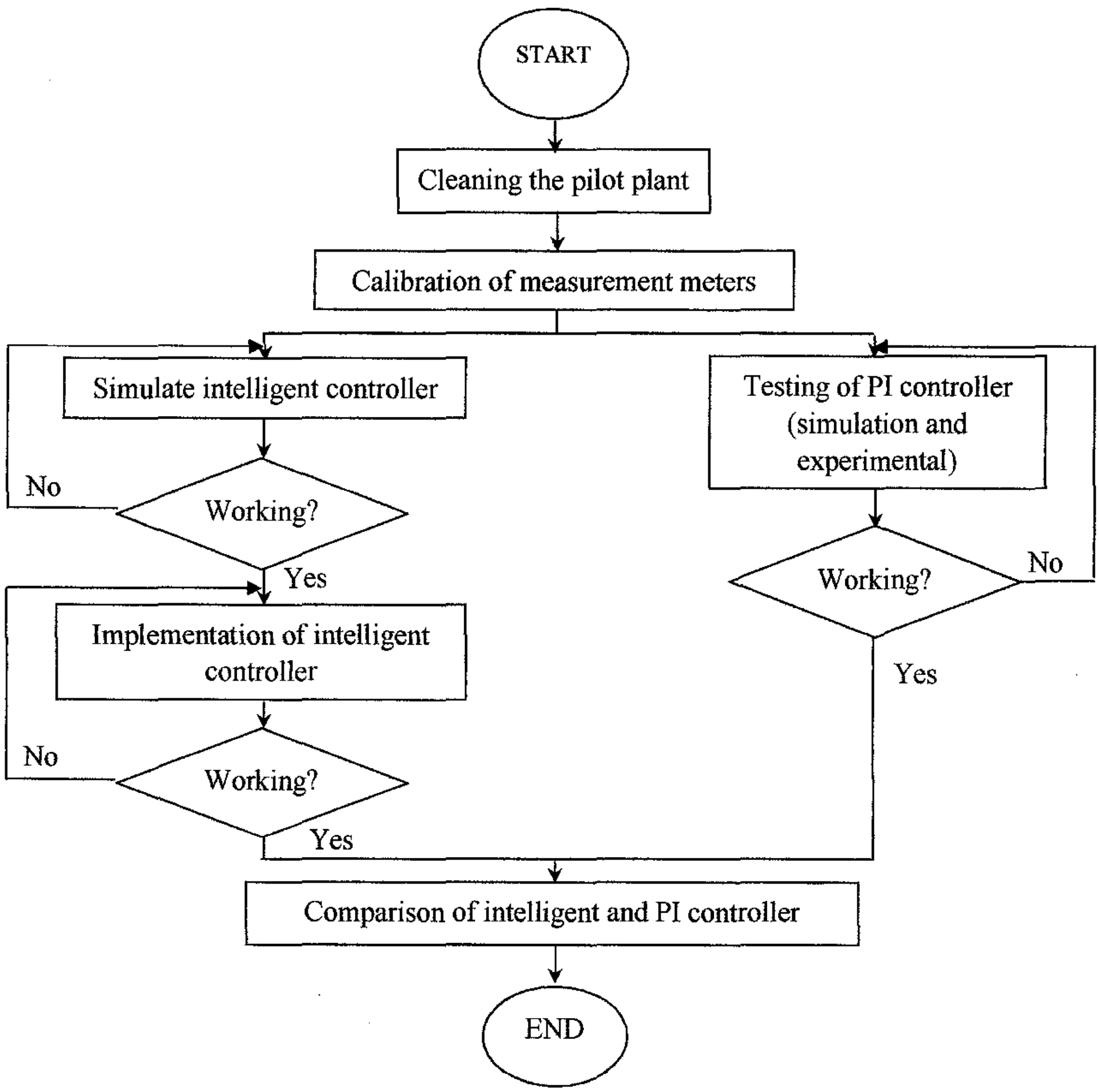


Figure 3: Flow chart of FYP

The entire flow chart of Final Year Project is shown in Figure 3. The planned milestone of the project is also being shown in Appendix 1. The milestone has covered the main activities of the project. There are 3 criteria to set the milestone: planned, trending and actual. The planned rows are setting the due date for the particular activity. Trending means the optimistic completion date in case of delay in planned completion date of a particular activity.

The research progress is divided into 3 parts: a) Pilot plant cleaning and calibration b) Simulation of conventional control strategy and advanced control strategy c) Implementation of advanced control strategy. Initial observation shows that both acid and alkaline tanks are contaminated by dirt. Cleaning is required to ensure accurate concentration of acid and alkaline. Further explanation will be discussed in Chapter 4. Besides, all measuring meters must be calibrated prior to experiment execution to ensure high accuracy of readings can be obtained.

For Part (b), both conventional and advanced control strategy are simulated by using MATLAB. Prior to simulation of control strategy, the process model obtained from other researcher must be validated to ensure the functionality and accuracy of the model. Figure 4 shows the MATLAB/ SIMULINK representation of the plant. The fundamental principles used to develop the model are shown in Appendix 2. PI controller is simulated to show the constraint of the conventional control strategy. Fuzzy logic is chosen as the desired advanced control strategy due to certain advantages. The performance of both control strategies is being compared.

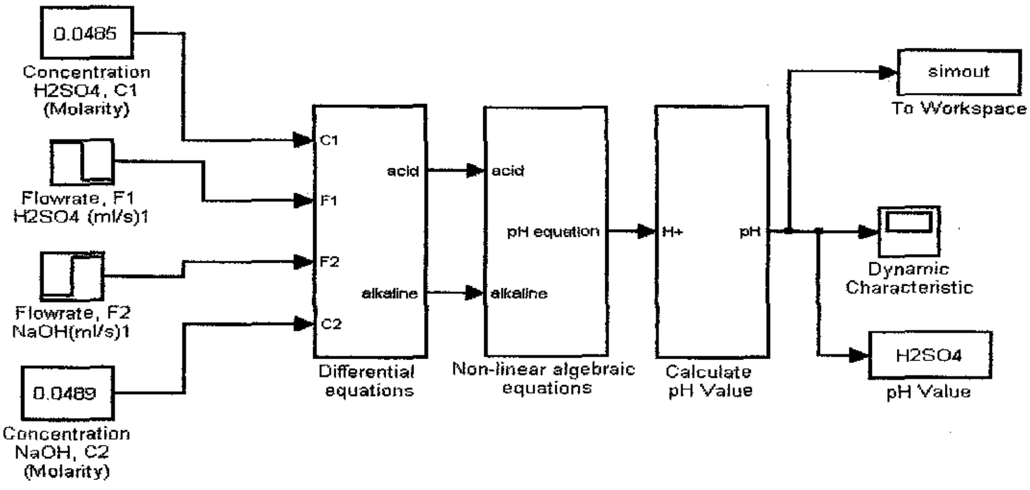


Figure 4: MATLAB/ Simulink model representation of pilot plant

For Part (C), the advanced control strategy simulated is implemented in the pilot plant. However, this part is not executed during this research due to poor condition of the pilot plant. Further explanation will be discussed in Chapter 4. Based on the grant chart, this research is consider completed on time without consider the implementation of advanced control strategy in the pilot plant.

3.2 Tools Required

This research is emphasizing on the pH neutralization pilot plant available at UTP lab. This pilot plant is scaled down of industrial instrumentation, measurement and actuation system used in the process industries. The entire system is connected to a computer for system controlling and process monitoring purposes. In other words, the whole system is controlling by a computer through software called MATLAB. A MATLAB based real time process model must be developed to control the pilot. This real time process model is different from the mathematical model used during simulation. The real time process model contains of specific blocks such as I/O mappings and pump's operation. The controlling of the system such as pump operation, opening and closing of the control valves can be executed through MATLAB. Besides, the data acquisition system in the pilot plant will record all the data in the plant and send them to the computer for display. The data obtained in the computer is the real time data captured by the instruments in the plant. The data acquisition system is capable of storing certain size of data for troubleshooting and graphical analysis. The piping and instrumentation diagram of the pilot plant can be found in Figure 5 while the figure of the pilot plant can be found in Appendix 3. Fuzzy logic toolbox available in MATLAB has been used to develop advanced control strategy. This toolbox provides necessary GUI to develop a new Fuzzy logic system. Tutorial files are available to ease the understanding and execution of the toolbox.

In more detail, there are five process variables that will determine the behavior of the pH neutralization process [6]. There are three main measuring instruments required in the pilot plant: pH meter, flow meter and conductivity meter. Table 1 shows the process variables that each instrument is measuring.

Table 1: List of process variable

No	Instrument	Process Variable
1	pH meter, AT 122	pH in reaction tank
2	Conductivity meter, CT100	Conductivity of acid
3	Conductivity meter, CT110	Conductivity of alkaline
4	Flow meter, FT 120	Flow of acid stream
5	Flow meter, FT 121	Flow of alkaline stream

Each instruments listed in Table 1 is shown is Appendix 4. Besides, all the tanks, agitator, and data acquisition system equipped in the pilot plant are shown in Appendix 4 as well.

$$V_{add} = \frac{(V \times C_d) - (V \times C_i)}{C_{raw}} \quad \text{...(9)}$$

V = volume of tank's solution

C_d = desired concentration

C_i = initial concentration in the plant

C_{raw} = raw materials concentration

V_{add} = Addition volume of acid / alkaline required

Table 2: Results of measuring instruments investigation Trial 1

Solution	Before addition of raw material		After addition of raw material		Add (mL)	Volume (L)
	Conductivity (ms)	Concentration (mol/cm³)	Conductivity (ms)	Concentration (mol/cm³)		
Acid	2.2	0.0163	9	0.0668	75.2	275
Alkaline	2.0	0.0126	11	0.0693	579.5	275

Table 3: Results of measuring instruments investigation Trial 2

Solution	Before addition of raw material		After addition of raw material		Add (mL)	Volume (L)
	Conductivity (ms)	Concentration (mol/cm³)	Conductivity (ms)	Concentration (mol/cm³)		
Acid	6.1	0.0453	9.9	0.0735	80	290
Alkaline	5.7	0.0126	10.5	0.0661	218.6	275

*Desired concentration is 0.05mol/cm³

Based on the results in Table 2 and Table 3, the calculation in the spreadsheet is not accurate and failed to prepare 0.05mol/cm³ of acid and alkaline solution. Further observation shows that the acid and alkaline tanks are contaminated by dirt. The contamination might cause some errors in the readings. The condition of the acid tank and alkaline tank are shown in Figure 6 and Figure 7 respectively. Therefore, the tanks must be cleaned before any experiment can be performed. Eventually, the dirt has been successfully removed after cleaning.

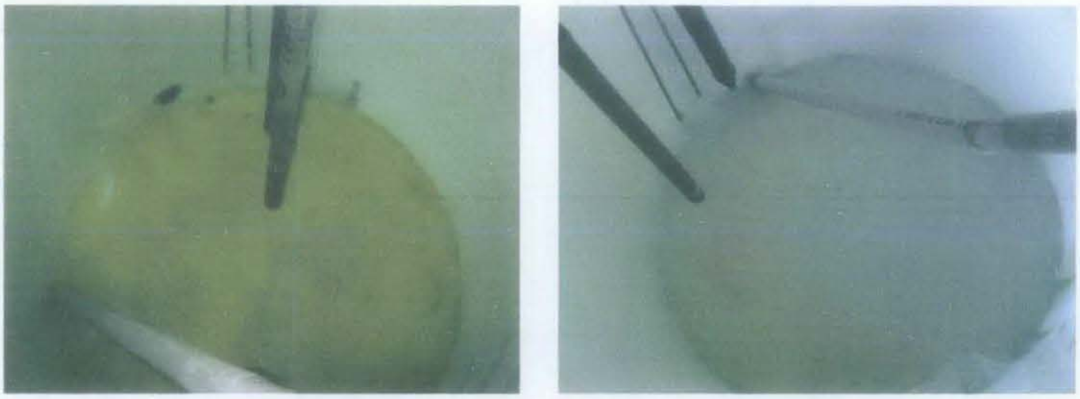


Figure 6: Condition of acid tank before (left) and after (right) cleaning

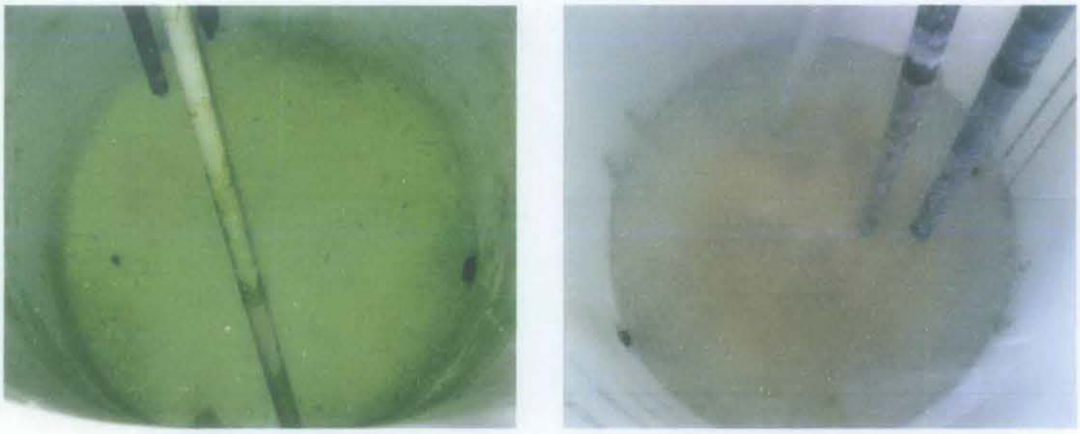


Figure 7: Condition of alkaline tank before (left) and after (right) cleaning

According to the technician, it has been ages since the last calibration executed. Therefore, all the measuring meters must be cleaned and calibrated. Calibration is required to ensure the accuracy of the readings. As a result, calibration has been performed for two pH meter (AT122 and AT130) and two conductivity meters (CT100 and CT110). AT122 is the pH meter in the process tank while AT130 is measuring the pH in buffer tank. Both pH meters are calibrated with standard pH buffer solutions: pH 4, pH 7 and pH 9. The results of calibration are shown in Table 4.

Table 4: Results of AT122 calibration (before offset)

Buffer pH	Measurement	Error	% Error
4	5.4	1.4	35
7	8.5	1.5	21.43
9	10	1	11.11

Based on the results in Table 5, the error of the calibration is too large. Thus, the offset setting of the pH meter is tuned. The offset setting is capable to compensate the error by adding positive or negative numbers to the current reading. The default offset value is 0. For AT122, the offset value is tuned to -1.56. In other words, the pH meter will display the pH value after minus 1.56 from the pH detected by the probe. The results of calibration after offset are shown in Table 5.

Table 5: Results of AT122 calibration (after offset)

Buffer pH	Measurement	Error	%Error
4	4.06	0.06	1.50
7	7.19	0.19	2.71
9	9.17	0.17	1.89

From Table 5, the errors of the reading have reduced drastically. Through changing the offset value, the pH meter still can be used for certain period before replacement. However, it is always advised to replace the out-of-tuned pH meter to ensure accuracy of the pH readings.

The same procedures are done to calibrate AT130 pH meter. Initial results show that the AT130 pH meter has the same condition as previous pH meter. However, the tuning of the offset is only -0.64. Compared to previous pH meter (AT122), AT130 is in better condition for usage. The results of calibration before and after offset are shown in Table 6 and Table 7.

Table 6: Results of AT130 calibration (before offset)

Buffer pH	Measurement	error	% error
4	4.7	0.7	17.50
7	7.9	0.9	12.86
9	9.8	0.8	8.89

Table 7: Results of AT130 calibration (after offset)

Buffer pH	Measurement	error	% error
4	4.16	0.16	4
7	7.17	0.17	2.43
9	8.99	-0.01	-0.11

Meanwhile, two conductivity meters have been calibrated. As mentioned earlier, a linear graph of concentration versus conductivity is required to determine the current concentration value. This graph can be obtained through calibration of the meters. During calibration of conductivity meters, 18M of acid and alkaline are being used as raw solution. These concentrated solutions are diluted with distilled water in order to prepare concentration required for calibration. The equation used to calculate the raw solution's volume needed is shown below.

$$M_{raw}V_{raw} = M_d V_T$$

$$V_{raw} = \frac{M_d V_T}{M_{raw}} \qquad \text{..} \quad (10)$$

V_{raw} = Volume of raw solution needed

M_d = Desired molarity needs to be prepared

V_T = Total volume prepared

M_{raw} = Molarity of raw solution (18M)

At the same time, the solutions prepared will be measured by a calibrated portable conductivity meter to show the accurate conductivity value. The portable calibrated conductivity meter is shown in Figure 8. The results of the experiment are shown in Table 8 (portable conductivity meter) and Table 9 (CT100) respectively.

A graph of conductivity versus concentration has been plot. Besides, a graph or error showing the value difference between portable conductivity meter and plant conductivity meter has been plot. The same experiment has been repeated for conductivity meter in alkaline tank (CT110).

Figure 8: Calibrated portable conductivity meter

Table 8: Results of portable conductivity meter

Concentration (M)	Portable conductivity meter (ms/cm)			
	Trial 1	Trial 2	Trial 3	Average
0.005	2.32	2.44	2.82	2.53
0.01	4.5	4.87	5.99	5.12
0.05	20.3	21.2	21.4	20.97
0.1	39.7	40.1	40.5	40.10
0.5	177	179.1	177.1	177.73

Table 9: Results of conductivity meter in acid tank (CT100)

Concentration (M)	CT100 (ms/cm)			
	Trial 1	Trial 2	Trial 3	Average
0.005	1.4	1.7	1.1	1.40
0.01	1.4	5.1	2.9	3.13
0.05	9.6	11.7	10.5	10.60
0.1	13.7	21.5	29.3	21.50
0.5	110.3	120.2	114	114.83

Table 10: Results of conductivity in alkaline tank (CT110)

Concentration (M)	CT110 (ms/cm)			
	Trial 1	Trial 2	Trial 3	Average
0.005	2.5	2.0	2.4	2.30
0.01	4.2	4.1	6.1	4.80
0.05	21.1	18.2	21.6	20.30
0.1	40.7	34.3	38.2	37.73
0.5	159.7	142.7	143	148.47

Table 11: Error of conductivity value between portable conductivity meter, CT100 and CT110

Concentration (M)	Error	
	CT100	CT110
0.005	1.13	0.23
0.01	1.99	0.32
0.05	10.37	0.67
0.1	18.60	2.37
0.5	62.90	29.26

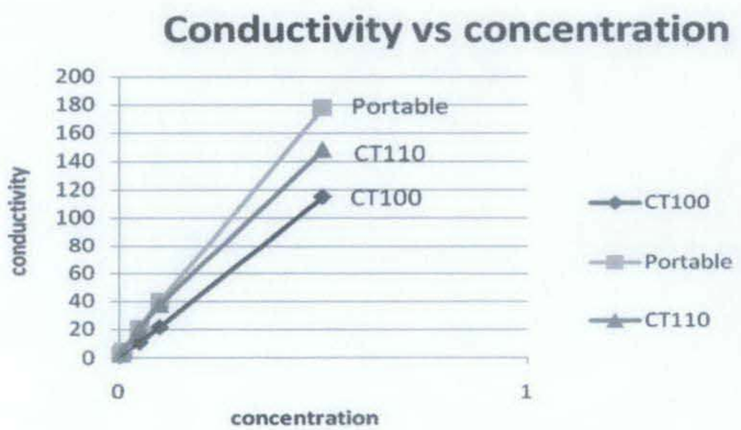


Figure 9: Graph of conductivity versus concentration for CT100 and CT110

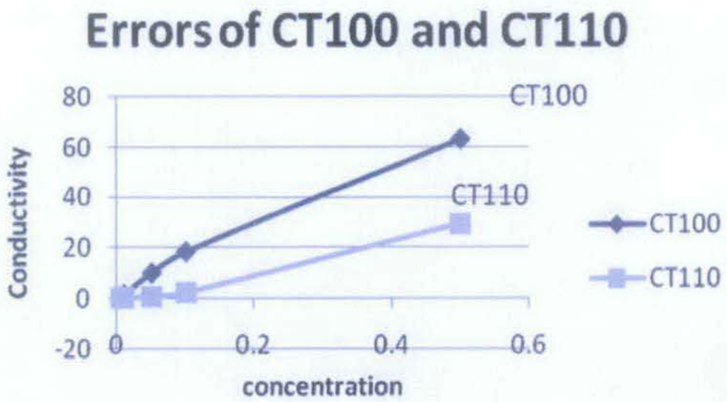


Figure 10: Graph of error between portable conductivity meter, CT100 and CT110

Based on the results, both conductivity meters do not show accurate values. Further observation shows that both meters have poor repeatability. Apart from conductivity meters, both control valves opening's flow rate (FCV120 for acid and FCV121 for alkaline) have been investigated. Results of investigation are shown in Figure 11 and Figure 12.

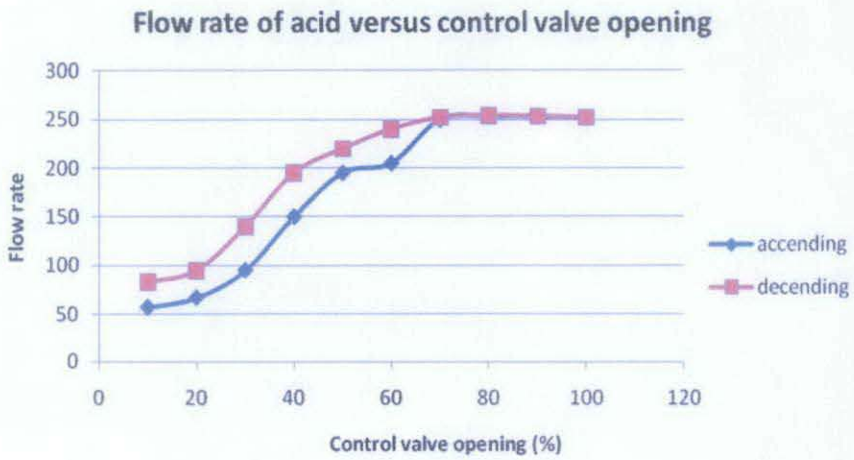


Figure 11: Graph of acid flow rate versus control valve opening (FCV120)

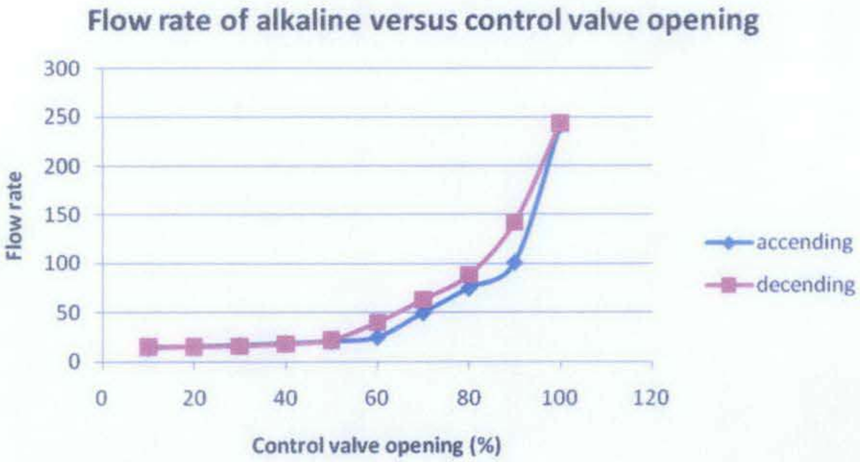


Figure 12: Graph of alkaline flow rate versus control valve opening (FCV121)

Based on the control valves investigation, acid control valve (FCV120) produces acceptable flow rate. However, alkaline control valve (FCV121) needs to be replaced. From Figure 12, significant flow rate starts after the control valve is opened more than 50%. Opening less than 50% only allows flow rate less than 20 L/h. This is not ordinary for control valve and reason behind low flow rate is unknown. Perhaps the control valve has been damaged after lack of maintenance.

From the all the calibration graphs, obviously the plant is not suitable to be used for experiment. Apart from this, researcher has noticed that the values of field instruments are not synchronized with the values displayed in MATLAB. This indicates some interfacing problems occur between MATLAB, data acquisition system and field instruments. The main factor that causes this terrible issue is still unknown. Anyway, failure in synchronization will directly affect implementation of new control strategy. Besides, this has put a strong challenge on accuracy of real time plant data. Due to this, several control strategies such as neural network and Fuzzy neural may be ignored due to lack of quality real time data.

The calibration results have suggested that the pilot plant requires major maintenance. High financial demand has upset the maintenance proposal. Due to this reason, the last section of the research: Implementation of advanced control strategy has been excluded from the research. Perhaps, this can be resumed by other researcher once the pilot plant is functioning at required performance.

4.2 Validation Of Pilot Plant Model

The simulation model of pH neutralization pilot plant is obtained from a researcher [6]. According to [6], the model built is based on the fundamental principles applied by [22] and [17]. The description of the model is shown in Appendix 2. Although the researcher has proven the functionality of the model, validation should be executed in order to verify the functionality of the model. The pilot plant model used is the same as shown in Figure 4. One experiment has been performed to validate the pilot plant model. The experiments executed are shown in Table 12.

Table 12: Experiment setup of pilot plant model validation

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

Actual experiment cannot be performed due to poor condition of the pilot plant as discussed in Chapter 4.1. As an alternative, the experimental result (Figure 13) obtained by [6] is used as reference in this research. The result obtained from [6] is assumed to be valid result that represents the real dynamic response of the pilot plant.

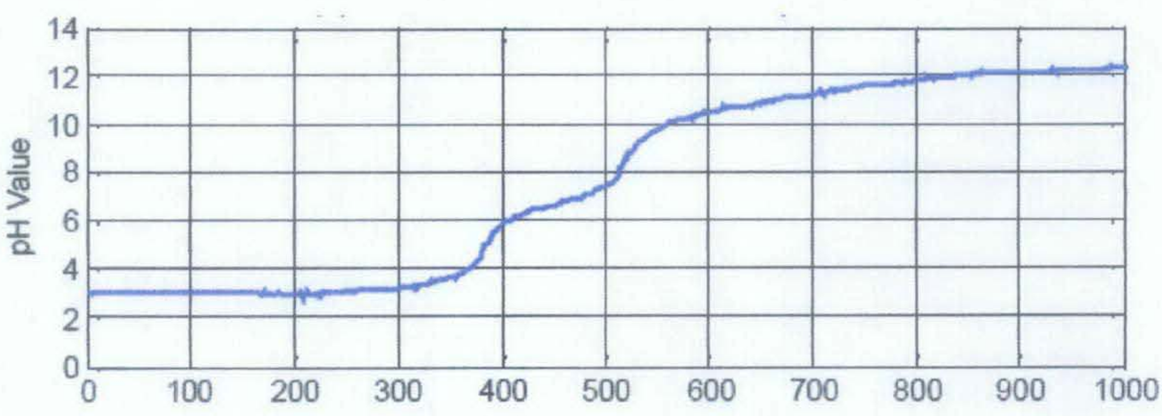


Figure 13: Experimental dynamic response of pilot plant

According to [6], 18M of acid and alkaline solutions are being used to prepare desired concentration of acid and alkaline. Distilled water has been added in order to reduce the concentration to desired level. In this experiment, the desired concentrations of acid and alkaline are 0.05M. However, the values showed by the measuring meters are not exactly 0.05M. This is believed that unknown source of hydrogen and hydroxyl ions existed in the tanks. Indirectly, this causes the ionic strength of the solution to decrease and therefore reduce the dissociation constant. In the simulation, the concentrations of acid and alkaline are set to 0.0485M and 0.0489M respectively because they are the experimental values obtained from the plant conductivity meters [6].

The simulation dynamic response of pilot plant model is shown as below.

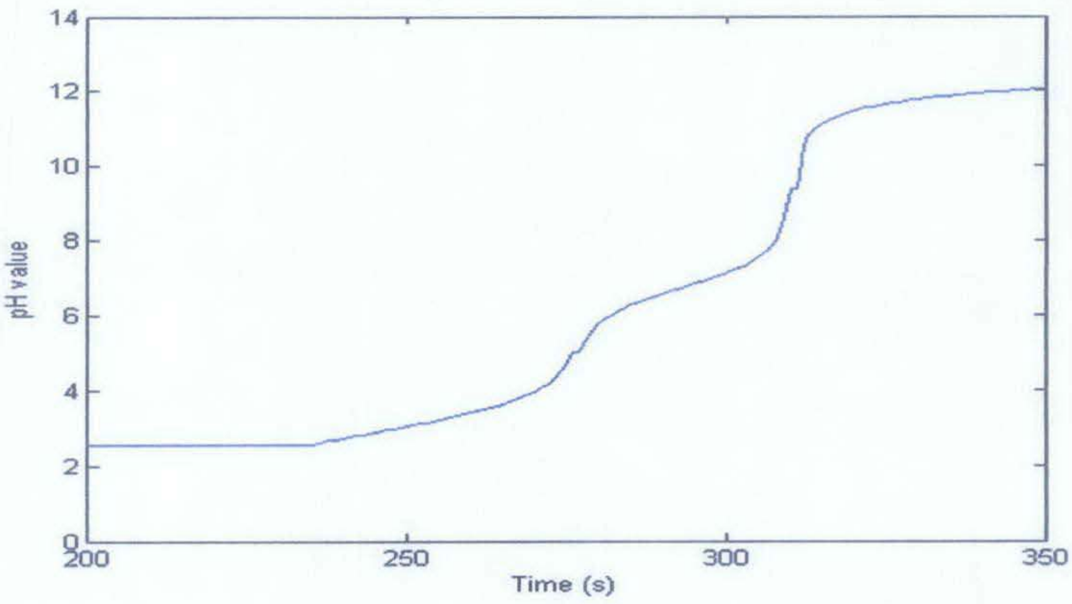


Figure 14: Simulation dynamic response of pilot plant model

Based on Figure 13 and Figure 14, the simulation result is similar apart from the reaction rate. The pilot plant model has faster response compare to the real pilot plant. However, this model is being used because the disassociation value of two graphs is similar. Overall, the model is still accepted. Therefore, this model is being used throughout the simulation of the research.

4.3 Investigation Of Control Strategy

4.3.1 Simulation Of PI Controller

Before any advanced controller can be designed and implemented, the conventional controller should be investigated. In this case, a PI controller is simulated. During the simulation, the model used will be the same as shown in Figure 4. The PI controller shown in Figure 9 is built based on Equation 11.

$$MV(t) = K_p\left[E(t) + K_i \int_0^{\infty} E(t)\right] \qquad (11)$$

Normal PID controller tuning methods such as Ziegler- Nicholas tuning method couldn't be performed due to poor condition of the pilot plant. Therefore, the PI controller's parameters are obtained based on trial and error basis. The value of K_p used in the simulation is 20 while the K_i value is 0.05. These values are selected because they can produce the best PI controller performance. The transfer function in Figure 15 represents the alkaline control valve's characteristic.

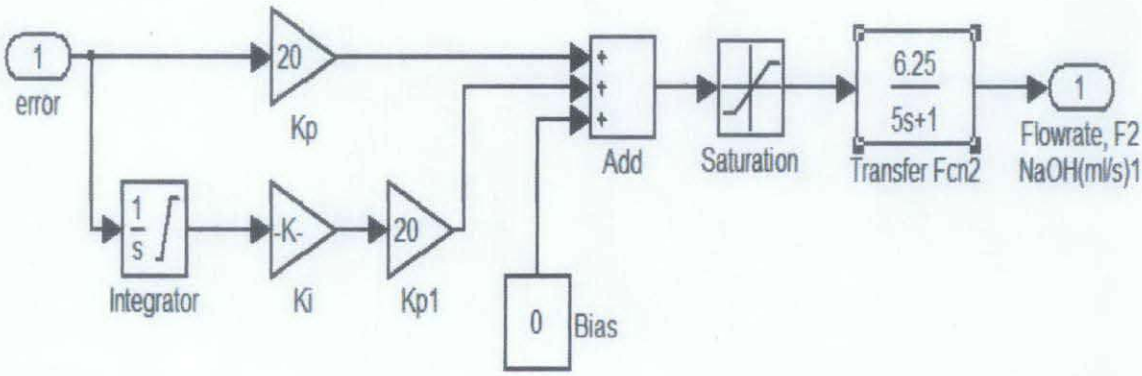


Figure 15: MATLAB/ Simulink representation of PI controller

The results of the simulation can be shown as below:

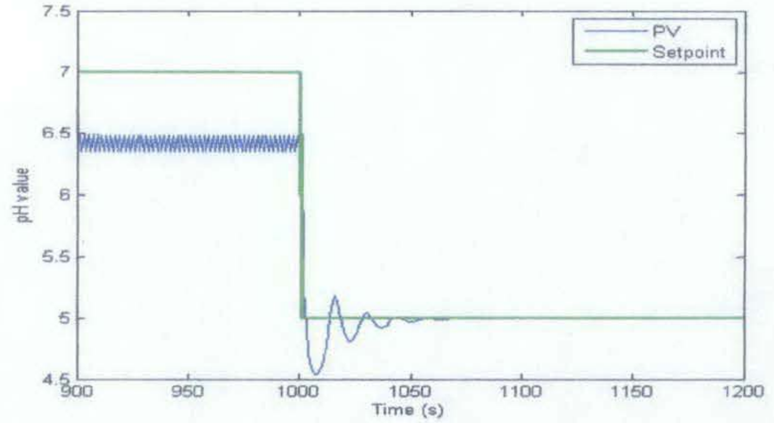


Figure 16: Simulation pH value of PI controller

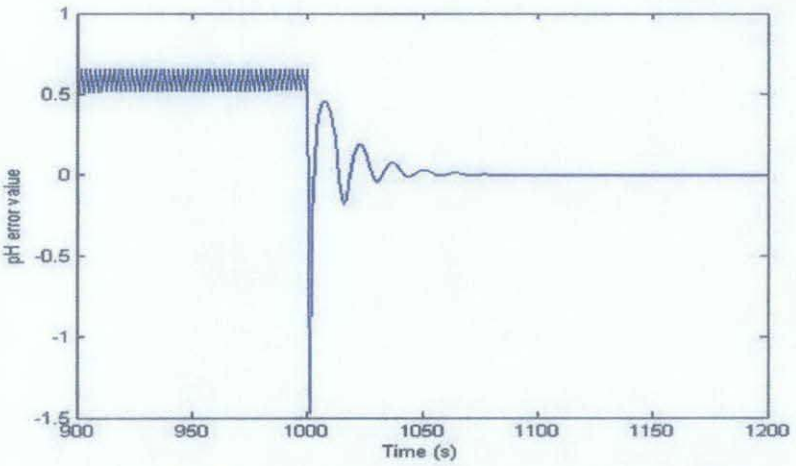


Figure 17: Simulation pH error value of PI controller

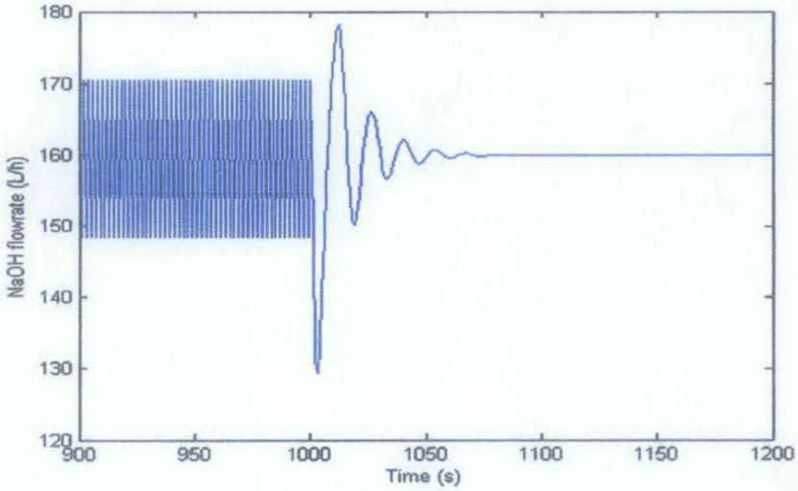


Figure 18: Simulation of NaOH flow rate

Figure 16 shows the simulation pH value of PI controller while Figure 17 shows the errors that occur during the simulation and Figure 18 shows the flow rate NaOH control valve. In the experiment, the flow rate of sulfuric acid is set to constant 80 L/h. According to Equation 3, two moles of alkaline is required to neutralize one mole of acid. In other words, the volume of alkaline required is double volume of acid. Based on the justification, the flow rate of NaOH should be 160 L/h.

As in Figure 16, from time 900s to 1000s, PI controller is unable to adjust the pH value according to set point. In fact, the pH value is oscillating between 6.4 and 6.5 with certain range of offset. As mentioned earlier, sulfuric acid is polyprotic acid which has two hydrogen ions to be donated. Therefore, sulfuric acid has two disassociation constants. Figure 19 shows the titration curve of sulfuric acid. From the titration curve (S-shaped curve), the disassociation constants of sulfuric acid are located at the critical region of pH control where increasing volume of alkaline causes very little change in the pH value. Most likely, this is due to high gain of pH neutralization process at the neutral region. This has verified that linear controller such as PI controller is unable to perfectly control nonlinear process. The controller is unable to determine the exact volume of alkaline needed because additional volume of alkaline during critical region doesn't result big changes in pH value.

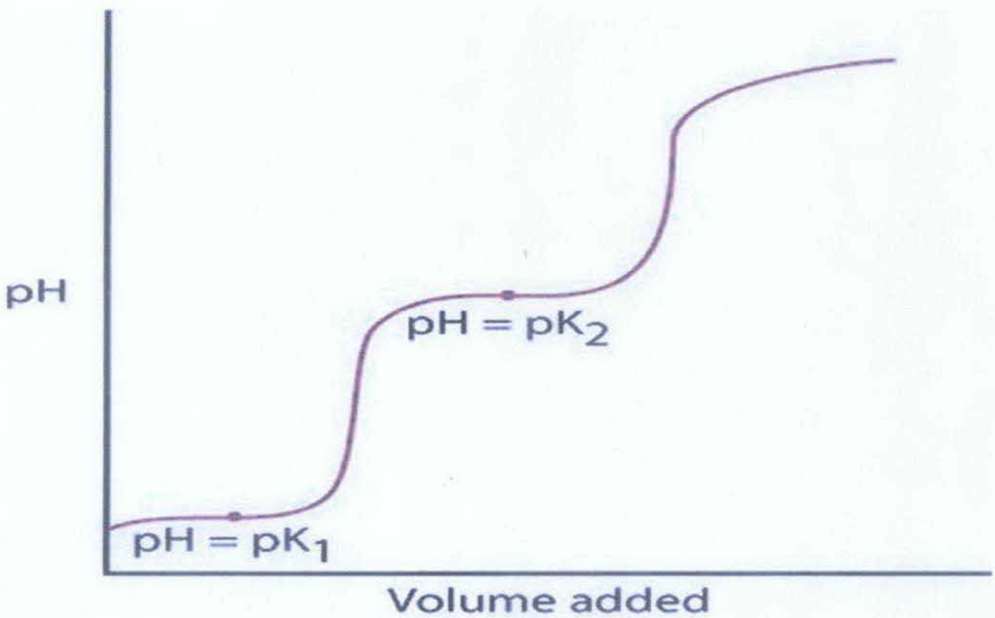


Figure 19: Titration curve of sulfuric acid

At the same time, Figure 18 shows that the control valve is operating at a very high frequency in order to adjust the flow rate of NaOH. This high frequency operation is bad for control valve because it will reduce the life span of the control valve. If the control valve is operating under such condition for a long time, the control valves will wear and tear in shorter time. In other words, the control valve might need to be serviced regularly and at the same time increasing the maintenance cost of the pilot plant.

From time 1000s to 1100s in Figure 16, PI controller shows promising performance. The controller is able to adjust the pH changes according to the set point. The oscillation of the control valve is acceptable because the settling time is short. This shows that PI controller still be able to control certain part of the process. Perhaps, pH 5 is located at the linear region of the titration curve which can be controlled by linear controllers such as PI controller.

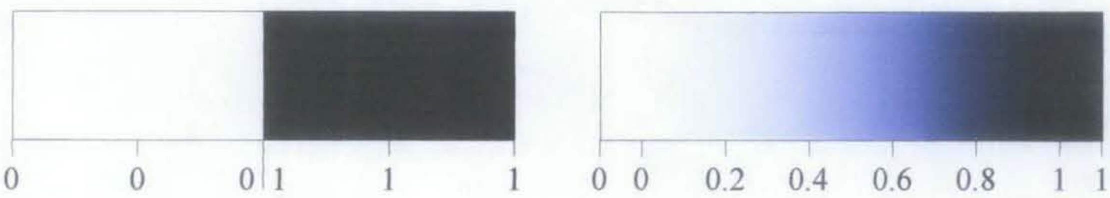
Overall, there are still rooms for improvements. From the operator point of view, consistency of the control performance is crucial. The error in PI controller can be eliminated by using controller which can control nonlinear process better. The ideal controller should be operating with high consistency yet high accuracy to ensure that the mixed solution is always maintained at the equivalence point. Besides, other control performances such as settling time, rise time and integral absolute error must be kept at minimum level.

4.3.2 Selection Of Advanced Control Strategy

The conventional control strategy (PI controller) simulated in Chapter 4.3.1 has some limitation towards controlling nonlinear process such as pH neutralization process. As a result, a new advanced control strategy is required to improve PI controller's performance. Based on literature review, Fuzzy logic controller has been chosen as the advanced control strategy in this research.

4.3.2.1 Introduction of Fuzzy Logic

Fuzzy logic was first introduced by Lofti A. Zadeh in his interesting paper entitled "Fuzzy Sets" [4], [6]. This paper describes the mathematics of a fuzzy set theory which then led to development of fundamental ideas of fuzzy logic. Zadeh extended the work on possibility theory into a formal system of mathematical logic, and introduced a new concept for applying natural language terms. This new logic for representing and manipulating fuzzy terms was called Fuzzy logic. Fuzzy set is a collection of elements in a universe of information where the boundary of the set contained in the universe is ambiguous, vague and "fuzzy" in some aspects. In classical set, the boundary is certain and rigid with only two conditions: "true" or "false". Meanwhile, fuzzy sets is multi-valued which deal with membership's degree from "0" to "1". Instead of just true and false, it is accepting that things can be partly true and partly false at the same time. In terms of mathematical value, classical set uses crisp input (only 1 and 0) while Fuzzy logic uses fuzzy input which is any values within 0 to 1. This can be graphically shown in Figure 20. Overall, Fuzzy logic is not logic that is fuzzy, but logic that is used to describe fuzziness [19].



$f_A(x) : X \rightarrow \{0, 1\}$, where

$$f_A(x) = \begin{cases} 1, \text{if } x \in A \\ 0, \text{if } x \notin A \end{cases}$$

$\mu_A(x) : X \rightarrow \{0, 1\}$, where

$\mu_A(x) = 1$ if x is totally in A;

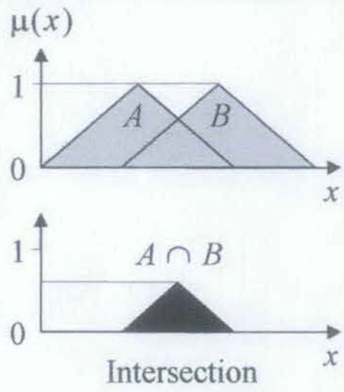
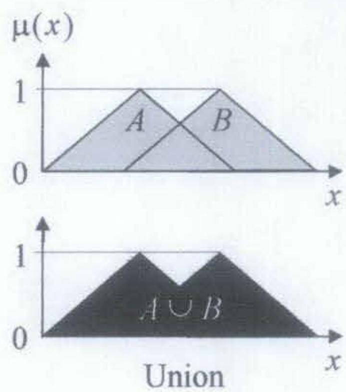
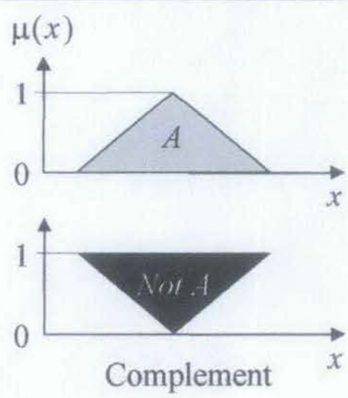
$\mu_A(x) = 0$ if x is not in A;

$0 < \mu_A(x) < 1$ if x is partly in A.

Figure 20: Mathematical representation of classical set (left) and fuzzy set (right)

Fuzzy set uses similar operators as classical set. These operators such and AND, OR and COMPLEMENT have the same name but different representation in Fuzzy logic. The representation for these operators can be seen from Table 13.

Table 13: Table of fuzzy operators

Operators	Mathematical representation	Graphical representation
Intersection	$\mu_{A \cap B}(x) = \min\,[\mu_A(x), \mu_B(x)]$ $= \mu_A(x) \cap \mu_B(x)$, where $x \in X$	
Union	$\mu A \cup B(x) = \max\,[\mu A(x), \mu B(x)]$ $= \mu A(x) \cup \mu B(x)$, where $x \in X$	
Complement	$\mu_{\neg A}(x) = 1 - \mu_A(x)$	

In Fuzzy logic, there are many types of membership functions to represent fuzzy set. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Among the typical membership functions used are: trapezoidal, Gaussian, triangle and etc. At the moment, there are no proper rules or laws that can determine which membership function is most suitable for respective applications.

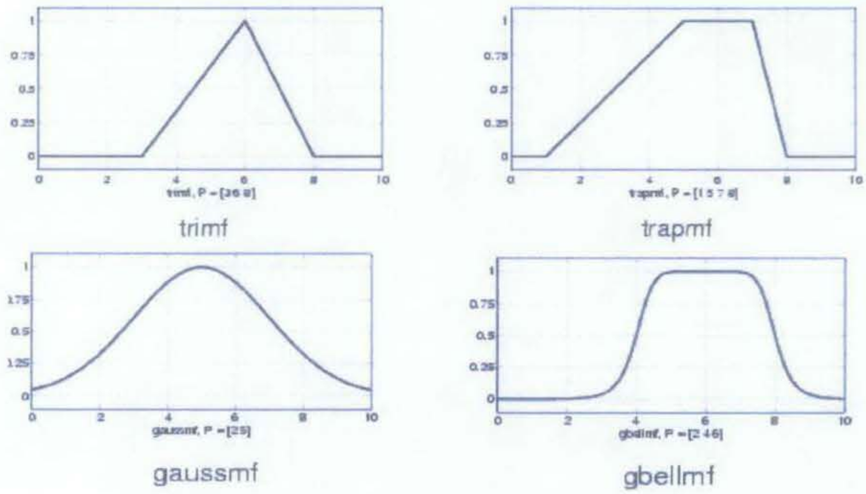


Figure 21: Typical membership functions in Fuzzy logic

Generally, Fuzzy logic controller (FLC) can be developed by completing three parts: Fuzzification, Fuzzy Inference System (FIS) and Defuzzification. The general architecture of FLC is show below.

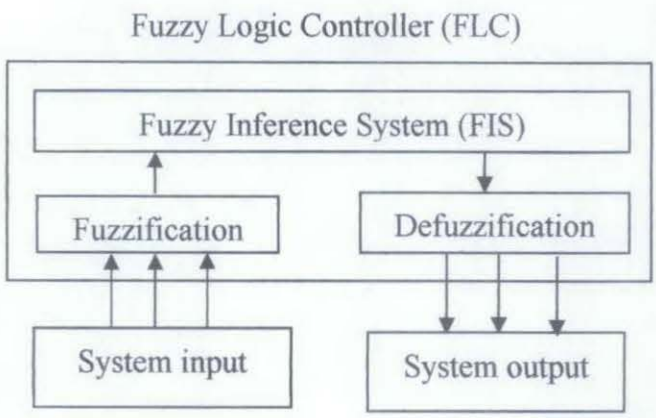


Figure 22: General architecture of Fuzzy Logic Controller (FLC)

Fuzzification is to transform crisp inputs into fuzzy inputs by allocating the inputs in appropriate membership function. Therefore, the membership functions' parameters must be determined prior to fuzzification process. The membership functions can be randomly chosen and the parameters are determined through trial and error method. Usually, the designer will have the initial guessing of parameters in order to achieve fine tuning faster. The same procedures are repeated for output memberships. In process control, the input membership functions will fuzzify the plant's process variable while output membership functions contain of manipulated variable's parameters.

For second part, Fuzzy Inference System (FIS) is described as a process that forms the mapping of fuzzy input sets to output sets. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type [19]. These two types of inference systems vary in the way outputs are determined during aggregation process. Mamdani- type inference system expects the output membership functions to be fuzzy set. Meanwhile, Sugeno-type is having constant or linear equations for the output membership functions. The rest of the structure is the same for both systems. In FIS, IF/THEN rules statements are used to map the input sets to the output sets. IF/THEN rules are equipped with a condition and an action to be taken. From time to time, the rules of FIS can be modified to obtained better controller performance. The last step before defuzzification is the aggregation process in which all the results of implication of each rule are combined into a single fuzzy set.

The last part of FLC is defuzzification. It is inverse process of fuzzification. In defuzzification, the fuzzy set outputs are transformed into single crisp value in order to actuate the final elements such as control valve. There are many methods to transform fuzzy set outputs to crisp input. In this research, centroid method has been used. This method will calculate the midpoint of aggregated implication through mathematical algorithm.

In this research, Fuzzy logic controller has been chosen because:

a) FLC is capable of controlling nonlinear process
b) FLC is capable of resembling human decision making process through fuzzy reasoning. This can produce accurate judgment based on important information
c) Fuzzy logic is easy to understand and formulate compare to other advanced control strategy such as neural network.

4.3.2.2 Structure of Fuzzy Logic Controller (FLC)

The advanced control strategy proposed for the pilot plant is shown below. This advanced control strategy will be simulated in MATLAB.

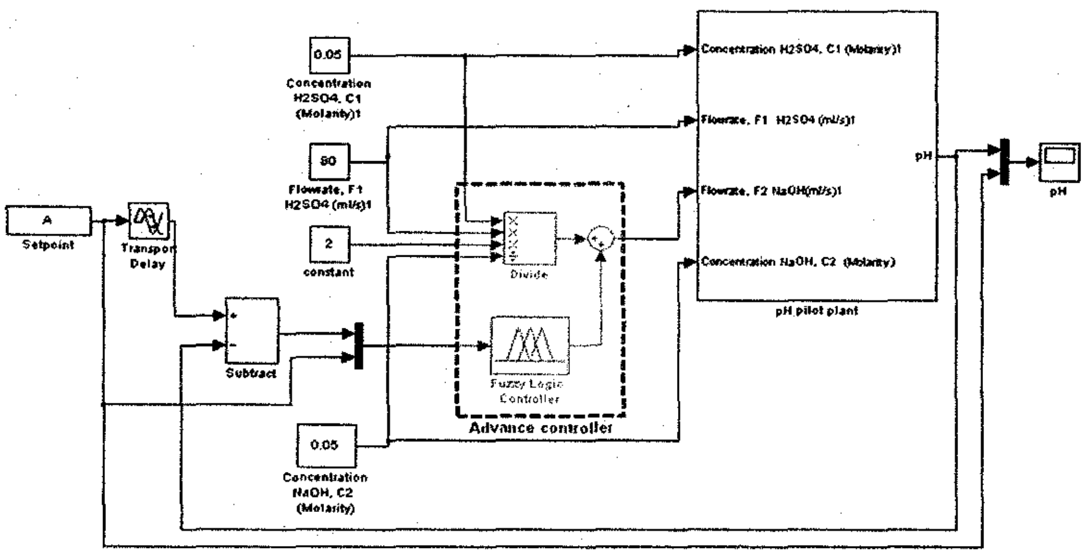


Figure 23: Overview of advanced control strategy designed for pilot plant

From Figure 23, the alkaline flow rate to the plant is the combination of FLC's output and output from "Divide" block. Based on Figure 23, the flow rate of alkaline is the addition of FLC's output with "Steady State Control" block's output. In this research, fuzzy logic is used to cater alkaline flow rate change after pH error is been detected by the controller. The "Steady State Control" block will determine the steady state flow rate required by the process. Actually, this block is developed base on Equation (4) and Equation (12). According to Equation (4), two moles of alkaline is required to neutralize 1 mole of acid. In other words, the volume of alkaline required for neutralize process is double of volume of acid.

$$Volume_{base} = \frac{Concentration_{acid} \times Volume_{acid} \times 2}{Concentration_{acid}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

The Fuzzy Inference System (FIS) designed is based on Mamdani approach. There are no a general rules or standards to select either Mamdani or Sugeno FIS. Based on literature review, most of the advanced controller developed for pH neutralization process is using Mamdani approach.

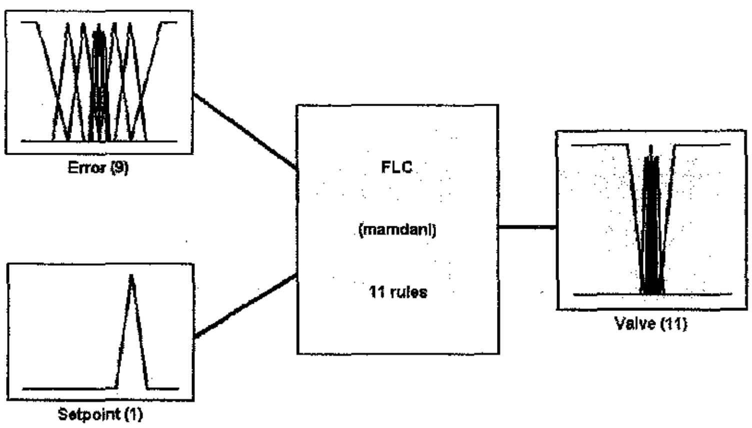


Figure 24: Structure of FLC developed

Based on Figure 24, the FLC developed consists of two inputs (error and set point) and one output (Valve). For input 1, error is the difference between the set point and the current plant's pH. The error value can obtained by using a subtract block as shown in Figure 23. The error block is configured with 9 membership functions and corresponding membership functions are shown in Figure 24. The range of error is set within -5 to 5 because typical pH is active between pH 2 to pH 12 with pH7 is assumed to be neutral point. Since the error value is obtained by set point minus current plant's pH, the error region can be either positive or negative. Two types of membership functions: triangle and trapezoidal functions are being used in input 1. The actual parameters used in Figure 25 are shown in Table 14.

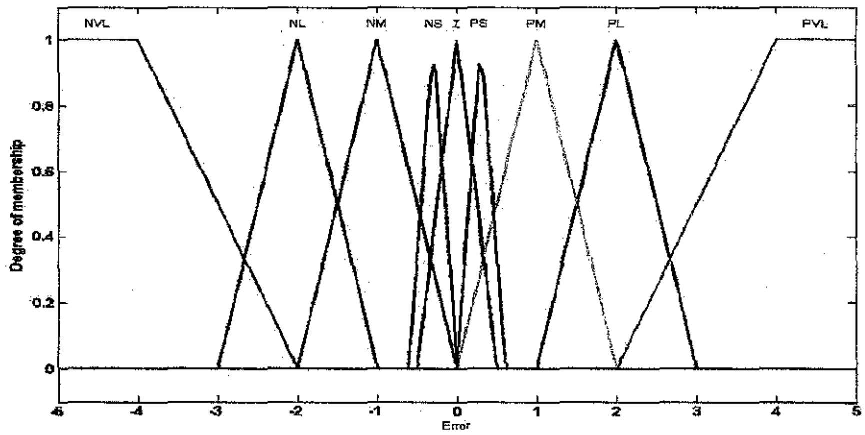


Figure 25: Membership functions of input 1 (error)

Table 14: Parameters for Input 1 (error block)

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 Medium	Triangle	-2	-1	0	
NL	Negative Large	Triangle	-3	-2	-1	
NVL	Negative Very Large	Trapezoidal	-5	-5	-4	-2

Input 2 (Set point) is developed to specifically control the process' high gain region (within pH 6 to pH 8). This input only has single triangle membership function. When the set point is fall within this region, special rules will be fired to output lower flow rate of alkaline which enable precise control of high gain region.

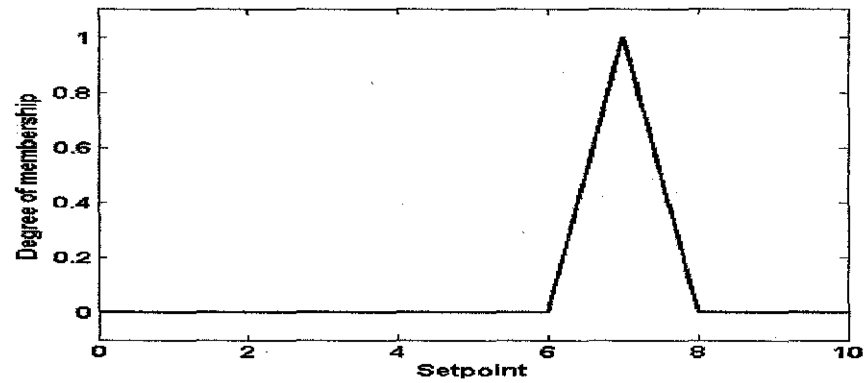


Figure 26: Membership functions of Input 2 (Set point)

The output of the controller contains of eleven membership functions which represent the flow rate of alkaline required to deal with change in process' pH. The output membership is range from -50L/h to 50L/h. However, most of the critical flow rate is range between -10 to 10. Positive region is to increase the flow rate while negative region will reduce the flow rate. Control valve operation will react to these changes by open or close the valve.

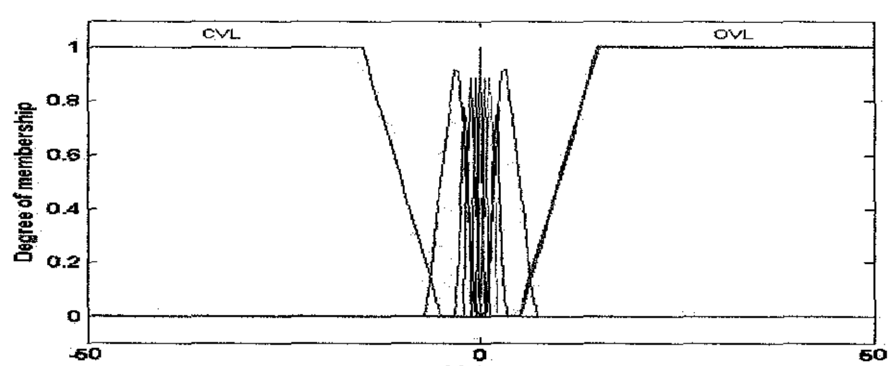


Figure 27: Membership functions of Output (valve)

Table 15: Parameters for Output (valve)

Symbol	Description	Types	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

After all the input and output parameters are determined, IF/ THEN rules are used to map the input memberships with corresponding output memberships. The mapping of FLC designed is shown in Table 16.

Table 16: IF-THEN rules statements for FLC

Error \ Setpoint	None	Special
Z	Z	-
PVL	OVL	-
NVL	CVL	-
PL	OL	OM
NL	CL	CM
PM	OS	-
NM	CS	-
PS	-	OVS
NS	-	CVS

The parameters' configurations are essential to determine the output response of FLC. If the output parameters are too sensitive towards input fuzzy set, the output response of FLC will be aggressive and versa vice. In other words, proper selection of parameters can easily affect the control performance of FLC. Therefore, these parameters must be configured according to control objectives of the controller. Besides, the mapping of input to output through IF/THEN rules statements play a major role in determine FLC's output response. Different mappings of input- output will produce different output response.

4.3.2.3 Simulation Of Fuzzy Logic Controller (FLC)

Two experiments have been performed to examine the performance of FLC in pH neutralization process control: a) Set point tracking b) Load disturbance. In set point tacking experiment, the set point to the controller is varying randomly to test the robustness of the controller at different desired pH. In the simulation, the concentration of acid and alkaline is set at 0.05mol/cm³ while the acid's flow rate is set constant at 80L/h. The results of the experiment are shown as below.

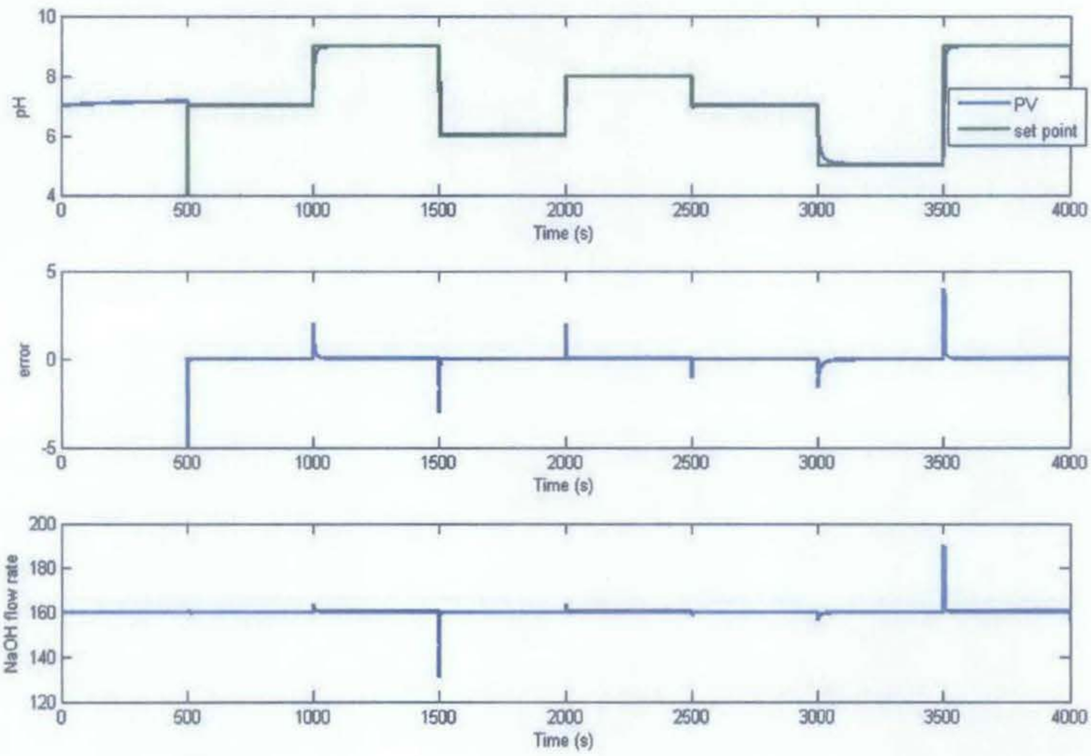


Figure 28: Results of set point tracking experiment

Based on Figure 28, FLC has been successfully control the process with different set points. The limitation of PI controller in controlling high gain region (pH 6 to pH 8) can be overcome by FLC. Besides, the high frequency oscillation of the control valve can be eliminated as shown in Figure 28. Although the flow rate of NaOH seems to be a high peak spike, in fact, it is just the time scale issue. The zoom-in display shows that the spike is a fast triangular change. In real time implementation, the high speed change of flow rate will not be an issue because the model used in the simulation has been proven faster than the pilot plant's dynamic response. Refer to Figure 29, the process reaches steady state without any overshoot and offset value. Besides, the settling time of the response is 30s which is slightly faster than PI controller. Overall, FLC has improved the PI controller's performance by producing satisfying results.

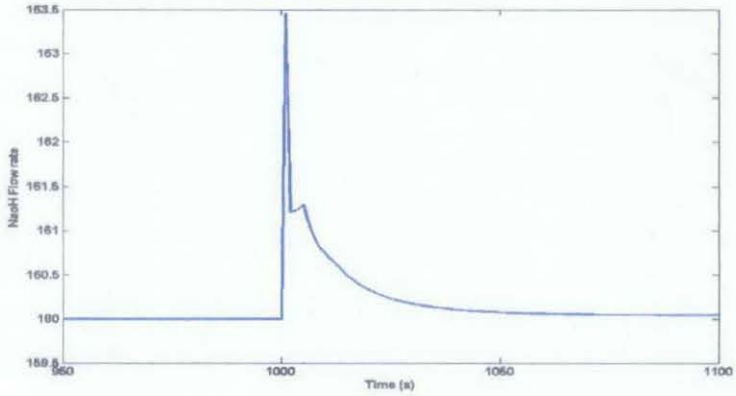


Figure 29: Zoom in display of NaOH flow rate

At the same time, the performance of the FLC is evaluated. Based on Figure 30, the pH set point is changed from 8 to 7 at time 2500s. Since there is drop is pH set point, the amount of alkaline required must be reduced. The error of the pH is -1 while input 2 is activated since the set point is pH 7. Based on Table 14, when the error is -1 (NL), the desired output is within -3 to -1. From Figure 30, when the error is -1, the FLC output is -1.2.

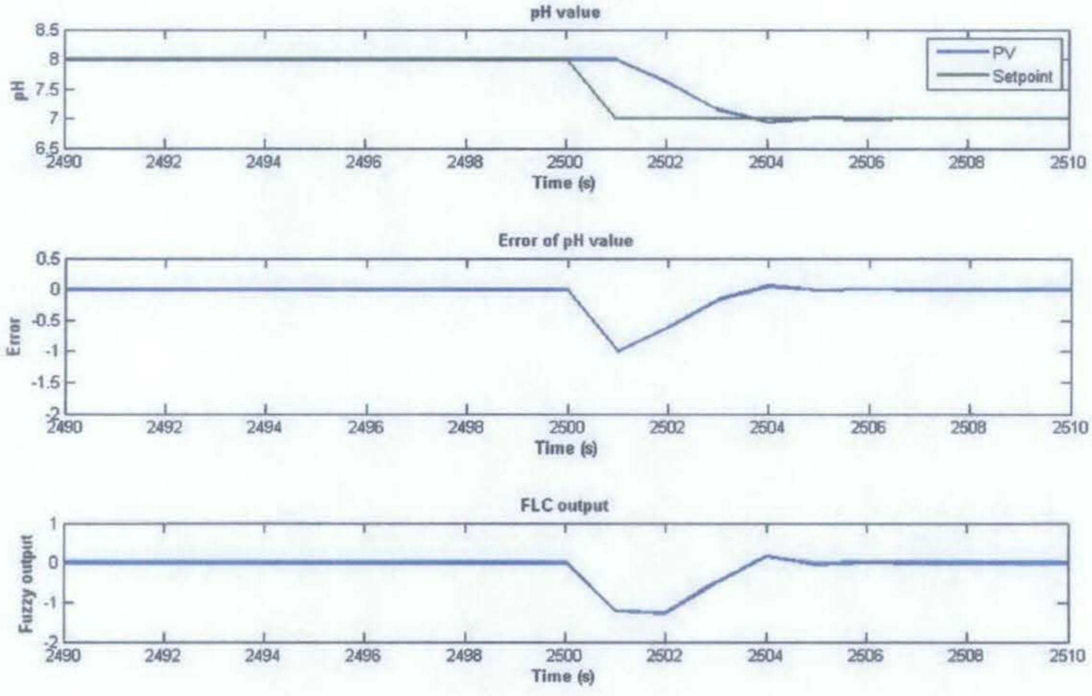


Figure 30: FLC control performance

The simulation results shown in Figure 30 can be verified by MATLAB. Figure 31 is one of the windows provided by Fuzzy Logic Toolbox which graphically indicates how the FLC designed works. When the error is -1 and the pH set point is 7, only certain rules will be fired. After defuzzification, the FLC output -1.21. This is the same as shown in Figure 30. This has proven the functionality of FLC in controlling the process. Yet, it shows the importance of accurate membership function's parameters and proper IF/THEN rules in FLC. As I mentioned earlier, there is no standard method of tuning the membership functions. In this project, the parameters of the membership functions are tuned through observing of pH error with the FLC output as shown in Figure 31. If the output is not satisfactory, researcher can retune the parameters immediately. Tuning is considered acceptable if FLC produces good trending of the process.

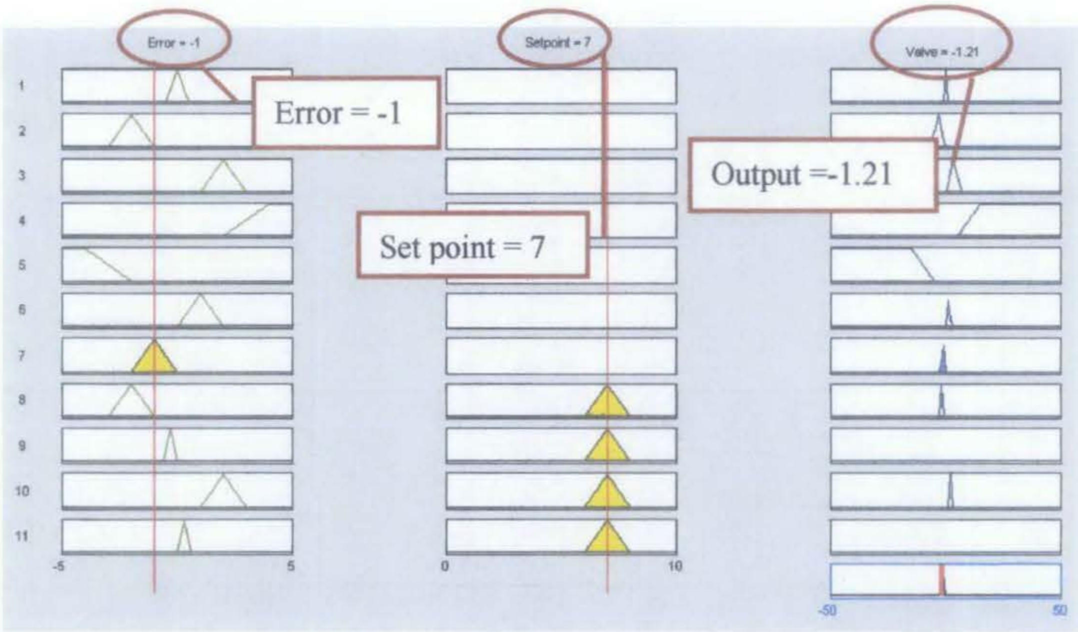


Figure 31: Verification of FLC output

On the other hand, FLC has shown great control performance against load disturbance. In this experiment, the load disturbance is acid's flow rate. Acid's flow rate is varying while the set point of the controller is maintained at pH 7. Based on the results, the pH set point is unchanged throughout the experiment and the alkaline flow rate varies according to the acid flow rate change. The FLC will be disabled when there is no error and the disturbance is controlled by "steady state" block. Basically, the principle of this control is based on Equation (3).

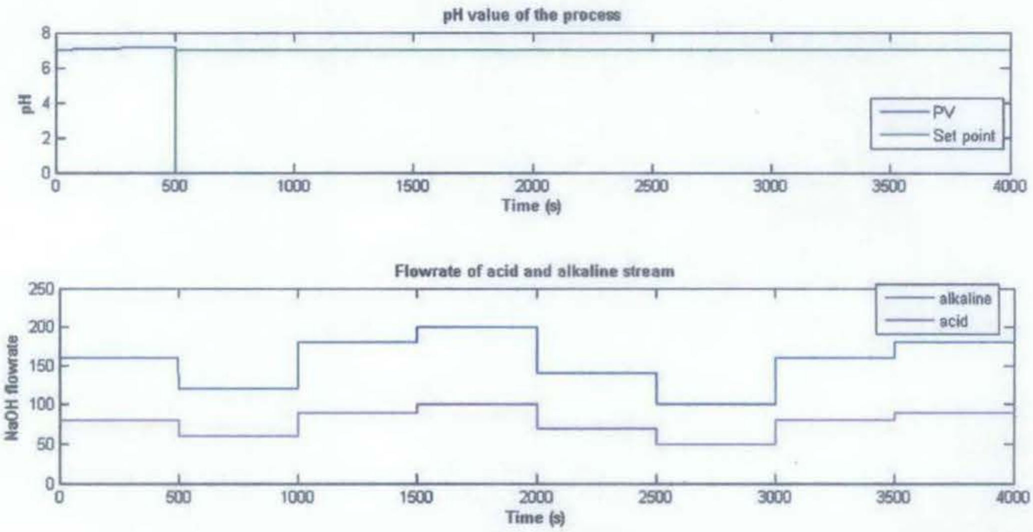


Figure 32 : Results of load disturbance experiment

Based on all simulation results, FLC has been proven more superior to PI controller by producing high accuracy and satisfying control performances. FLC controller is capable of controlling the high gain region of the process with high accuracy. Besides, FLC will not be causing any high frequency oscillation of control valve which will reduce the life span of the control valve. Overall, all the limitations of PI controller discussed have been overcome by FLC. This may be due to excellent judging ability of fuzzy logic through fuzzy reasoning and fuzzy inference system. The overall performance comparison of FLC and PI controller is shown in Table 17.

Table 17: Comparison of FLC and PI controller

Criteria	FLC	PI
Zero offset	Yes	No for high gain region
Reaching steady state	Yes	No for high gain region
MV overshoot	2.5%	12%
Settling Time	Fast (30-40s)	Fast (30-50s)
Stable	Yes	No for high gain region

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

pH neutralization is always being used as the benchmark to investigate appropriate control strategy to all the nonlinear processes. Based on the literature review, there are many methods to be used as the control strategy for pH neutralization process. Each method has its own advantages and disadvantages. Prior to controller simulation, the pilot plant has been cleaned and calibration has been performed on most of the measuring meters. The calibration shows poor results and the condition of the pilot plant does not allow any proper experiment execution. Meanwhile, the model of the pilot plant has been validated. The results of validation suggest that the model has faster response than the pilot plant. However, this model is still being accepted throughout the research. The simulation results of PI controller show that there are still rooms for improvements. The range of error could be minimized by other tuning methods. The advanced control strategy, Fuzzy Logic Controller (FLC) has been successfully improved the performance of PI controller especially its ability to control high gain region with high accuracy. Besides, FIC has shown promising ability to deal with load disturbance. As a conclusion, the objectives of the research have been achieved

5.2 Recommendation

According to calibration results, major maintenance should be performed on the plant. From the experiments performed, the results show that the major instruments in the plant are not functioning correctly. This has led to cancelling of advanced controller implementation for this research. Once the pilot plant is functioning properly, the advanced control strategy simulated in this research can be implemented to examine its real time application performance. Besides, other type of fuzzy inference system such as Sugeno approach can be investigated in order to investigate the influence of different fuzzy inference system on the control performance. Perhaps, the FIC developed in this research can be optimized by using certain algorithms such as genetic algorithms and neural network.

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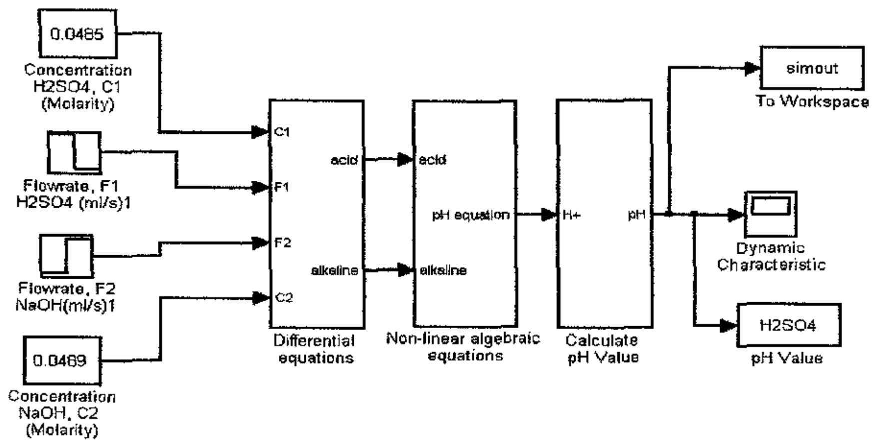
Appendix 1: Main milestone of the project

No.	Detail/ Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Literature review	Actual																												
2	Cleaning the pilot plant	Planned																												
		Trending																												
		Actual																												
3	Calibration	Planned																												
		Trending																												
		Actual																												
4	PI controller simulation	Planned																												
		Trending																												
		Actual																												
5	Advance controller simulation	Planned																												
		Trending																												
		Actual																												
6	Advance controllers implementation	Planned																												
		Trending																												
		Actual																					Not performed							
7	Final report and technical paper	Actual																												

Appendix 2: Mathematical model of pilot plant

The mathematical model used throughout the research is fully referred to [6] and [17]. The model developed is shown below.



Model used throughout the research

From Equation (4), two equations can be derived to express the pH process in CSTR. These two equations are built in Differential Equation block.

$$V\frac{dx}{dt} = F_1 C_1 - (F_1 - F_2)\alpha \quad \text{.......(1)}$$

$$V\frac{d\beta}{dt} = F_2 C_2 - (F_1 + F_2)\beta \quad \text{.......(2)}$$

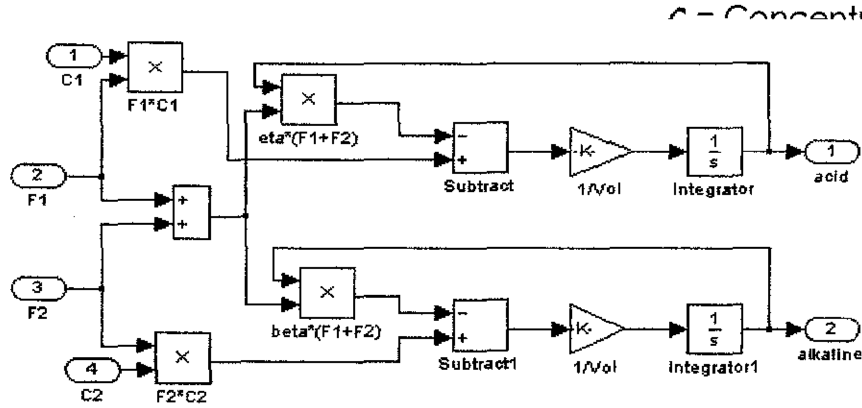
V = total volume of reactor tank

F_1 = Flow rate of acid

F_2 = Flow rate of alkaline

C_1 = Concentration of acid

= Concentration of



Differential equation block

The non- reactant components in the system are ∝ for acid and β for alkaline. These variables can be defined as

$$\alpha = [H_2SO_4] - [HSO -] + [SO_4^{-2}] \quad \ldots\ldots\ldots\ldots(3)$$

$$B = [Na+] \quad \ldots\ldots\ldots\ldots(4)$$

The next step is to derive the electroneutrality condition of the non- reactant components. Based on the principle of electroneutrality, all solutions are neutral.

The total electroneutrality condition is

$$[Na^-] + [H^-] = [OH^-] + [HSO_4^-] - [SO_4^{-2}] \quad \text{---------}(5)$$

The equilibrium constant expressions that apply to the acid- base system are,

i) Water (H_2O)

$$K_w = [H^-][OH^-] \quad \ldots\ldots\ldots\ldots(6)$$

ii) Sulphuric acid (H_2SO_4)

$$K_1 = \frac{[H^+][HSO_4^-]}{H_2SO_4} \quad \ldots\ldots\ldots\ldots(7)$$

$$K_2 = \frac{[H^+][SO_4^{-2}]}{HSO_4^-} \quad \ldots\ldots\ldots\ldots(8)$$

The quantity K_w (constant value for the ionic product of water) is equal to 1.0×10^{-14}. There are two acid disassociation constants for sulphuric acid $K_1 = 1.0\times10^{13}$ and $K_2 = 1.2\times10^{-2}$ since sulphuric acid falls under diprotic acid category which has two equilibrium points or disassociation constants.

The pH value can be calculated by using equation below:

$$pH = -\log_{10}[H^+] \quad \ldots\ldots (9)$$

Equation (5) needs to be solved in order to find the value of hydrogen ion, $[H^+]$. After Equation (3), (4), (6), (7) and (8) are substituted into Equation (5), the final equation can be written as polynomial equation (10).

$$[H^+]^4 + a_1[H^+]^3 + a_2[H^+]^2 + a_3[H^+]^1 + a_4 \quad \ldots\ldots (10)$$

Where the coefficient a_1 to a_4 are defined as follows:

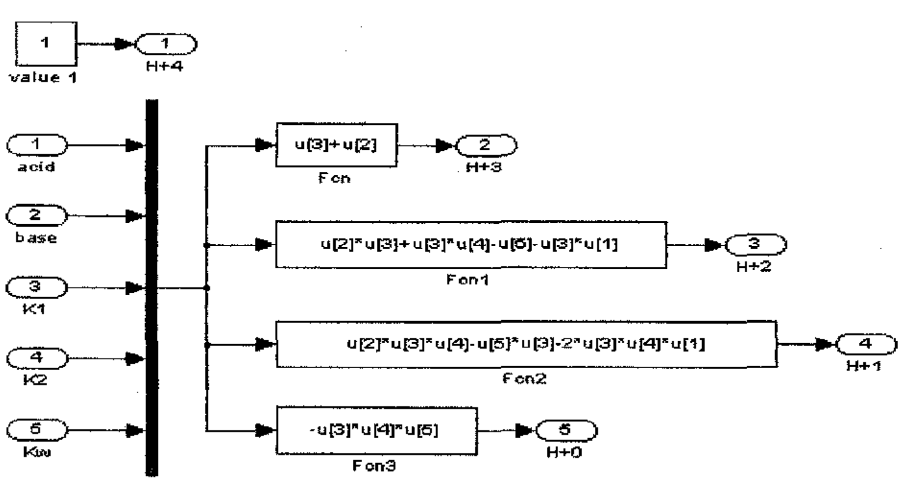
$$a_1 = K_1 + \beta \quad \ldots\ldots (11)$$

$$a_2 = \beta K_1 + K_1K_2 - K_w - K_w\alpha \quad \ldots\ldots (12)$$

$$a_3 = \beta K_1K_2 - K_1K_w - 2K_1K_2\alpha \quad \ldots\ldots (13)$$

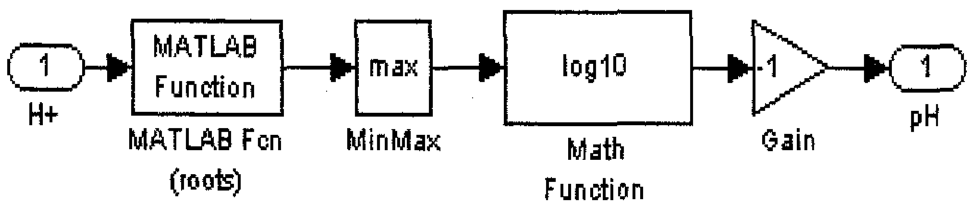
$$a_4 = -K_1K_2K_w \quad \ldots\ldots (14)$$

Equation (11) to (14) are defined in nonlinear algebraic equation block as shown in figure below



Nonlinear algebraic equations block

The pH block contains a mathematical function block to calculate the log value of hydrogen ion in order to display the real pH of the process.



pH calculating block

APPENDIX 3: Photograph of pH neutralization pilot plant

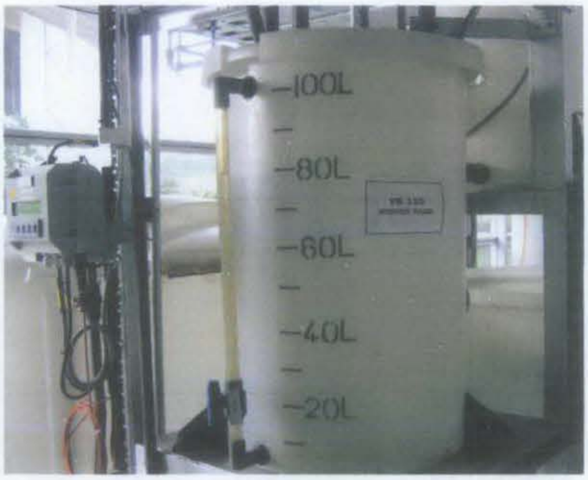
APPENDIX 4: Instruments in pH neutralization pilot plant

Control Valves

Pumps

Flow meters

Reactor tank



Buffer tank

Alkaline tank

Acid tank

Agitator

Control room's computers